ISRIC

INTERNATIONAL SOIL REFERENCE AND INFORMATION CENTRE

The Impact of Land Degradation on Food Productivity

Case studies of Uruguay, Argentina and Kenya

Volume 1: Main Report

S. Mantel
V.W.P. van Engelen

rivm
research for man and environment

UNEP

Report 97/01

The Impact of Land Degradation on Food Productivity

Case studies of Uruguay, Argentina and Kenya

Volume 1: Main Report

S. Mantel
V.W.P. van Engelen

January 1997

ISRIC

International Soil Reference And Information Centre

UNEP

United Nation Environment Programme

riVM research for man and environment

National Institute of Public Health and Environment

Correct citation:
Mantel, S. and V.W.P. van Engelen, 1997. *The Impact of Land Degradation on Food Productivity - Case studies of Uruguay, Argentina and Kenya. Volume 1: Main report*. Report 97/01, International Soil Reference and Information Centre, Wageningen.

Inquiries:
c/o Director, ISRIC
P.O. Box 353
6700 AJ Wageningen
The Netherlands

Telefax: +31-317-471700
E-mail: SOTER.ISRIC@WUR.NL

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

Land units may differ in their resistance to erosion and in their resilience to human-induced and climatic changes. Moreover, the impact of degradation on functional properties of land and its productive capacity may differ between land units and/or soils. The present study elaborates a mixed qualitative/quantitative methodology for assessment of the impact of erosion on productivity of a land use system, given the variability in natural conditions (e.g. soils, landform and climate). This approach is applied to three countries, situated in two regions; South America (Uruguay and part of Argentina) and East Africa (Kenya), with different types of land use and in highly varying agro-ecological conditions. A chain of models was used to study the impact of erosion on crop production. The studies were based on national 1:1 M scale Soil and Terrain (SOTER) databases that were compiled for northern Argentina, Kenya and Uruguay. Soils and terrain attributes are linked to a Geographical Information System (GIS), permitting spatial analysis. For stratification of climatic data the Agro-Ecological Zones (AEZ) map of South America (in the case of Uruguay and Argentina) and of Africa (for the case of Kenya), (FAO, 1994) were used. Only the spatially dominant soil component by AEU was considered in the analysis. For these dominant soils of each mapping unit suitable for the land use, the potential yield before and after an erosion scenario of 20 years was calculated. The impact of change in soil properties, influencing crop performance, induced by removal of topsoil through sheet erosion, is analyzed in this study. In the two countries in Latin America the soil erosion affected mostly the physical properties of the soils, resulting in a calculated yield reduction between 25 and 50%. In Kenya the largest yield reduction was mainly due to loss in soil fertility. Potential yields after erosion were mostly ranging from 25 to more than 50% of the current situation. A complete set of maps of Uruguay and a selection of maps of Argentina and Kenya Figure in this report, while the remaining maps of Argentina and Kenya, together with Pedo-Transfer Functions are published in a separate volume.

ACKNOWLEDGEMENTS

This study has been prepared in the framework of a United Nations Environment Programme (UNEP) sponsored collaborative activity between the National Institute of Public Health and Environment (RIVM), The Netherlands and the International Soil Reference and Information Centre (ISRIC) in collaboration with the Dirección de Suelos y Aguas, Uruguay, the Instituto de Suelos of INTA/CIRN, Argentina and the Kenya Soil Survey.

We thank Ms. J.W. Resink for her collaboration and for preparing the GIS figures. Mr. B. Wesselman assisted in the erosion hazard assessment for Kenya. The assistance of Mr. P. Tempel with the design of database extraction procedures and the running of the crop simulation model is gratefully acknowledged.

ACRONYMS

AEU	= Agro-Ecological Unit
AEZ	= Agro-Ecological Zone
ACZ	= Agro-Climatic Zone
ALES	= Automated Land Evaluation System
AMDASS	= AgroMeteorological Data Systems
DSyA	= Dirección de Suelos y Aguas
FAO	= Food and Agriculture Organisation of the United Nations
GEO	= Global Environmental Outlook
GIS	= Geographic Information System
INTA/CIRN	= Instituto Nacional de Technología Agropecuaria/Centro de Investigaciones de Recursos Naturales
ISCO	= International Soil Conservation Organization
ISRIC	= International Soil Reference and Information Centre
KSS	= Kenya Soil Survey
LUT	= Land Utilization Type
PTF	= Pedo-Transfer Function
RIVM	= Rijksinstituut voor Volksgezondheid en Milieuhygiëne
SOTAL	= Model for physical land evaluation using ALES
SOTER	= Soils and Terrain Digital Database
SWEAP	= SOTER Water Erosion Assessment Programme
UNEP	= United Nations Environment Programme
USLE	= Universal Soil Loss Equation
WOFOST	= World Food Studies

1 INTRODUCTION

1.1 Impact of land degradation on productivity

Land degradation is here defined as the decline in biophysical functions of a tract of land. This loss can affect productivity and biodiversity and is thus defined as a permanent loss of the original functions. One of the major processes that causes land degradation is soil degradation that can consist of loss of topsoil caused by wind and/or water erosion.

In 'Precious Earth', a document produced in the scope of the past ISCO conference in Bonn, is stated that: "Science faces the challenge of assessing the impact of soil erosion on agricultural production" (Hurni, 1996).

Human-induced soil degradation by water erosion is one of the most destructive and certainly most extensive phenomena worldwide, and is fast becoming recognized as a key issue in affecting global food security (e.g. Barrow, 1991). Of the total land surface of 13,069 x 10^6 ha about 1,094 x 10^6 ha or 8% is affected by some form of water erosion. When taken as a proportion of the used land (Oldeman, 1994) it increases towards 24%. The major cause for soil degradation is deforestation and removal of natural vegetation (43%), 29% is due to overgrazing, 24% is caused by improper management of the agricultural land, and 4% is a result of over-exploitation of the natural vegetation (Oldeman *et al.*, 1991). In the coming decades an increase in the pressure on land is foreseen as a result of a predicted doubling world population (United Nations, 1992). As possibilities for expansion of agricultural land are limited, this would imply taking in use marginal lands (Biswas, 1994). Therefore an increase in food production is necessary per hectare of arable land.

Land units may differ in their resistance to erosion and in their resilience to human-induced changes and climatic changes. Moreover, the impact of degradation on functional properties of land and its productive capacity may also differ between land units and/or soils. If the seriousness, and therewith the need for conservation measures or alternative land uses, is to be made explicit, the initial productive capacity of a land use system must be known as well as the effect of erosion on this productive capacity (Driessen, 1986). Currently, there is increased attention for environmental degradation impact on food productivity and it has been an important issue during the 1996 FAO World Food Summit. Few studies have quantified the impact of soil water erosion on productivity (Young, 1994). Some field trials with de-surfacing soils revealed productivity losses between 15 and 45% in grain yields (Biot and Lu, 1995).

In the context of their Global Environmental Outlook (GEO) project, UNEP expressed the need for a quantified assessment of the impact of soil/land degradation on food production, at different scales (UNEP/EAP, 1995). In this context ISRIC has been asked to carry out a number of studies, at levels ranging from continental to national:

a) A global assessment of the vulnerability of land to water erosion at a scale of 1:5 M, on a 2° by 2° grid (Batjes, 1996a)

b) A qualitative assessment of water erosion risk at a scale of 1:5 M, for a small section of the SOTER database of Latin America (Batjes, 1996b)

c) A mixed qualitative/quantitative assessment on the impact of water erosion on food productivity using the 1:1 M SOTER databases of Argentina, Uruguay and Kenya (present study).

This study elaborates a mixed qualitative/quantitative assessment of water erosion impact on wheat production in Uruguay and Argentina and on maize production in Kenya over a timespan of 20 year. The study was executed in collaboration with the national soil institutes, i.e. INTA/CIRN (Argentina), DSyA (Uruguay) and KSS (Kenya). The erosion risk assessment of Uruguay was elaborated by DSyA and that for Argentina by INTA/CIRN.

The various models, the sources of the data, and the methodological approach are described in Chapter 2. Results are given in Chapter 3 and the conclusions are presented in Chapter 4. A discussion on the followed methodology and the used dataset is described in Chapter 5. Maps with the intermediate and final modelling results for Uruguay illustrate the text of Chapter 3, while also the final maps of Argentina and Kenya figure in this chapter. All other maps of Argentina and Kenya are given in the appendices published in a separate volume. Some of the methods for completion of data can also be found in the latter volume.

1.2 Models for scenario studies

Models are analytical tools for schematizing a complex reality. For estimation of crop performance there are many types of models, differing in level of complexity and data requirements. Apart from qualitative or expert models, which are exclusively based on 'reasoned intuitive estimates' (Van Diepen *et al.*, 1991), we can discriminate between:

1) statistical (empirical) models that relate growth or yield to selected environmental and management factors on the basis of regression analysis,

2) parametric models (multiplying factors that are considered relevant), which are in fact qualitative of nature. Results can be satisfactory when calibrated for specific conditions,

3) mechanistic or deterministic models that describe fundamental physical and/or chemical processes in mathematical functions.

In this study, use is made of the third type of model that calculates crop performance as a fundamental process over specific temporal intervals. The advantages of such dynamic crop growth modelling are (van Diepen *et al.*, 1991):

a) the dynamic nature of land qualities is taken into account as processes are simulated in time steps, depending on rates of change, and

b) as the basic processes are mathematically described, yield can be predicted at any location in principle, although models do need calibration as each parameter and function in a models has its own inaccuracy and the resulting errors accumulate in the simulated final crop yield.

Models are attractive tools for studying processes or systems, especially when the actual processes are expensive or difficult to measure. In this study the objective is to estimate the impact of erosion on productivity of a land use system, given the variability in natural conditions (e.g. soils, landform and climate) on a national basis. For that purpose a chain of models is used for studying the impact of erosion on crop production.

2 METHODOLOGY

2.1 Data and models

Data on terrain and soils are taken from national 1:1 M Soil and Terrain (SOTER) databases that were compiled for Uruguay, northern Argentina and Kenya. In the SOTER approach, mapping units are described as a unique combination and pattern of terrain units, terrain components and soil components (Van Engelen and Wen, 1995). The soils and terrain attributes are linked to a Geographical Information System (GIS), permitting spatial analysis. Climatic data were taken from SOTER climate files and supplemented by AMDASS data (FAO, 1992).

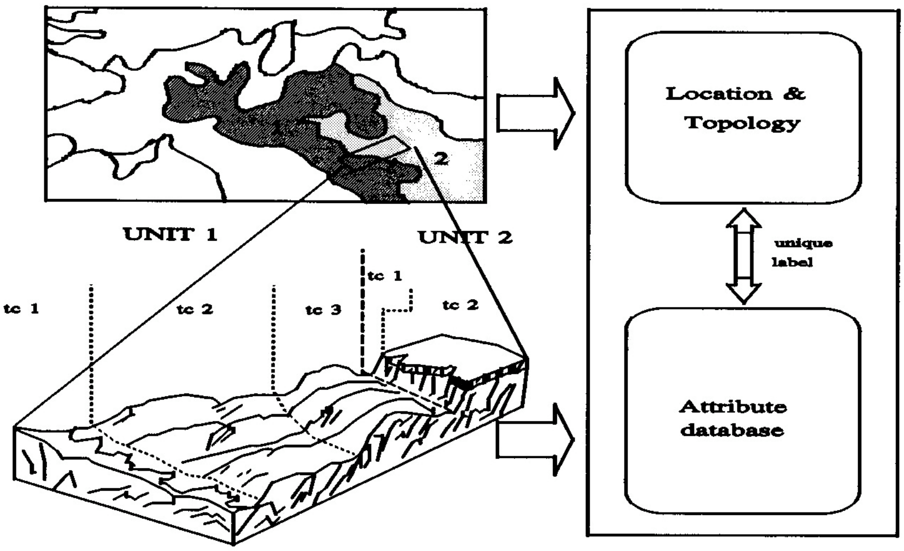


Figure 1. SOTER units and their terrain components (tc), attributes and location (Source: van Engelen and Wen, 1995).

A mixed qualitative/quantitative land evaluation approach was followed similar to the method described by Van Lanen *et al.* (1992). For the qualitative land evaluation an ALES-based model was used (SOTAL). Risk of water erosion was estimated by means of an USLE based model (SWEAP). Crop growth was simulated using quantitative models.

The models used in various steps in the procedure are (Fgure 2):

1) An *expert model* that is used for discriminating between land units suitable and unsuitable for a defined type of land use. SOTAL (Mantel, 1995) is a qualitative model for physical land evaluation developed in ALES, the

Automated Land Evaluation System (Rossiter, 1990). The Land Utilization Types (LUTs) selected for this study are characterised by 11 land use requirements and are evaluated by 'matching' the land use requirements with the corresponding land qualities. The sufficiency of the land quality 'availability of water' is determined separately with a water balance model.

2) A *crop simulation model* was used for the calculation of the potential yield of the selected crop under the reigning agro-ecological conditions (soil, climate) and after 20 years of simulated soil erosion. The WOFOST model calculates potential, water-limited and nutrient-limited crop production (Van Diepen *et al.*, 1989). Potential production is the 'bio-physical production ceiling', as determined by solar radiation and temperature. Water-limited production refers to crop production additionally limited by availability of water. The nutrient-limited production is calculated with a submodule based on Janssen *et al.,* (1990); which is defined as the potential production, limited by availability of soil nutrients.

3) An *erosion risk assessment model* that calculates the hazard for erosion for the land use under consideration. This risk is translated in loss of topsoil over a 20 year period. SWEAP, the SOTER Water Erosion Assessment Program (Van den Berg and Tempel, 1995), was developed to facilitate mapping of water erosion risk using SOTER data. Two erosion risk assessment models are implemented in the model subsystem, of which the Universal Soil Loss Equation, USLE (Wishmeier and Smith, 1978) modified to handle SOTER data, was selected for the present study.

Extraction programs allow for an automated data transfer between SOTER, the SOTAL evaluation model, and SWEAP.

2.2 Methods and basic assumptions

The procedure applied in this study is displayed in Figure 2 with an explanation in this chapter. Locations of climatic stations in the studied countries were plotted on the Agro-Ecological Zones (AEZ) map of South America (in the case of Uruguay and Argentina) and of Africa (for the case of Kenya), (FAO, 1994). Stations were considered representative for the AEZ in which they are located. Within each AEZ, boundaries were drawn using Thiessen polygons in such a way that each polygon is assigned a station. The overlay of this derived AEZ-map with the SOTER unit map, yielded new units combining climatic data with soil and terrain information. These Agro-Ecological Units (AEUs) formed the basis for evaluation. SOTER units often consist of more than one soil component. Only the spatially dominant soil component by AEU was considered in the analysis.

