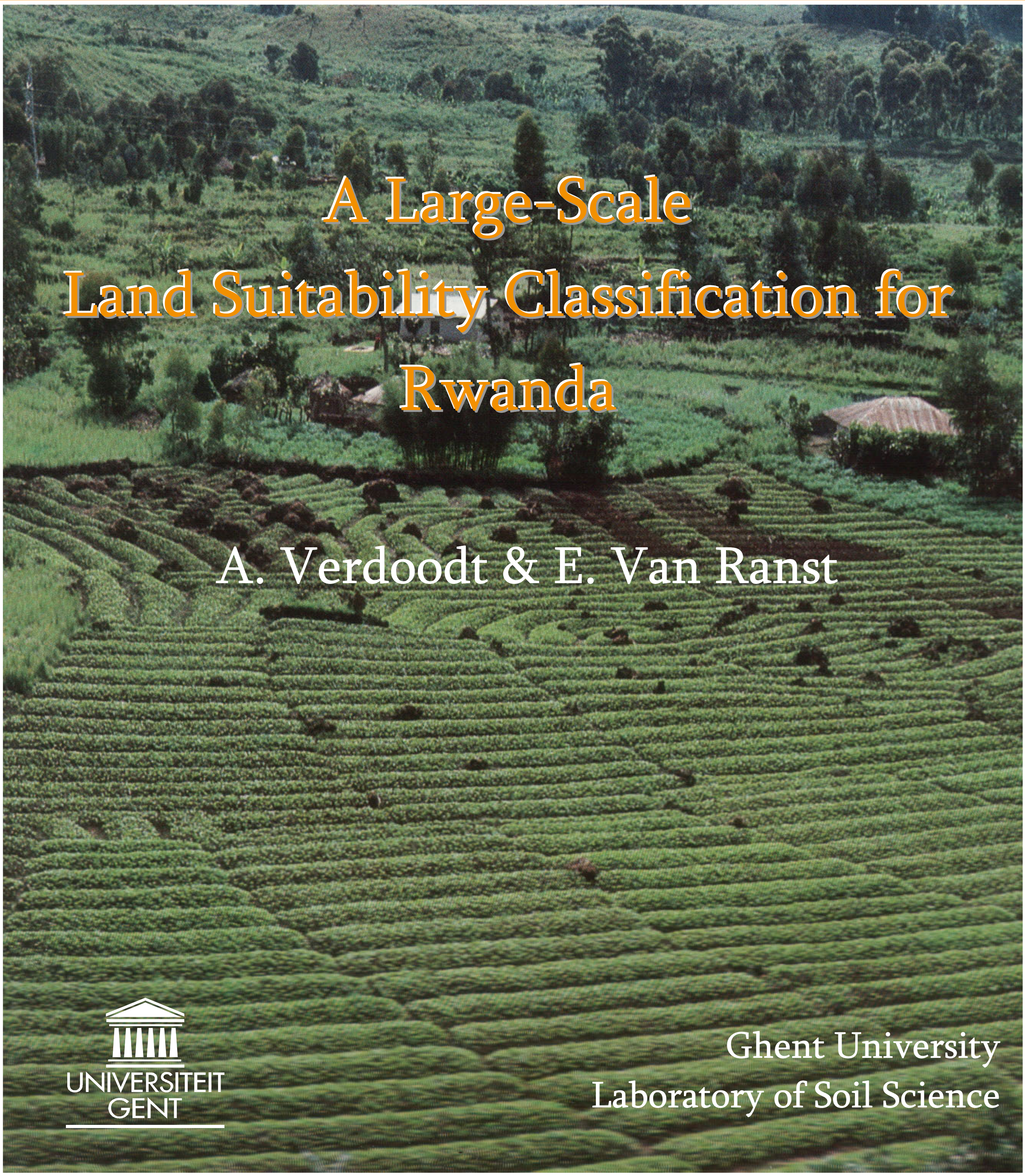
Land Evaluation for Agricultural Production in the Tropics



A Large-Scale Land Suitability Classification for Rwanda

A. Verdoodt & E. Van Ranst

UNIVERSITEIT GENT

Ghent University
Laboratory of Soil Science

In response to ongoing land degradation and decreasing yields, the new agricultural policy in Rwanda is oriented towards intensification, regionalisation and specialisation, based on optimal use of the available natural resources. Through the integration of experimental knowledge, geographical information systems and land evaluation tools, the authors elaborated two land classification systems that permitted to explore the available resources and offer guidelines for their rational exploitation. The land capability classification procedure at scale 1:250,000, identifying the capability of the land for crop production, grazing and forestry, permitted to select the arable land. The crop-specific land suitability classification for 12 subsistence and industrial crops revealed the options for a stronger regionalisation of the Rwandan agriculture.

Title of related interest:

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A. Verdoodt and E. Van Ranst

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CHAPTER 1. INTRODUCTION

1.1. Focus on Rwanda

Rapid population growth and declining agricultural productivity affect the livelihoods and very survival of millions of rural households throughout sub-Sahara Africa. Perhaps nowhere have these effects been deeper or have they created greater hardship than among the farm population of Rwanda, where over 90 % of the people live in rural areas and where virtually all, rural households are engaged in agriculture (Clay, 1996).

1.1.1. Physical environment

Rwanda is a small mountainous country of 26,338 km² located at the centre of Africa, and enclosed by Uganda in the North, Tanzania in the East, Burundi in the South and Congo in the West. The landscape is dominated by hills with forested tops and cultivated hillsides ending in marshy valleys. Because of the high altitude, ranging between 970 and 4,507 m, this equatorial country is characterised by a sub-equatorial climate. Temperature is relatively stable during the year, and ranges between 15 and 25 °C depending on the altitude. The highlands also receive more rainfall (> 2,000 mm annually) than do the lowlands, where the annual rainfall totals drop below 1,000 mm. Two rainy seasons, centred round April and November, and alternating with two dry seasons, can be distinguished. Nevertheless, even though the annual rainfall is relatively well distributed, rainfall events are erratic, especially in the East.

1.1.2. Agriculture

The diversity in climatic conditions allows an important diversification from crops suited for tropical areas to crops adapted to temperate climatic conditions. The favourable temperature regime allows three agricultural seasons yearly. Two of these seasons correspond with the two rainy seasons. From June to September, a third harvest is possible of crops cultivated in the imperfectly to poorly drained valleys. Historically, Rwandan farmers settled along the upper ridges of their hillsides where soils were more fertile and cultivation was a simpler task than it was further down on the steeper slopes and in the marshy valleys. Immediately surrounding the household compound, they planted groves of bananas and other essential crops. Beyond the inner ring of bananas, a series of outer rings was customarily used to meet other nutritional needs of their households. The first one was cultivated intensely with annual crops for both home consumption and sale. Further down the hillside they grew coffee. Beyond the coffee plots, the slope of the hillside was often at its steepest. The farmers reserved these areas for pasture and woodlots as well as for less important crops with frequent fallow periods. At the very outer rings, toward the base of the slope and in swampy valleys, they raised sweet potatoes and vegetables along ridges that were built to facilitate water drainage (Clay, 1996).

1.1.3. Problems of land scarcity and demographic pressure

In this small and very densely populated country, food production is insufficient to feed the population, nowadays exceeding 8 millions of inhabitants. In the past, Rwandan farmers have been able to exploit other areas of the country in response to the growing demographic pressure. In particular they moved to the drier eastern provinces that were previously the domain of the pastoralist population. Today, in absence of unoccupied lands, farmers cultivate the same holdings year after year and in an increasingly intensive fashion. Land scarcity now has compelled farmers all over the country to depart from their traditional system and convert pastures and woodlots into cropland and cultivate fragile, steep-sloping fields. On average, the farms are smaller than 1 hectare (Clay, 1996). Other characteristics of the subsistence agriculture in Rwanda are the lack of individual and regional specialisation, a weak integration between agriculture and the economic markets and an important dependence on the climatic conditions (Imerzoukene and Van Ranst, 2001). Beans and sorghum, supplemented by sweet potatoes, cassava and peas are the principle food staples. Coffee and tea are important cash crops. Erosion and nutrient mining however, result in a serious decrease of the physical and chemical soil fertility and affect crop yields.

1.1.4. Facing food insecurity and land degradation

The government recognizes the environmental threats and food insecurity and follows a new agricultural policy, emphasising the importance of:

- regional specialisation in order to profit from the environmental diversity of Rwanda and to maximise the yields of the most suitable crops in each region;

- diversification of the agricultural production in order to meet the national and international demands and integrate agriculture on the economic markets;
- intensification through the use of additional inputs (fertilisers) in order to increase the yields;
- optimal valorisation of all available land through feasible practices controlling the availability of water and nutrients; and
- education of the farmers so that they are able to select relevant management options (Imerzoukene and Van Ranst, 2001).

Knowledge of the soils, their properties and their spatial distribution, is indispensable for the agricultural development of Rwanda as it opens opportunities for a more rational management of the land resources. During the soil survey project entitled “Carte Pédologique du Rwanda”, started in 1981 and realised through a cooperation between the Rwandan Ministry of Agriculture, Livestock and Forestry and the Belgian government, much of this essential soil information at scale 1:50,000 has been gathered, analysed and stored in a large digital database. In addition, this database is being extended with information on the hydrology, topography and climate. The resulting natural resources database has become the key instrument for the description of the physical environment that farmers face in the different agricultural regions of the country and for the evaluation of the agricultural potentialities.

1.2. Focus on land evaluation

Whereas the necessary input data for the agricultural research mainly became available through the realisation and updating of the digital natural resources database, the methods for investigation of the agricultural potential of land have been found in the research topics on land evaluation. This book describes the development and application of two qualitative land evaluation tools, adapted to the specific environment in Rwanda.

1.2.1. Land capability classification

The land capability classification system is mainly based on data that became available during the reconnaissance soil survey. Land, in this context, is defined by the landscape and physical and chemical soil properties of the soil map units at scale 1:250,000. The classification system offers a framework for the description of this natural resources database and determines the capability of the land for crop production, pastures, forestry and conservation or recreation.

1.2.2. Land suitability classification

The land suitability classification incorporates crop-specific requirements to determine the suitability of the land for the cultivation of several crops. Land, at this level, is not only determined by the topographic and edaphic properties at scale 1:250,000 but also by monthly climatic data recorded in several meteorological stations. The same procedure can be repeated at regional level using the soil maps at scale 1:50,000.

1.3. Outline

Chapter 2 summarises briefly the activities of the soil survey project that initiated the creation of the large natural resources database of Rwanda. It concludes with a description of the agricultural zones of Rwanda, defined by Delepierre in 1974. Chapter 3 and 4 describe the land capability classification and land suitability classification, respectively. The internal structure of both chapters is more or less alike and starts with a description of the input data, followed by the elaboration of the methodology and ending with a description and discussion of the results. Chapter 5 summarises the main results with respect to the agricultural potential of the Rwandan land revealed by the application of both land evaluation tools.

CHAPTER 2. HISTORICAL BACKGROUND

2.1. Project "Soil map of Rwanda"

In Rwanda, information on the available land resources was gathered, stored and analysed during the project named "Carte Pédologique du Rwanda". The amount of information was so large that the only practical way to store, manipulate and access the information was through the use of a computerized database. Today, this digital soil database is extended with other land resources data, and several applications using geographical information systems (GIS) and remote sensing have been conducted, directing the way to sustainable land use.

2.1.1. Soil survey

The soil survey of Rwanda started in 1981 and was finalized in 1994. Initially, the intention of the soil survey was to map Rwanda at a scale 1:100,000. However, the geologic and geomorphologic complexity of the Rwandan land and the multiplication of rural projects required more detailed soil information, which resulted in a modification of mapping scale to 1:50,000. This semi-detailed soil survey, based on extensive use of aerial photographs and fieldwork, was accomplished through several steps (Birasa *et al*., 1990):

- elaboration of a physiographic map;
- execution of the reconnaissance survey;
- identification of pilot zones for semi-detailed soil survey;
- establishment of a soil legend;
- drawing of the complete soil map covering Rwanda; and
- performing a final field check

2.1.2. Elaboration of the digital land resources database

From 1989 onwards, the soil maps and all observation points with their corresponding data were stored in a master natural resources database using GIS and database software. Stopped in 1994 due to the war in Rwanda, the digital storage of the soil data was later finalized at Ghent

University, Belgium (1998-2000). Both the activities in Rwanda and at Ghent University were financed by BADC (Belgian Administration for Development Cooperation).

Topographic data

The base maps for the soil survey were the 43 topographic maps at a scale 1:50,000 that became available after 1987. These maps contained contour lines at an equidistance of 25 m. Additionally they also supplied the limits and names of the administrative units at different levels (provinces, villages, hills), together with the hydrologic network, the road infrastructure and the land use. Numerisation of the topographic data was realised by scanning the hardcopy maps and vectorising, geo-referencing and coding of the digital data. ArcView software and the 3-D Analyst extension were used to derive a digital terrain model (DTM) for each of the 43 topographic map sheets (Van Ranst and Imerzoukene, 2001). These DTMs are useful to derive slope maps or to perform other analyses with regard to hydrology and erosion.

Soil data

The national soil survey resulted in the elaboration of 43 soil maps, at a scale 1:50,000 covering the whole of Rwanda. The soil units were mainly associations or complexes of soil series. More than 2000 soil profiles, corresponding to 176 different soil series had been described and analysed. The automation of the soil data started with the digitising of the hardcopy maps by use of the GIS software ARC/INFO. Each soil unit received a unique label that was related to a numerical database with the tabulated properties of each soil series. A colour legend was designed to group the different soil units according to their parent material, profile development, depth or drainage, texture and stoniness. Other thematic layers, extracted from the topographical maps, were added to complete the soil maps with information on the administrative units, the road infrastructure and the hydrographical network. Later, also the location of the soil profiles was digitised.

The spreadsheets containing the profile description and analytical information were imported in an Access database. Relationships were built between three tables, containing the general profile information, the horizon descriptions, and the horizon analytical data. Querying the database was thus much simplified. Through the use of the unique soil profile number, these numerical data can be easily linked with the cartographic data. Moreover, the Access database offered a framework for adding additional data and making reports.

These soil survey data were also simplified to produce maps at scale 1:250,000 of landscape units, soil associations, important rivers and roads and the largest administrative units such as the provinces and villages.

Climatic data

During the national soil survey, a time series of monthly climatic data, recorded from 1974 to 1989 in 197 meteorological stations by the Rwandan meteorological service has been gathered too. Rainfall data were available for each of these stations. Temperature and humidity have been measured in part of them, while the values for the other stations have been estimated through a correlation with the altitude. All numerical data were stored in an Access database. Small maps with the location of the meteorological stations, the isotherms and the isohyets were produced, broadly illustrating the different climatic zones of the country. Again, both databases can be linked through a common field, in this case the name of the meteorological station, to analyse the spatial variability of the climate.

Recently, the climatic database has been extended with data from the Meteorological Service in Kigali. This database contained daily temperature, rainfall, relative humidity, sunshine duration, wind direction and wind speed data, recorded in different meteorological stations over a time period varying from a few years to several decades, depending on the station.

2.1.3. Land resources database: a tool for future research

The structure and potential use of the Rwandan soil database is given in Fig. 2.3. GIS is an indispensable tool for map analysis and design of land evaluation purposes. The labels of each soil mapping unit, forming the skeleton of the final soil database, are related to the tabular database containing essential soil properties, to form an integrated soil coverage, comprising both spatial and descriptive data. As such, numerous typical maps, i.e. soil fertility and land suitability maps, can be derived from the soil map and plotted automatically. The soil data systems can also be linked to quantitative land evaluation models to predict parameters as expected crop yields and population supporting capacity. The database is thus a powerful tool for agricultural and land use planning purposes in Rwanda. As such, the soil survey is at the same time the output of a valuable project, and the input for future research (Van Ranst *et al.*, 2001).

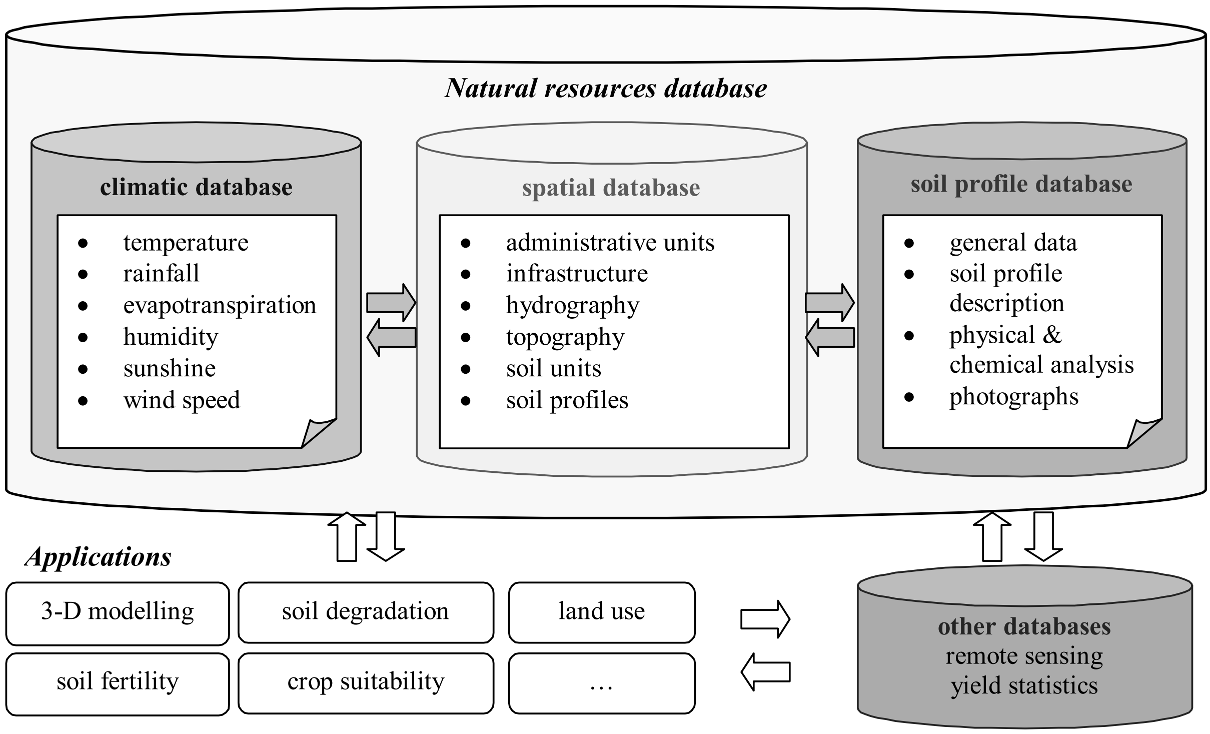
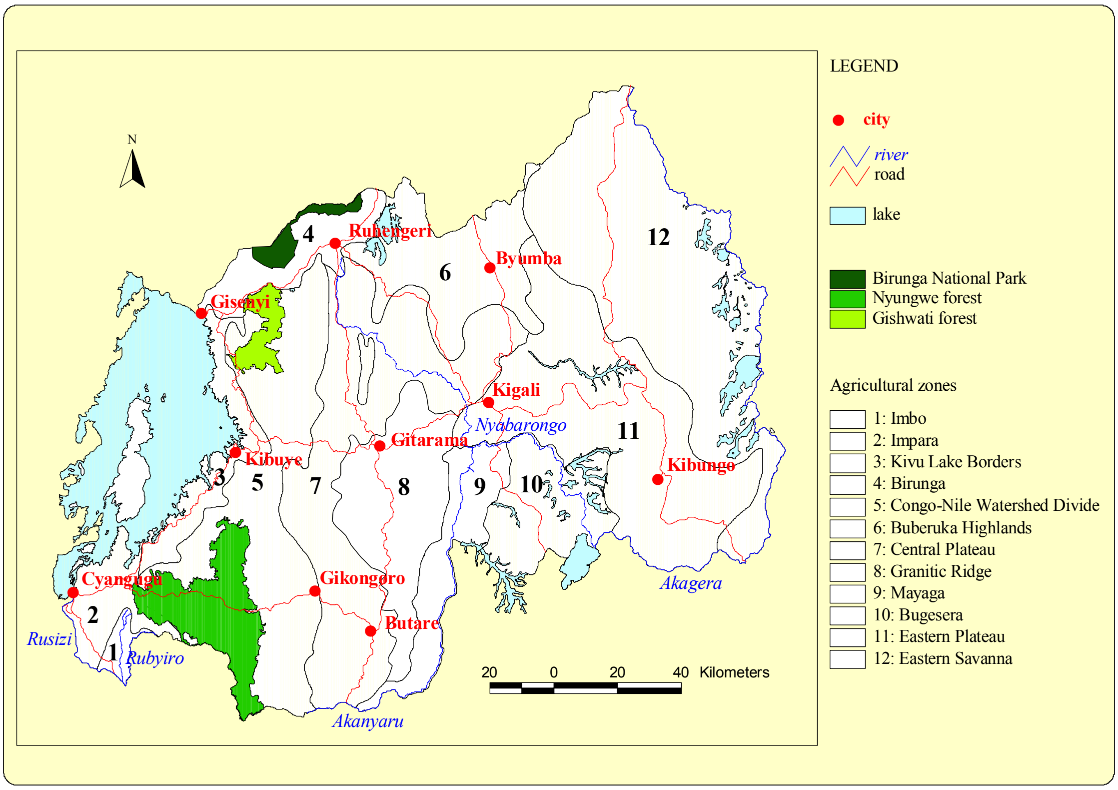


Fig. 2.3: Structure and potential use of the natural resources database

2.2. Agricultural zones in Rwanda

Land productivity depends on the chemical and physical properties that characterise the soil. These properties vary with the underlying parent material that weathers into mineral soil upon the impact of climatic elements such as temperature and rainfall. The nature of this substrate, the slope gradient, the altitude, the natural vegetation and the management practices further influence the degree of soil conservation or erosion. The agricultural potential of a region results from the interaction of all these interdependent factors. As such, Delepierre (1974) delimited 12 agricultural zones in Rwanda, based on differences in altitude, rainfall regime and soil properties (Map 2.1). Each zone has a unique combination of land resources that determines the range of well-adapted crops. A brief description of the climatic, topographic and edaphic characteristics of these zones has been given below.



Map 2.1: Agricultural zones in Rwanda

Imbo

The Imbo, located in Southwest Rwanda, is the smallest agricultural zone. Its centre, made up by the alluvial valleys of the Rusizi and Rubyiro includes the lowest point of the country, at an altitude of 970 m. A series of mountain ridges however, attaining an altitude of 1,400 m characterise its borders. An average temperature of 24 °C and a dry season of 3 months characterise the tropical climatic conditions. The annual rainfall totals increase considerably from about 1,050 mm in the South to 1,600 mm in the North. The high temperatures and abundant rainfall together with the good quality alluvial soils and the possibilities for irrigation offer many possibilities for an intensive and productive agriculture.

Impara

The Kivu Lake, the Imbo and the forest on the Congo-Nile Mountain Ridge border the second agricultural zone of the Impara. Its altitude ranges between 1,400 and 1,900 m. With increasing altitude, the annual rainfall increases from 1,300 to 2,000 mm, while the temperature decreases from 22 °C to 19 °C. The very fine clayey soils, developing from basalt, have a high agricultural potential at least if they are not leached out by the abundant rainfall. The mild climate, associated with abundant rainfall, generates optimal conditions for the cultivation of a lot of traditional and industrial crops.

Kivu Lake Borders

The shores of the Kivu Lake, extending from an altitude of 1,460 m near the lake up to 1,900 m on the western slopes of the Congo-Nile mountain chain, constitute the third agricultural zone. The lake tempers the climate of the region, characterised by a temperature ranging between 19 and 22.5 °C and an average annual rainfall between 1,150 and 1,300 mm. Nevertheless, within the agricultural zone, clear differences in rainfall amounts have been recorded. The South and North are clearly more humid than the central region of Kibuye. With respect to the soilscape, moderately fertile soils developing on shales and granites have been recorded on the gently sloping hillsides, while the abrupt slopes are strongly eroded, leaving skeletal soils.

Birunga

The agricultural zone of the Birunga groups the volcanic soils that descend from the limit of the national park at an altitude of 2,500 m to an altitude of 1.900 m near Ruhengeri and even below 1,600 m near Gisenyi. Regularly distributed rainfall, varying between 1,300 and 1,600 mm and fertile soils create favourable conditions for agricultural production. Limitations due to the generally limited soil depth have been removed by cultivating the crops on small ridges created when ploughing or harrowing the fields.

Congo-Nile Watershed Divide

The fifth agricultural zone occupies the highland area, extending from the Nyungwe forest in the South and to the Gishwati forest in the North, that divides the country into two watersheds. All rivers on the left side of this mountain chain drain into the Congo River, while all rivers on its right side drain into the Nile. The lower altitude boundary is 1,900 m and corresponds to the altitude above which most crops of the tropical lowlands are badly adapted. The tops of the mountain chain surpass an altitude of 2,500 m. In the North, the annual rainfall varies between 1,300 and 1,500 mm, while in the South annual rainfall totals between 1,400 and 1,800 mm have been recorded. On the mountaintops in the Nyungwe forest, it rains more than 2,000 mm annually. This abundant rainfall has totally leached the soils that were developing from poor parent materials such as sandstone, quartzite, quartzophyllite and granite. Where the forest has been cleared, also the mineral reserves of the litter layer are rapidly consumed and poor soils are left. Although the inhabitants improve the soils near their residence and cultivate several traditional crops, this region has a vocation for forestry in the first place.

Buberuka Highlands

In the North of Rwanda, high altitude plateaus traversed by quartzitic chains that attain an altitude of 2,300 m characterise the agricultural zone of the Buberuka Highlands. Its the lower altitudinal limit corresponds to 1,900 m. It rains about 1,200 mm annually and there is a dry season of 2 months. The soils of this region are generally more fertile than those of the Congo-Nile Watershed Divide, leaving more options for agricultural production. Nevertheless, also in this region, the potential for forestry is high.

Central Plateau

The large region of hills and valleys between the Congo-Nile mountain chain and the Granitic Ridge, at the centre of the country, is referred to as the Central Plateau. At an average altitude of 1,700 m, the annual rainfall amounts to 1,200 mm and the average temperature attains 19 °C. If the humus-bearing horizons are conserved, the soils can be used for the cultivation of a whole range of climatically adapted crops.

Granitic Ridge

The agricultural zone of the Granitic Ridge differs from the Central Plateau because of its soils developing on granitic material. Its average altitude is 1,600 m and the annual rainfall is about 1,100 mm. The convex ridges and rounded, gravelly hills are used for pasture and forest. Crop cultivation is mainly concentrated on the concave hill slopes.

Mayaga

The Mayaga constitutes a narrow agricultural zone, extending over the two borders of the Akanyaru River. In the northern part, the landscape is characterised by hills and valleys that are regularly inundated. The altitude varies between 1,350 and 1,500 m. The landscape of the southern part is much more abrupt, rough and dominated by quartzite chains. Next to differences in topography, the southern part is also characterised by slightly higher annual rainfall totals, varying between 1,100 and 1,200 mm. In the North, it rains about 1,000 to 1,100 mm annually. Also the soilscape is strongly variable. Rock outcrops characterise the hill tops. Humus-rich, gravelly soils are found on the upper slopes, while the younger soils of the footslopes generally have a higher productivity.

Bugesera

The Bugesera is a large plateau located at an altitude of 1,300 to 1,500 m and bordered by the fluvial depositions of the Nyabarongo. A more recent erosion cycle superimposed a new drainage system and resulted in a landscape of smaller isolated plateaus with deep strongly weathered soils, intersected by dry valleys with very gentle slopes. From a climatic viewpoint, this agricultural zone is dry and warm, characterised by an annual rainfall varying between 850 and 1,000 mm, a dry season lasting for three months and an average temperature of about 21 °C.

The best soils for crop cultivation are found on the colluvial deposits bordering the marshes and lakes. Nevertheless, the agricultural potential of this region is generally low and the region mainly has a pastoral vocation.

Eastern Plateau

North of the Bugesera, Delepierre defined the agricultural zone of the Eastern Plateau. This vast zone, located at an altitude of about 1,500 m is in fact the extension of the Central Plateau into the drier East. The landscape is characterised by hills with large, horizontal tops and steep slopes. In the eastern part of this region, enormous quartzite chains cross the landscape. It rains about 900 to 1,000 mm annually. The hilltops are covered with deep humus-rich soils. On the convex upper slopes, outcropping laterite crusts and gravelly soils have been reported. The fields on the steep slopes are strongly eroded and are mainly used as pasture land. In the East, shallow degraded soils dominate the soilscape and only the soils of the footslopes have some agricultural potential.

Eastern Savanna

All the lowlands in the extreme East of Rwanda belong to the Eastern Savanna. This agricultural zone is characterised by a gently sloping landscape with hills that are intersected by large valleys. The altitude generally varies between 1,250 and 1,600 m. Climatically, the region is warm and dry. The average temperature is about 21 °C, while the erratic rainfall amounts to less than 900 mm annually and the dry season lasts for 4 months. The best soils of the region are those with some vertic properties, found in the large valleys. Nevertheless, they still require some important investments in irrigation and machinery. As such, also this region mainly has a pastoral vocation.

The main characteristics of the agricultural zones have been summarised in Table 2.1. Table 2.2 gives an overview the most important traditional and commercial crops of each agricultural zone. With respect to Map 2.1, the reader should keep in mind that it shows the forested land during the seventies. Today, large parts of these forests have been cleared for crop cultivation.

Table 2.1: Characteristics of the agricultural zones in Rwanda

zone		*altitude(m)*			*rainfall(mm)*			*soil*	*agricultural value*
n°	*name*	*min*	*avg*	*max*	*min*	*avg*	*max*		
1	Imbo	970	1,100	1,400	1,050	1,200	1,600	alluvial	excellent
2	Impara	1,400	1,700	1,900	1,300	1,400	2,000	very fine, red, < basalt	good
3	Kivu Lake Borders	1,460	1,600	1,900	1,150	1,200	1,300	shallow, clay loam	excellent-good
4	Birunga	1,600	2,200	2,500	1,300	1,500	1,600	volcanic	excellent
5	Congo-Nile Watershed Divide	1,900	2,100	2,500	1,300	1,600	2,000	humiferous, acid	moderate
6	Buberuka Highlands	1,900	2,000	2,300	1,100	1,200	1,300	laterite soil	good
7	Central Plateau	1,500	1,700	1,900	1,100	1,200	1,300	humiferous	good
8	Granitic Ridge	1,400	1,600	1,700	1,050	1,100	1,200	coarse, gravely	moderate
9	Mayaga	1,350	1,450	1,500	1,000	1,050	1,200	clayey, < schists	very good
10	Bugesera	1,300	1,400	1,500	850	900	1,000	strongly weathered	poor
11	Eastern Plateau	1,400	1,500	1,800	900	950	1,000	laterite soil	moderate–good
12	Eastern Savanna	1,250	1,400	1,600	800	850	900	strongly weathered	very poor

Table. 2.2: Crop production in the agricultural zones in Rwanda

crop	*agricultural zone*											
	1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*
banana	+	+	+	+		+	+	+	+	+	+	
cassava	+	+	+	+				+	+	+	+	+
sweet potato	+	+	+	+		+	+	+	+	+	+	+
potato				+	+	+						
groundnut	+	+	+					+	+	+	+	+
soybean							+					
common bean	+	+	+	+		+	+	+	+	+	+	+
pea				+	+	+						
sorghum		+	+	+		+	+	+	+	+	+	+
maize		+	+	+	+	+	+	+	+	+	+	+
wheat					+	+						
cotton	+											
rice	+											
sugar cane	+											
yam							+	+				
coffee		+	+				+	+	+		+	
tea		+			+							
pyrethrum				+								
quinquina		+										
tobacco				+								

CHAPTER 3. LAND CAPABILITY CLASSIFICATION

3.1. Introduction

Increasing social demands put a high pressure on the natural resources of Rwanda and different land uses often apply for the same piece of land. Nevertheless, agricultural production should keep pace with population growth and therefore an optimal land use with regard to economical returns, food security, and ecological awareness is of highest priority. Decisions on land use changes and regionalisation of cultures should be based on a comprehensive analysis of the production systems themselves and the potentials of the natural resources, i.e. climate, topography, hydrology, and pedology. A general appraisal of the capability of the land for agricultural production gives useful information for the selection of preferential land uses. Arable lands can be grouped according to their potentials and limitations for sustained production of the commonly cultivated crops. Non–arable land units are grouped according to their potentials and limitations for the production of permanent vegetation.

Information linked to the national soil map at a scale 1:250,000 has been used to assess the national land capability for agricultural production. The procedure is primarily based on the USDA Land Capability Classification developed by Klingebiel and Montgomery (1966), but changes have been made relevant for the production environment in Rwanda. The procedure permitted to evaluate the actual and potential capability of the land. An integrated assessment of topography, drainage, physical and chemical properties of the land units determined the actual land capability for climatically adapted crops. The introduction of management practices related to terracing, drainage and fertilisation resulted in the assignment of the potential land capability. A flowchart of the different procedures has been illustrated in Fig. 3.1.

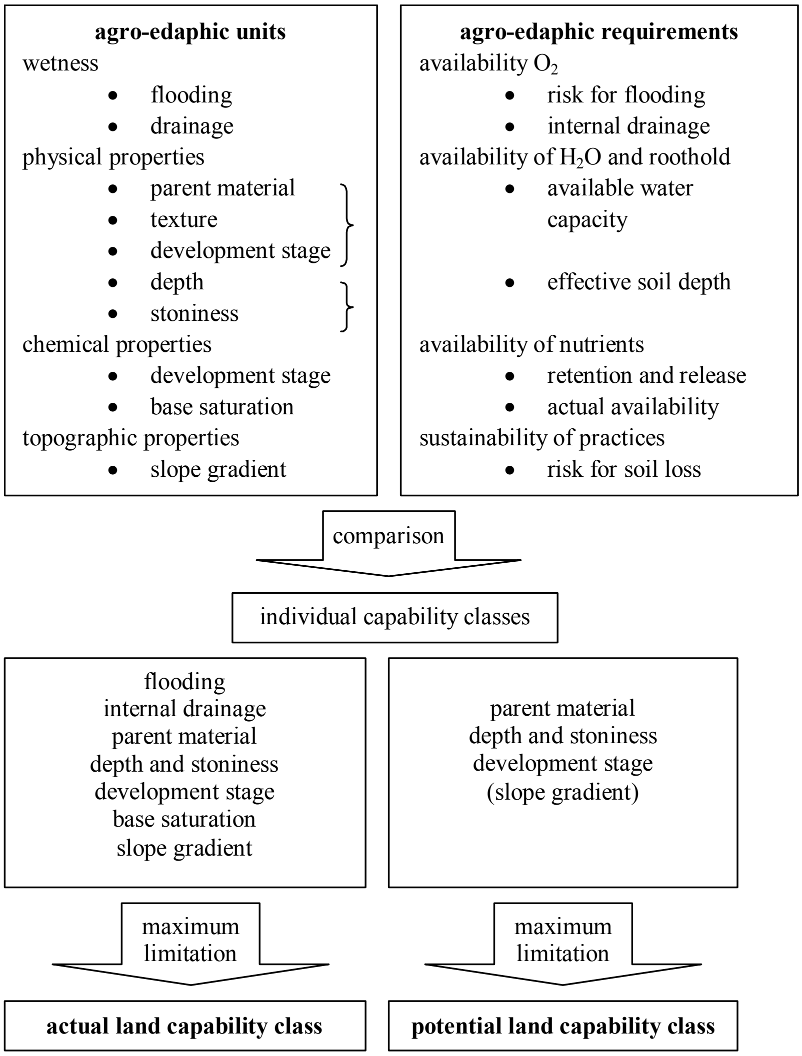


Fig. 3.1: Flowchart of the land capability classification procedure designed for Rwanda at scale 1:250,000

3.2. Soil map at scale 1:250,000

When asking: "What are the main landscape and soil properties determining the capability of the soil for sustained agricultural production?" a whole range of landscape and soil characteristics or qualities affecting land productivity could be summed. The capability classification, however, had to be performed using data that became available with the analysis of the data linked to the soil map at scale 1:250,000. This map consisted of 1,107 units, while two cartographic legends were designed to describe landscape and soil.

3.2.1. Landscape

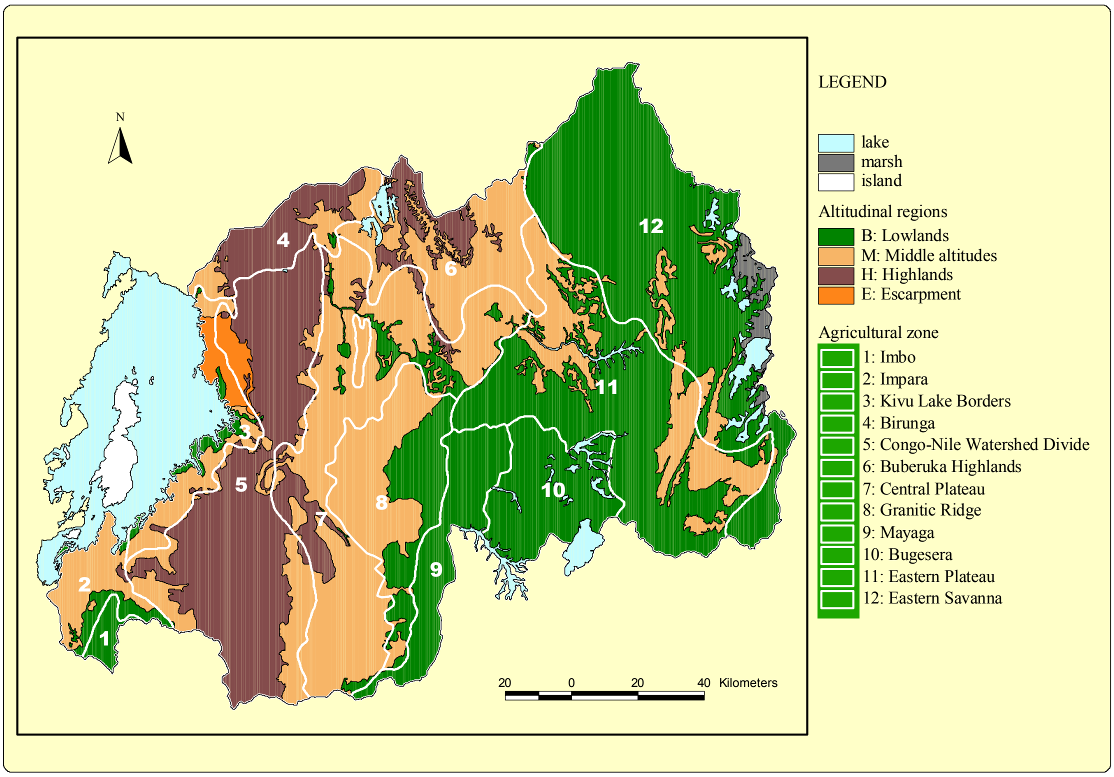
With regard to a brief description of the landscape, a cartographic legend has been designed summarising the information on altitudinal zone, geomorphology and slope gradient:

AB12

with	A	= symbol for altitudinal zone
	B	= symbol for geomorphology
	1	= number referring to the dominant slope class
	2	= number referring to the secondary slope class

Altitudinal zone

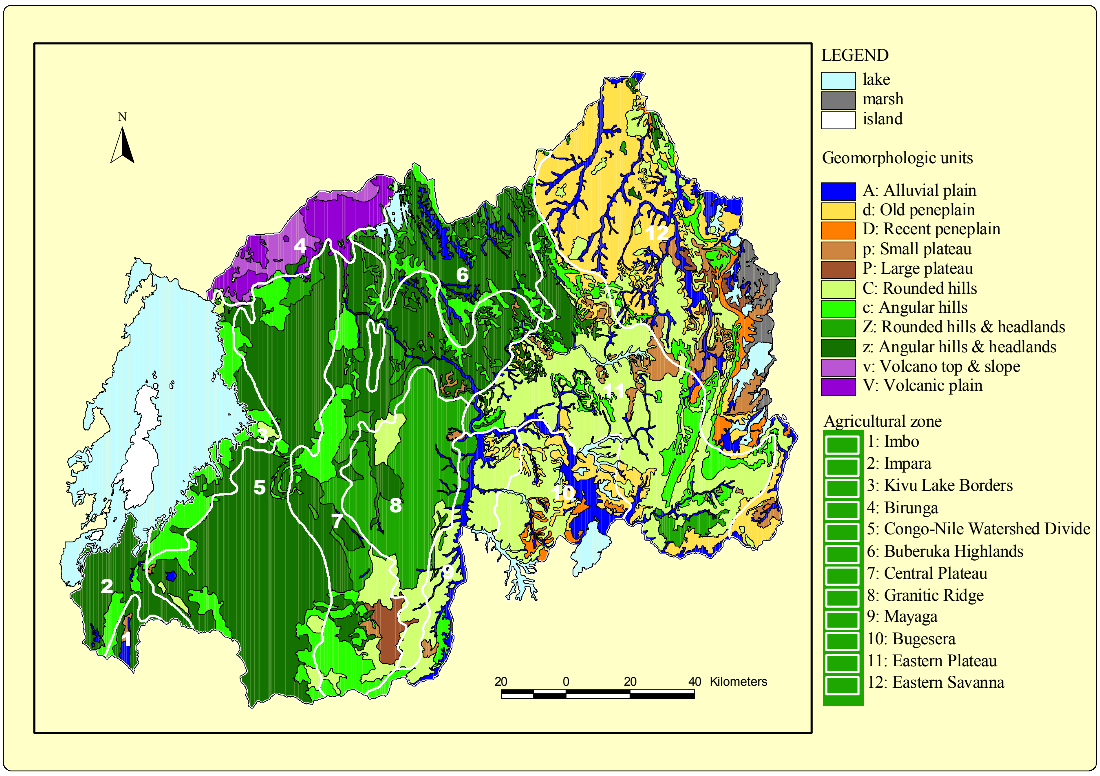
The first parameter indicates whether the unit belongs to the highlands at an altitude over 2,100 m; the middle altitudes situated between 1,600 and 2,100 m; the lowlands at an altitude below 1,600 m; or the escarpment from the Congo-Nile Watershed Divide towards the Kivu Lake. The lowlands, middle altitudes, and highlands occupy 38, 32, and 17 % of the territory, respectively. The very steep escarpment is only found over 1 % of the land area. Marshes, islands and lakes have been grouped separately and occupy 13 %. The symbols used in the cartographic landscape legend, their description and the spatial distribution of the altitudinal zones have been illustrated in Map 3.1.