The potentially suitable AEUs for the LUTs considered - mechanized, low input wheat in Uruguay; mechanized, medium to high input wheat in Argentina and low input, rainfed maize for Kenya - were separated from the unsuitable ones using SOTAL (a

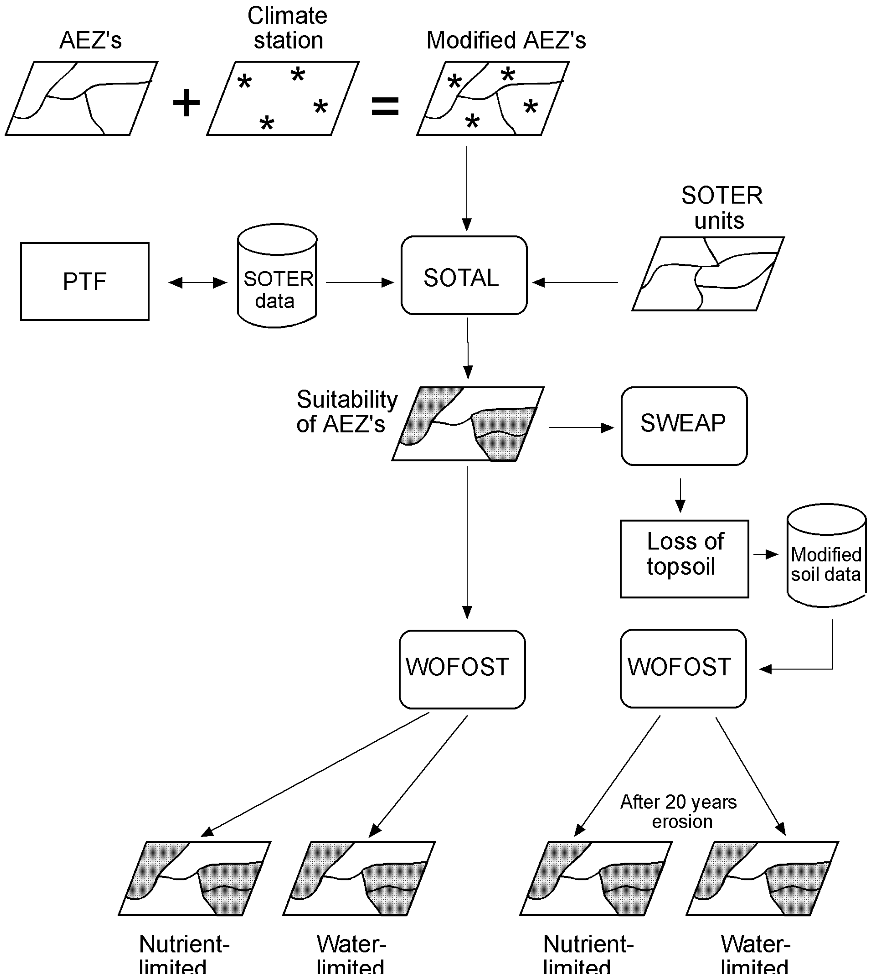


Figure 2. Flow chart of modelling process.

model for physical land evaluation using ALES). Further analyses using WOFOST and SWEAP were limited to the potentially suitable units for which some details are given in Table 1.

Table 1. Total number and suitable Agro-Ecological Units (AEU) per country.

Country	total AEU's		suitable AEU's	
	number	x 10^3km^2	number	% of area
Northern-Argentina	949	404	591	74
Uruguay	617	172	289	47
Kenya	5451	582	2117	21

For the WOFOST input file, the required fertility parameters were averaged over the top 20 cm. Hydraulic parameters not present in the SOTER database were estimated on the basis of dominant texture using pedo-transfer functions based on research by Rijtema (1969). 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.

Other land characteristics needed as input in WOFOST, but not always represented in the SOTER data-set, are P-Olsen and bulk density. Bulk density was estimated using a pedo-transfer function (PTF) based on measured data stored in ISRIC's profile dataset. The PTF allowed for estimation of the bulk density from the particle size distribution of the soil. Incorporation of organic matter into the regression formula did not yield higher r^2 figures. For the case of Kenya a PTF of bulk density was developed on the basis of measured bulk density values (N=181) in the SOTER dataset of Kenya. This function was then used to fill the data gaps in the same dataset. For a description of the PTFs see volume 2, appendix 3. Missing phosphorus data (P-Olsen) were substituted with mean topsoil P-values, stratified per soil unit of the Soil Map of the World (FAO-Unesco, 1974), derived from ISRIC's profile dataset.

In the followed approach it is assumed that water erosion occurs in the form of sheet erosion and not as rill or gully erosion. With the loss of topsoil in four scenario's (0, 10, 25 & 50 cm top soil loss over 20 years) nutrients are lost with the removal of soil particles from the toplayers. In many soils fertility decreases with depth (except for young soils on basic parent material and soils in arid zones). Water retention characteristics and conductivity may decrease with soil depth. The impact of change in soil properties, influencing crop performance, induced by removal of topsoil through sheet erosion, is analyzed in this study.

2.3 Definition of Land Utilization Types (LUTs)

2.3.1 Uruguay

Major kinds of Land Use

The dominant Major kind of Land Use (MLU) in Uruguay is permanent pasture. It was estimated that in 1992, 90% of agricultural land was used as permanent pasture, while the remaining 10% was used for arable farming (9-10%) and permanent crops (<1%) (FAO, 1995). Land use in Uruguay for arable farming linearly increased from 1.33 x 10^6 ha to 1.403 x 10^6 ha from 1961 to 1980, then stayed constant at that acreage between 1976 and 1980 and then linearly decreased to 1.26 x 10^6 ha, reaching a constant acreage in 1986 (see Figure 3). At present wheat cultivation is hardly practised in Uruguay. The Land Utilization Type as defined for this study was therefore based on the practice of wheat cultivation in the past.

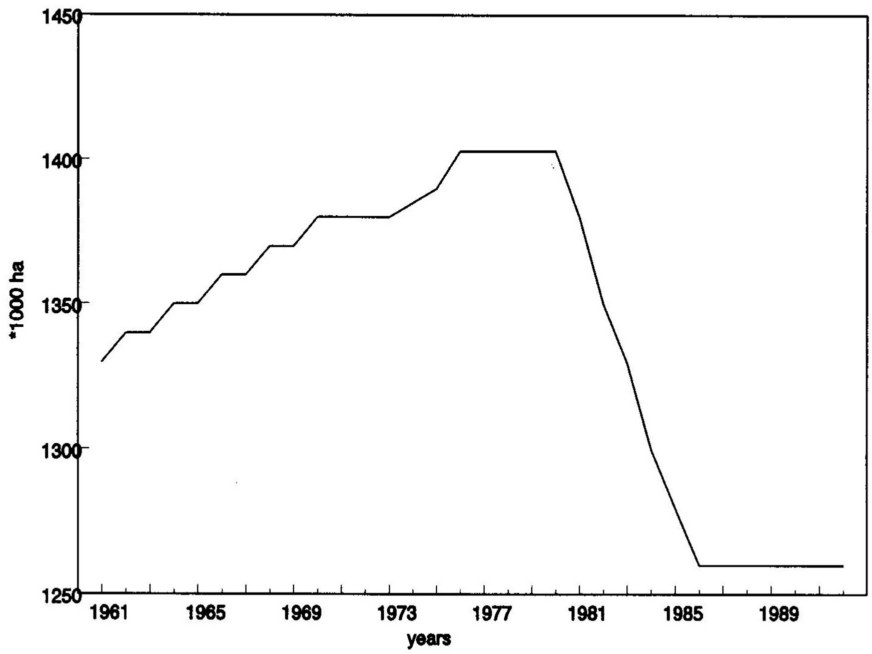


Figure 3. Trend in acreage of land used for arable farming in Uruguay (after FAO, 1995).

Definition of Land Utilization Type

The defined Land Utilization Type was low input, mechanised rainfed wheat cultivation (single crop per year). Cultivation practises include conventional tillage (molderboard, chisel and off-set disk), incorporation of crop residue before sowing and no fertilization. Sowing date (end of) May, harvest (around) November.

2.3.2 Argentina

Major kinds of Land Use

Wheat is an important grain crop in Argentina. Maize, in terms of national production, is equally important. Permanent pasture is presently the dominant Major kind of Land Use (MLU) in Argentina. According to FAO (1995), 83% of land used for agriculture was used as pasture in 1992. The remaining acreage was used for rainfed arable farming (15%), irrigated agriculture (1%) and permanent crops (1%). In the area considered in this study, the dominant land use is rainfed arable farming (cultivation of wheat). National production of wheat shows an increasing trend over the years, as is shown in figure 4 for the period 1961 to 1994.

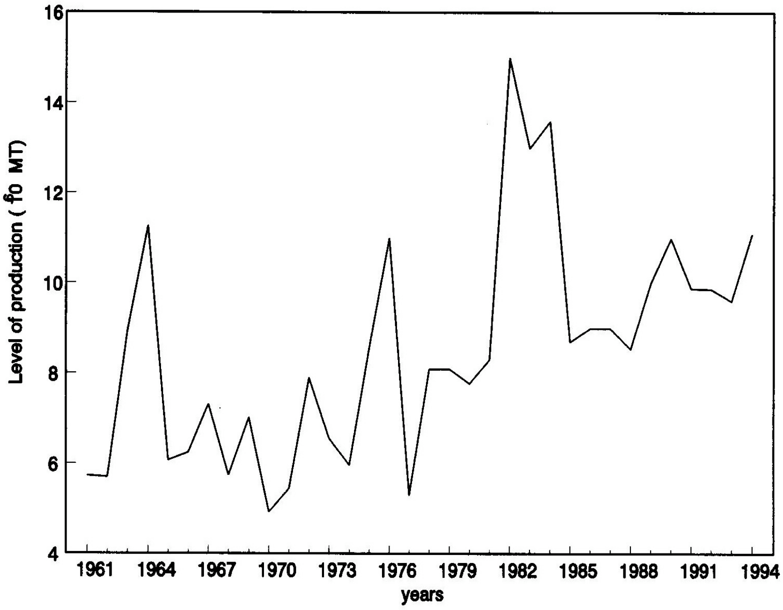


Figure 4. Wheat production trend in Argentina (after FAO, 1995).

Definition of Land Utilization Type

Wheat is the dominant crop in this gently undulating part of Argentina, where deep and well drained soils prevail. Wheat is grown with moderate to high input and under a high to medium technology level (fully mechanized) and with moderate labour intensity. Average farm size ranges from 50 to 100 hectares. About 60% of the land users are land owners, while the remaining 40% are tenants. Land preparation is done using a mouldboard plough. Herbicides are used and fertilizers are applied in doses of 100-200 kg urea ha^{-1} (average 70 kg pure N ha^{-1}) and 65-130 kg superphosphate (average 20 kg pure P ha^{-1}). Wheat is sown half July (northern area) to end of July (southern part of study area) and harvest is around November.

2.3.3 Kenya

Major kinds of Land Use

Maize is the dominant food crop in Kenya and its cultivation is widespread. It is grown in areas that receive at least 630 mm of reliable rainfall a year and at altitudes below approximately 2000 metres. Total production of maize in Kenya has increased over the years (Figure 5). Other cereals grown in Kenya are sorghum, millet, wheat and barley. Due to an increasing population, the pressure on land is high. Population has increased from 24.5 million in 1991 to 27.3 million in 1994 (FAO, 1995).

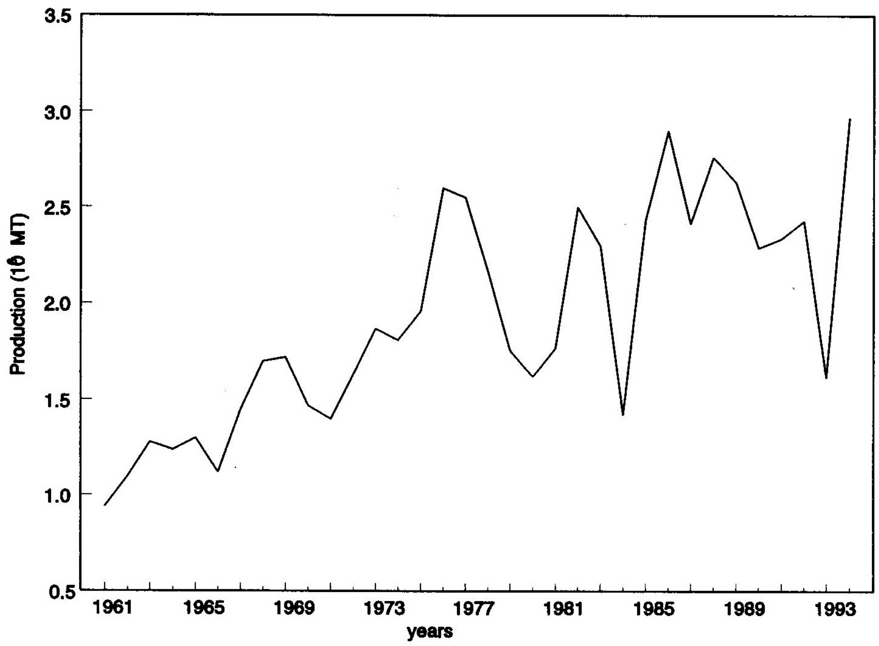


Figure 5. Maize production trend in Kenya (after FAO, 1995).

Definition of Land Utilization Type

The defined Land Utilization Type for Kenya was low input, rainfed maize cultivation (single crop per year), low technology. Farm size is generally small and cultivation practises include manual tillage ('hoe-farming'), stubble is left for grazing or is incorporated before sowing. No or limited use is made of chemical fertilizer. The sowing date is in (the end of) March and harvest is (around) July-August. Sowing and harvest dates vary with thermal and moisture zones. In most parts of Kenya the rainfall pattern is bimodal and two crops can be grown in a year with maize as the major crop in the first growing season. In this study only the major growing period and major food crop is considered c.q. maize in the principle growing season.

2.4 Assessment of areas suitable for defined LUTs

2.4.1 Uruguay

The dominant soil types in Uruguay are deep, well drained and fertile soils (Phaeozems; FAO, 1988). The criteria for assessment of the suitable land units for the defined LUT (low input, mechanized wheat cultivation) were defined in consultation with the Dirección de Suelos y Aguas. Fertility characteristics were given a high weight in rating for assessment of the overall suitability, as in the defined LUT no fertilizer input is used and wheat is grown depending on natural fertility.

2.4.2 Argentina

The area in Argentina evaluated for suitability for wheat is a flat area, situated west of Buenos Aires and the Paraná river and an adjoining area in the north which is situated between the Paraná and Uruguay rivers ('Entre Rios'). Deep, well drained and fertile soils (Phaeozems; FAO, 1988) are among the dominant soils. Soils experiencing waterlogging for part of the year (hydromorphic soils) are also found in the area. Criteria for suitability assessment for the defined LUTs (medium to high input, mechanized wheat cultivation) were defined in consultation with the Argentinean soils institute, INTA/CIRN. Slope is a crucial land property for assessment of land suitability for this LUT as it largely determines the possibilities for mechanisation. Fertility characteristics are not given a high weight in rating for overall suitability, as possible macro-nutrient deficiencies during the growing season are counterbalanced through fertilizer applications (urea and superphosphate).

2.4.3 Kenya

In view of agro-ecological conditions, Kenya is far more variable than both Argentina and Uruguay. This is mainly due to extreme differences in altitudes within Kenya (causing local climate differences) and in landforms and lithology (a.o. influencing soil formation). Therefore agricultural potential in Kenya also shows greater extremes.

The availability of water to the maize crop during the growing season is an important land quality in the suitability assessment. This quality is not only determined by the amount and distribution of rainfall, but also by the length of the period the crop needs water, e.g. by the length of the growing period. The length of growing period is a function of the physiological properties of the crop (variety) and the temperature and day length at the site and is therefore strongly linked with altitude as the growing period increases with altitude. In studying water availability for a maize crop, a water balance model was used that incorporates an algorithm for calculating crop development on the basis of a variety specific heat requirement for development. In each time step of the model calculation, the positive difference between the threshold temperature for development (below which crops cannot develop) and the average daily temperature is calculated, yielding the effective temperature sum. The crop is fully mature when the cumulative effective temperature sum has reached the value of the heat requirement of the crop. In this way the relative development stage of the crop (affecting crop coefficient used for calculating actual transpiration) can be determined.

2.5 Crop yield assessments for different scenarios

2.5.1 Introduction

The WOFOST model (Van Diepen *et al.*, 1986, 1991, Van Keulen and Wolf, 1986) calculates crop yields under three principal growth constraints. This results in theoretically defined situations that are hierarchically ordered according to increasing analytical complexity. The effect of principle growth constraints are evaluated by making separate calculations of:

1) the 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) the water-limited yield, additionally reflecting the influence of limited or excessive water supply, and

3) the nutrient-limited yield.

2.5.2 Constraint-free yield

Dry-matter accumulation of the crop is quantified under the prevailing weather conditions, i.e. as a function of radiation, temperature and crop characteristics. Other factors influencing crop growth are considered optimal at this production level. State variables characterize the changing situation of the crop and the soil at any moment and are updated after each time-step. Radiation and temperature are examples of forcing variables that determine the rate of the simulated processes. Constants are for instance the carbon dioxide content of the air and soil depth. Yield potential varies with the absorption of light, the fraction of net assimilate production that is to be invested in new plant matter, the losses incurred in maintenance respiration, and the efficiency with which the remaining assimilates are converted to structural plant matter (De Wit and Van Keulen, 1987).