Map 3.1: Altitudinal regions in Rwanda (derived from soil map at scale 1:250,000)

Geomorphology

Map 3.2 illustrates the spatial distribution of the main geomorphologic units. The "landscape of thousand hills" dominates the country. In the agricultural regions of the Congo-Nile Watershed Divide and the Buberuka Highlands, these hills are usually accompanied by headlands. The legend further makes a distinction according to the type of hilltops: rounded or angular. The Northwest is characterised by the cones of several volcanoes, their slopes and the volcanic plain. Old and recent peneplains are found in the North- and Southeast. In the East and South some large and small plateaus have been noted, while alluvial plains join the great rivers running through Rwanda.

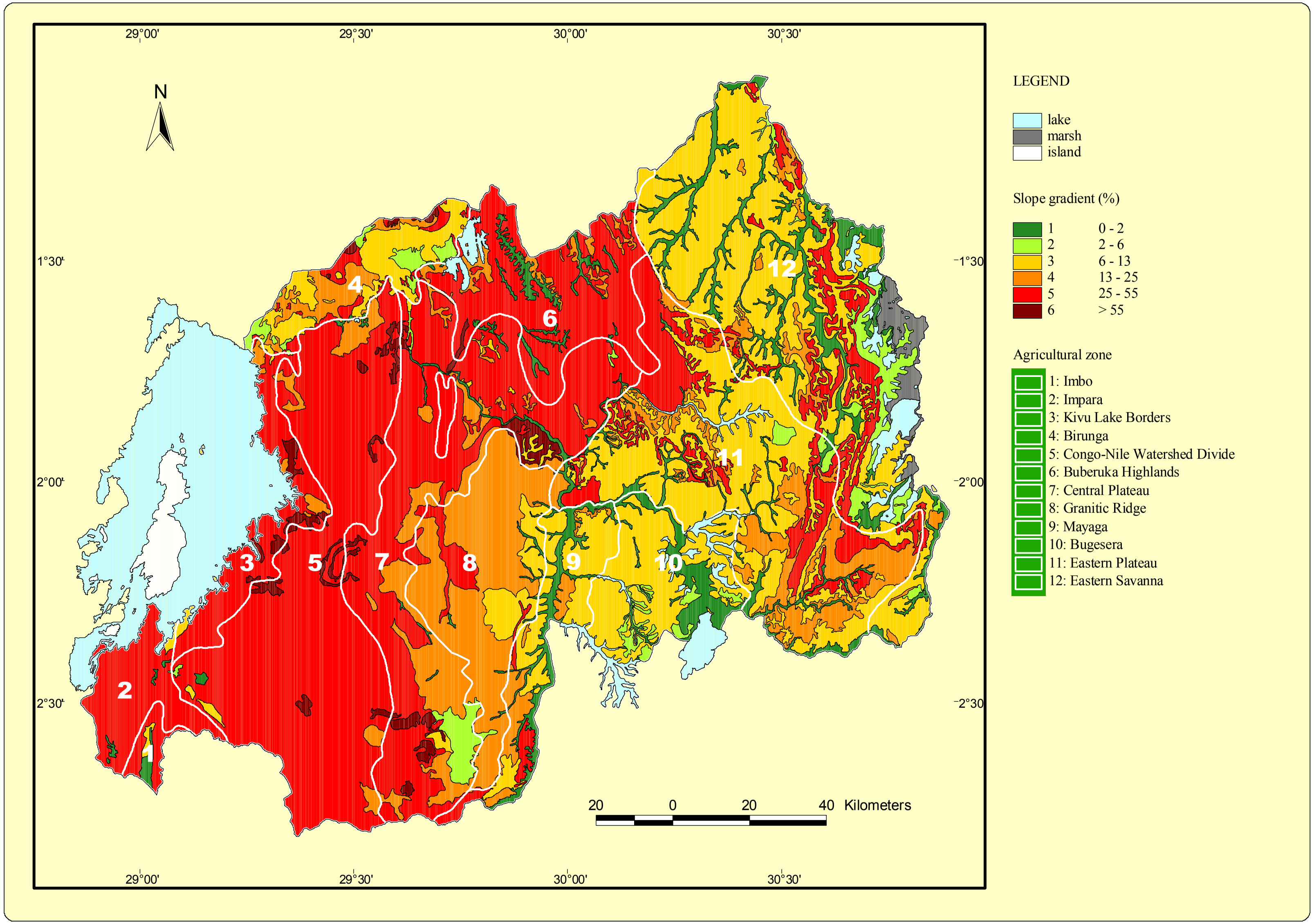


Map 3.2: Geomorphologic regions in Rwanda (derived from soil map at scale 1:250,000)

Slope gradient

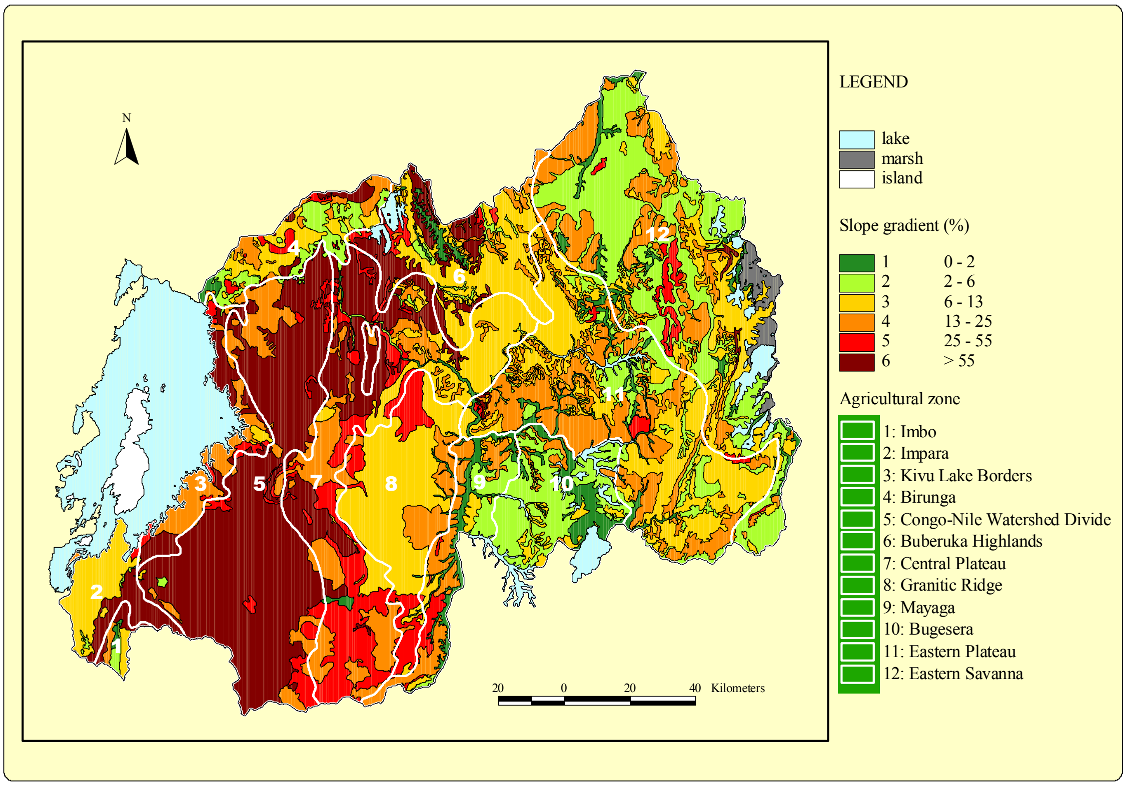
In this very diverse landscape, the slope gradient varies dramatically too. Six different slope classes have been distinguished: 0–2 %, 2–6 %, 6–13 %, 13–25 %, 25–55 %, and > 55 %, represented by the numbers 1, 2, 3, 4, 5 and 6, respectively. The spatial distribution of the dominant slope classes has been illustrated in Map 3.3.

The alluvial plains and plateaus are relatively flat, with slope gradients ranging from 0 to 6 %. The steepness of the peneplains varies from 6 to 13 %, while the landscape of thousand hills is characterised by slopes varying between 13 and 25 %. The high altitude areas of the Congo-Nile Watershed Divide and the Buberuka Highlands are very steeply sloping, with gradients exceeding 55 % at some spots. The degree of inclination in the volcanic region is variable, ranging from 2 to 55 % or even more. A comparable variability is found in the East.



Map 3.3: Dominant slope gradient in Rwanda (derived from soil map at scale 1:250,000)

Analysis of the associated slope classes, illustrated in Map 3.4, reveals the presence of more gentle slopes in the East, Northwest and Southwest. The associated units of the Congo-Nile Watershed Divide, however, are characterised by very steep associated slopes.



Map 3.4: Associated slope gradient in Rwanda (derived from soil map at scale 1:250,000)

Table 3.1 gives an overview of the areal extent of both the dominant and the associated slope classes. Although slope gradients exceeding 55 % are never really dominating the landscape, except in 2 % of the area, they are frequently found associated to more gently slopes. Most units of the soil map are characterised by a gradient between 6 and 55 %. The occurrence of flat to nearly flat land is very rare.

Table 3.1: Areal extent of the dominant and associated slope gradient at scale 1:250,000

slope gradient		*area*	
symbol (-)	*class (%)*	*(km²)*	*(%)*
dominant slope classes			
1	0 – 2	1,735	7
2	2 – 6	715	3
3	6 – 13	6,408	27
4	13 – 25	3,756	16
5	25 – 55	10,469	45
6	> 55	404	2
total		*23,487*	*100*
associated slope classes			
1	0 – 2	1,137	5
2	2 – 6	3,907	17
3	6 – 13	6,002	26
4	13 – 25	5,089	22
5	25 – 55	1,924	8
6	> 55	5,429	23
total		*23,487*	*100*

3.2.2. Soil units: morphological and physical properties

Next to the landscape, the soil map also offers information concerning the dominant, secondary and eventually tertiary soil units. Each soil unit is characterised by a soil legend, summarising its morphological and physical characteristics:

A.B12.c

with A = parent material
B = development stage
1 = texture and depth
2 = drainage
c = diagnostic subsoil properties related to stoniness or the presence of a lithic, paralithic or petroferric contact at shallow depth.

The characteristics of the dominant soil units have been described in more detail below.

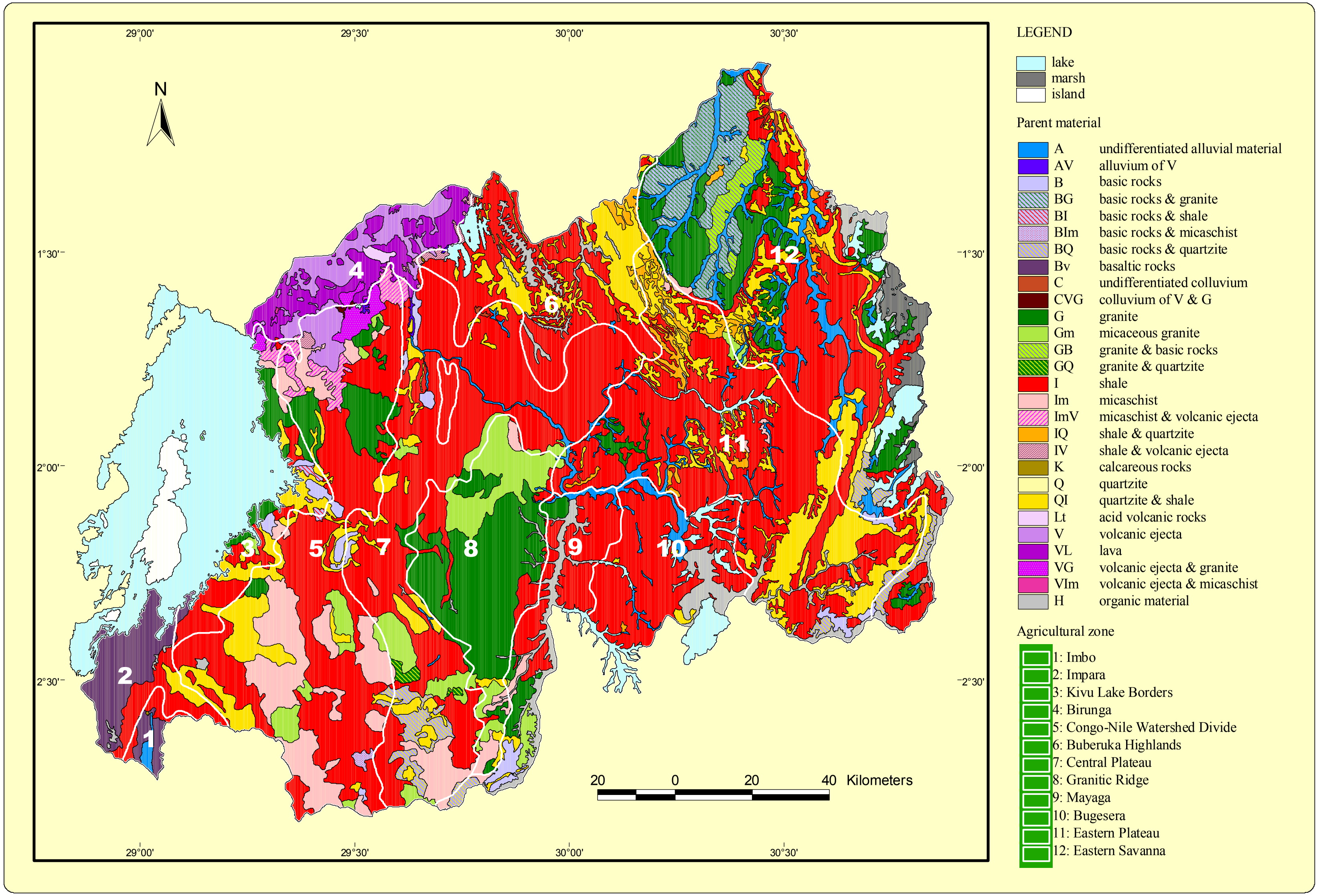
Parent material

The impressive geologic and geomorphologic history of Rwanda resulted in a high diversity of parent materials. The areal extents of these parent materials have been summarised in Table 3.2, while their spatial distribution can be studied in Map 3.5.

Pure shale, and quartzite intervening with shale dominate the lithology of the country with an areal extent exceeding 50 %. Granite is the third most important parent material, covering 11 % of the land. It is especially important in the northeastern savanna and in the agricultural zone of the Granitic Ridge. At some spots in the Congo-Nile Watershed Divide and the Central Plateau, the shale and granite have been slightly metamorphosed, resulting in the formation of schist, micaschist, and micaceous granite. Alluvial and organic materials occupy 4 and 3 %, respectively. Other parent materials that occupy more than 1 % of the total area are basic rocks, basaltic rocks, volcanic ejecta and lava.

Table 3.2: Areal extent of the parent material of the dominant soil units at scale 1:250,000

parent material		*area*	
symbol	*description*	*(km²)*	*(%)*
A	alluvial material	903	4
B	basic rocks	251	1
BG	basic rocks & secondary influence of granite	526	2
BQ	basic rocks & secondary influence of quartzite	346	1
Bv	basaltic rocks	508	2
G	granite	2,520	11
Gm	micaceous granite	908	4
H	organic material	807	3
I	shale	10,883	46
Im	micaschist	1,164	5
IQ	shale & secondary influence of quartzite	293	1
QI	quartzite & secondary influence of shale	2,754	12
V	volcanic ejecta	471	2
VL	volcanic lava	497	2
other		655	3
total		*23,487*	*100*



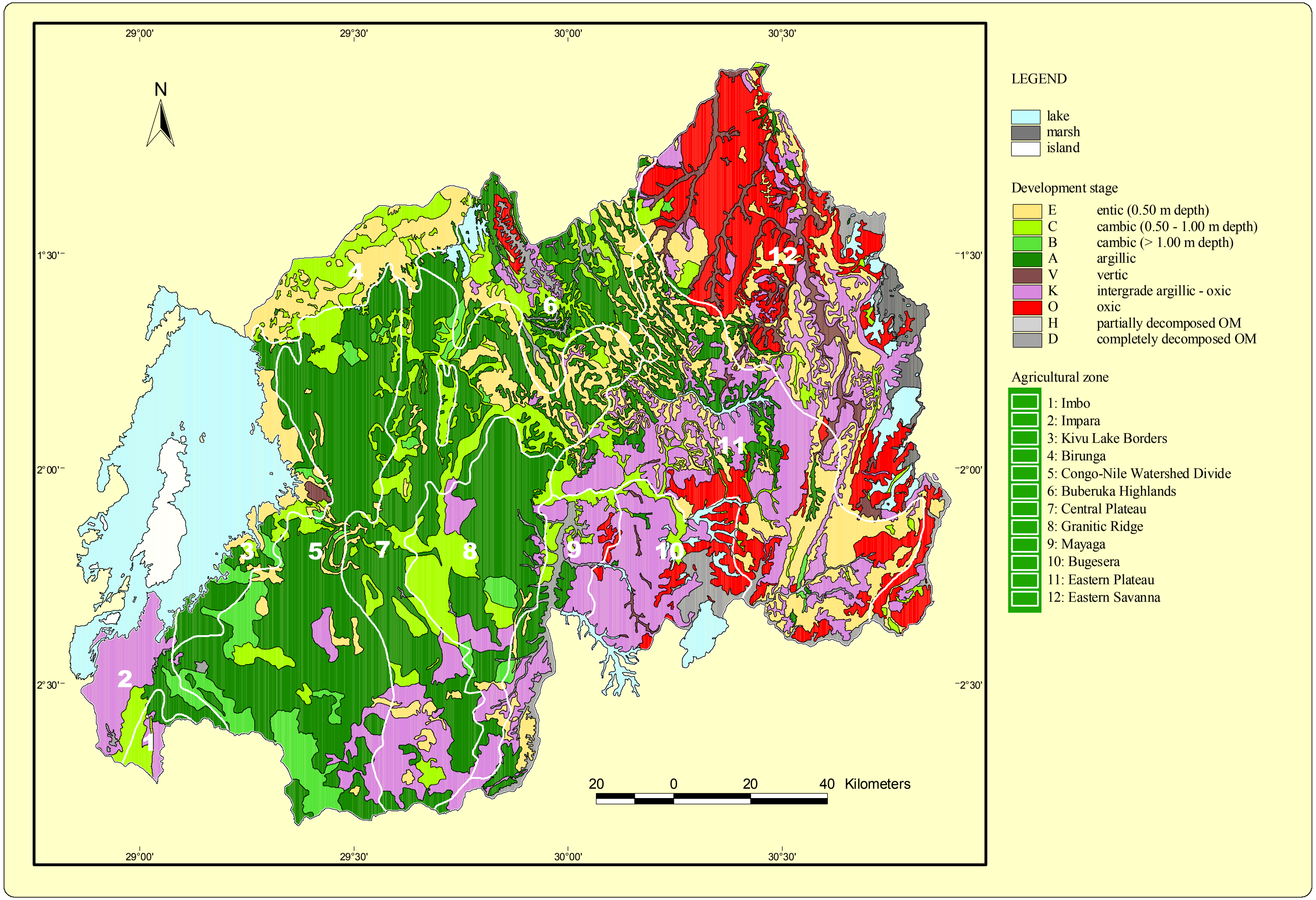
Map 3.5: Parent material of the dominant soil units in Rwanda (derived from soil map at scale 1:250,000)

Development stage

The soil development stage is equally diverse (Map 3.6). In 33 % of the soils a well-developed argillic horizon has been recorded (Table 3.3). It is the dominant development stage found in the western and north-central part of the country. In the East and in the old volcanic region of the Impara, most soils are characterised by an intergrade between an argillic and oxic horizon, covering 19 % of the area. The absence of any diagnostic horizons or the presence of a cambic horizon is characteristic for soils developing on quartzite ridges, volcanic materials, on the steeply sloping areas of the escarpment from the Congo-Nile Watershed Divide towards the Kivu Lake, the Congo-Nile Watershed Divide and Central Plateau. In the Northeast, in the East near the Akagera River and in the Bugesera, ultimate weathering resulted in the formation of oxic horizons. The valleys of these regions are frequently filled with strongly decomposed organic material or with soil showing vertic properties, occupying 3 and 2 % of the country, respectively.