2.5.3 Water-limited yield

Assimilation, i.e. reduction of atmospheric CO_2 to carbohydrates $(CH_2O)_n$, is the fundamental process in plant growth. With the intake of carbon dioxide through the stomatal openings in plant leaves, water is lost through transpiration. When plants are exposed to drought they close their stomata, in order to avoid more water loss, thereby reducing carbon dioxide intake, and consequently assimilation (and thereby plant growth) is hampered. Water losses from the system are through transpiration and evaporation and supply is through rainfall. The buffering capacity of the soil, which determines how much of the rainfall will be available to the plant, causes the growth rate of plants to depend only indirectly of the forcing variable: rainfall.

Soil constants needed to simulate the water fluxes in the soil, e.g. water retention and conductivity characteristics, are not measured on a routine basis in soil surveys and thus mostly absent in the SOTER database. Hydraulic parameters were therefore estimated on the basis of dominant texture using pedo-transfer functions based on research by Rijtema (1969). Changes in crop yield as a function of water availability, due to altered hydraulic characteristics as a consequence of erosion (loss of topsoil), are therefore in this study a consequence of texture shifts and change in rootable depth.

2.5.4 Nutrient-limited yield

Calculation of 'available' nutrients

The availability of nutrients to crops is difficult to assess quantitatively, because key parameters are often very variable in both time and space. Furthermore, measurements of relevant indicators for the nutrient capacity of soils is problematic. Soil and seasonal variability make a determination of generic critical levels of soil test values difficult. Nutrient elements in a soil may occur in many forms, and are, depending on the conditions, more or less available to a crop. This availability does not only depend on soil factors, such as soil temperature, pH and moisture conditions, but also on weather conditions and farm management practices. Moreover, crops differ in their demand for nutrients and some crops are more efficient in extracting elements than others. A relationship of local validity between soil test value and yield can be quantified with the help of multiple regression. However, as regression equations for soil test calibration are both site and season specific, one should repeat such work in both space and time in order to represent a range of uncontrollable variables (Sumner, 1990). 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(H_2O) are diagnostic criteria (Janssen *et al.*, 1990, Smaling and Janssen, 1993). In calculation of the nutrient-limited yield, it is assumed that no other factors, e.g. water deficit, hampers growth.

Assessment of fertility parameters

The potential supply of available nutrients was assessed according to above-mentioned 'QUEFTS'-methodology. A QUEFTS module is incorporated in WOFOST 4.3 (Pulles *et al.*, 1991). The potential supply of nutrients is an input for this module and was calculated, using the QUEFTS regression equations, on the basis of the available SOTER data. Bulk density and phosphorus are rarely collected on a routine basis during soil surveys and are therefore often under-represented or even lacking in Global and National databases such as SOTER and WISE. Nutrients are mostly presented in soil analysis as a percentage of the weight of the sieved and dried sample and not on a volumetric basis. To convert figures of soil fertility indicators and water content based on weight percentage to figures on a volumetric basis, which are needed for a wide range of analysis, bulk density is crucial. For the GEO study, based on the 1:1 M and 1:5 M SOTER databases, it was necessary to fill data gaps on soil bulk density using simple PTFs (see par 2.2).

Data on phosphorus content on soils was lacking in most cases, but is an essential input parameter in the QUEFTS module of WOFOST. However, for enabling the scenario studies, and considering that P-Olsen is a mandatory QUEFTS-input parameter, missing P-Olsen data for topsoils (0-20/50 cm) were derived from P-Olsen figures averaged, per FAO soil unit, from the WISE database. The total sample population was 1528 for the 106 soil units considered on the Soil Map of the World (see par. 2.2).

The lack of P-Olsen data (creating the need for PTF-generated figures), the high spatial and temporal variability of the soil fertility parameters, their questioned adequacy for assessing the availability of nutrients and the fact that the QUEFTS-model was calibrated for Kenya (and not for Uruguay and Argentina) make that the figures related to the nutrient limited scenarios should all be interpreted qualitatively (as relative to other scenarios) and not quantitatively.

2.6 Assessment of the erosion risk

2.6.1 Introduction

For all areas that have been evaluated as suitable for the land use under consideration (wheat in Argentina and Uruguay and maize in Kenya with specified management and technology levels), the soil erosion risk was calculated using the SWEAP programme (van den Berg and Tempel, 1995). For Argentina the assessment was done by INTA/CIRN, for Uruguay by DSyA and for Kenya by ISRIC in consultation with KSS. In SWEAP, a SOTER application programme, two erosion risk assessment models are implemented in the model subsystem, of which the Universal Soil Loss Equation (USLE, Wishmeier and Smith, 1978), was used for this study. The equation is as follows:

$$A = R \times K \times LS \times C \times P$$

in which:

A	=	total soil loss (in t ha^{-1})
R	=	rainfall erosivity
K	=	soil erodability
LS	=	slope length and gradient
C	=	cover factor of the vegetation/crop
P	=	management factor

The scale of the study (1:1 M) does not permit the quantification of soil loss in t ha^{-1}. Instead, a qualitative unit (erosion hazard unit) has been used. In the conclusions of this chapter some remarks will be made with respect to the relation between actual measurements of soil loss and the calculated values of the USLE.

The USLE has been developed for (large scale) erosion plots in the USA and some modifications have been introduced to allow for use of (small scale) SOTER data in the programme. E.g. the LS factor assessment has been modified for the use of the type of slope information that is present in the database. Cover and management factors have been taken from various sources. For more detail about SWEAP the user is referred to Van den Berg and Tempel (1995).

2.6.2 Methodology

A first step in the methodology is the geographical linking of rainfall erosivity data with land data (soil, crop, management). Two approaches have been applied:

a) manual linking of rainfall data with SOTER units. While extracting the required soil, slope and land use data from the database, a link was manually established with a climate station considered representative for the SOTER unit. This approach has been applied in Argentina and Uruguay.

b) geographical overlay of ecological zones, considered homogeneous with respect to rainfall characteristics (erosivity), potential evapo-transpiration and temperature characteristics (length of growing period), with SOTER units. For this approach the agro-ecological zones were used as a first subdivision of a territory in areas with similar rainfall characteristics. When the obtained areas contained more than one climate station, a further subdivision of the ACZ was made using Thiessen polygons. The obtained rainfall zones were overlaid with the SOTER units in a GIS. This approach has been used in the Kenya study.

The second step is running of SWEAP with the input data obtained under a) or b).

It is to be noted again that only for the areas suitable for wheat, c.q. maize, such calculations were made.

The erosion risk for Argentina and Uruguay was calculated for mechanized cultivation of wheat, with stubble ploughed in before sowing. No erosion control measures are taken. For Kenya erosion risk was calculated for a maize crop, with stubble incorporated before planting and absence of erosion control measures.

2.6.3 Discussion

The USLE has been designed for the calculation of soil losses in t ha^{-1}. Considering the scale of study and the fact that the parametric model is not calibrated for the range of conditions as represented by the climatic and SOTER databases of the countries that were studied, it is not considered justifiable to present the results on an absolute scale. Therefore, a presentation of the results in qualitative terms has been chosen: erosion hazard units (EHUs). This allows for a comparison between the various areas within a country but does not give an absolute soil loss potential.

Comparison of the calculated results of erosion risk with measured erosion on experimental plots was possible for a limited number of cases. That was the case for a SOTER unit in the southwest of Uruguay where the measured soil loss was approximately 30 % lower than indicated by SWEAP. This is probably due to a difference in land use for the plot and the land use defined in the SWEAP scenario, differences in the land characteristics like slope gradient and length due to generalization in the SOTER unit.

Comparison between values obtained for the K factor revealed some differences. In general the K factor as calculated for the erosion studies in Uruguay was 10 -20 % lower than the one calculated by SWEAP. This could be due to the fact that the nomograph developed by Wishmeier and Smith (1978) does not cater for soil organic carbon contents of more than 4%. In Uruguay a modified nomograph is used.

2.7 Definition of erosion scenario

2.7.1 Methodology

The soil erosion risk, calculated in the preceding paragraphs, has been used as the basis for a scenario of simulated soil loss over a period of 20 years. The start and end situations are the basis for the production calculations in the next chapters.

Erosion hazard for the dominant soil in an AEU, expressed in t ha^{-1} yr^{-1}, were taken as a basis for definition of a scenario for future soil erosion: 0, 10, 25 and 50 cm of topsoil loss over a 20 year period, respectively. New WOFOST input files were created for these scenarios.

It was assumed that no change in the land use scenarios, as defined in chapter 2.3, would occur.

The loss of topsoil has been calculated as follows:

$$L = 10^{-4}\, EHU \times Y \times 10^{3}\, BD^{-1}$$

in which:

L	=	topsoil loss in m
EHU	=	soil erosion risk (expressed in t ha^{-1} yr^{-1})
Y	=	number of years in the scenario (in this case 20)
BD	=	bulk density of the topsoil (in g cm^{-3})

2.7.2 Discussion

No account is taken of the possibility 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 and, ultimately, to the sea. 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 RESULTS

3.1 Uruguay

Suitability

As land units were evaluated for cultivation of wheat depending on natural soil fertility (no fertilizers added), the 'availability of nutrients' had a significant impact on overall suitability. The land quality 'possibilities for mechanisation' was also important, the LUT includes full mechanisation and land with excessive rock outcrops or with steep slopes (>15%) are not suitable. Other limitations, although small in occurrence, were related to soil depth and drainage conditions. Water availability during the growing season was no limitation, except for the coarse textured soils. Less than half of the country (46%), is considered suitable for this type of land use (see Figures 6 for statistics and 7a for the map).

Erosion risk assessment and scenario definition

The erosion risk map of Uruguay (Figure 8a) based on SWEAP calculations, shows that the soils are vulnerable to water erosion when a wheat crop is cultivated. The relative differences in erosion risk are considerable (see also Figure 6).

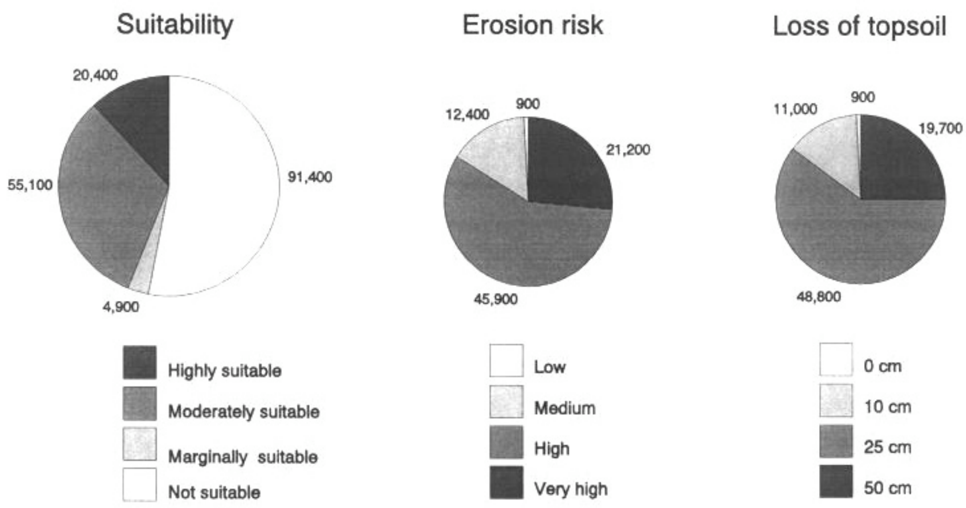


Figure 6. Proportions of suitability, erosion risk and loss of topsoil under wheat in Uruguay (figures in km^2), based on spatially dominant soils within each SOTER unit.

The results translated into loss of topsoil (Figure 8b) are equally distributed over the classes. Only the lowest class, 0 cm top soil loss over 20 years, has a limited

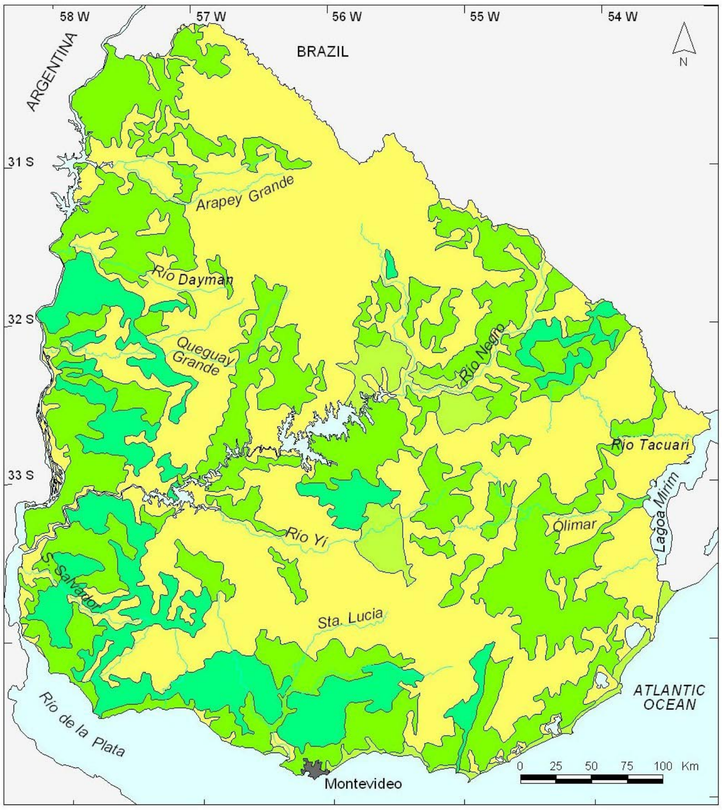


Figure 7a.

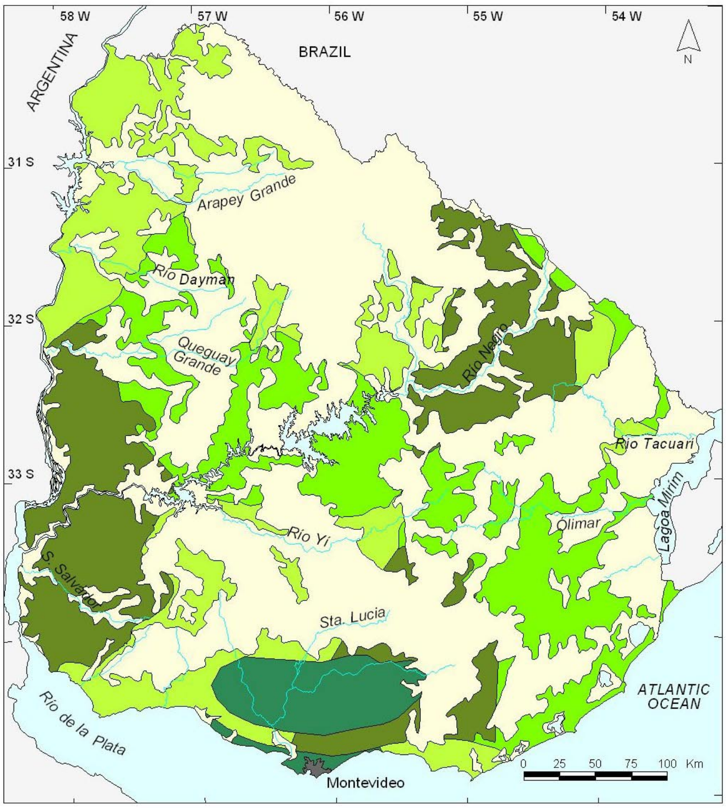


Figure 7b.

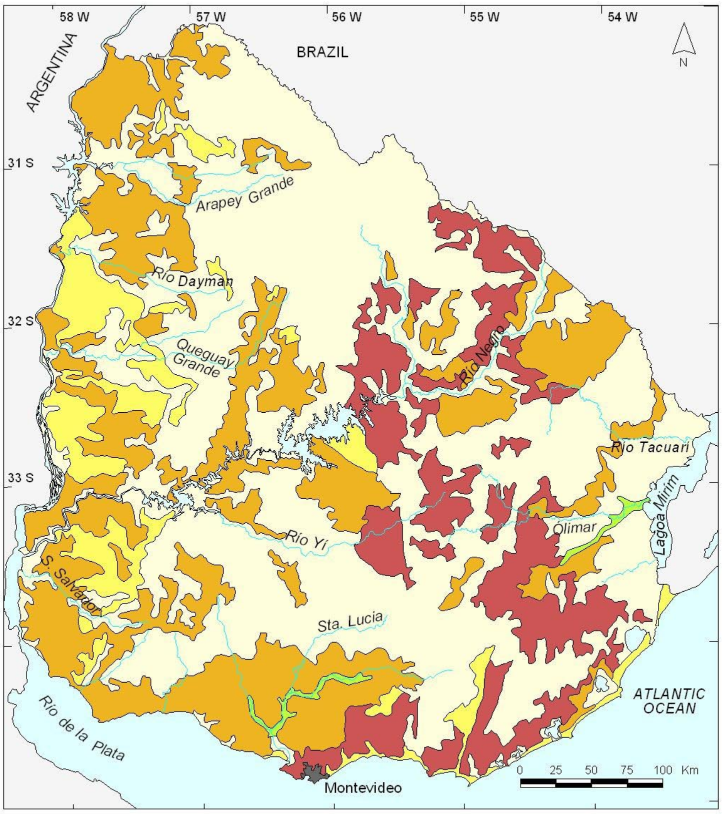


Figure 8a.