Table 3.3: Areal extent of the development stage of the dominant soil units at scale 1:250,000

development stage		*area*	
symbol	*description*	*(km²)*	*(%)*
E	recent, minimal & shallow weathering, absence of a diagnostic subsurface horizon, lithic or paralithic contact at 0.5 m or less	3,845	16
C	recent, moderate & moderately deep weathering, presence of a cambic horizon, lithic or paralithic contact between 0.5 m and 1.0 m	2,810	12
B	moderate & deep weathering, presence of a cambic horizon	835	4
A	intense & deep weathering, presence of an argillic horizon	7,647	33
V	presence of a horizon with vertic properties	559	2
K	ultimate & deep weathering, presence of an intergrade argillic-oxic horizon	4,549	19
O	ultimate & deep weathering, presence of an oxic horizon	2,433	10
H	partially decomposed organic material	10	<1
D	strongly decomposed organic material	797	3
total		23,487	100

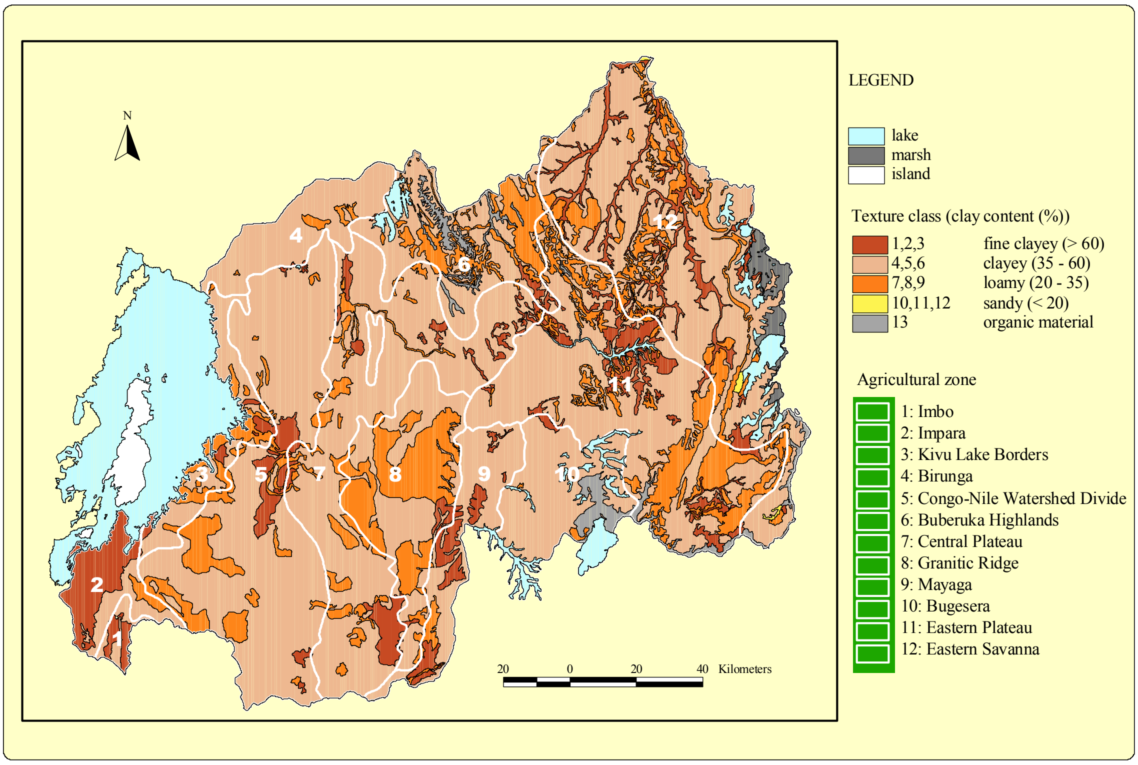


Map 3.6: Development stage of the dominant soil units in Rwanda (derived from soil map at scale 1:250,000)

Texture and soil depth

Soil texture and soil depth have been represented by one combined symbol, a number ranging from 1 to 12. The 4 intervals [1,3], [4,6], [7,9], [10,12] denote the different texture classes. The first number of each of these intervals identifies the shallow soils, with a soil depth below 0.50 m. The second number within each interval represents the soils that are between 0.50 and 1.00 m deep, while the last number corresponds to the deep soils, exceeding 1.00 m in depth. The soil texture symbol of organic material is a "w" or number 13. Their soil depth has been assumed greater than 1.00 m.

With respect to soil texture, only the clay percentage has been supplied and sandy, loamy, clayey and fine clayey soil units have been distinguished. Seventy percent of the soils of Rwanda are clayey with a clay content varying between 35 and 60 % (Map 3.5, Table 3.4).



Map 3.7: Soil texture classes of the dominant soil units in Rwanda (derived from soil map at scale 1:250,000)

Table 3.4: Areal extent of the texture class of the dominant soil units at scale 1:250,000

texture class based on clay content		*area*	
symbol	*description (% clay)*	*(km²)*	*(%)*
1, 2 & 3	fine clayey, > 60	2,378	10
4, 5 & 6	clayey, 35–60	16,193	70
7, 8 & 9	loamy, 20–35	4,086	17
10, 11 & 12	sandy, < 20	22	<1
13 or w	organic material	807	3
total		*23,487*	*100*

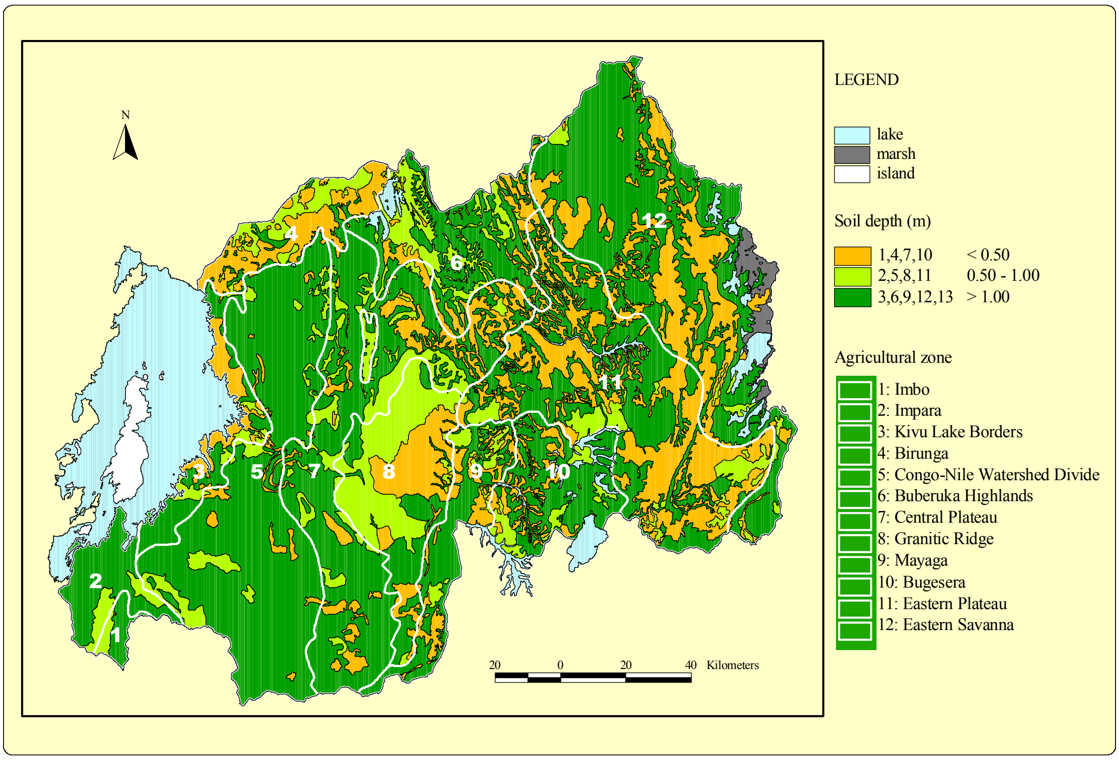
Soils developing on granite or shale intervened by quartzite are loamy and generally have a clay content between 20 and 35 %. This texture class occupies 17 % of the land surface. Very clayey soils are developing on the old volcanic materials of the Impara. Also the Vertisols of the eastern valleys are characterised by a clay content over 60 %. Together they make up 10 % of the area.

Comparison of Map 3.7 with Map 3.5 illustrates this correlation of texture with parent material. Coarse (sandy) materials are found only rarely. Determination of the physical properties of organic soils is prone to errors and therefore, these units have been evaluated separately.

Table 3.5 and Map 3.8 illustrate the areal extent and spatial distribution of the soil depth classes of the dominant soil units of the soil map at scale 1:250,000. Sixty percent of the soils in Rwanda is deeper than 1 m. In steeply sloping areas, however, on quartzite, granite or volcanic materials, soil depth can be between 0.50 and 1.00 m (15 %), or even shallower (25 %).

Table 3.5: Areal extent of the soil depth of the dominant soil units at scale 1:250,000

soil depth		*area*	
symbol	*class (m)*	*(km²)*	*(%)*
1, 4, 7 & 10	< 0.5	5,936	25
2, 5, 8 & 11	0.5 – 1.0	3,409	15
3, 6, 9, 12 & 13	> 1.0	14,141	60
total		*23,487*	*100*



Map 3.8: Soil depth classes of the dominant soil units in Rwanda (derived from soil map at scale 1:250,000)

Stoniness and the presence of a lithic, paralithic or petroferric contact

In 19 % of the soils, soil depth is limited due to the presence of important amounts of stones and gravel of different origin (Table 3.6). Volcanic ejecta limit soil depth in the Birunga. Laterite is frequently found in the strongly weathered soils of the East. Also soils developing on granite, quartzite and sandstone, offering varying degrees of resistance to weathering, are often characterised by significant amounts of rock fragments, quartzite or sandstone gravel. Calcareous materials strongly influence the physical and chemical properties of some Vertisols.

In addition to high volumes of coarse fragments, soil depth can also be limited by the presence of a lithic, paralithic or petroferric contact (Table 3.7). Shallow lithic or paralithic contacts are frequently found in the steeply sloping areas of the quartzite ridges and occupy 22 % of the land surface. Petroferric contacts limit soil depth in some strongly weathered soils of the East, extending over 3 % of the land surface. Volcanic bombs associated with lava limit soil depth in the volcanic region.

Table 3.6: Areal extent of coarse fragments in the dominant soil units at scale 1:250,000

origin of the coarse fragments		*area*	
symbol	*description*	*(km²)*	*(%)*
no	no specific subsoil properties	18,993	81
c	laterised rock fragments	69	0
d	volcanic bombs	59	0
g	rock fragments	243	1
j	saprolite	38	0
k	calcareous subsoil	298	1
l	petroplinthite, laterite	1,005	4
q	quartzite	1,100	5
x	volcanic ash	260	1
z	sandstone	1,422	6
total		*23,487*	*100*

Table 3.7: Areal extent of lithic, paralithic, or petroferric contacts in the dominant soil units at scale 1:250,000

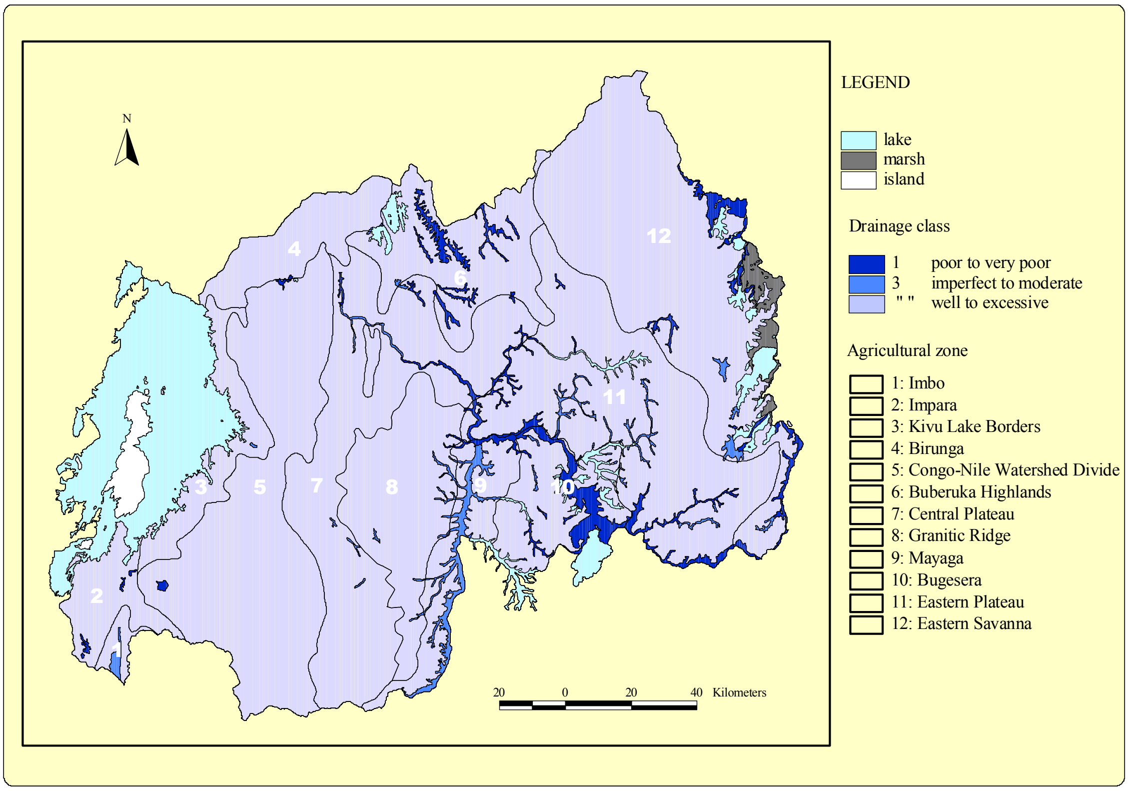
character of the contact		*area*	
symbol	*description*	*(km²)*	*(%)*
no	no contact	17,041	73
d	volcanic bombs & lava	497	2
dl	petroferric contact	678	3
r	lithic or paralithic contact	5,271	22
total		*23,487*	*100*

Drainage

The soils of Rwanda are generally well to excessively drained as they occupy 95 % of the area. Exceptions are found in the valleys of highlands and lowlands. These valley soils are moderately to imperfectly drained in 2 % of the cases, but sometimes drainage is even worse, resulting in poorly or very poorly drained soils, found in 4 % of the land area. The symbol and areal extent of the different drainage classes is summarised in Table 3.8. The Rwandan territory also includes some lands that are permanently flooded. These marshes, characterised by a very poor drainage too, occupy 208 km². The spatial distribution of the drainage classes has been shown in Map 3.9.

Table 3.8: Areal extent of the drainage class of the dominant soil units at scale 1:250,000

drainage		*area*	
symbol	*class*	*(km²)*	*(%)*
“ “	well to excessive	22,236	95
1	very poor to poor	838	4
3	imperfect to moderate	413	2
total		*23,487*	*100*



Map 3.9: Drainage classes of the dominant soil units in Rwanda (derived from soil map at scale 1:250,000)

3.2.3. Soil units: chemical properties

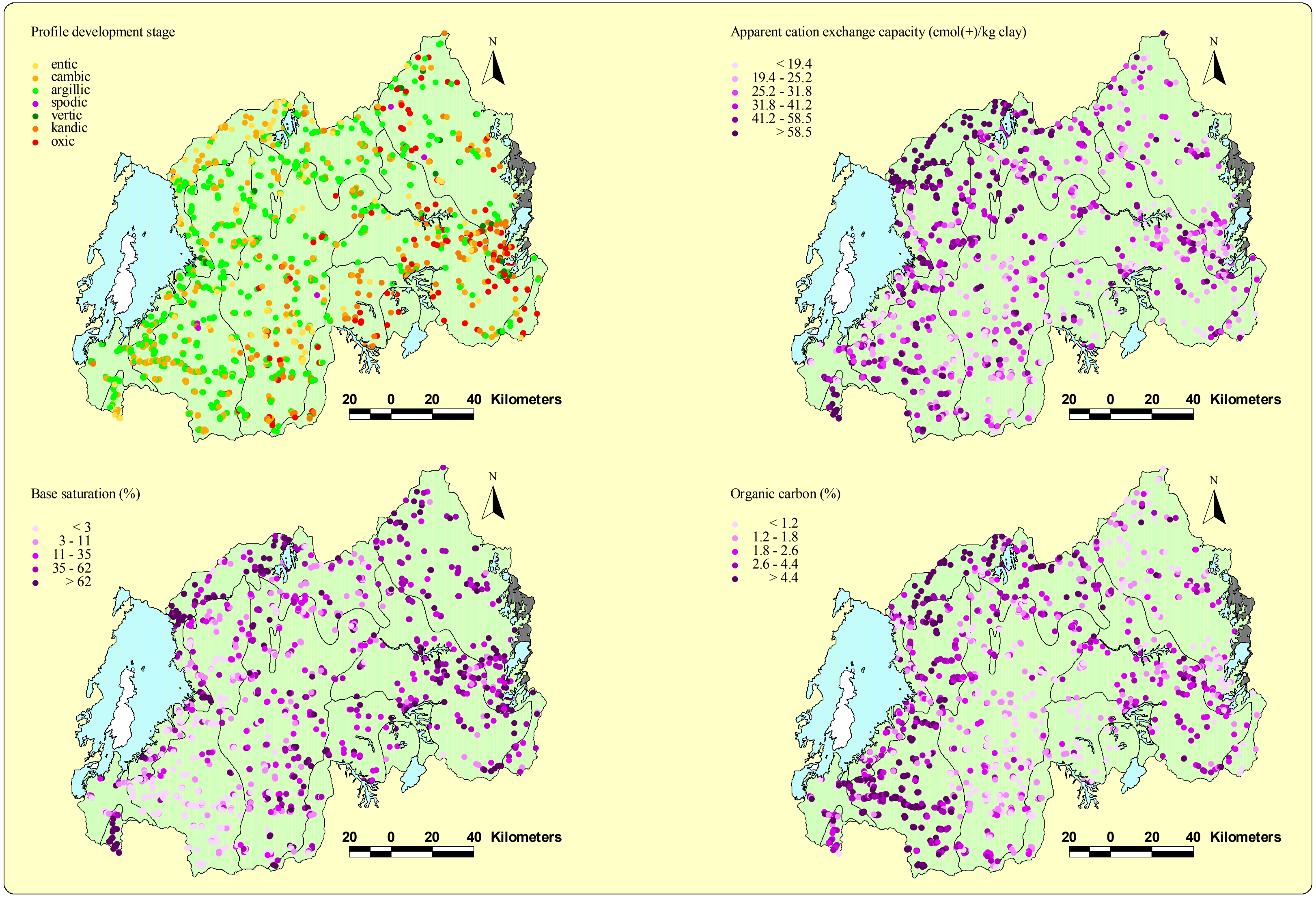
The development stage, which has been inserted in the cartographic legend of the soil units, is an expression of the natural fertility of the soil provided that its classification not only reflects the cation exchange capacity, but also the base saturation and the organic carbon content. The assignment of the development stage at this level, however, has been based on morphological properties, recognizable in the field. A more sound evaluation of the natural fertility of these soil units was realised by querying the chemical data stored in the soil profile database.

In Map 3.10, a quantile classification procedure was used to illustrate the spatial distribution of the development stage, the apparent cation exchange capacity (ACEC) at 0.50 m depth or above a lithic contact, and the weighted average base saturation (BS) and organic carbon (OC) content in the upper 0.25 m of the soil profiles stored in the database. The map illustrates the degree of dependency of these chemical parameters with climate and development stage.

In order to estimate the ACEC, BS and OC content of all soil units at scale 1:250,000, the correlation of these chemical parameters with climate and development stage was studied through a numerical analysis of the profile database.

Apparent cation exchange capacity

Except for the agricultural region of the Birunga, profiles with an ACEC below 24 cmol(+) kg^{-1} clay are found all over the country (Map 3.10). Several of these soils are still in a recent development stage and pre-weathered materials that have been rejuvenated, eventually through human action, are quite common. Consequently, an unambiguous correlation between ACEC, development stage and climate was not directly perceptible.



Map 3.10: Development stage, apparent cation exchange capacity (at 0.50 m) and weighted average base saturation and organic carbon content (upper 0.25 m of soil surface) of the profiles of the soil database of Rwanda

As the weathering stage generally increases from West to East, it could be expected that the lowest ACEC values would be found in the East. Table 3.9 illustrates this dependence, although strongly weathered soils with an ACEC below 16 cmol(+) kg^{-1} clay never dominate. In total, the ACEC at 0.50 m depth, or just above a lithic, paralithic or petroferric contact has been calculated for 1,289 soil profiles. Most soil profiles of the database are characterised by an advanced weathering stage, with an argillic, intergrade argillic–oxic, or oxic horizon. Nevertheless, the ACEC of these soils is still relatively high. The nutrient retention of the clay exceeds 25 cmol(+) kg^{-1} in 68 % of the profiles. Only 8 % of the soil profiles has been characterised by an ACEC below 16 cmol(+) kg^{-1} clay. The relative importance of these low activity clays clearly increases with the weathering stage. All soils with vertic properties have an ACEC exceeding 24 cmol(+) kg^{-1} clay. The exchange capacity of the clay fraction could not be determined on organic soils. Nevertheless, thanks to the exchange capacity of organic matter, a lot of nutrients can be retained in these soils too. The soil development stage generally reflects the decline in ACEC and thus is an indicator for the nutrient retention capacity of the Rwandan soils.