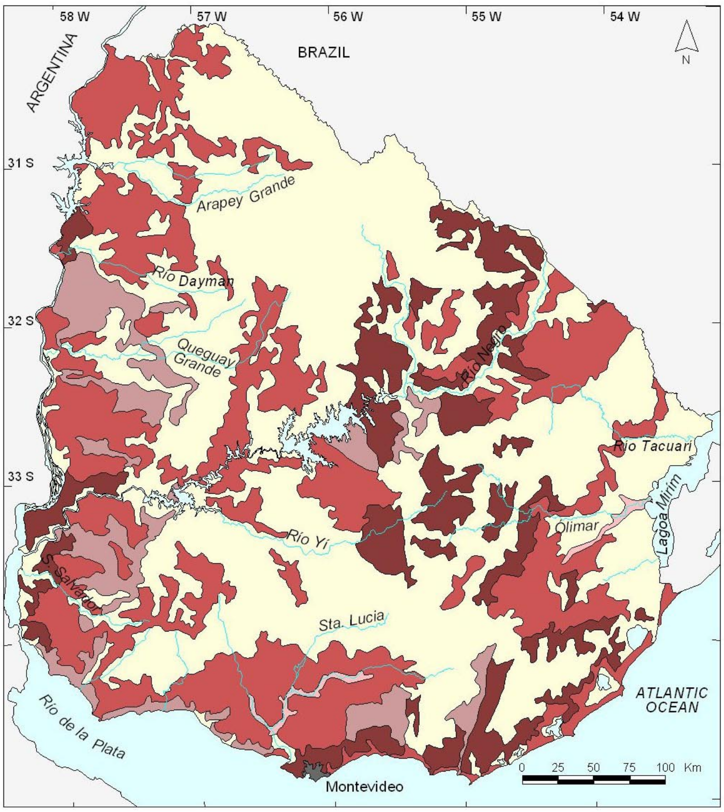


Figure 8b.

occurence. In areas where in the past wheat was cultivated, in particular the zone north of the capital Montevideo, severe erosion has taken place (Molfino, *pers. comm.*). This tallies with the model outcome for this area. Under the current land use, grazing, the situation has stabilized.

Observations on erosion in the extreme west of Uruguay, where continuous cropping combined with conventional tillage is applied, indicate an increase in erosion damage ranging from moderate to severe (Terzaghi, 1996). In the erosion scenario these soils are in the classes of 10 or 25 cm loss of topsoil, a comparable result.

Crop production potentials

The agro-ecological zones in the south of Uruguay in which Montevideo is situated, as well as North of the capital, have a very high yield potential of > 4 t ha^{-1} (see Figure 7b). A Northwest-Southeast running zone in the central part of Uruguay has yield potentials that range between 3 and 4 t ha^{-1}. In the West and Northeast of the country, potential yields are between 2 and 3 t ha^{-1}. In the remaining parts of the country potential yields are between 1 and 2 t ha^{-1}. Proportions of the yields in the various scenarios are shown in Figure 9.

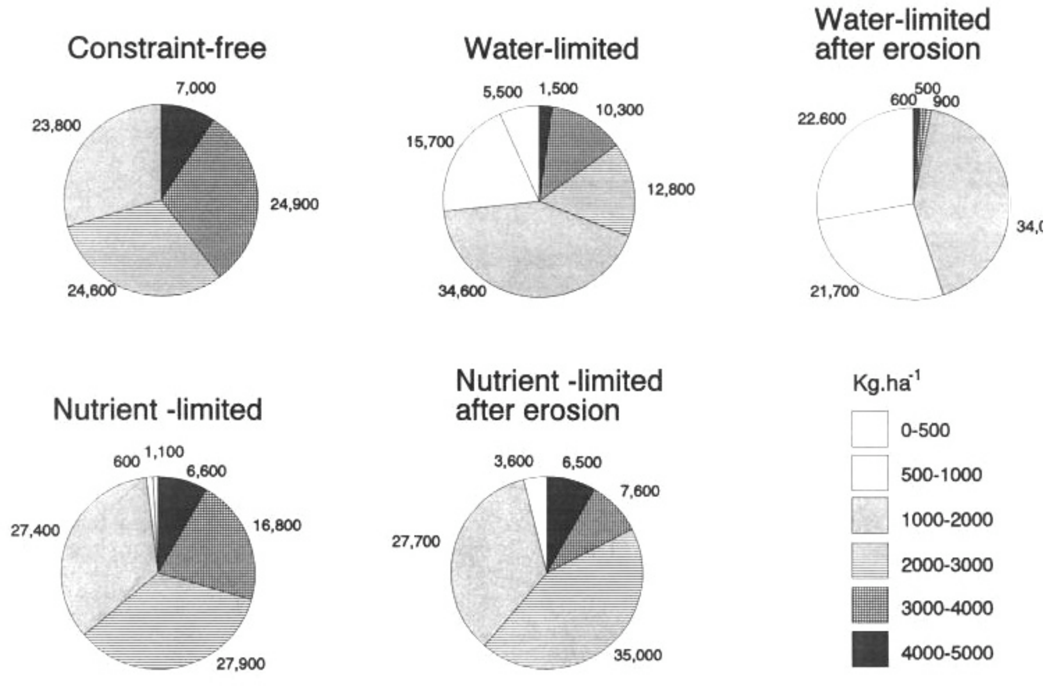
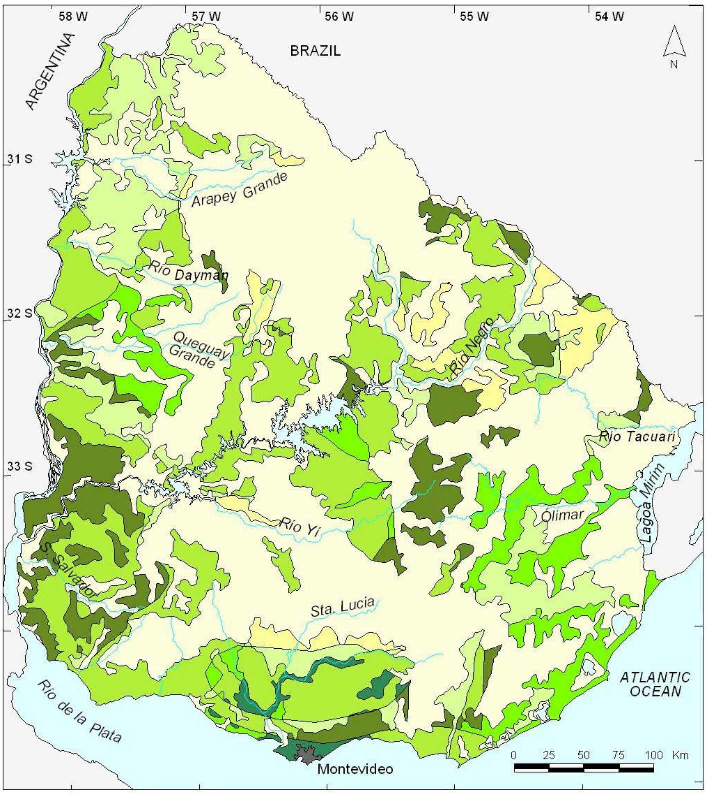


Figure 9. Proportions of yields in the various scenarios in Uruguay (figure s in km^{-2}), based on spatially dominant soils within each SOTER unit.

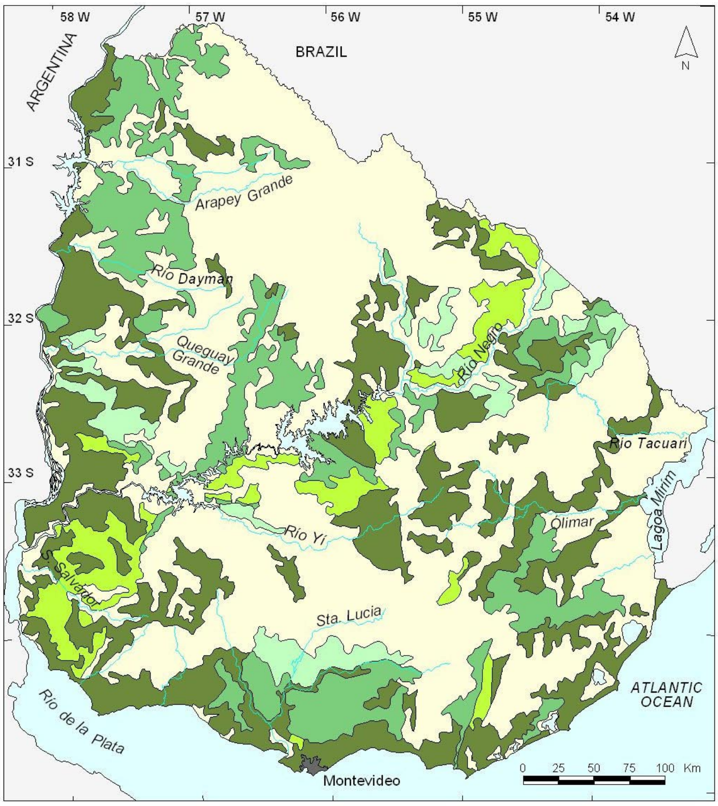


POTENTIAL WATER-LIMITED WHEAT YIELD

Yield (kg · ha^{-1})

- 0-500
- 500-1000
- 1000-2000
- 2000-3000
- 3000-4000
- 4000-5000
- Not applicable
- Water
- Town
- Other country
- River
- Unit boundary

Figure 10a.



RELATIVE WATER-LIMITED WHEAT YIELD

Relative yield (%)

- 0-25
- 25-50
- 50-75
- 75-100
- Not applicable
- Water
- Town
- Other country
- River
- Unit boundary

Figure 10b.

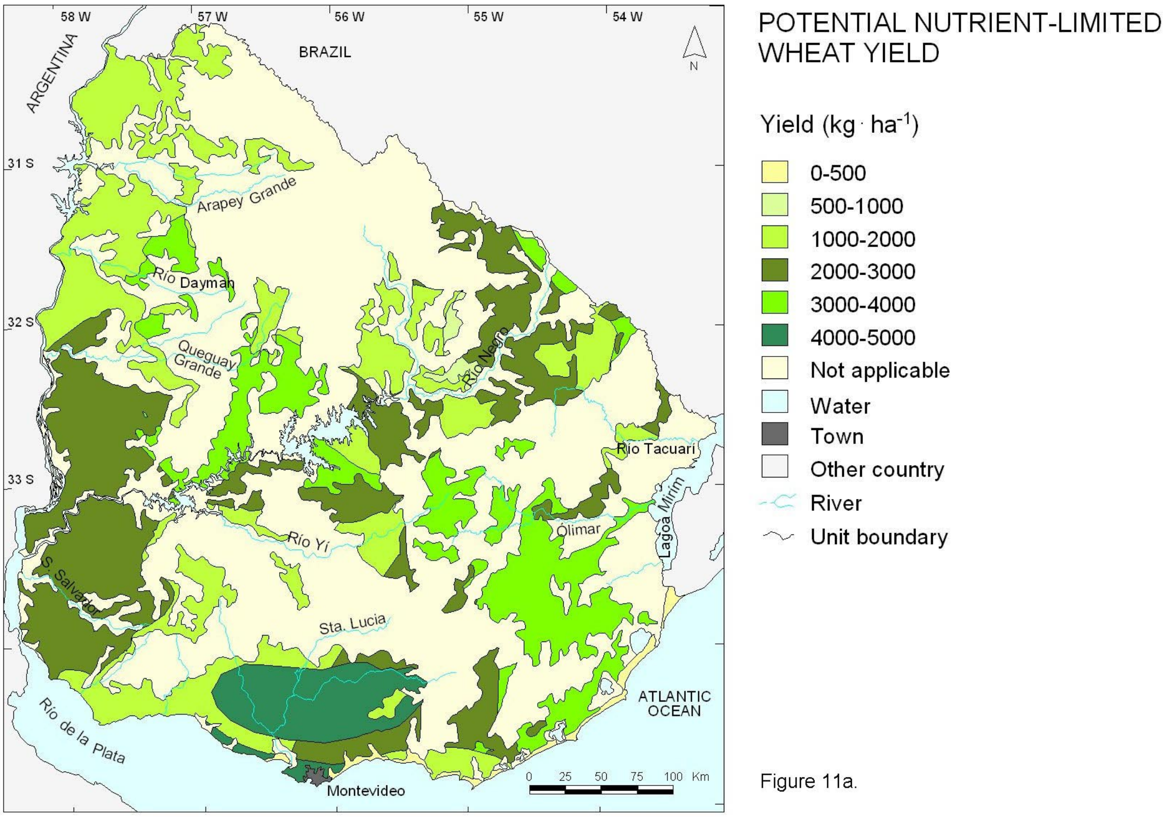


Figure 11a.

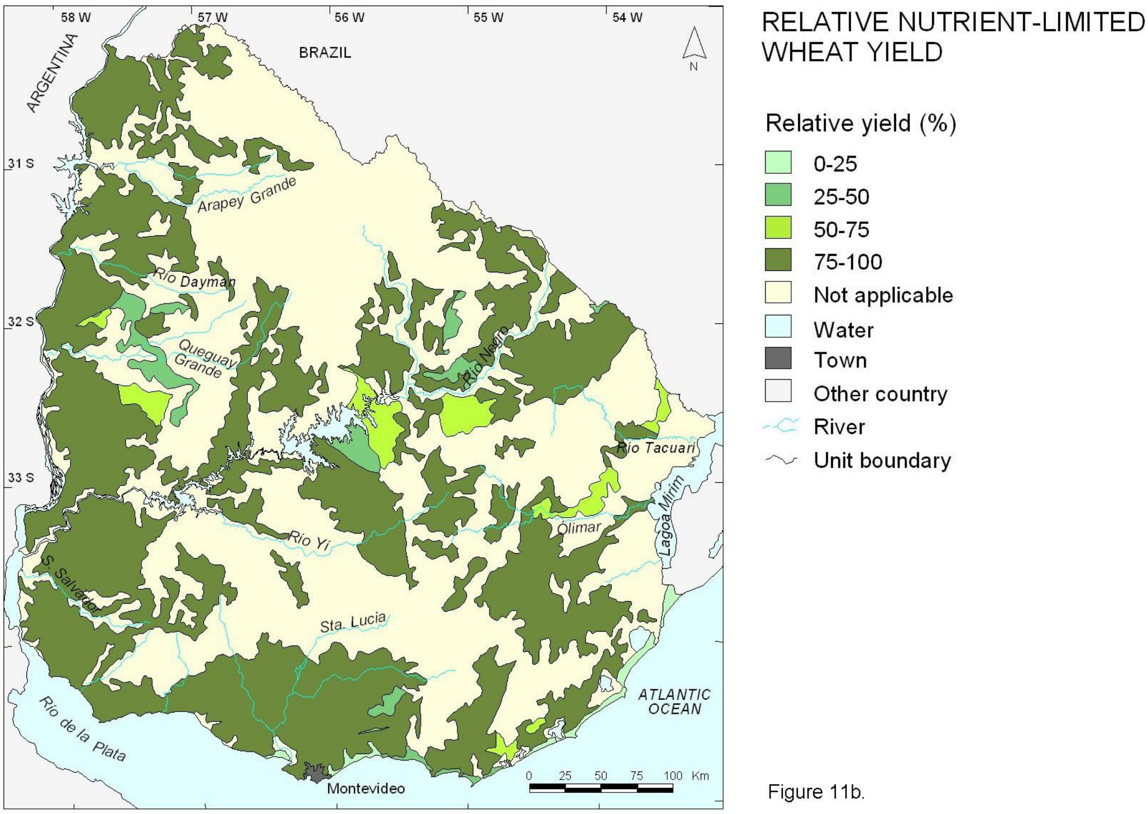


Figure 11b.

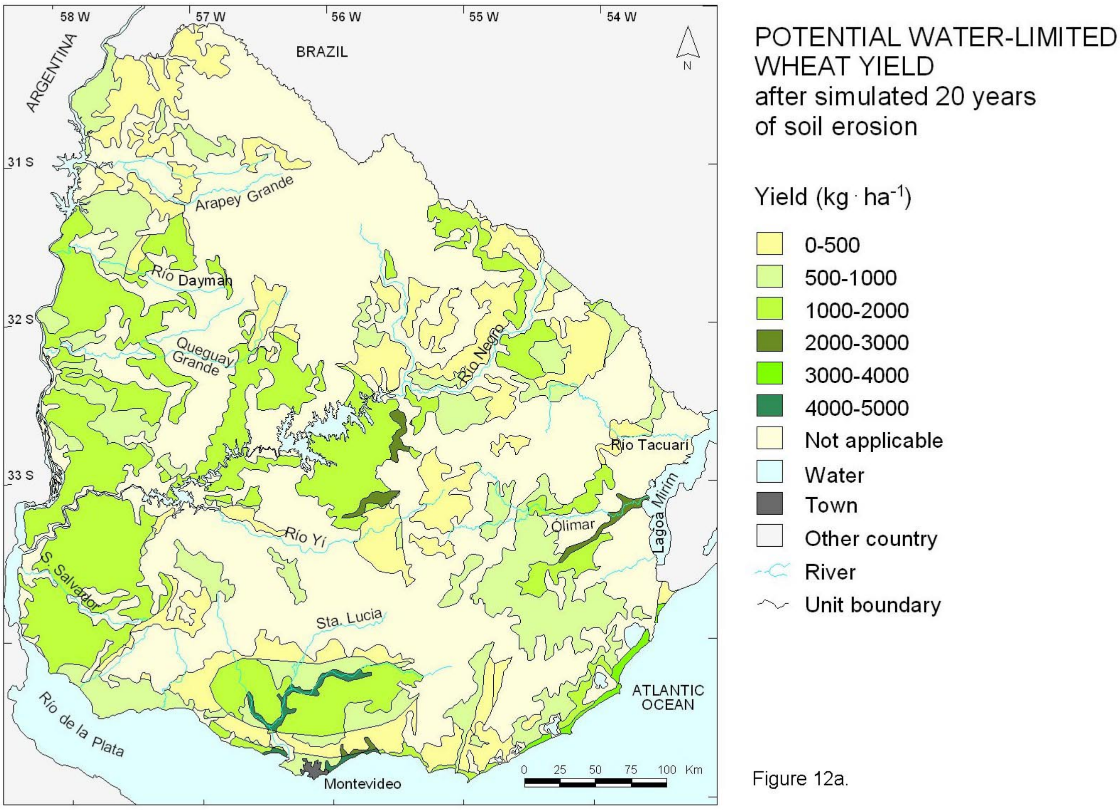


Figure 12a.

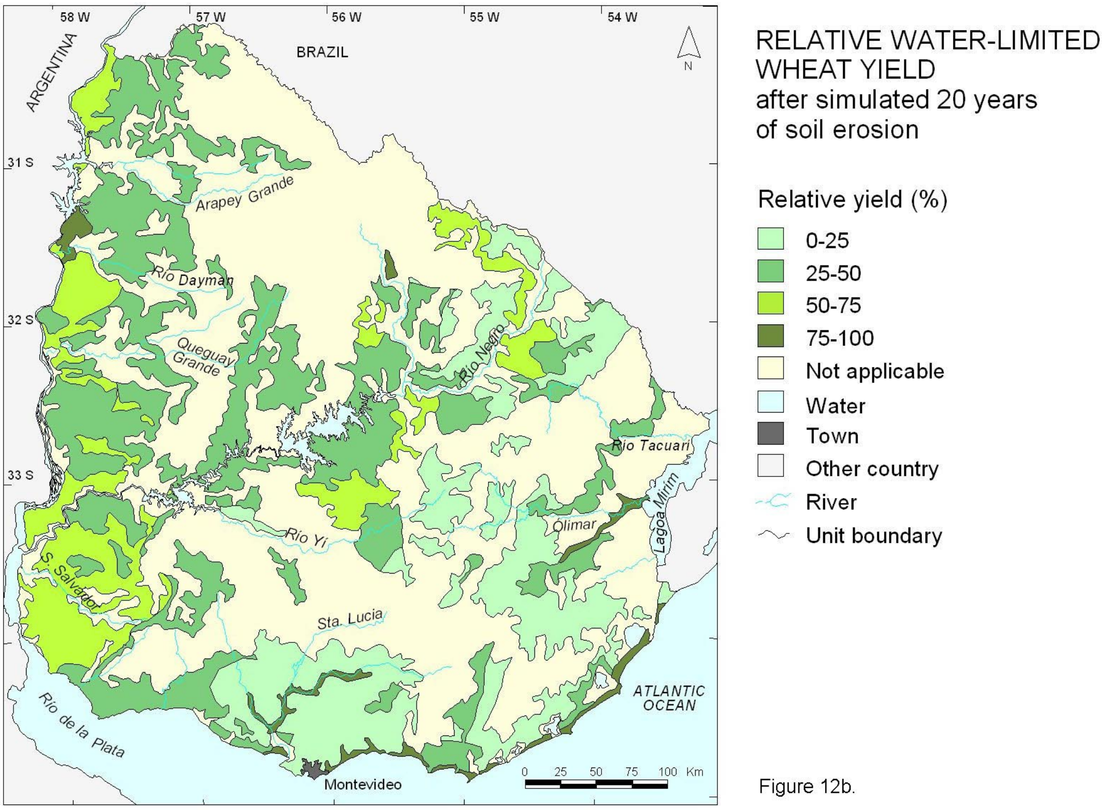
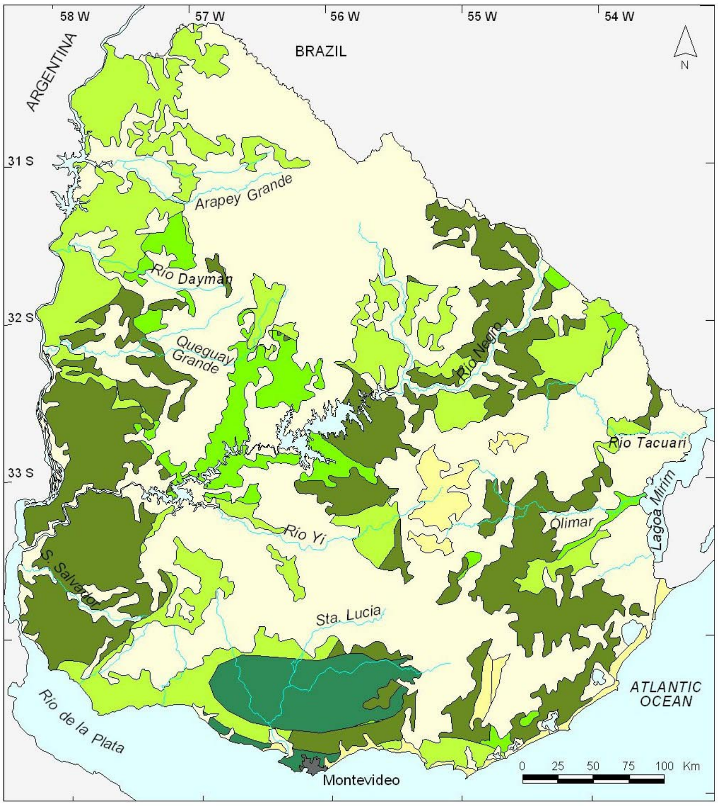


Figure 12b.

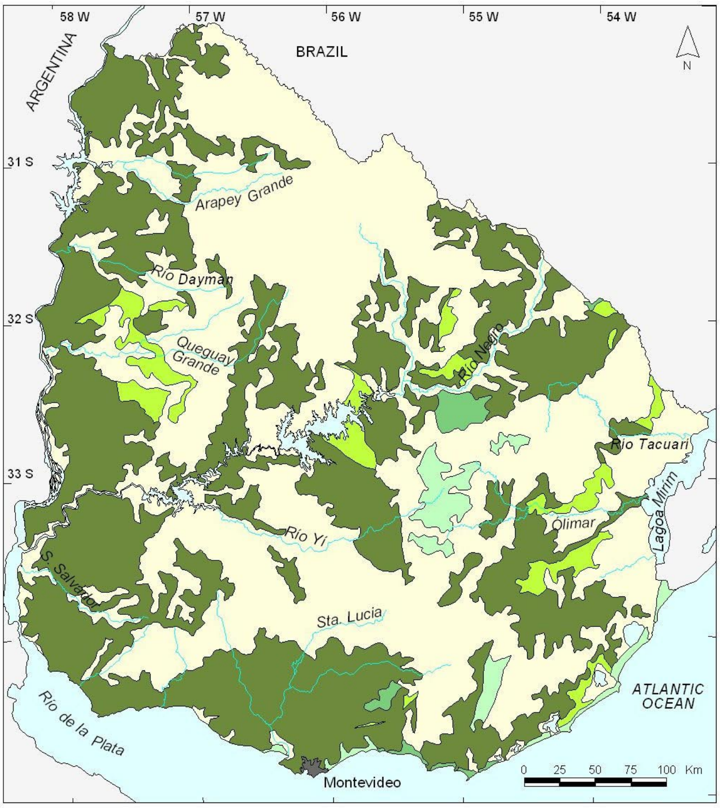


POTENTIAL NUTRIENT-LIMITED WHEAT YIELD
after simulated 20 years of soil erosion

Yield (kg · ha^{-1})

- 0-500
- 500-1000
- 1000-2000
- 2000-3000
- 3000-4000
- 4000-5000
- Not applicable
- Water
- Town
- Other country
- River
- Unit boundary

Figure 13a.



RELATIVE NUTRIENT-LIMITED WHEAT YIELD
after simulated 20 years of soil erosion

Relative yield (%)

- 0-25
- 25-50
- 50-75
- 75-100
- Not applicable
- Water
- Town
- Other country
- River
- Unit boundary

Figure 13b.

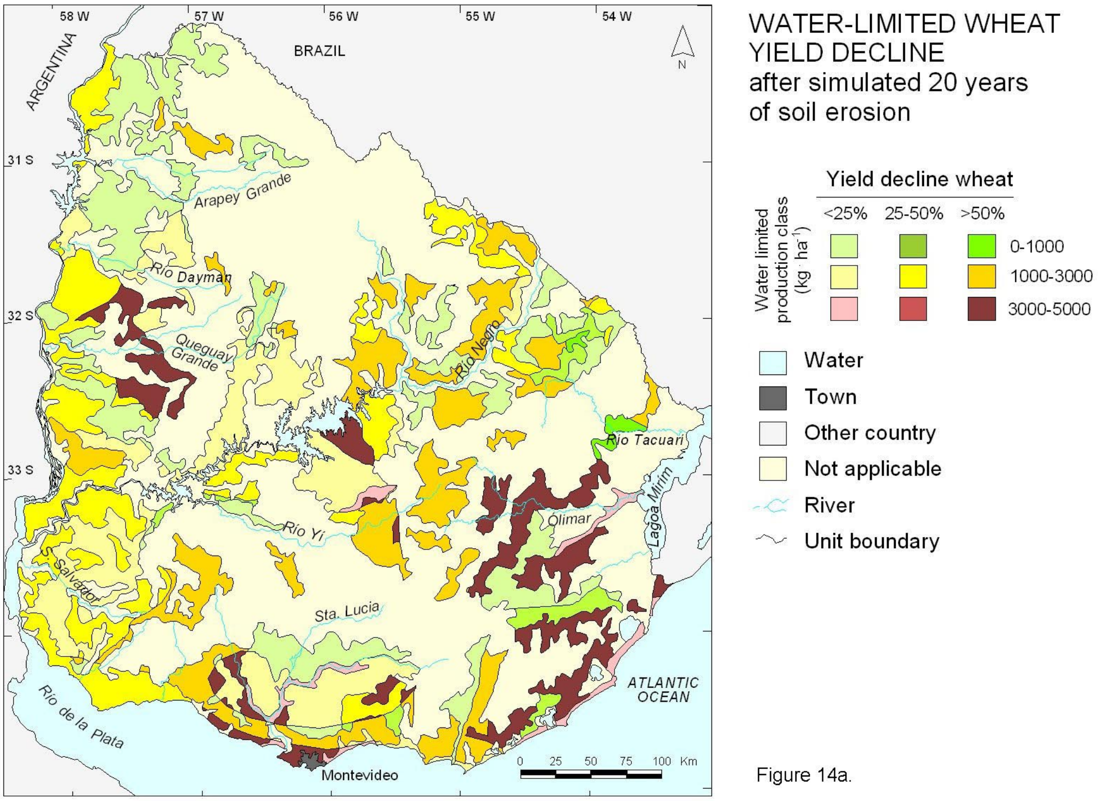


Figure 14a.

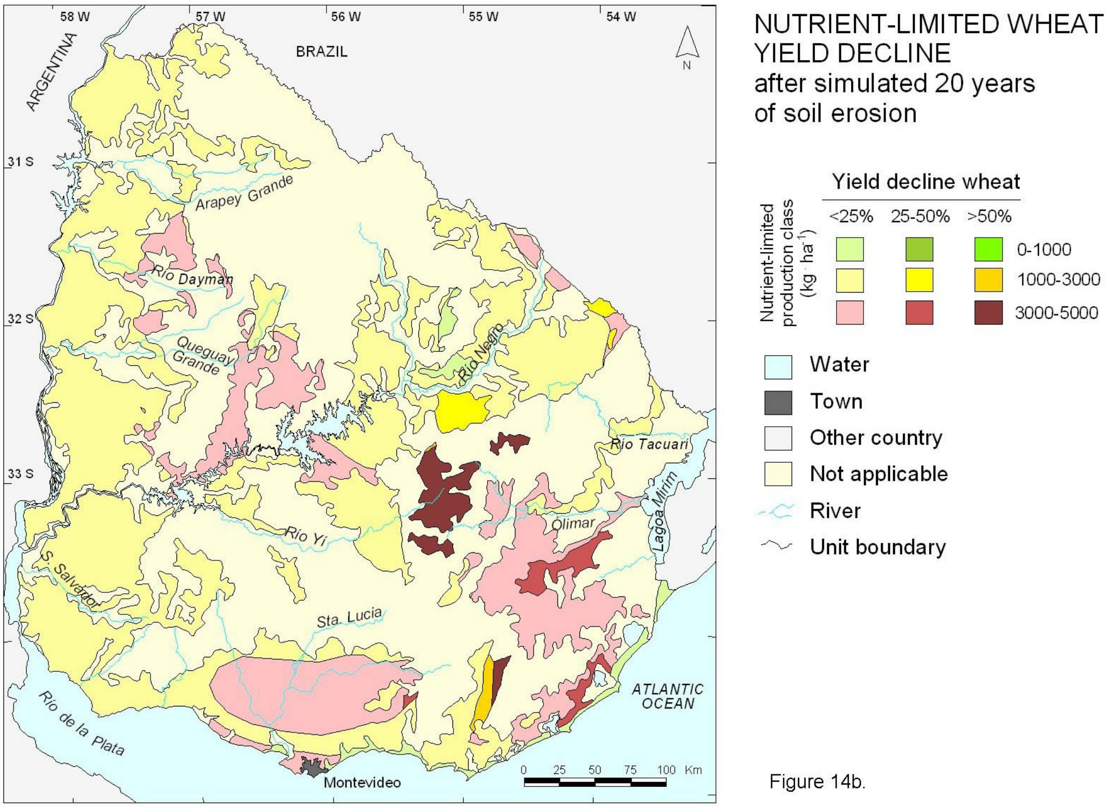


Figure 14b.