Table 3.9: Number and percentage of soil profiles per development stage and ACEC class

ACEC	*development stage*					
(cmol(+) kg^{-1} clay)	*E*	*C*	*A*	*V*	*K, O*	*total*
number of profiles						
> 25	104	184	432	24	132	*876*
16 - 25	16	27	180	0	84	*307*
≤ 16	9	7	44	0	46	*106*
total	*130*	*218*	*656*	*24*	*262*	*1,289*
% of profiles						
> 25	81	84	66	100	50	*68*
16 - 25	12	12	27	0	32	*24*
≤ 16	7	3	7	0	18	*8*
total	*10*	*17*	*53*		*20*	*100*

Base saturation

From Map 3.10 it is clear that the BS increases from the highlands to the lowlands. High BS values are also characteristic for the profiles in the volcanic plain. The spatial distribution of the BS thus is strongly influenced by climate and parent material. The rather low correlation between development stage and the weighted average BS in the upper 0.25 m of 1,265 profiles has been illustrated in Table 3.10. Soils with vertic properties generally have a high BS. In all other soils, however, the BS exceeds 50 % or drops below 20 % in most of the cases. Most profiles of the database, 50 %, are strongly leached. Especially those with an argillic horizon are characterised by a very low BS status. With 29 % of the profiles, soils with a high BS occupy the second place.

Table 3.10: Number and percentage of soil profiles per development stage and BS class

BS	*development stage*					
(%)	*E*	*C*	*A*	*V*	*K, O*	*total*
number of profiles						
> 50	48	52	151	36	75	*362*
35 - 50	15	27	61	1	37	*141*
20 - 35	16	19	54	1	44	*134*
≤ 20	46	118	362	1	101	*628*
total	*125*	*216*	*628*	*39*	*257*	*1,265*
% of profiles						
> 50	38	24	24	92	29	*29*
35 - 50	12	13	10	3	14	*11*
20 - 35	13	9	9	3	17	*11*
≤ 20	36	54	58	3	39	*50*
total	*10*	*17*	*50*	*3*	*20*	*100*

The BS status of most soils in Rwanda is thus not only dependent on their development stage. It is also strongly related to the leaching strength of the climate and to the composition of the parent material. Both parameters were two of the main determinants for the delineation of the agricultural zones. As such, the profiles for which the BS was calculated were grouped according to their development stage, BS and their location in a specific agricultural zone (Table 3.11).

Table 3.11: Number of profiles grouped according to development stage (DS), base saturation (BS) and agricultural zone

DS	BS	agricultural zone											
(-)	(%)	1	2	3	4	5	6	7	8	9	10	11	12
E	> 50	8	1	4	13	3	3	2	17	1	1	1	5
	35 – 50	0	0	1	3	2	0	3	3	0	0	1	4
	20 – 35	0	0	2	1	3	1	5	4	0	0	2	1
	≤ 20	0	0	4	4	15	3	11	6	1	0	7	1
C	> 50	5	2	8	12	2	4	10	12	8	0	21	6
	35 – 50	0	1	0	5	1	1	5	2	2	0	4	1
	20 – 35	0	0	3	3	5	5	5	5	3	0	8	1
	≤ 20	0	4	11	5	45	10	27	8	3	0	4	0
A	> 50	9	2	22	10	12	15	64	44	40	0	34	59
	35 – 50	1	4	5	0	16	9	17	13	9	0	10	11
	20 – 35	1	3	3	0	17	13	25	11	8	0	2	9
	≤ 20	1	12	32	0	174	23	61	28	25	0	3	24
V	> 50	0	3	4	0	0	0	1	0	0	1	2	15
	35 – 50	0	0	0	0	0	0	0	0	0	0	0	0
	20 – 35	0	0	0	0	0	0	0	0	0	0	0	0
	≤ 20	0	0	0	0	0	0	0	0	0	0	0	0
K	> 50	0	0	0	0	0	1	18	13	14	19	17	34
	35 – 50	0	0	0	0	0	0	5	8	6	5	9	6
	20 – 35	0	0	0	0	0	0	7	10	6	8	3	10
	≤ 20	0	7	3	0	9	5	22	20	20	17	3	16
O	> 50	0	0	0	0	0	0	1	3	1	2	13	29
	35 – 50	0	0	0	0	0	1	2	0	0	2	8	10
	20 – 35	0	0	0	0	0	1	2	0	1	1	9	5
	≤ 20	0	0	0	0	1	1	12	0	2	1	2	2

The high base status of the profiles located in the agricultural zones of the Imbo (1), Bugesera (10) and Eastern Savanna (12), all zones with a relatively low annual rainfall, is striking. Very favourable nutrient amounts have also been registered in soils developing on recent volcanic material in the agricultural zone of the Birunga (4). In both cases, the base status is, except for some minor differences, independent on development stage. Another striking feature is the extremely low BS of all profiles found in the agricultural zone of the Congo–Nile Watershed Divide (5), due to its high rainfall amounts and poor parent material. Most soils of the Impara (2), and especially those with an advanced weathering stage, have a comparably low base status. The shallow soils with an entic development stage of this region, however, show very high amounts of retained basic cations. Near the Kivu Lake (3) and in the Buberuka Highlands (6), the BS varies from moderate to very low with increasing development stage and weathering. Soils of the Central Plateau (7) with an argillic or intergrade argillic-oxic horizon have a high or a very low BS. Often, these differences correspond to the effects of adding fertilizers or organic material. The amount of available nutrients in soils with a different development stage generally is low. No clear correlation between BS, climate and parent material has been remarked in the agricultural zones of the Granitic Ridge (8) and Mayaga (9). In the agricultural zone of the Eastern Plateau (11), most profiles have a favourable nutrient status, except for those developing on quartzite ridges, showing an entic development stage and a very low base status. The highest base status has been recorded in profiles showing an argillic horizon.

This dependency between BS, agricultural zone and development stage allowed to estimate the BS of each soil unit at scale 1:250,000 following an integrated assessment of nutrient retention capacity of the soils and leaching strength of the climate (Table 3.12). Where none of the BS classes was really dominant, a risk-sensitive, cautious estimation of the weighted average BS has been made. The soil units of the soil map at scale 1:250,000 were thus intersected with the map of the 12 agricultural zones and the BS of all 1,362 soil units was assessed.

The areal extent of the different BS classes has been summarised in Table 3.13 and Map 3.11. None of the four BS classes dominates the country. Soils with a BS ranging between 35 and 50 % occupy the largest area, covering 35 % of the soil units. They are particularly extensive in the East, where the exchange complex in most units, except for the valleys and quartzite ridges, is occupied by moderate amounts of basic cations. Also the units within the agricultural zone of the Granitic Ridge belong to this class.

Table 3.12: Key for estimating the BS of the soil units at scale 1:250,000

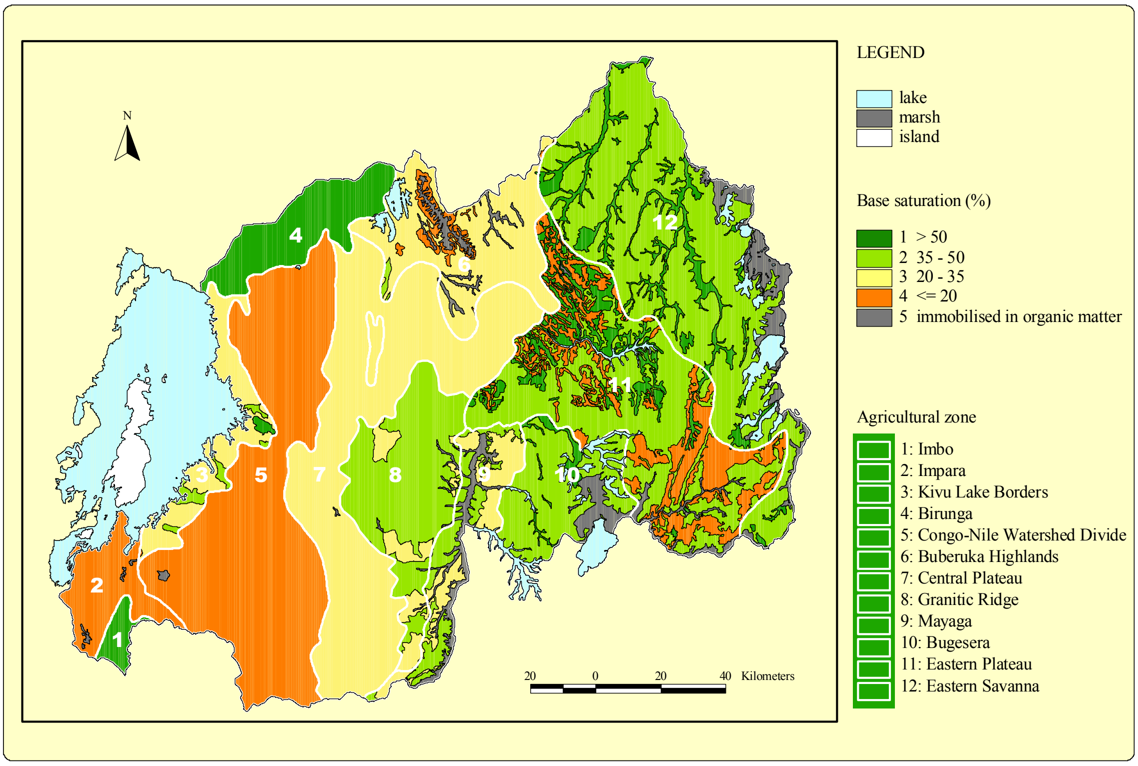
agricultural zone (-)	*development stage* (-)	*BS* (%)
1	-	> 50
2	-	≤ 20
3	E, C, A	20-35
	K	≤ 20
4	-	> 50
5	-	≤ 20
6	E, C, A	20-35
	K, O	≤ 20
7	-	20-35
8, 9	E, C, A	35-50
	K, O	20-35
10, 12	C	> 50
	E, A, K, O	35-50
11	E	≤ 20
	C, K, O	35-50
	A	> 50
-	V	> 50

One fourth of the total land area is occupied by soils with a BS between 20 and 35 %. This class groups the units in the agricultural zones of the Kivu Lake Borders and the Central Plateau and also the strongly weathered units of the Mayaga.

The strongly leached soil units of the Impara, the Congo-Nile Watershed Divide in the West and the poor soils developing on quartzite ridges in the East are characterised by a very low BS not exceeding 20 %. Together they occupy another 25 % of the total land area.

Table 3.13: Areal extent of the BS class of the dominant soil units at scale 1:250,000

base saturation		*area*	
symbol	*class (%)*	*(km²)*	*(%)*
1	> 50	2,376	10
2	35 – 50	8,214	35
3	20 – 35	6,224	26
4	≤ 20	5,866	25
5	nutrients immobilised in organic matter	807	3
total		*23,487*	*100*



Map 3.11: Estimated base saturation of the dominant soil units in Rwanda (derived from soil map at scale 1:250,000)

All the Vertisols found throughout the country are characterised by the same high BS, while comparable BS values have also been found in the Birunga and the Eastern Plateau, in soils characterised by an argillic development stage. In the Eastern Savanna, soil units with a cambic horizon belong to this BS class. Together they occupy only 10 % of the area. The organic soils have been grouped in a separate class. The high amounts of nutrients that they contain are generally immobilised in the organic matter.

Organic carbon

With respect to the OC content, the highest values have been noted in the Birunga, the Congo-Nile Watershed Divide, the Buberuka Highlands, the Eastern Plateau and the Imbo (Map 3.10). In the other agricultural zones, the OC content is strongly variable, but generally lower than 1.2 %. The turnover rate of organic matter is clearly higher in the warm East than in the cool West.

In order to analyse the numerical data, three OC classes have been created corresponding to those defined in the crop requirement tables by Sys *et al*. (1993). The distribution of these OC classes per agricultural zone has been illustrated in Table 3.14.

Table 3.14: Number and percentage of soil profiles per agricultural zone and OC class

O.C	*agricultural zone*											
(%)	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*
number of profiles												
≥ 1.2	21	37	83	53	370	98	163	58	28	10	154	96
0.8 – 1.2	2	1	14	4	8	9	55	35	11	8	17	51
< 0.8	1	2	9	1	4	3	17	16	3	5	3	18
total	*24*	*40*	*106*	*58*	*382*	*110*	*235*	*109*	*42*	*23*	*174*	*165*
% of profiles												
≥ 1.2	88	93	78	91	97	89	69	53	67	43	88	58
0.8 – 1.2	8	3	13	7	2	8	23	32	26	35	10	31
< 0.8	4	5	8	2	1	3	7	15	7	22	2	11
total	*100*	*100*	*100*	*100*	*100*	*100*	*100*	*100*	*100*	*100*	*100*	*100*

In the agricultural zones of the Imbo (1), Impara (2), Birunga (4), Congo-Nile Watershed Divide (5), Buberuka Highlands (6), and Eastern Plateau (11), the OC content generally exceeds 1.2 %. The importance of this OC class slightly decreases in the agricultural zones of the Kivu Lake

Borders (3) and the Central Plateau (7). A high variability in OC content has been recorded in the soil profiles of the Granitic Ridge (8), Mayaga (9), Bugesera (10), and the Eastern Savanna (12). Differences are due to changes in microclimate, parent material, topographic position and land use. Nevertheless, the share of the profiles with an OC content dropping below 0.8 % is limited. Consequently, the OC content of the topsoil is only rarely limiting crop production options and this parameter was not included in the suitability classification procedure.

The quality of the organic matter, however, is generally low (Goemaere, 2000). Especially in the Rwandan lowlands and in the agricultural zone of the Granitic Ridge, management strategies that increase the OC content of the topsoil might have a beneficial effect on the other soil properties and finally also on crop yield. Nevertheless, the OC content being dependent on local influences, the chemical fertility of the land units has been represented only by their ACEC and BS.

3.3. Land capability classification procedure

3.3.1. Definition of land capability classes

The capability of the Rwandan land to sustain different forms of agricultural land use primordially depends on the possibilities for mechanisation and management strategies to reduce the risk for erosion. Consequently, depending on the slope gradient, the land units have been classified as arable land and pasture, forest and wildlife habitats. Within the gently sloping areas, soil depth determines the possibilities for terracing and the rootable depth for the cultivation of crops. Shallow land units that can't be terraced should be used as pasture land. The capability of the arable land further depends on the availability of water, oxygen and nutrients. Important parameters influencing these land qualities are water holding capacity, aeration, nutrient retention capacity, and nutrient supply capacity. These parameters have been assessed through an evaluation of soil depth and stoniness, parent material, risk for flooding, internal drainage, development stage and BS.

Eight different capability classes, groups of land units that have the same degree of limitation, have been distinguished. These classes illustrate the general capability of a land unit for agricultural use. The classification criteria are based on the range of crops that can be cultivated and the importance of conservation practices required. The soil is better when a wide range of crops can be cultivated. When this range of crops becomes narrower the suitability of the land decreases at class level. The risks of soil damage or limitation become progressively greater from class 1 to class 8. Conservation practices taken into consideration are related to the prevention of physical and chemical soil deterioration and to the improvement of the air- and water relation (Sys *et al*., 1991).

Capability classes 1 to 4 have been designed to classify the arable land according to its potential for the cultivation of different upland crops and according to the management techniques that are required to ensure sustainable production. The slope gradient of these units should be 25 % or less. With increasing capability class, the number of crops that can be cultivated decreases, and the level of management increases from ordinary techniques to very careful management strategies. Capability class 5 groups those land units that are located in valleys with an impeded drainage, with organic materials, or with a serious risk for flooding. These land units might be suitable for the production of lowland crops, after the application of very careful to exceptional management techniques. Capability classes 6, 7 and 8 group land units that are actually not to be used as arable land, due to the shallow soil depth and/or very steep slopes. These fragile environments should be protected as a habitat for wildlife, as forests, or through their use as pasture. An overview has been presented in Table 3.15.

Capability class 1

The land units of capability class 1 are not subjected to flooding and are well to excessively well drained. The soils are deep and developed on volcanic, basaltic or basic materials, resulting in favourable physical soil properties with a high water holding capacity and workability. Also the chemical properties allow an optimal growth of the crops, thanks to the high natural fertility of the soil, or its high responsiveness to fertilisers. Base saturation of these units exceeds 50 %, while their nutrient retention capacity and nutrient supply is guaranteed by the low degree of weathering expressed through the absence of diagnostic horizons or the presence of a cambic horizon. The landscape is nearly flat, with a slope gradient limited to 2 %, and combined with the great soil depth, this excludes any risk for erosion. Consequently, these land units are very suitable for most crops, except for tea, which generally prefers deep, well drained but acid soils. They are actually not suited for irrigated rice, but this crop can be grown successfully after management of the valleys. Ordinary management techniques are sufficient to allow a continuous agricultural production of most upland crops.

Capability class 2

The land units belonging to capability class 2 are still very suitable for most crops and actually unsuitable for irrigated rice. However, the landscape and soil properties changed such that the cultivation of tea is feasible, although it gives only marginal yields. The land units of this capability class are still not subjected to flooding and are well to excessively well drained. It groups deep soils with no lithic or paralithic contact or important amounts of gravel within the upper one meter. The physical soil properties of these units, developing on shale, micaschist, alluvial and colluvial material, resulted in a slightly reduced workability, structural stability or water holding capacity. Or, the nutrient holding capacity is somewhat lower, expressed through the advanced degree of profile development with an argillic horizon, or a BS between 35 and 50 %. Consequently, careful management related to the restoration of the cation balance might be required for continuous agricultural production. The landscape is nearly flat to gently sloping with slope gradient ranging between 0 and 13 %, and ordinary to careful management strategies (strip cropping, large terraces) are sufficient to reduce the risk for erosion.

Capability class 3

The number of practical alternatives for local farmers to cultivate these land units is clearly less than for soils in class 2. This can be due to one individual or several limiting landscape and soil properties. Moderately to imperfectly drained soils belong to this class. The limited productivity can also be due to a moderate soil depth, limited between 0.50 and 1.00 m, or less favourable physical properties with regard to water holding capacity, structure and workability of units developing on granite and quartzite. In some land units crop production is limited due to the low natural fertility of the soil and high costs for fertilisation as the BS decreases below 35 % and the nutrient retention capacity of strongly weathered soils with intergrade argillic-oxic or oxic horizons is strongly reduced. The slope gradient varies between 0 and 13 %. Terracing might be required in some cases. Consequently, these units are moderately suitable for most crops, marginally suitable for tea, and actually unsuitable but potentially suitable for rice. Continuous cultivation should be ensured through careful management related to wetness or soil loss problems. If the natural fertility of the units is limiting, very careful management should increase the possibilities for sustainable cultivation of crops.

Capability class 4

Land units grouped into capability class 4 are characterised by deep to moderately deep soils in a rolling landscape with slope gradients varying between 13 and 25 %, or by strongly leached soils having a BS below 20 %. Soil depth may be less than 0.50 m, provided that this is due to a high degree of stoniness, and not to the presence of a lithic, paralithic or petroferric contact. The internal drainage may be excessively well to imperfect. The water holding capacity, soil structure and workability may vary considerably, as long as organic materials are excluded. Soils belonging to capability class 4 give marginal yields when they are used for the cultivation of less demanding to moderately demanding crops. The production of very demanding and moderately demanding crops is actually not feasible. Very careful management related to the restoration of the cation balance and the reduction of the erosion risk, is required for continued sustainable production and may increase the potential capability of these units. Nevertheless, due to the low BS, it can be expected that these units are very suitable for the production of tea.

Capability class 5

Capability class 5 has been designed to group all poorly drained valley soils that can be cultivated during the dry season or that should be used for pastures. These land units are also suitable for the production of irrigated rice. The land units belonging to this class thus have all very specific properties reflected in the risk for flooding, the poor to very poor drainage or the presence of organic soil materials. Apart from the wetness problems and the limited workability and structural stability of these soils, they can also have fertility problems. Exceptional management is required in marshlands that can be used as ponds for the production of fish, associated to the cultivation of lowland crops on elevated ridges.

Capability class 6

Land units of capability class 6 are characterised by the combination of a shallow soil depth due to the presence of a lithic, paralithic or petroferric contact at less than 0.50 m depth, or an entic development stage, and gently slope hillsides not exceeding 25 %. Terracing of these shallow soils is practically impossible, and consequently the actual and potential use of these land units will be limited to pastures. If the natural fertility of these units is rather low, the use of improved pastures might have a positive influence on nutrient availability. If the slope gradient, however, is 13 % or less, strip cropping might reduce the erosion risk and some upland crops could be cultivated.

Capability class 7

Capability class 7 groups those units that are found in mountainous regions with a slope gradient ranging between 25 and 55 %. The recommended land use on these units is forestry, but exceptional management techniques can increase the land use options considerably, especially if soil depth is moderate to deep and terraces can be built. The deeper, strongly leached units within this capability class are actually also marginally suitable for the production of tea. If the soil depth is too limited for the production of deep-rooted trees, the land use should be limited to the conservation of the natural vegetation and protection of the wildlife.