Comparisons of the water- and nutrient-limited yields (Figures 10a and 11a) with the constraint-free yield, show that yield gaps (relative yields of Figures 10b and 11b) are generally small for nutrient-limited yield (Figure 11b) and larger for water-limited yield (Figure 10b). About half of the country has a yield gap of 25% or more. It is shown that limitations to wheat growth are mostly related to soil physical conditions and not to soil fertility.

Yield decline

The severe erosion scenario - most units loose 25 or 50 cm topsoil over 20 years - leads to a considerable impact on water-limited wheat productivity. The results are shown as potential water-limited wheat yield after 20 years of erosion in Figure 12a and as a ratio between potential water-limited wheat yield after 20 years of erosion and constraint-free yield in Figure 12b. Comparing the map of the erosion scenario (Figure 8a) and the water-limited yield decline map (Figure 14a), it can be seen that there is no clear relation between the two. Certainly, for some cases the worst scenario leads to the highest yield decline, but there are also cases where a lower loss of topsoil leads to a high yield decline. This is the case in e.g. soils that have a limited depth resulting in a severe decline of soil moisture storage after removal of a relatively thin surface layer.

Interpretation of the nutrient-limited yield decline (Figure 14b) is more straightforward. Nutrient-limited yield potential on the generally fertile and organic matter rich soils is little affected by topsoil erosion. Apparently the availability of nutrients is not altered to the extent that it negatively influences yield capacity after varying (but considerable amounts) of loss of topsoil. The few units that show a decline of more than 50% (in the central-East and Southeast of the country) are all units with an assigned worst case scenario of 50 cm loss of topsoil.

3.2 Argentina

Suitability

The dominant soils in the larger part of the study area in Argentina (75%) are suitable for medium to high input wheat cultivation (see map 1, in volume 2, appendix 1 and Figure 15 for the proportions). In this area of Argentina, no major limitations for mechanisation exist. Where land units were rated unsuitable, nutrient availability was the dominant constraint. In most cases this was due to a moderately to strongly alkaline soil (pH > 8-8.5). Another important constraint, causing units to be unsuitable, was a low rootable soil volume. Water availability during the growing season was no limitation, except on the coarse textured soils.

Erosion risk assessment and scenario definition

The erosion risk map for the area in Argentina (Map 2, Volume 2, Appendix 1) shows a more alarming picture than may be expected on the basis of the topography of the area, where gentle slopes predominate. High silt contents and long slopes (hundreds up to thousands metres) are the cause of the high risk for erosion in half of the area (see Figure 15). Still the calculated erosion risk scenario and the defined topsoil loss scenario (Map 3, Volume 2, Appendix 1) is less severe than in the more undulating terrain in Uruguay.

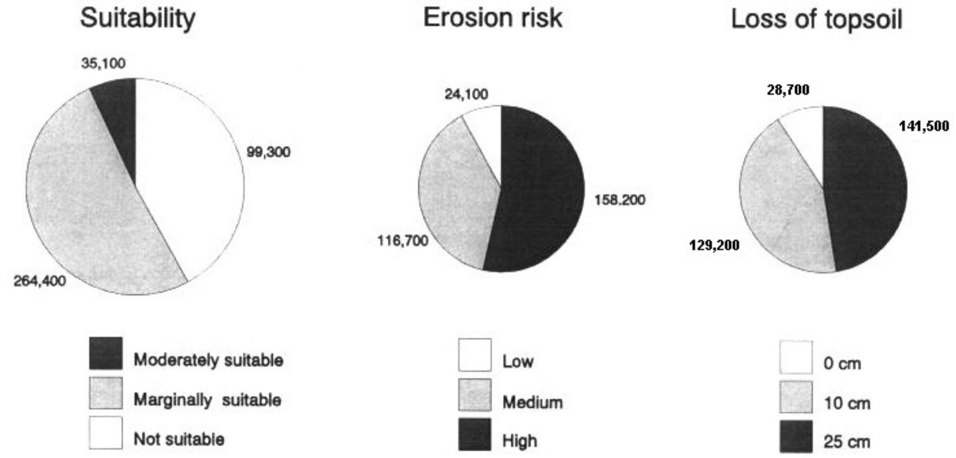


Figure 15. Proportions of suitability, erosion risk and loss of topsoil under wheat for Argentina (figures in km^{-2}), based on spatially dominant soils within each SOTER unit.

Crop production potentials

The calculated crop production levels (Maps 4-8 in Volume 2, Appendix 1) indicate possibilities and constraints within prevailing bio-physical conditions and allow for an estimate of yield decline as a consequence of loss of topsoil due to water erosion. The area directly around and extending west of Buenos Aires has a very high yield potential of > 6 t ha^{-1}. In the other parts of the area yields vary between 2 and 4 and between 4 and 6 t ha^{-1}, except for two areas in the extreme West and Northeast of the study area, where potential yields decline to 1-2 t ha^{-1}. Yields in the Northwest of the area are very low (< 0.5 t ha^{-1}). This is explained by the fact that the average and minimum temperatures are too high for this spring wheat variety, as a cooler period is needed for germination and flowering. Average temperatures range between 10.6 °C and 22.7 °C in the month of sowing and increase during the growing season. Consequently, temperatures are never lower than 10.6 °C.

The gap between water limited and constraint-free yield increases to the west of the area, indicating drier conditions (see map relative water-limited yield). The consequence of assigning one representative station to a agro-climatological zone for model calculations is illustrated in the yield maps. On the constraint-free yield map a zone of lesser productivity can be seen, in between two higher productivity zones (west of Buenos Aires, just left of the middle in the southern part of the area). The results are not necessarily wrong, but certainly the boundaries will be transitional instead of abrupt. However that holds for the other climatic boundaries too, and for that matter, for the soil boundaries.

Nutrient-limited yields before erosion are in the same range as constraint-free yields for the whole area. This indicates optimal fertility conditions for this LUT, with the given fertilizer applications, and absence of extremes in soil reaction (pH), organic carbon and potassium.

As nutrient-limited yield is higher than the water-limited yield, the physical limitations to wheat growth appear to be higher than those related to soil fertility. Soils in the area are generally deep and moderately, to highly fertile and the LUT includes the addition of nitrogenous and phosphorous fertilizer. The general picture that emerges from these maps, is that moisture and nutrient limitations to growth are low, since nutrient-limited and water-limited yield gaps are small.

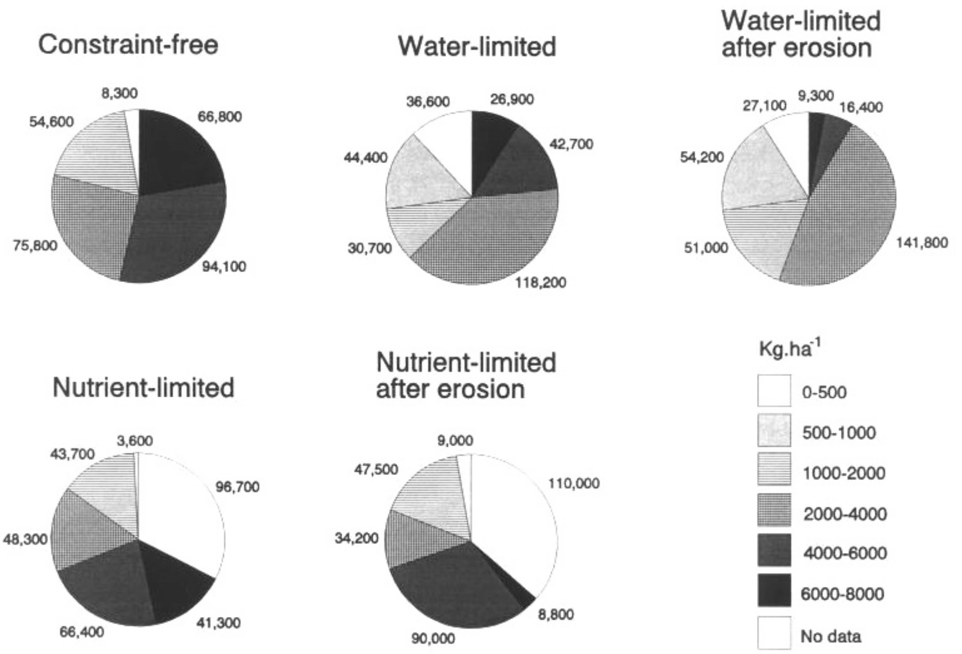


Figure 16. Proportions of yields in the various scenarios in Argentina (figures in km^{-2}), based on dominant soils within each SOTER unit.

WATER-LIMITED WHEAT YIELD DECLINE after simulated 20 years of soil erosion

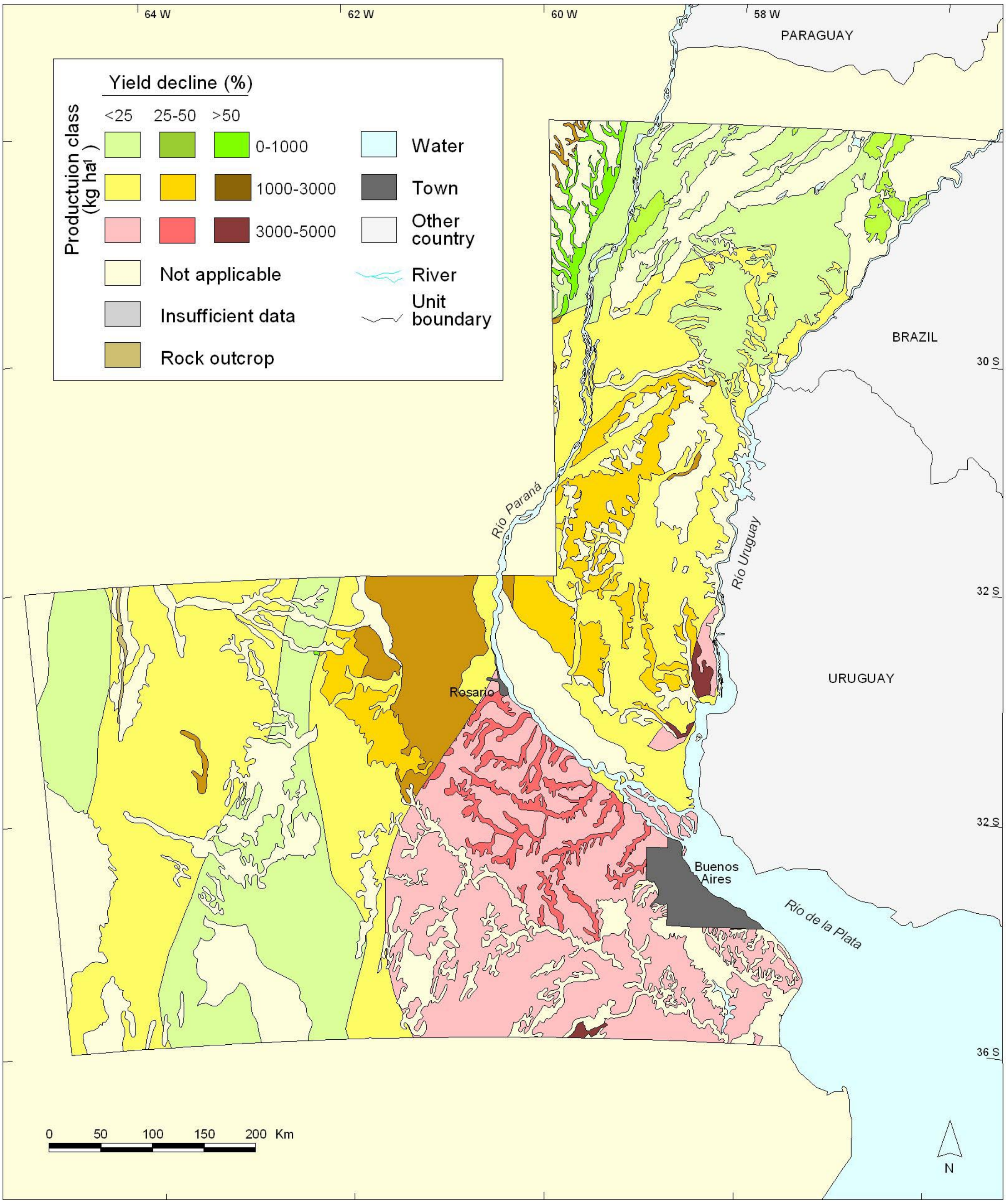


Figure 17.

NUTRIENT-LIMITED WHEAT YIELD DECLINE after simulated 20 years of soil erosion

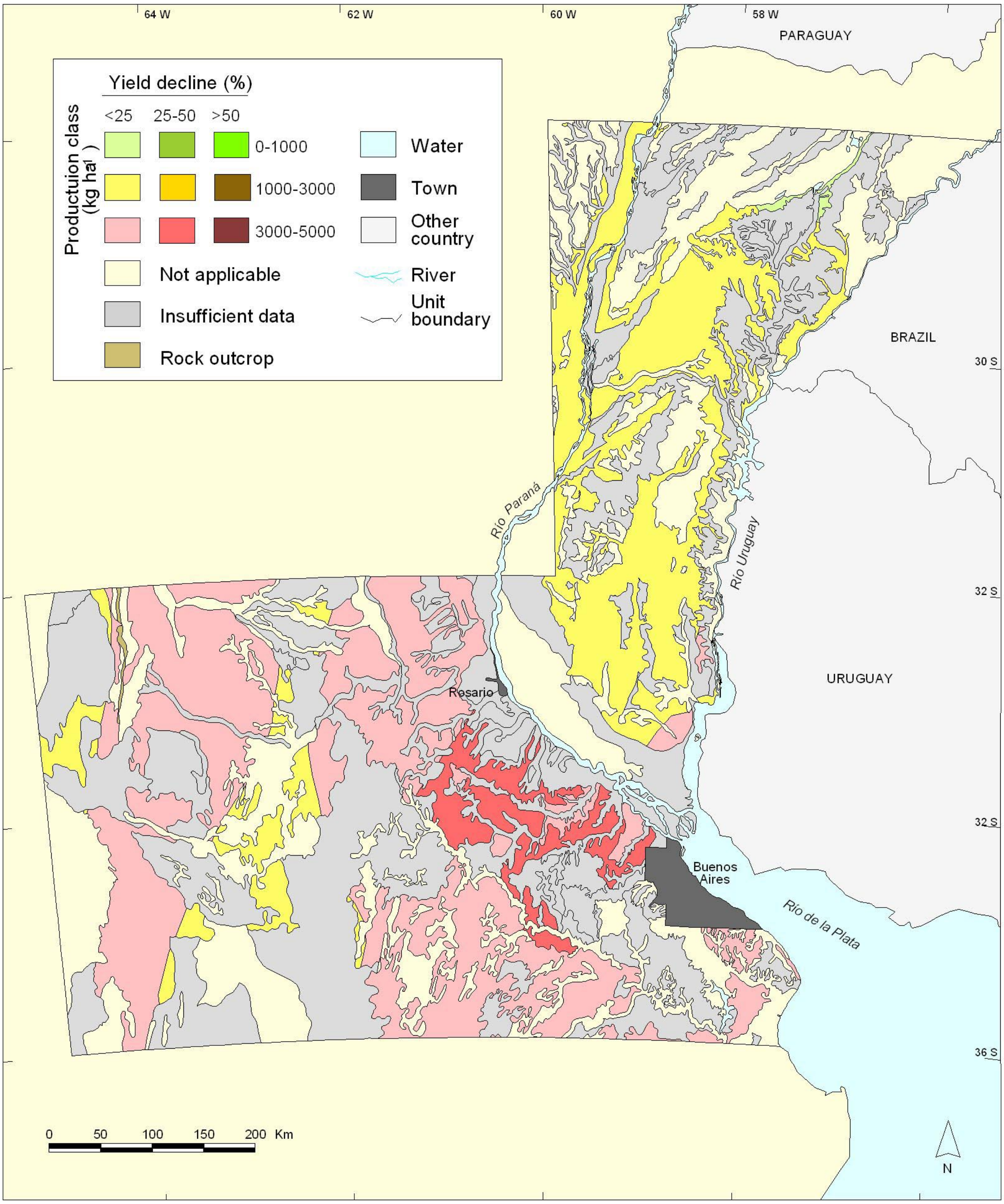


Figure 18.