Table 3.15: Overview of the land characteristics defining the 8 land capability classes in Rwanda

parameter	*capability class*							
	1	*2*	*3*	*4*	*5*	*6*	*7*	*8*
Risk for soil loss								
- slope gradient (%)	0-2	0-13	0-13	0-25	-	0-25	25-55	>55
Wetness control								
- flooding	no	no	no	no	yes	-	-	-
- internal drainage	well	well	well to imperfect	well to imperfect	moderate to very poor	-	-	-
Physical properties								
- parent material[a]	only V-Bv-B	all except G, Q, H	all except H	all except H	all	-	-	-
- depth of stoniness (m)	>1.00	>1.00	>0.50	>0.00	>0.00	>0.00	-	-
- depth of contact (m)	>1.00	>1.00	>0.50	>0.50	>0.50	>0.00	-	-
Chemical properties								
- development stage[b]	E-C	E-A	E-O	E-O	-	-	-	-
- base saturation (%)	>50	>35	>20	≥0	-	-	-	-

[a] V: volcanic material; Bv: basalt; B: basic material; G: granite; Q: quartzite; H: organic material

[b] E: entic; A: argillic; O: oxic

Capability class 8

In Rwanda, lands can be unsuitable for any form of agricultural production, in upland areas with slope gradients exceeding 55 %. Nevertheless, the natural vegetation of these zones should be protected, as it can be important habitats for wildlife.

3.3.2. Definition of land capability subclasses

Subclasses are groups of capability units within classes that have the same kinds of dominant limitations for agricultural use. Some soils are subjected to erosion if they are not protected, while others are naturally wet and must be drained if crops are to be grown. Some soils are shallow or have nutrient deficiencies. The capability classification system developed for Rwanda distinguishes 9 different subclasses, reflecting management levels related to drainage problems, erosion risks, and fertility problems.

Drainage problems

Wetness is severely limiting the cultivation of common crops in the marshlands and other organic soils that can be frequently flooded. Exceptional management of these areas with the digging of ponds for aquaculture and use of this material to build ridges for the cultivation of lowland crops can increase considerable the agricultural capability of these zones, indicated by subclass "W". The design of drainage systems or the creation of ditches and ridges are some very careful management strategies that can increase the capability of very poorly to poorly drained units indicated by subclass "wW". The imperfectly drained to moderately drained units require careful management to reduce the negative impact of the slightly impeded drainage. Subclass "w" has been used to characterise the management for these land units.

Risk for erosion

The construction of terraces is only allowed where the soil depth exceeds 0.50 m and slope steepness is 55 % or less. Terracing will not be recommended if this management investment doesn't result in an increase of the land capability for arable land. Pasture lands are not terraced. Where the slope gradient ranges between 2 and 13 %, careful or very careful management strategies are required to reduce land losses upon erosion. A careful management with contour tillage is sufficient as long as the degree of inclination is 6 % or less. Nevertheless, strip cropping or gradual terraces with bands of grasses or banana trees might be preferred, especially in steeper areas. If the slope gradient is less than 13 %, terraces of at least 14.5 m width are sufficient, provided that the terraces are maximally 2 m high. All units that require a comparable management have been indicated by subclass “t”. Very careful management with gradual terraces that are 14.5 to 8.0 m wide is required if the slope gradient varies between 13 and 25 %. These units are recognizable by their subclass “tT”. If the actual slope gradient is even more, between 25 and 55 %, terraces should be constructed that are 8 to 3.5 m wide, and the assigned subclass is “T”.

Fertility problems

Management strategies for the improvement or maintenance of the nutritious status of the soil have only been recommended if they resulted in an increase of the capability for arable land. Harvesting crops always depletes the soil nutrients, and therefore an ordinary management with the application of 500 kg ha^{-1} of grinded limestone every three years has been recommended on the most fertile soils with an estimated BS exceeding 50 %. A yearly application of 250 kg ha^{-1} of grinded limestone, should maintain the productivity of land units with a BS ranging between 35 and 50 %. Recommendation of this careful management has been indicated by subclass “f”. Where the BS varies between 20 and 35 %, a very careful management “fF” has been recommended. This includes the annual application of 500 kg ha^{-1} of grinded limestone during 2 years, followed by a yearly application of 250 kg ha^{-1}. The more strongly depleted units require an exceptional management with annual applications of 500 kg ha^{-1} during 4 to 6 consecutive years, followed by the yearly application of 250 kg ha^{-1}. This intensive management has been recommended on land units with subclass “F”. Indication of these subclasses together with capability class 6 reflects the choice for improved pastures to increase the natural fertility of the land.

3.3.3. Capability classes of the individual landscape and soil parameters

The capability classes and management levels, discussed before, were the basis for the assignment of capability levels to the individual landscape and soil parameters. Both flooding and drainage limit the aeration of the soil and might impose oxygen stress to sensitive crops. Soil depth and stoniness directly influence the water holding capacity of the soil and the possibilities for root development. They also have to be taken into account when determining the possibilities for terracing. The parent material and soil structure determine the water holding capacity, the workability and the supply of nutrients upon weathering. The nutrients that are actually retained also depend on the weathering stage of the soil, expressed by the presence or absence of diagnostic horizons and by the leaching strength of the climate, which has been evaluated by an estimation of the BS of all land units, depending on their profile development and soil climate. Finally, slope gradient has an important influence on the sustainability of the land use, especially related to land losses due to erosion, but also to the water availability and workability. An overview of the criteria defining the capability classes of the individual landscape and soil parameters has been presented in Table 3.16.

Flooding

Flooding can be expected in very poorly drained and strongly decomposed organic soils with an indication of "w" in the texture symbol to which a capability class of 5 has been assigned. In all other soil units there's no risk for flooding, and consequently, they have been grouped to capability class 1.

Internal drainage

Poorly to very poorly drained soils have been grouped in class 5, while imperfectly to moderately drained soils correspond to capability class 3. All other well to excessively well drained soils have been assigned to capability class 1, posing no problems for crop production.

Soil depth and stoniness

Soils deeper than 1 m pose no problems for agricultural use and have been grouped in capability class 1. When soil depth is moderate, i.e. limited between 0.5 and 1.0 m, the unit has been assigned to capability class 3. Shallow soils that are less than 0.5 m deep due to the presence of gravel have been grouped to capability class 4. However, when soil depth is limited to 0.5 m or less due to the presence of a lithic or paralithic contact, or due to the absence of diagnostic horizons, the assessment was much more severe and resulted in the assignment of capability class 6.

Parent material

The most favourable soil physical properties are found in soils derived from pure volcanic, basaltic, basic and calcareous materials. Also volcanic alluvial materials and parent materials dominated by volcanic ejecta but with some granitic influence offer favourable properties. All these units got a capability class 1 for their physical properties. Shale, micaschist, and micaschist influenced by another lithological substrate such as volcanic ejecta and quartzite are the parent materials grouped into capability class 2. Also basic materials with intervening secondary granite, shale, micaschist, or quartzite, volcanic ejecta influenced by secondary materials different from granites, and colluvial material of volcanic ejecta and granite, are all classified in the same class. Their physical properties are still favourable for crop production. Granitic, micaceous granitic, granitic–quartzitic, granitic–basic, quartzitic, and quartzitic–schistic parent materials belong to capability class 3. Soils developed from these parent materials are generally characterised by a low water holding capacity and high stoniness. The capability classification of the alluvial and colluvial soils of undifferentiated materials further depends on their development and texture. Soils showing vertic properties have been assigned to capability class 2. When no vertic properties have been noticed and the texture is fine clayey, clayey, or loamy to sandy, the corresponding capability classes are 1, 2, and 3, respectively. The worst physical properties have been noticed in organic soil materials that got a capability class 5.

Development stage

Although analysis of the profile data points out that most soils in Rwanda have an ACEC of at least 25 cmol(+) kg^{-1} clay, it was decided to include this land characteristic in the capability evaluation because of its importance for fertilisation strategies. The most favourable chemical conditions have been found in recently developing soils with an entic or cambic development stage. They have been assigned to capability class 1. Capability class 2 groups all soils with an intergrade cambic–argillic, argillic, or vertic development stage. The strongly weathered soils, characterised by an intergrade argillic-oxic or oxic horizon, have been grouped in capability class 3. Finally, soils developing in organic materials, whether they are strongly or only partially decomposed, have been assigned to capability class 5.

Table 3.16: Overview of the criteria defining the capability classes for all landscape and soil parameters in Rwanda

parameter	*capability class*							
	1	*2*	*3*	*4*	*5*	*6*	*7*	*8*
Risk for soil loss								
- slope gradient	0-2	2-13	-	13-25	-	-	25-55	>55
Wetness control								
- flooding	no	-	-	-	yes	-	-	-
- internal drainage	well	-	moderate to imperfect	-	poor to very poor	-	-	-
Physical properties								
- parent material[a]	V-Bv-B	I, A, C	G, Q	-	H	-	-	-
- depth of stoniness	>1.00	-	>0.50	>0.00	-	>0.00	-	-
- depth of contact	>1.00	-	>0.50	>0.50	-	>0.00	-	-
Chemical properties								
- development stage[b]	E-C	A	K-O	-	-	-	-	-
- base saturation	>50	>35	>20	≥0	-	-	-	-

[a] V: volcanic material; Bv: basalt; B: basic material; I: schists; A: alluvium; C: colluvium; G: granite; Q: quartzite; H: organic material

[b] E: entic; C: cambic; A: argillic; K: intergrade argillic – oxic; O: oxic

Slope gradient

According to the investments required for strip cropping or terracing, the slope gradient classes have been assigned to the following capability classes: units with a slope gradient of 2 % or less have been grouped into capability class 1; those with a slope gradient ranging between 2 and 13 %, 13 and 25 %, and 25 and 55 %, have been assigned to capability classes 2, 4 and 7, respectively; and capability class 8 characterises those units with a degree of inclination exceeding 55 %. As the evaluation of slope gradient and soil depth/stoniness has such a great impact on the capability classification, the maximum capability class resulting from a combined evaluation of these two parameters has been illustrated in Table 3.17.

Table 3.17: Capability classification according to slope gradient and soil depth

soil properties			*capability classes*		
slope (%)	*depth (m)*	*limitation (-)*	*slope (-)*	*depth (-)*	*overall (-)*
≤ 2	> 1.00		1	1	1
	0.50 – 1.00			3	3
	≤ 0.50	stoniness		4	4
	≤ 0.50	contact[a]		6	6
2 – 13	> 1.00		2	1	2
	0.50 – 1.00			3	3
	≤ 0.50	stoniness		4	4
	≤ 0.50	contact		6	6
13 – 25	> 1.00		4	1	4
	0.50 – 1.00			3	4
	≤ 0.50	stoniness		4	4
	≤ 0.50	contact		6	6
25 – 55	> 1.00		7	1	7
	0.50 – 1.00			3	7
	≤ 0.50	stoniness		4	7
	≤ 0.50	contact		6	7
> 55	> 1.00		8	1	8
	0.50 – 1.00			3	8
	≤ 0.50	stoniness		4	8
	≤ 0.50	contact		6	8

3.3.4. Actual and potential capability

Regarding the overall capability classification of the land, a distinction has been made between the potential and actual capability. Soil depth and stoniness, parent material, and development stage, all parameters inherent to the land unit, determine its potential capability. Slope gradient can be corrected through terracing provided the soil is sufficiently deep. If terracing is unfeasible, the evaluation of slope gradient should be added to the potential capability. The actual capability is determined by these former properties together with those that might limit the capability of the unit actually, but whose limitation can be removed by adapted management. Risk for flooding, internal drainage, BS and eventually an integrated evaluation of slope and soil depth have thus been inserted in the evaluation procedure too. The maximum capability class of the individual landscape and soil parameters finally determines the actual and potential capability.

3.4. National land capability

The capability classification procedure, designed for application in Rwanda, resulted in the creation of several maps at scale 1:250,000 showing the individual capability of the different landscape and soil parameters and the final actual and potential capability. The whole procedure has been performed twice, once for the dominant soil units and once for the associated soil units of the soil map.

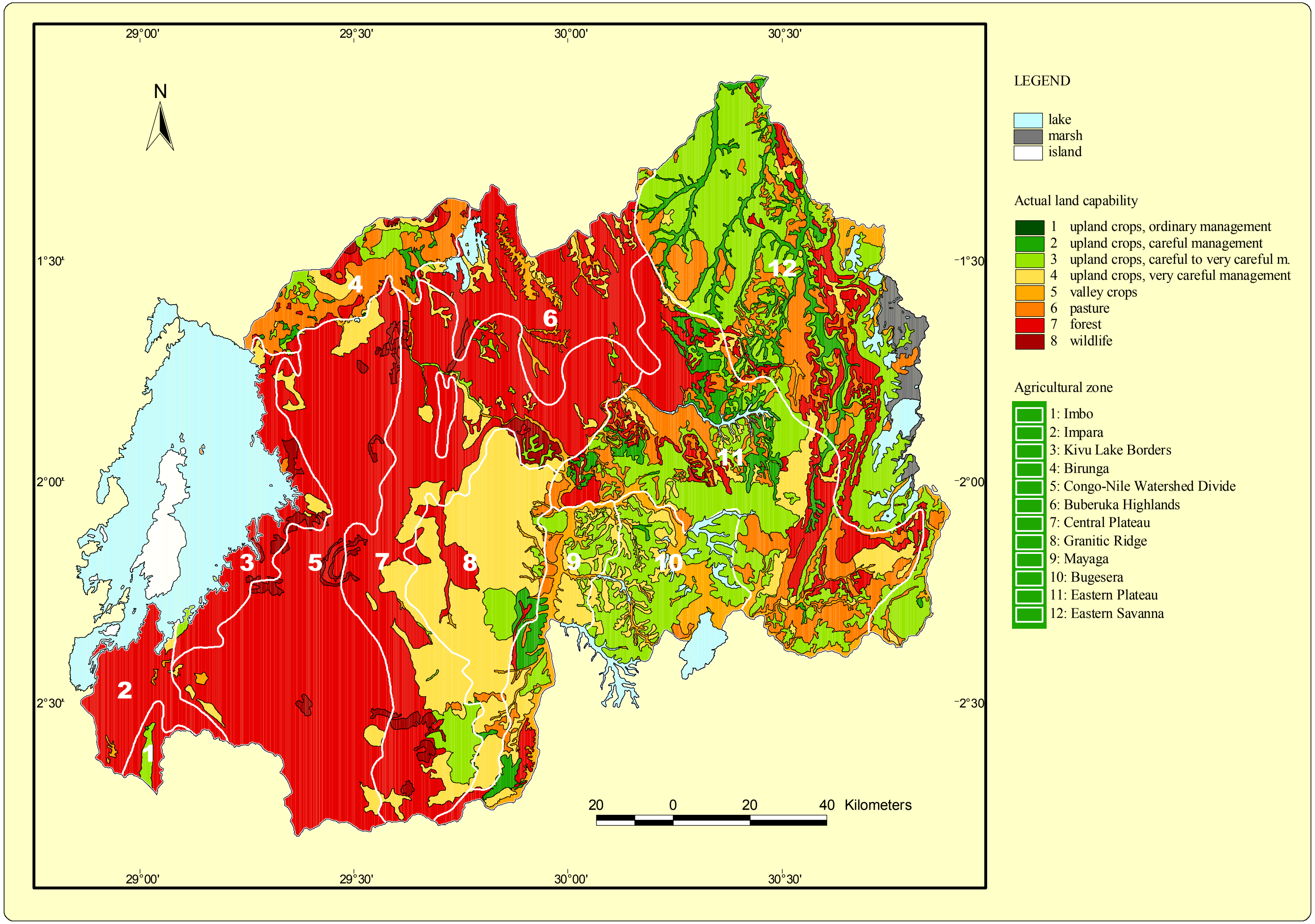
3.4.1. Actual and potential capability of the dominant soil units

Actual capability

Actually, half of the Rwandan territory has been classified as non-arable land (Map 3.12, Table 3.18). Very steep units on the Congo-Nile Watershed Divide occupy 2 % and their management should be directed towards nature conservation. The agricultural zones of the Impara, the Congo-Nile Watershed Divide and large parts of the Buberuka Highlands have been classified suitable for forestry, together with the quartzite ridges in the East. They occupy 45 % of the land area and were largely forested in the past, although more and more land is actually deforested and cultivated. The units classified as suitable for pasture, occupy 10 % and largely correspond to the units of the volcanic plain and the East, where the soil depth is strongly reduced by a lithic contact or abundant coarse fragments.

The valleys of the Akanyaru, Nyabarongo, and Akagera and the organic soils in the Buberuka Highlands are actually suitable for pasture, for the cultivation of crops during the dry season and for irrigated rice.

One fifth of the country has been classified into capability class 3 and as such corresponds to land suitable for the cultivation of most crops. In the East and South, careful management related to the prevention of erosion and the restoration of the nutrient balance is required to ensure a sustainable agricultural production. In the imperfectly drained valleys, drainage systems are needed to control the wetness problems. Also several units located on the volcano slopes belong to capability class 3 because of the relatively high slope gradient that should be reduced by terracing.



Map 3.12: Actual capability of the dominant soil units in Rwanda (derived from soil map at scale 1:250,000)

The agricultural zone of the Granitic Ridge is largely marginally suitable for the production of low demanding crops. The main limitations are related to the risk for erosion and the low availability of water on the generally moderately deep soils, limited before 1.00 m depth by granite gravel. As such, a very careful management oriented towards erosion prevention is often required. The most strongly weathered soils of the South additionally require a very careful management restoring the cation balance. In total, this capability class occupies 15 % of the area.

Table 3.18: Areal extent of the actual capability classes of the dominant soil units at scale 1:250,000

capability classes		*area*	
symbol	*description*	*(km²)*	*(%)*
1	very suitable for most crops; unsuitable for tea; valleys are potentially suitable for irrigated rice	1	<1
2	very suitable for most crops; marginally suitable for tea; valleys are potentially suitable for irrigated rice	1,078	5
3	suitable for most crops; marginally suitable for tea; valleys are potentially suitable for irrigated rice	4,578	19
4	marginally suitable; deep soils are very suitable for tea; marginally suitable for low demanding crops; actually unsuitable for demanding crops	3,524	15
5	suitable for pasture, valley cropping during the dry season, irrigated rice and eventually tea	1,074	5
6	suitable for pasture; actually unsuitable for crops; potentially suitable for low demanding crops after exceptional management	2,358	10
7	suitable for forests; actually unsuitable for crops; potentially suitable for low demanding crops after exceptional management	10,469	45
8	land with serious limitations	404	2
total		*23,487*	*100*

Very suitable land units are found in the eastern valleys with Vertisols, in the Birunga, in the Mayaga and around the Muhazi Lake in the agricultural zone of the Eastern Plateau. These latter two places are characterised by the frequent occurrence of deep, moderately weathered soils with an argillic horizon developing from shales and schists. In the Birunga, the best capability class was assigned to some deep soil units of the volcanic plain. Capability class 1 corresponds to only one deep and moderately weathered soil unit, characterised by an argillic horizon developing in volcanic material.

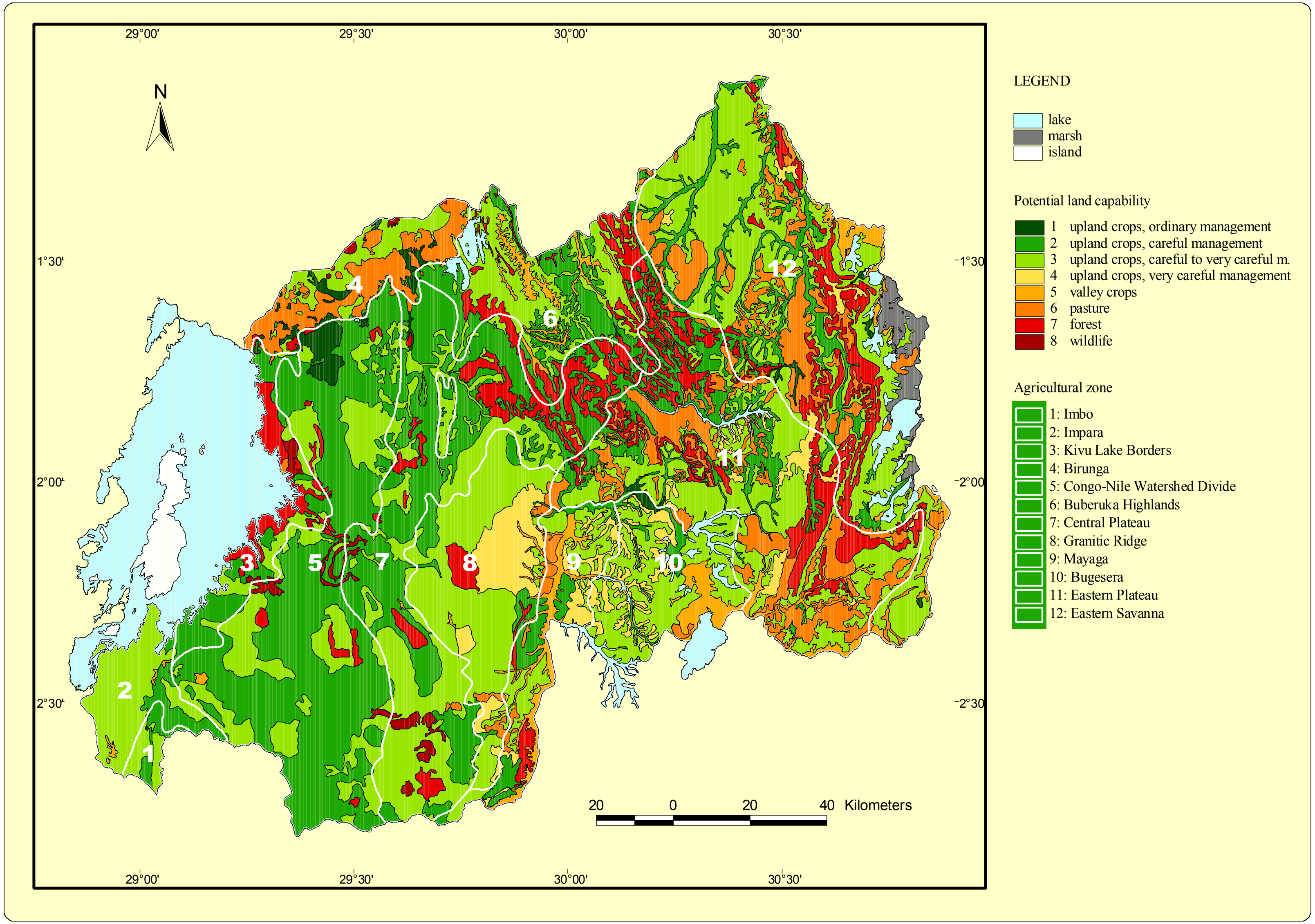
Potential capability

According to the potential capability classification 80 % of the country is arable. As such, appropriate management techniques significantly increase the capability of the land, especially in the West. The spatial distribution of the potential capability has been illustrated in Map 3.13 and an overview of the areal extent of each class has been reported in Table 3.19.

Although only 1 % of the territory attains capability class 1, 30 and 40 % of the area is classified into capability classes 2 and 3, respectively. While the land area belonging to capability class 4 reduces to 4 % after terracing and the application of fertilisers, the land area belonging to class 5 reduces to 3 %, following the appropriate management strategies for the reclamation of these wetlands. Nothing changes with respect to the land area restricted for pastures. The soil depth of these land units excludes terracing. The importance of capability class 7, however, decreases drastically from 43 to 10 %, as most strongly sloping land units are terraced. Exceptional management of some land units belonging to capability class 8 further resulted in a reduction of the areal extent of this class to only about 1 %.

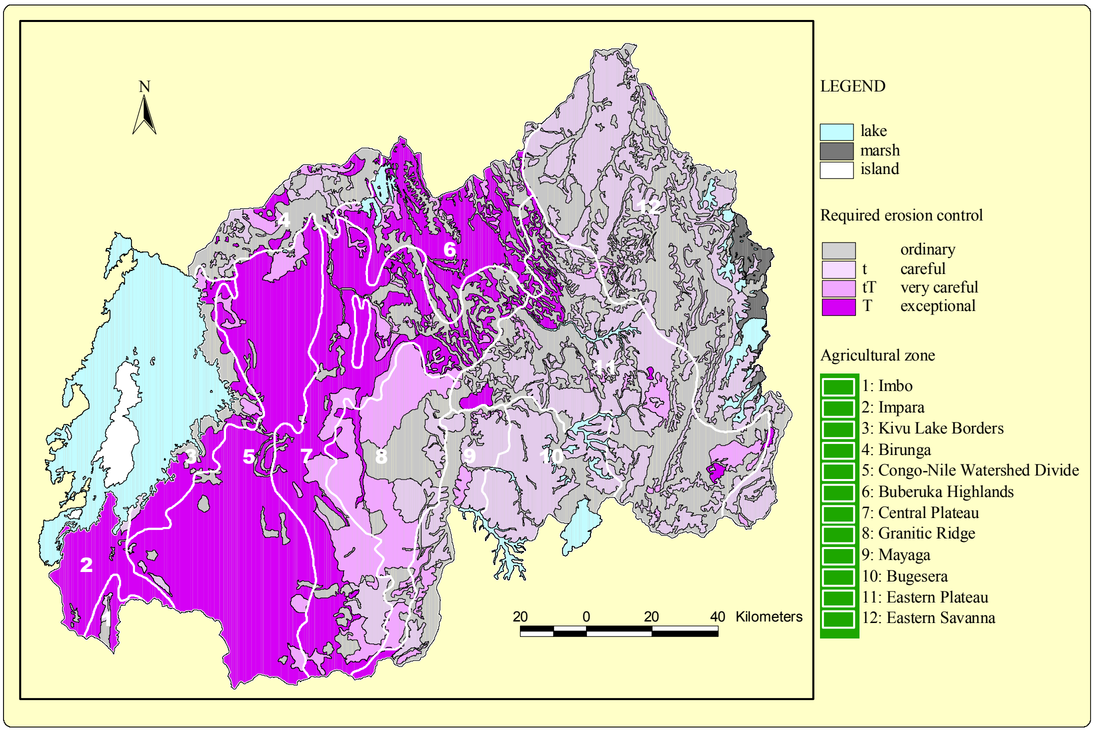
Table 3.19: Areal extent of the potential capability classes of the dominant soil units at scale 1:250,000

capability classes	*area*	
symbol	*(km²)*	*(%)*
1	285	1
2	7,063	30
3	9,398	40
4	1,004	4
5	807	3
6	2,358	10
7	2,382	10
8	189	1
total	*23,487*	*100*

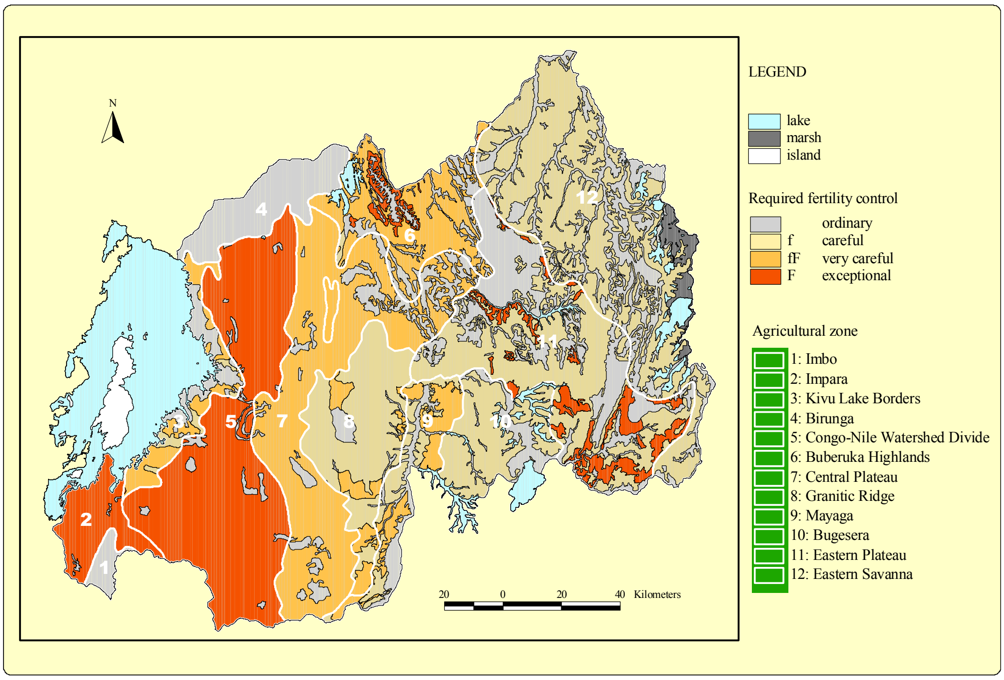


Map 3.13: Potential capability of the dominant soil units in Rwanda (derived from soil map at scale 1:250,000)

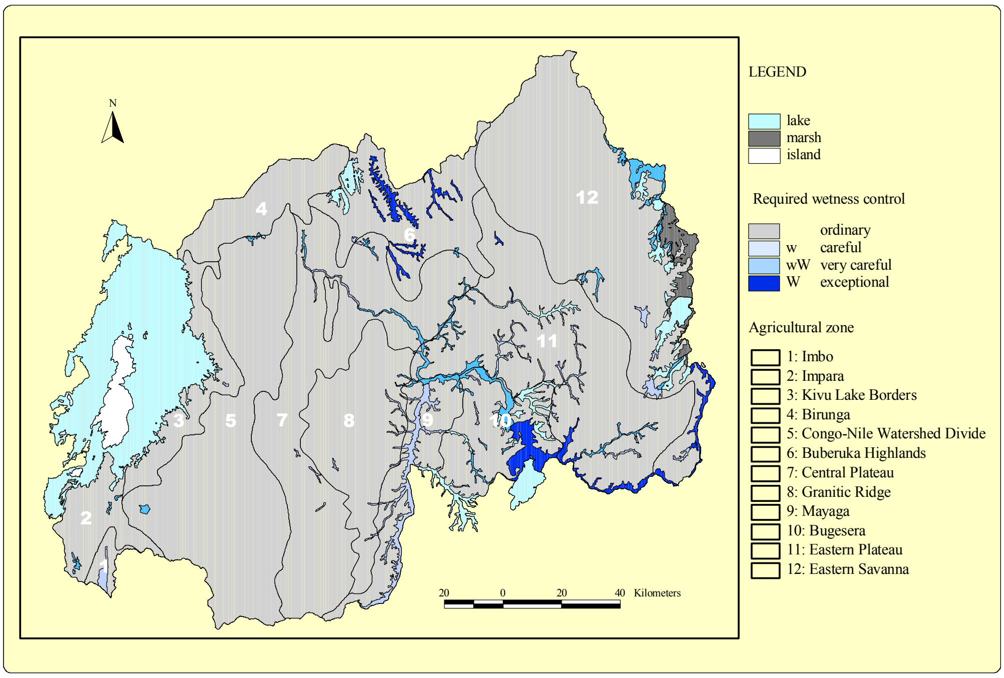
An overview of the necessary management strategies that have to be realised to obtain the potential land capability, has been given in Maps 3.14, 3.15 and 3.16. From a comparison of the actual and potential capability of the different units, it turns out that improved management has the greatest impact on the suitability of the land for crop production when they are applied in Western Rwanda. In Eastern Rwanda, the low nutrient retention capacity and the presence of physical limitations to root development can't be improved and hypothecate the agricultural potential of the region.



Map 3.14: Capability subclasses for erosion control of the dominant soil units in Rwanda (derived from soil map at scale 1:250,000)



Map 3.15: Capability subclasses for fertility control of the dominant soil units in Rwanda (derived from soil map at scale 1:250,000)



Map 3.16: Capability subclasses for wetness control of the dominant soil units in Rwanda (derived from soil map at scale 1:250,000)

3.4.2. Actual and potential capability of the associated soil units

Actual capability

When classifying the associated map units, the relative importance of the different capability classes changes considerably compared to the capability classification of the dominant land units. The actual capability of the associated soil units has been illustrated in Table 3.20 and Map 3.17. Striking differences have been recorded in the highlands as well as in the lowlands.

The associated land units of the Congo–Nile Watershed Divide, characterised by very steep slopes, have been classified as land that needs special attention with respect to nature and soil conservation. Any form of agricultural land use in the actual landscape and soil conditions is to be avoided. The actual capability of the other high altitude belts increased because the associated land units are clearly less steep than the dominant ones. This resulted in a marginal suitability for agricultural production in the Impara and the southern borders of the Kivu Lake following the low BS that can be expected in the strongly leaching environment.

The actual capability of the Birunga still varies considerably between capability class 2 and 8, depending on soil depth and slope gradient. Land use in the Buberuka Highlands should be oriented towards lowland crops in the valleys, upland crops on the hills, and pasture on the shallow land units. Some associated units have been characterised by very steep slopes and should be protected. The overall capability of this region, however, is clearly higher than for the dominant units of this zone.

In the middle altitude belt of the Central Plateau; the actual capability varies between class 3 and 8. Especially in the South, slope gradient increases considerably, and according to the capability classification the land use should be directed towards forestry. In the agricultural zone of the Granitic Ridge, however, the associated units are composed out of relatively deep soils in a gently sloping landscape. Parent material and BS determine the capability class in these regions.

Also the capability of the Eastern Plateau generally increases. The shallow and steep land units of the appalachian relief in the North and the quartzite ridges in the South are associated to deeper soils where the landscape is less abrupt. Nevertheless, the actual capability of the South is generally limited to class 4 and consequently only marginal yields can be expected when these land units are cultivated. A very good production environment has been recorded around the Muhazi Lake.

Table 3.20: Areal extent of the actual capability classes of the associated soil units at scale 1:250,000

capability classes		*area*	
symbol	*description*	*(km²)*	*(%)*
2	very suitable for most crops; marginally suitable for tea; valleys are potentially suitable for irrigated rice	1080	5
3	suitable for most crops; marginally suitable for tea; valleys are potentially suitable for irrigated rice	4,879	21
4	marginally suitable; deep soils are very suitable for tea; marginally suitable for low demanding crops; actually unsuitable for demanding crops	4,572	20
5	suitable for pasture, valley cropping during the dry season, irrigated rice and eventually tea	1,315	6
6	suitable for pasture; actually unsuitable for crops; potentially suitable for low demanding crops after exceptional management	3,780	16
7	suitable for forests; actually unsuitable for crops; potentially suitable for low demanding crops after exceptional management	1,922	8
8	land with serious limitations	5,417	24
total		*23,487*	*100*

The presence of laterite crusts at shallow soil depth strongly limits the capability of the northeastern peneplains, while steep slopes limit the actual capability of the associated land units in the Mayaga. The moderate to imperfect drainage limits the capability of the lowland valleys to class 3 with a moderate suitability for most crops.

Potential capability

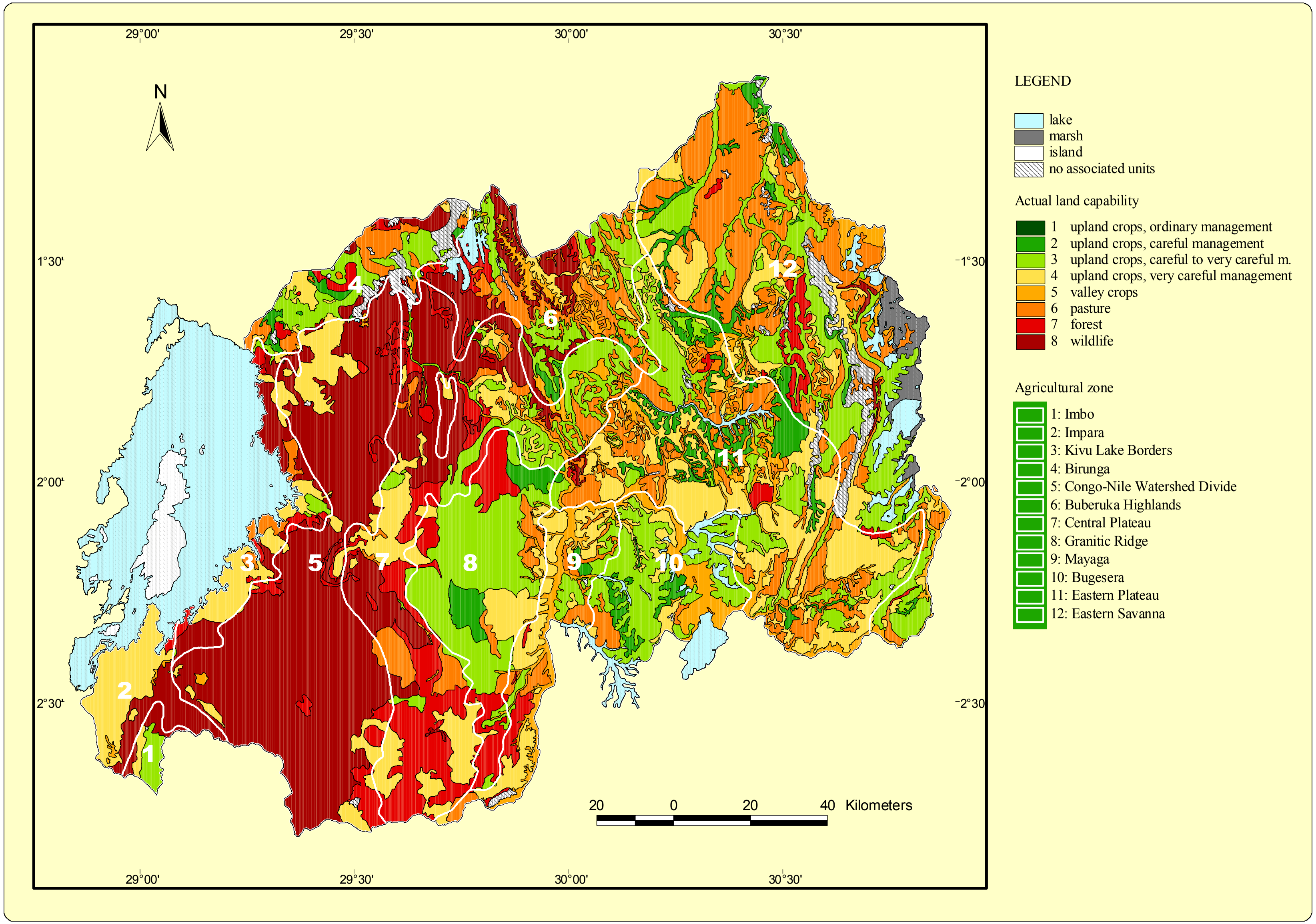
With respect to the associated map units, major improvements in land capability are realised by appropriate management practices applied in the highlands and at middle altitudes, while the land capability in the lowlands generally remains unchanged. Table 3.21 summarises the potential capability of the associated land units, while Map 3.18 illustrates its spatial distribution.

The high risk for erosion and low nutrient status of the associated land units of the Congo–Nile Watershed Divide can be corrected through exceptional management with construction of very small terraces and intensive fertilisation. Consequently, the potential capability of these land units increases considerably so that most crops can be cultivated with varying success.

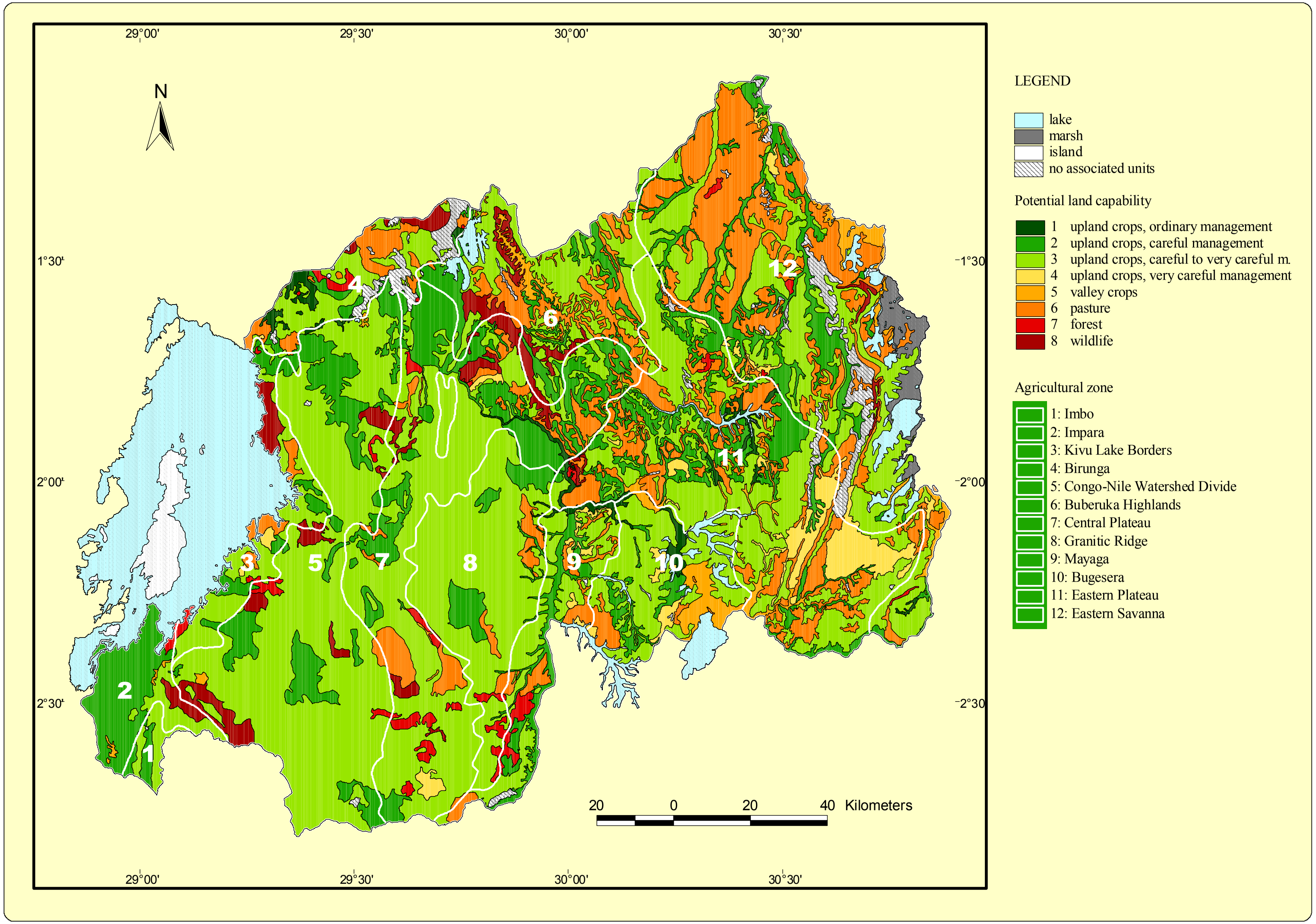
A comparable conclusion can be drawn for the climatic regions of the Kivu Lake Borders and the Buberuka Highlands. The old volcanic soils of the Impara can be made suitable for the cultivation of most crops after appropriate management, while the potential suitability of most land units in the Birunga varies from class 1, very suitable, to class 3, suitable for most crops. Only on those units where bombs or lava limit soil depth, the land use is restricted to pasture, forest or recreation. Construction of terraces and very careful fertilisation also increases the capability of the Central Plateau.