Yield decline

Maps 9-12 in Volume 2, Appendix 2, illustrate the yields after simulated 20 years of soil erosion, while some statistics are given in Figure 16. The yield decline after years of simulated erosion is shown in Figures 17 and 18.

The map of nutrient-limited yield and the nutrient-limited yield decline map show that nutrient-limited yield would be little affect by top soil erosion. Only the area directly west of the capital, that had a topsoil loss scenario of 25 cm over 20 years, shows a yield decline of 25-50% in the high potential productivity class of 6-8 t ha^{-1}. The rest of the country is all in the <25% yield decline class. Apparently, the generally deep and moderately to highly fertile soils are reasonably unaffected in nutrient related productivity characteristics. Furthermore, the fertilizer additions will mask or diminish a possible effect of a lowered natural fertility capacity as a consequence of topsoil erosion.

Water-limited wheat yield potentials seem relatively unaffected by topsoil erosion. Only part of the moderate to high productivity zone (4-6 t ha^{-1} and 1-4 t ha^{-1}) N/NW of Buenos aires shows a high decline (25-50% and >50%). In the outer NW corner of the area, a >50% yield decline is shown for a low potential productivity area (0.5-1 t ha^{-1}). In this drier zone, the impact of changes in texture and hydraulic characteristics as a consequence of removal of topsoil by erosion can indeed be expected to be higher.

3.3 Kenya

Suitability

In the assessment of land suitability for maize in Kenya, the availability of water to the maize crop during the growing season is an important land quality. About 70% of the country is too dry for growing maize with a reasonable chance of success (see map 1 in volume 2, appendix 2 and Figure 19). Only in the coastal area and in the central and western highlands, sufficient water is available during the growing season. Areas at altitudes higher than 2000 m are unsuitable; temperatures are too low and growing periods too long. In the remaining not-too-dry areas, low soil fertility is a major constraint (very acid soils with an extremely low organic carbon content). Other limitations are excess of salts, poor drainage conditions and a low rootable soil volume.

Erosion risk assessment and scenario definition

The erosion hazard analysis has yielded Figures ranging from 0 to 1000 t ha-1 yr^{-1} (1000 is the default maximum output). When interpreted quantitatively this is rather high. In Ethiopia a wide range of annual soil losses were recorded on 54 test plots with varying slope (gradient and length), crop pattern and annual rainfall in multiple

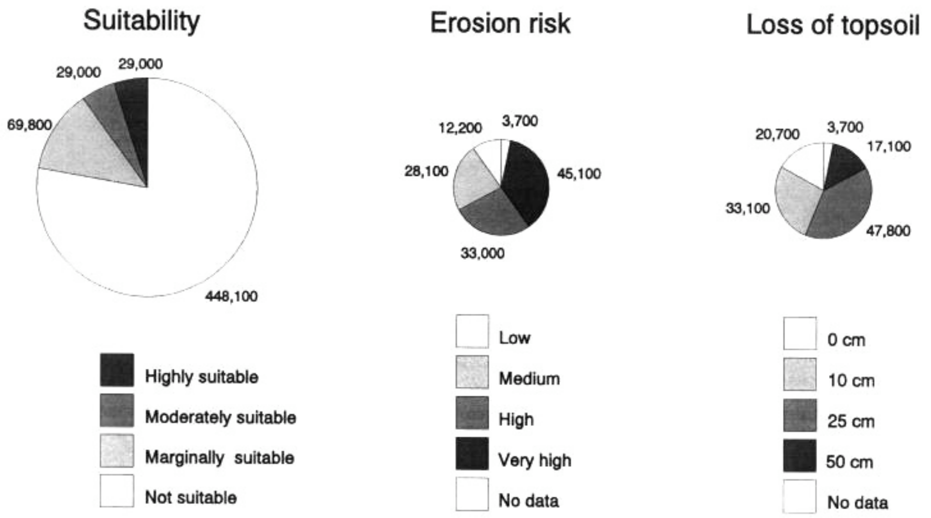


Figure 19. Proportions of suitability, erosion risk and loss of topsoil under maize in Kenya (figures in km^{-2}), for spatially dominant soils within each SOTER unit.

years (Hurni, 1985). Soil loss ranged from 0 t ha^{-1} yr^{-1} (e.g. 42% slope, 15 m length, 1038 mm annual rainfall and dense grass cover) to 300 t ha^{-1} .yr^{-1} (16% slope, 15 m length, 1831 mm annual rainfall and a crop of teff). It was decided to make a transformation of SWEAP units (ranging from 0-1000) to soil loss units within the boundaries of the extremes measured in Ethiopia (0-300 t ha^{-1} yr^{-1}). The assumption was that the deviation of SWEAP units from 'Ethiopian soil loss scale' is lower in the low SWEAP estimates and is higher in the higher ranges of SWEAP estimates. Therefore an exponential function was made for transformation of SWEAP units into soil loss estimates. Figure 20 shows a plot of the SWEAP transformation function.

In this function X represents the SWEAP calculated soil loss unit, Xt is the transferred X to the Ethiopian measured scale. For the case of Kenya the dominant factor determining hazard of erosion was the slope factor.

The map of erosion risk under maize shows a high variability. Erosion risk is highest in areas with high rainfall, with sloping lands and with soils derived from Basement rocks, in particular Acrisols and Luvisols. In the erosion scenario more than half of the units are assumed to loose 25 cm of topsoil or more over 20 years.

Crop production potentials

The suitable areas in Kenya have a high potential for growing maize. Solar radiation and temperatures are generally such that constraint-free yields are high: 10,000 - 15,000 kg ha^{-1} (see Map 2, Volume 2, Appendix 2 and Figure 19 for statistics). Obviously, water-limited yields are considerably lower (Map 3, Volume 2, Appendix 2). This is likely to be due to irregular rainfall patterns, and low water holding capacity, limited soil depth or excessive drainage of soils.

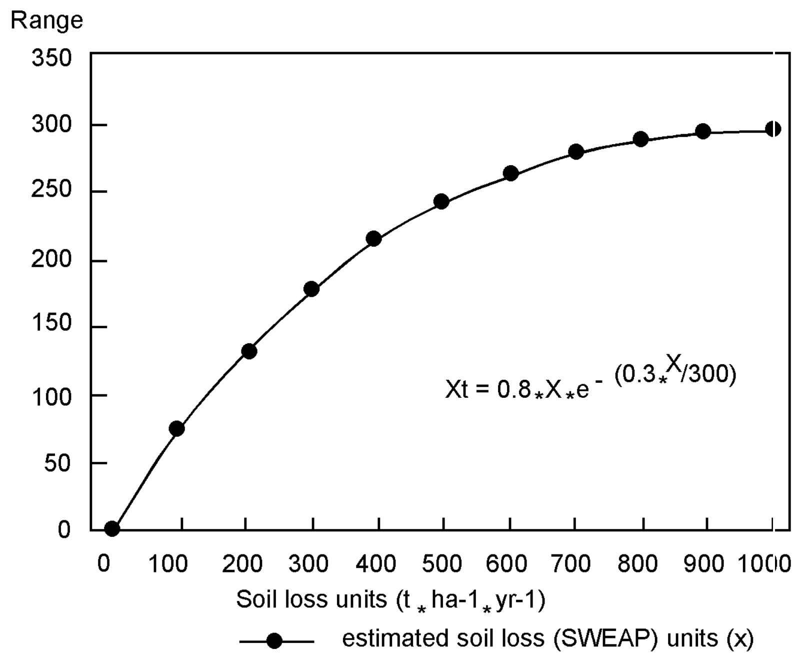


Figure 20. Transfer of SWEAP units to t ha^{-1} yr^{-1}soil loss.

Nutrient-limited yields (Map 4, Volume 2, Appendix 2) are very low for the major parts of the country suitable for growing maize: 60% of the dominant soils of the SOTER units have a nutrient-limited yield $\leq$ 2.5 t ha^{-1}, and 89% $\leq$ 5 t ha^{-1}. Some areas of Kenya have well drained, deep and highly weathered soils, which are deficient in major plant nutrients. Soils in West Kenya are notorious for their extremely low fertility (especially low in phosphorous). In the coastal areas, coarser textured soils predominate, with a low nutrient holding capacity.

Yield decline

In the very steep patches of land in the central and central-western part of Kenya, water-limited yield decline is higher than 50%. Notwithstanding this, the general trend shown in Figure 21 indicates that for many areas the soil physical properties would be little affected with the removal of top layers by prolonged sheet erosion. This may be explained by the fact that the dominant soils in Kenya considered suitable for maize growing have good physical properties: Ferralsols, Nitisols, etc. Nutrient-limited yields (Map 7, Volume 2, Appendix 2) are more affected by the loss of topsoil. This can be expected for many soils (Ferralsols) where the organic top layer largely determines actual fertility. The nutrient-limited yield decline after 20 years of erosion (Figure 21) shows a clear decrease. However, for many subsoils data on fertility characteristics are lacking. Therefore, many soils have insufficient data for the calculation of nutrient-limited yields after erosion and they are white in Figure 21.

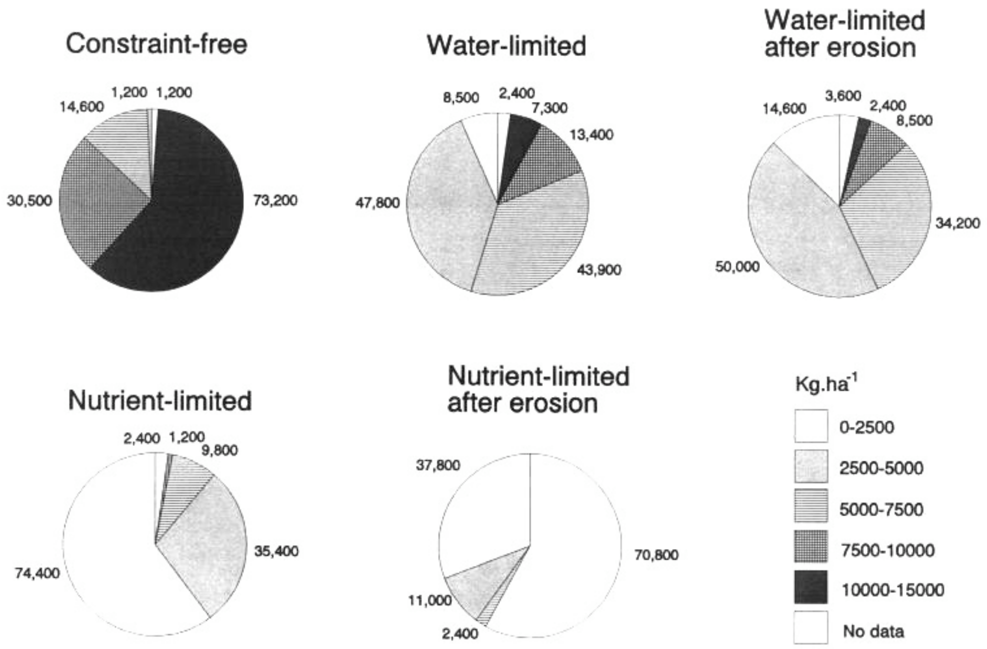


Figure 21. Proportions of maize yields in the various scenarios in Kenya (figures in km^{-2}), based on spatially dominant soils within each SOTER unit.

WATER-LIMITED MAIZE YIELD DECLINE after simulated 20 years of soil erosion

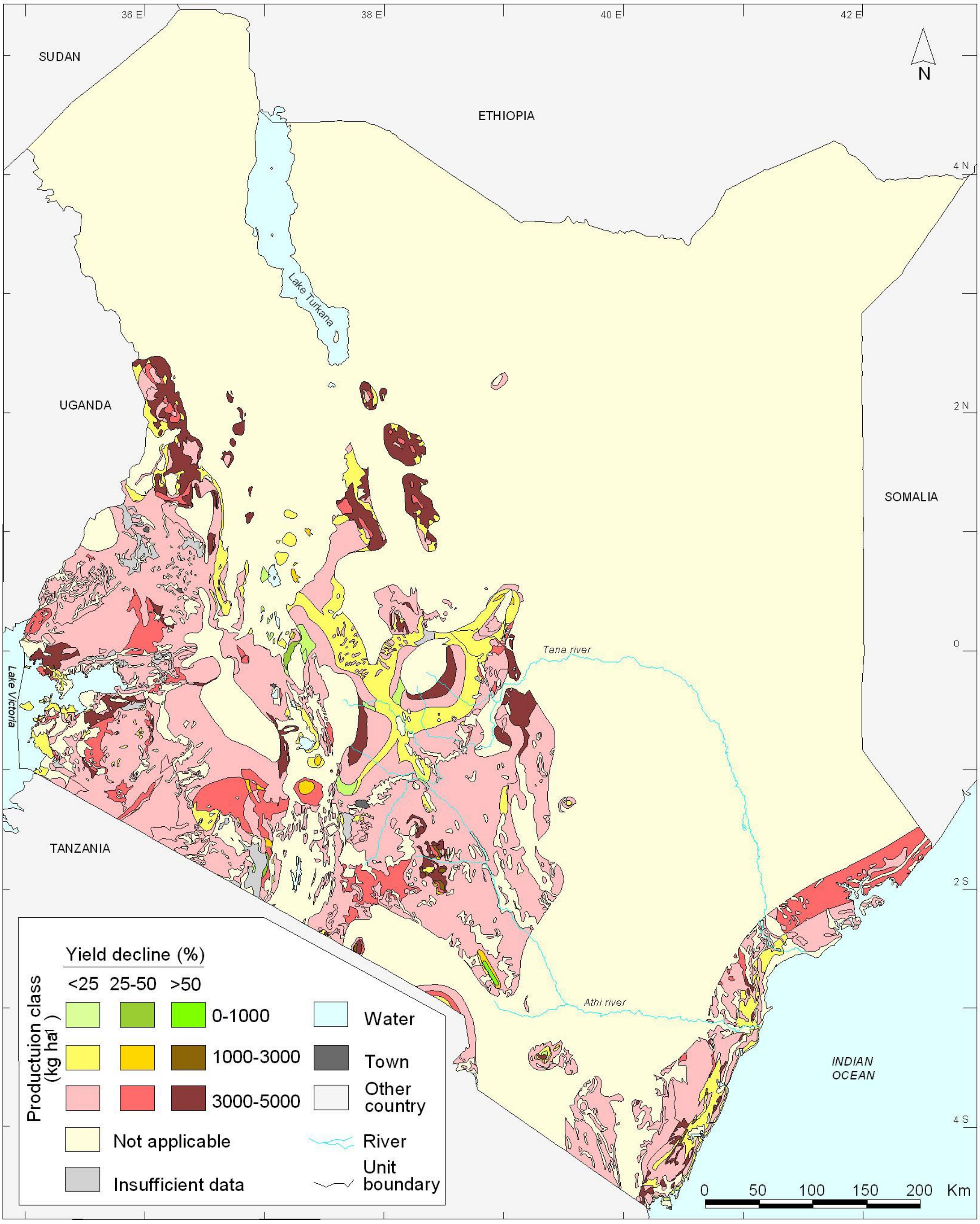


Figure 22.

NUTRIENT-LIMITED MAIZE YIELD DECLINE after simulated 20 years of soil erosion

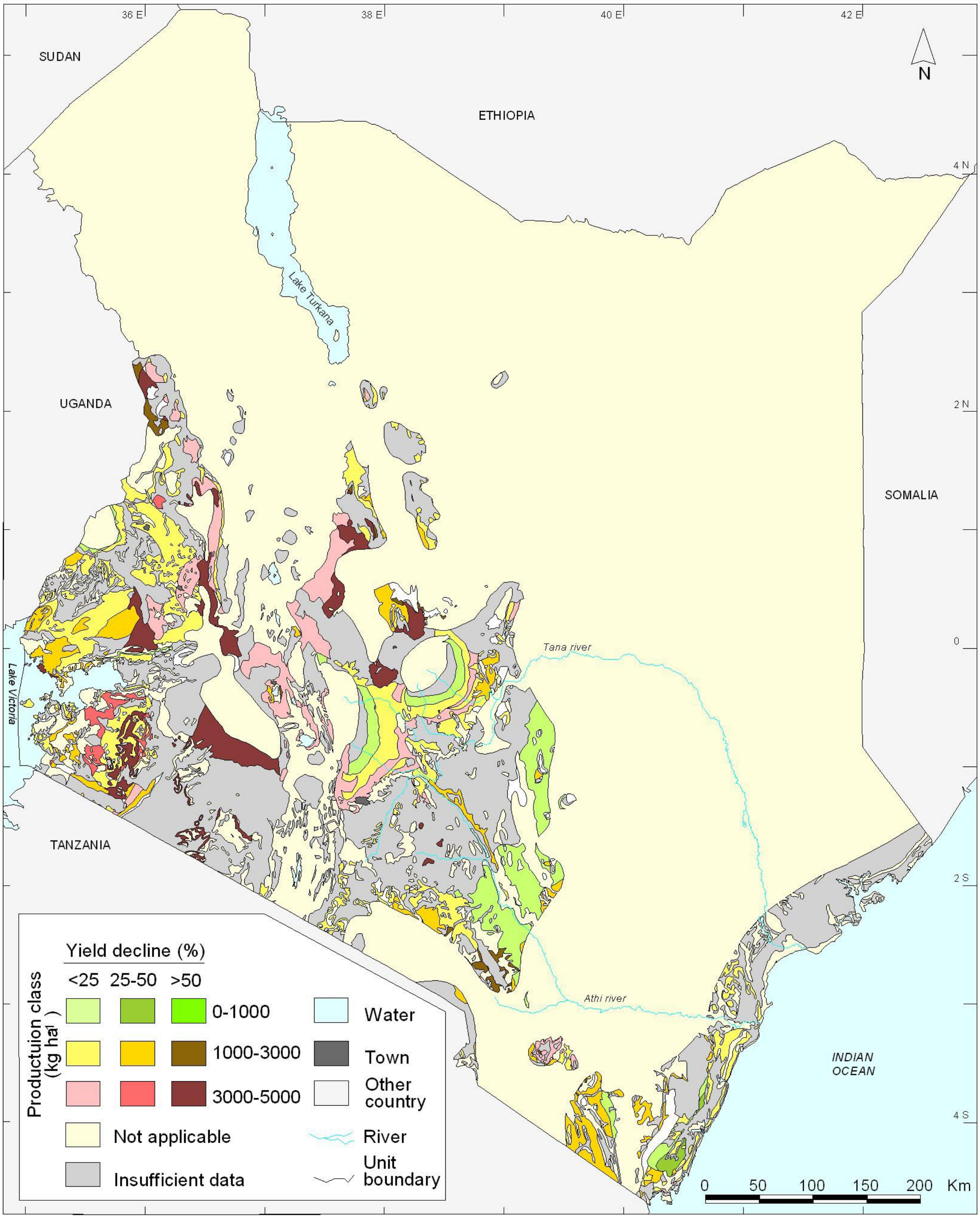


Figure 23.

4 CONCLUSIONS

The assessment of priorities areas for conservation measures, alternative land-uses or adopted land management techniques requires spatial information about land use systems and processes that take place within or between land units. This research has shown the potential of national SOTER databases for a scope of environmental assessments using varying techniques and models. A mixed qualitative/quantitative methodology was presented for erosion - productivity impact assessment.

This study supports the general idea that the impact of soil erosion on land productivity differs between terrain and soil units. It is shown that the deep soils rich in organic matter that predominate in Uruguay and Argentina will be less affected by varying degrees of soil erosion than many of the (deeply weathered) soils in Kenya. This was clear for the calculated nutrient-limited yield potentials, but was less obvious for water-limited yield potentials. Fertile soils may have a limited soil depth or have coarser textured or denser subsoils, which causes a potential water-limited yield decline when the topsoil is removed, and, on the other hand, chemically poor soils may have good physical properties (like Ferralsols).

The presented methodology for erosion - productivity assessment would become most useful when linked to socio-economic models. Once fully integrated, such pressure-state-response models provide a powerful tool to guide the planning of soil conservation at the regional level using the scenario analysis (Batjes, 1996a).

It would add to the value of the national SOTERs to include the results of the various studies (land evaluation, erosion hazard, crop production potentials, agro-regionalisation, etc) in separate files in the database. This file would give - for a combination of SOTER units and AEZs - for instance the suitability for different crop systems, calculated crop productivity potentials, erosion hazard, etc. With inclusion of socio-economic variables - by links to a socio-economic database - SOTER would become a national resources database to be used by specialists of varying disciplines, allowing for a wide range of integrated studies.

Uruguay

About half of the country is considered unsuitable for low input and mechanized wheat cultivation only considering dominant soils. Uruguayan soils are vulnerable to water erosion when a wheat crop is cultivated. Although relative differences in erosion risk are considerable, yield gaps (with constraint-free yield) are generally small for nutrient-limited yield and larger for water-limited yield. Limitations to wheat growth in Uruguay are mostly related to soil physical conditions. For the worst case scenario a considerable impact on potential water-limited wheat productivity is seen, although no clear relationship was found between the yield decline and severity of erosion (scenario). Nutrient-limited yield capacity of the generally fertile and organic matter rich soils is little affected by loss of topsoil. Only a few units which were assigned the worst scenario, show a yield decline of >50%.

Argentina

The larger part of this area in Argentina is considered suitable for medium to high input wheat cultivation. High silt contents and long slopes (hundreds up to thousands metres) are the cause of the high risk for erosion in well over half of the area. Moisture and nutrient limitations to growth are apparently low, since nutrient- and water-limited yield gaps are small. Yield decline after topsoil loss is affecting both nutrient- and water-limited yields. As potential yields are mostly limited by water stresses and fertility levels of most soils are adequate, is appears that yield decline due to losses in soil moisture characteristics is the major consequence of topsoil erosion. Fertilizer applications as practised in this land utilisation type can mask the effect of possible soil fertility constraints or decrease in soil fertility as a consequence of top soil erosion.

Kenya

A major part of Kenya is too dry for growing maize with a reasonable chance of success. The major part of Kenya where maize can be grown is estimated to be highly to very highly vulnerable to erosion, for which slope is the dominant determining factor. The suitable areas in Kenya have a high potential for growing maize. However, considerable yield gaps were found and they may be explained by low soil fertility, poor soil physical conditions or irregular rainfall patterns.

In the very steep patches of land in the central and central-western part of Kenya, water-limited yield decline is very high (>50%). Nutrient-limited yield potentials are more affected by the loss of topsoil which may be explained by low fertility status of many soils (o.a. Ferralsols) for which the organic top layer largely determines actual fertility conditions.

5 DISCUSSION

Basic data sets for evaluation

Since the use of soil survey data has shifted from map and report production to database development that allow for automated interpretations for various purposes, emphasis in sampling and soil description in present and future surveys should be on the possible uses of the data in several fields of analysis (model input requirements). For assessments on constraints and potentials for land use and land management, not all of the soil data inventoried in standard soil surveys are relevant and, on the other hand, land properties that reflect the functioning of land are not always measured on a routine basis. This often applies to soil physical data -data on water holding capacity, bulk density and conductivity of the soil- and some of the fertility parameters required by models (e.g. P-Olsen in the QUEFTS methodology). These data are sometimes only available for the topsoil but in the erosion scenario they are also required for the subsoil.

This study showed that SOTER databases provide a solid basis for a wide range of interpretations. Relatively few data gaps existed in the national SOTER databases used in this study (covering large areas) and, where they existed, transfer functions were used to infer the characteristics from key soil parameters. Moreover, in Kenya where soil profile data were not measured, estimated data were used (see Map 13 in Volume 2, Appendix 2). National institutes should put high priority to filling data gaps of relevant land properties. Additional measurements allow for development of local PTF=s on the basis of which values can be inferred from other land properties.

The quality of model output can never be better than that of the basic data. Uncertainty in model output is determined by several factors in particular the assumptions and generalizations in the models (especially for expert- and parametric models):

1) the method used for spatial aggregation and linking of climate and soil and terrain data

2) the representativity, completeness and quality of the basic data; this does not only apply to soil, terrain and climatic data, but also to the crop variety data in the files of the crop growth simulation model

3) the representativity of applied PTF's for filling of data gaps

4) translation of erosion hazard units into a erosion scenario.

Suitability assessments

Assessments of areas suitable for the defined LUT=s using an ALES based model as a first stratification of the data, proved to be efficient. National experts assisted in definition of the criteria and judging the outcomes. Ideally field checks should complement the expert judgements. The model can be extended with other regionally relevant crops and, especially when including economic parameters, and provide information on options and limitations for land use - 'agro-regionalization'- on a national basis.

Erosion hazard unit and scenario definition

The USLE cannot predict deposition. No account is taken of the possibility of soil deposition related with soil removal. Erosion tends to be overpredicted. Assumptions were made when translating the erosion hazard units into topsoil loss classes over a 20 year time span. It was felt, however, that not the exactness of the predicted thickness of the top soil layer lost over 20 years was most important, but that a scenario was defined that takes the variability of land an climate into account.

Production calculations

The calculated crop production levels indicate possibilities and constraints within prevailing bio-physical conditions and allow for an estimate of yield decline as a consequence of loss of topsoil due to water erosion. The production levels calculated under differing agro-ecological conditions, are comparable to LUT's. The constraint-free yield is approximated in irrigated, high input agriculture (most constraints are counterbalanced or neutralized), water-limited production is approximated in rainfed, high-input agriculture. Although the complexity of the actual farmer's environment is not simulated (e.g. the effect of pest 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. This research was conducted to study the impact of soil erosion on bio-physical functions of land. A follow-up of this study using scenario=s that take into account socio-economic conditions would be a valuable extension of this research.

The crop growth model applied is essentially a point model. The model was run on point data, which are considered representative of basic -internally homogeneous-mapping units. The overlay of climate with soils- and terrain maps yielded new units; Agro-Ecological Units (AEUs), which formed the basis for further evaluation. Within these units, only the spatially dominant soil component was considered in the analysis. The fact that the compound nature of the SOTER units were not taken into account, distorts the outcome when represented on maps. However, the study was meant to highlight trends for different scenario=s and therefore basing the analysis on spatially dominant soils was considered justified.

In some cases the texture shift as a consequence of simulated loss off topsoil, caused the water-limited yield 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.

REFERENCES

Barrow, C.J., 1991. Land Degradation C Development and Breakdown of Terrestrial Environments, Cambridge University Press, Cambridge.
Batjes, N.H., 1996a. Global assessment of land vulnerability to water erosion on a 2E by 2E grid. Land Degradation & Development, 7(4), p. 353-365.
Batjes, N.H., 1996b. A qualitative assessment of water erosion risk using the 1:5 M SOTER database for Argentina, south-east Brazil and Uruguay. Working Paper and Preprint 96/04. ISRIC, Wageningen.
Biot, Y. and X.X. Lu, 1995. Loss of yield caused by soil erosion on sandy soils in the UK. Soil Use and Management, 11, 157-162.
Biswas, M.R., 1994. Agriculture and Environment: A review, 1972-1992. Ambio, 23, 192-197.
De Wit, C.T., and H. van Keulen, 1987. Modelling production of field crops and its requirements. Geoderma, 40, 253-265.
Driessen, P.M., 1986. Erosion hazard and conservation needs as a function of land characteristics and land qualities. In: Land Evaluation for Land-Use Planning and Conservation in Sloping Areas (ed W. Siderius), p. 32-39. ILRI, Wageningen.
FAO, 1988. FAO-Unesco Soil Map of the World, Revised Legend, with corrections. World Soil Resources Report 60. FAO, Rome.
FAO, 1992. AMDASS, AgroMeteorological Data Systems, FAO Agroclimatic data bases. FAO, Rome.
FAO, 1994. Digitized Maps of the Major Climatic Divisions and Lengths of Growing Period Zones for the Developing World. FAO, Rome.
FAO, 1995. The State of Food and Agriculture 1995. FAO Agriculture Series, 28. FAO, Rome.
FAO-Unesco, 1974. Soil Map of the World (1:5,000,000), Volume 1-10. Unesco, Paris.
Hurni, H., 1985. Erosion, Productivity, Conservation Systems in Ethiopia. In: Soil Conservation and Productivity, 1, 2. Proceedings IV International Conference on Soil Conservation, Maracay, Venezuela. p. 654-674.
Hurni, H., 1996. Precious Earth: From Soil and Water Conservation to Sustainable Land Management. International Soil Conservation Organisation(ISCO) and Centre for Development and Environment (CDE), Berne.
Janssen, B.H., F.C.T. Guiking, D. van der Eijk, E.M.A. Smaling, J. Wolf and H. van Reuler, 1990. A system for quantitative evaluation of tropical soils (QUEFTS). Geoderma, 46, 299-318.
Mantel, S., 1995. The Automated Land Evaluation System applied to SOTER, with an example from West Kenya. Working Paper and Preprint 95/03. ISRIC, Wageningen.
Oldeman, L.R., 1994. The global extent of soil degradation. In: Soil Resilience and Sustainable Land Use (eds Greenland D.J. and I. Szabolcs), p. 99-118. CAB International, Wallingford.
Oldeman, L.R., R.T. Hakkeling and W.G. Sombroek, 1991. World Map of the Status of Human-induced Soil Degradation. Explanatory note. UNEP-ISRIC, Nairobi, Wageningen.
Pulles, J.H.M., J.H. Kauffman and J. Wolf, 1991. A user friendly menu and batch facility for the crop simulation model WOFOST v4.3. Working Paper and Preprint 91/09. ISRIC, Wageningen.
Rijtema, P.E., 1969. Soil moisture forecasting. ICW Nota 513-III. ICW, Wageningen.
Rossiter, D.G., 1990. ALES: a Framework for Land Evaluation using a Microcomputer. Soil Use and Management, 6, 7-20.
Smaling, E.M.A. and B.H. Janssen, 1993. Calibration of QUEFTS, a model predicting nutrient uptake and yields from chemical fertility indices. Geoderma 59, 21-44.
Sumner, M.E., 1990. Field experimentation: Changing to meet current and future needs. In: Soil testing: Sampling, Correlation, Calibration and Interpretation (Eds J.R. Brown, T.E. Bates and M.L. Vitosh), 3rd edition. SSSA special publ. 21, Madison.
Terzaghi, A., 1996. Soil Management for Improvement of Soil Physical Characteristics related to Erosion in Uruguay. PhD. Thesis. Wageningen.
UNEP/EAP, 1995. Report on the UNEP/RIVM Workshop on UNEP's Pilot Global Environmental Outlook Project Focusing on Land Degradation and Food Production. Meeting reports, UNEP/EAP.MR/95/4. RIVM, Bilthoven.
United Nations, 1992. Long Range World Populations Projections (1950-2150). Department of International Economic and Social Affairs, New York.
Van den Berg, M. and P. Tempel, 1995. SWEAP, A Computer Program for Water Erosion Assessment applied to SOTER. Documentation version 1.5. SOTER Report 7. ISSS, Wageningen.
Van Diepen, C.A., H. van Keulen, J. Wolf and J.A.A. Berkhout, 1991. Land evaluation: from intuition to quantification. Adv. Soil Sci. 15, 139-204.
Van Diepen, C.A., J. Wolf, H. Van Keulen and C. Rappolt, 1989. WOFOST: a Simulation Model of Crop Production. Soil Use and Management, 5, 16-24.
Van Engelen, V.W.P. and T.T. Wen (eds), 1995. Global and National Soils and Terrain Digital Databases (SOTER), Procedures Manual (revised edition). UNEP, FAO, ISSS, ISRIC, Wageningen.
Van Keulen, H. and J. Wolf (Eds), 1986. Modelling of Agricultural Production: Weather, Soils and Crops. Simulation Monographs. Pudoc, Wageningen.

Van Lanen, H.A.J., M.J.D. Hack-ten Broeke, J. Bouma and W.J.M. de Groot, 1992. A mixed qualitative/quantitative physical land evaluation methodology. Geoderma, 55, 37-54.
Wishmeier, W.H. and D.H. Smith, 1978. Predicting rainfall erosion losses - a guide to conservation planning. Agriculture Handbook No. 537. US Dept. of Agriculture Washington D.C.
Young, A. 1994. Modelling changes in soil properties. In: Soil Resilience and Sustainable Land Use (eds Greenland D.J. and I. Szabolcs), p. 423-447. CAB International, Wallingford.