High slope gradients are a major limitation of the many associated map units of the East. Very careful management reduces the risk for erosion, but even then the potential capability is determined by soil properties that are inherently limiting the land productivity, such as a parent material that gives poor soils with regard to water and nutrient availability (granite, quartzite), an advanced weathering stage with a low nutrient holding and water holding capacity, or the presence of a laterite crust limiting the soil depth. The generally favourable soil properties of the valleys of the Akanyaru, Nyabarongo and Akagera, allow the cultivation of valley crops on the imperfectly drained soils during the third agricultural season or, if these soils are drained, the cultivation of most crops during the rest of the agricultural year.

The spatial distribution of the management strategies that can improve the land capability for agricultural production generally corresponds to those found for the dominant land units. Exceptional management related to erosion control and fertility is required in the West, and its importance decreases with decreasing altitude. The drainage problems of the associated units are more extended than that of the dominant units, but their extension remains limited to the valleys.



Map 3.17: Actual capability of the associated soil units in Rwanda (derived from soil map at scale 1:250,000)



Map 3.18: Potential capability of the associated soil units in Rwanda (derived from soil map at scale 1:250,000)

Table 3.21: Areal extent of the potential capability classes of the associated soil units at scale 1:250,000

capability classes	*area*	
symbol	*(km²)*	*(%)*
1	275	1
2	4,623	20
3	12,052	52
4	633	3
5	493	2
6	3,780	16
7	333	1
8	776	3
total	*23,487*	*100*

3.5. Discussion

The capability classification designed for Rwanda, allows the evaluation of the capability of each land unit of the soil map at scale 1:250,000 for different land uses. These land uses have been defined in a very general way: demanding crops, less demanding crops, tea, irrigated rice, valley crops, pasture and forestry. The general way of defining land uses doesn't permit a validation and calibration of this methodology using real world crop yields. Yet, the principle purpose of this capability classification is to identify possible limitations of the natural resources found in Rwanda. In fact, it is a very general interpretation of the soil map at scale 1:250,000 in terms of agricultural production.

The actual capability classification stresses the impact of the steep topography and leaching character of the climate in the humid West, Southwest and North, giving land units that are sensible to soil loss and nutrient shortage. Many of these units, however, are suitable for the production of tea. The rather limited agricultural potential of the volcanic zone is due to the presence of shallow soils developing on lava and volcanic ash. In reality, the region is very promising as these problems can be eliminated through the creation of ridges and ditches, and the cultivation of crops on the ridges. In the East and Southeast, the actual capability is generally promising except for the land units corresponding to the steep quartzite ridges or those where laterite crusts seriously limit soil depth.

The potential capability illustrates that some management related to fertilisation and erosion, can considerably increase the suitability for crop production of the western areas, while the East is characterised by inherently limiting soil properties that can't be improved through economically viable management. The land use capability of the Eastern Savanna is hypothecated by the strong degree of weathering or shallow soil depth above a petroferric contact. Exceptions to this general rule are found in the region around Muhazi Lake, where most soils are deep, clayey, well drained, rich in basic cations and organic material. In the Central Plateau, it is the granitic origin of the soils, characterised by a low water holding capacity and high degree of stoniness, that limits their use to less demanding crops. The various land use types that are possible in the valleys – pasture, valley cropping, and irrigated rice – determine the required management strategies for the agricultural development of these land units.

The national capability classification at scale 1:250,000 thus allowed the characterisation of the edaphic environment for crop production and the identification of major problems limiting the agricultural production in Rwanda. The national scale of this procedure has also some drawbacks as the mapping detail and the number of parameters that can be included in the classification procedure are limited and depending on the information offered by the soil map. As such, also management strategies other than drainage, fertilisation and terracing might be applied in Rwanda to increase the agricultural potential of promising regions. Nevertheless, the land capability classification is a promising method for a general assessment of the capability of the Rwandan territory for agricultural production, summarising its most important environmental opportunities, challenges and inherent problems.

CHAPTER 4. LAND SUITABILITY CLASSIFICATION

4.1. Introduction

The land capability classification was designed to identify the arable lands of Rwanda at scale 1:250,000. These arable land units are all characterised by a slope gradient below 25 % and a soil depth exceeding 0.50 m. Yet, the other physical and chemical soil properties affecting crop growth are considerably variable. Additionally, the diversity in climatic environments offers the Rwandan farmer the opportunity to cultivate temperate, humid tropical, or dry tropical crops, depending on the temperature and rainfall regime of his land. Qualitative land evaluation methods offer sound guidelines in the initial stages of land use planning studies, when a broad spectrum of land use alternatives and vast areas of agricultural land still have to be explored. In a land suitability classification the land is classified according to its suitability for the cultivation of a specific crop through a comparison of the crop-specific requirements with the actual or potential land characteristics.

Elaboration of an agro-climatic map at scale 1:250,000 permitted to assess the agro-climatic suitability of the Rwandan temperature and rainfall regimes for the cultivation of a whole range of crops. The landscape and soil properties that are linked to the soil map, produced at the same scale, have been used to assess the agro-edaphic suitability. The cereals sorghum and maize, the tubers cassava, sweet potato and potato, the legumes bean and pea, and the oil crops groundnut and soybean are representative for the Rwandan subsistence agriculture. Also included in the analysis are the fruit tree banana and the cash crops tea and arabica coffee.

Definition of the crop requirements was based on the expert knowledge of the soil surveyors formerly active in the project “Carte pédologique du Rwanda” (Birasa *et al*., 1992) and on the requirements designed by Sys *et al*. (1993). With the introduction of management strategies controlling soil loss, internal drainage and fertility, both the actual and the potential suitability could be assessed. A flowchart of the different procedures has been illustrated in Fig. 4.1.

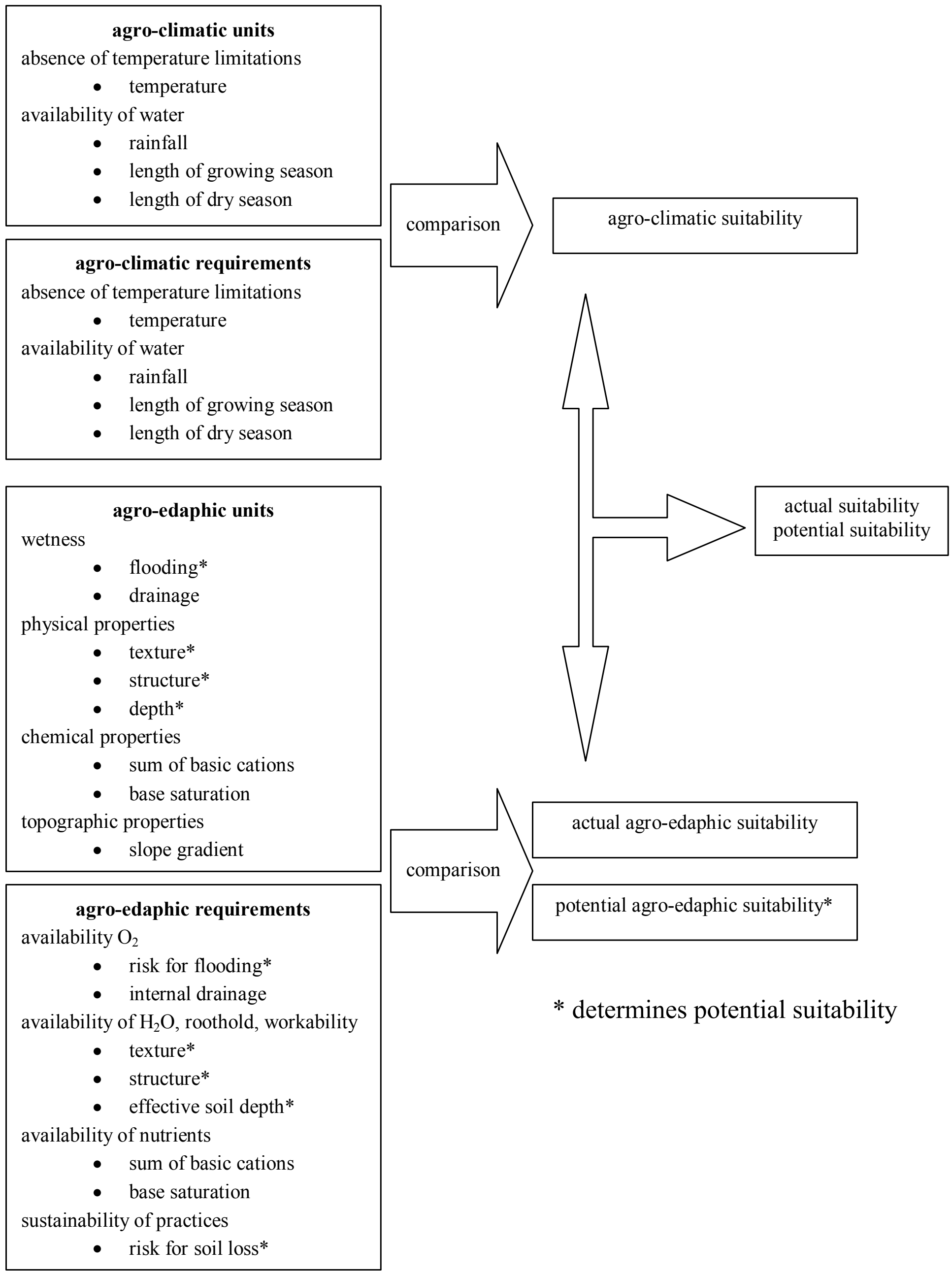


Fig. 4.1: Flowchart of the land suitability classification procedure designed for Rwanda at scale 1:250,000

4.2. Land characteristics

4.2.1. Agro-climatic zones

In Rwanda, the most relevant climatic parameters related to crop production are rainfall and temperature. Monthly temperature, rainfall and humidity data, recorded at 197 stations during the period 1974-1989 have been organised in a database and missing temperature and humidity data have been extrapolated following regression equations based on altitude. Combination of these data with the expert knowledge of soil surveyors working all over Rwanda resulted in several climatic maps.

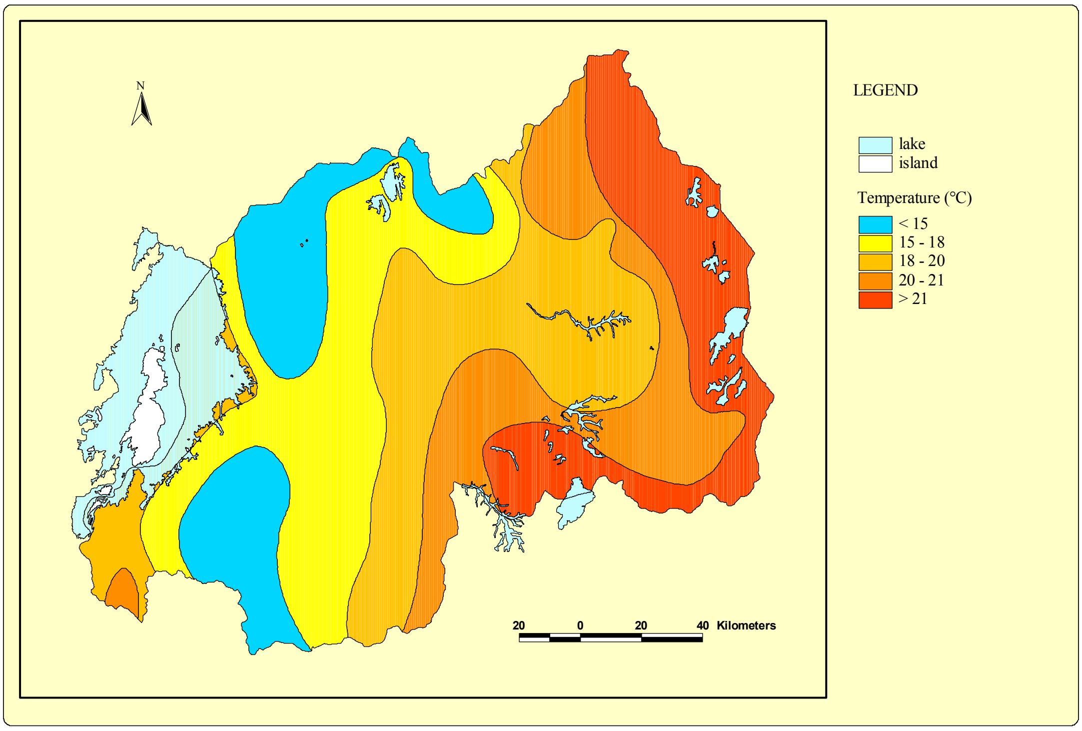
Temperature

The mean annual temperature is strongly related to the altitude (Map 4.1). In the extreme East and Southeast, mean annual temperatures exceed 21 °C, while they fall below 15 °C at the highest altitudes of the Buberuka Highlands, the Birunga and the Congo-Nile Watershed Divide.

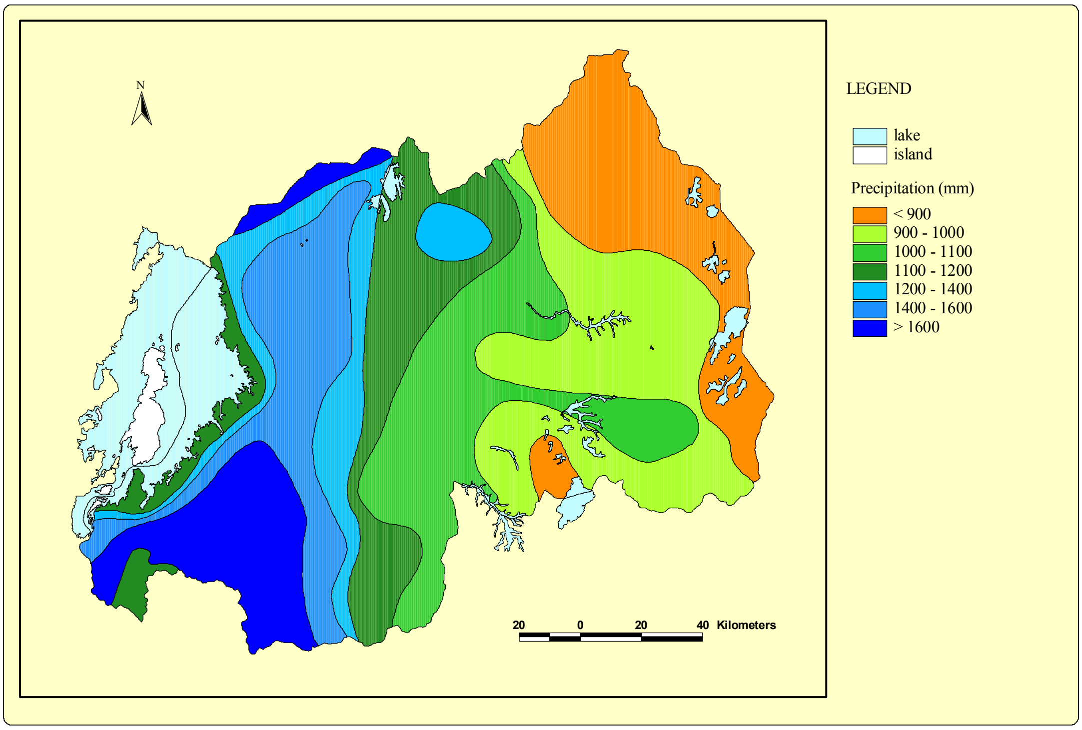
In this equatorial country, annual variations in temperature are negligible. Diurnal fluctuations, however, regularly exceed 12 °C and their impact on crop production should not be underestimated (Ravelingien, 2001).

Rainfall

An enormous variability in space and time characterises the Rwandan rainfall regime. Rainfall totals generally increase from East to West, although the positive correlation of rainfall with altitude is not strongly pronounced (Map 4.2). Orographic rainfall strikes the eastern slopes of the Congo-Nile mountain chain, while the western slopes are much drier as the föhn-wind prevents the formation of clouds. In southwest Rwanda, the southeastern wind, moistened by its passage over the Tanganyika Lake, gives rise to abundant rainfall as it strikes the western flanks of the mountain chain (Ravelingien, 2001). As such, annual rainfall exceeds 1,600 mm in the volcanic region, in the southern part of the Congo-Nile Watershed Divide and in the Impara. The Eastern Savanna and the central part of the Bugesera are significantly drier, receiving less than 900 mm rainfall annually.



Map 4.1: Temperature distribution in Rwanda

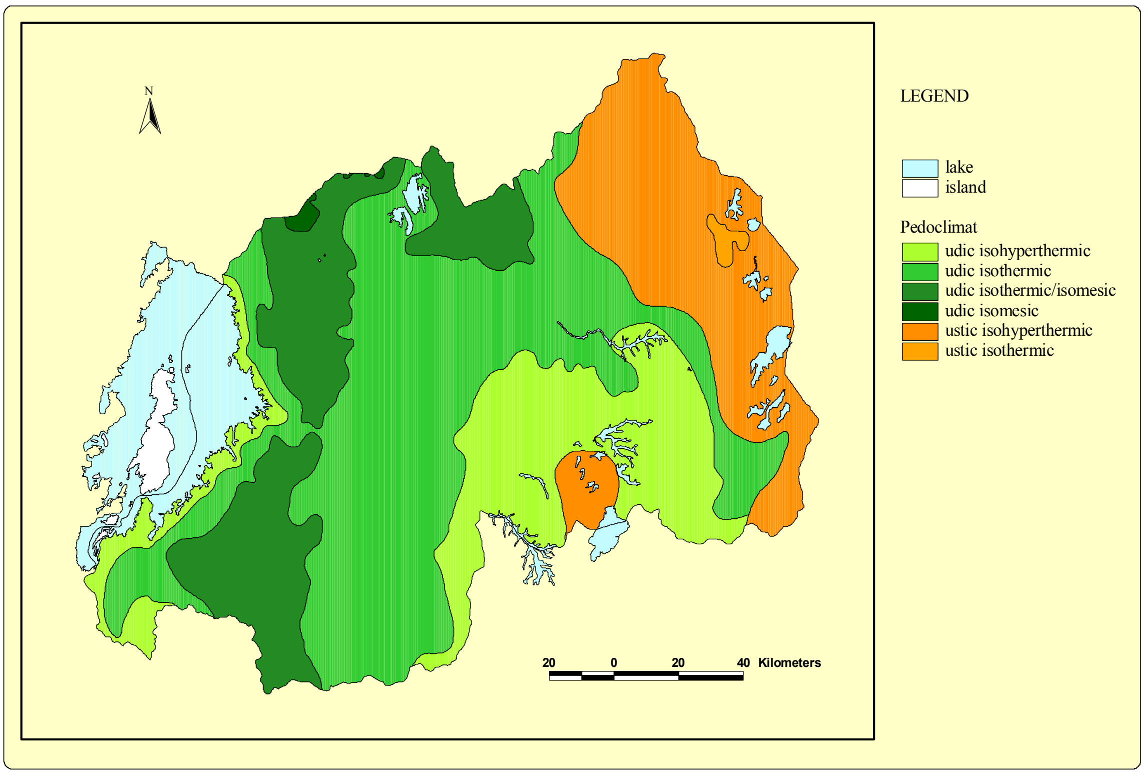


Map 4.2: Rainfall distribution in Rwanda

Temporal changes in rainfall frequency have a serious impact on crop production too. Generally, two rainy seasons and two dry seasons can be distinguished: (1) a short rainy season from mid September to mid December; (2) a short dry season from the second part of December to the beginning of February; (3) a long rainy season from February to the end of May; and (4) a long dry season from the beginning of June to the first half of September. The total length of the growing period increases from East to West. In the eastern lowlands, the dry season lasts for four months. Year-round humid conditions are found in the region of the volcanoes, while also the southern part of Congo-Nile Watershed Divide enjoys a favourable rainfall distribution.

Soil temperature and rainfall regime

Following the criteria of the Soil Survey Staff (1975), two soil moisture regimes and three soil temperature regimes have been identified in Rwanda. Map 4.3 illustrates their spatial distribution.



Map 4.3: Soil moisture and temperature regime in Rwanda

The agricultural zone of the Eastern Savanna and the central part of the Bugesera are characterized by a ustic soil moisture regime, with a sequence of distinctly dry and wet seasons. All other agricultural zones of Rwanda have a udic soil moisture regime and enjoy a more uniformly distributed rainfall over the year.

With increasing altitude, the soil temperature regime evolves from isohyperthermic in the lowlands, characterised by temperatures equal or higher than 22 °C, to isomesic on the volcano slopes, where the annual temperature ranges between 8 and 15 °C. Additionally, the Kivu Lake has a smoothing effect on the soil temperature regime recorded along its borders.

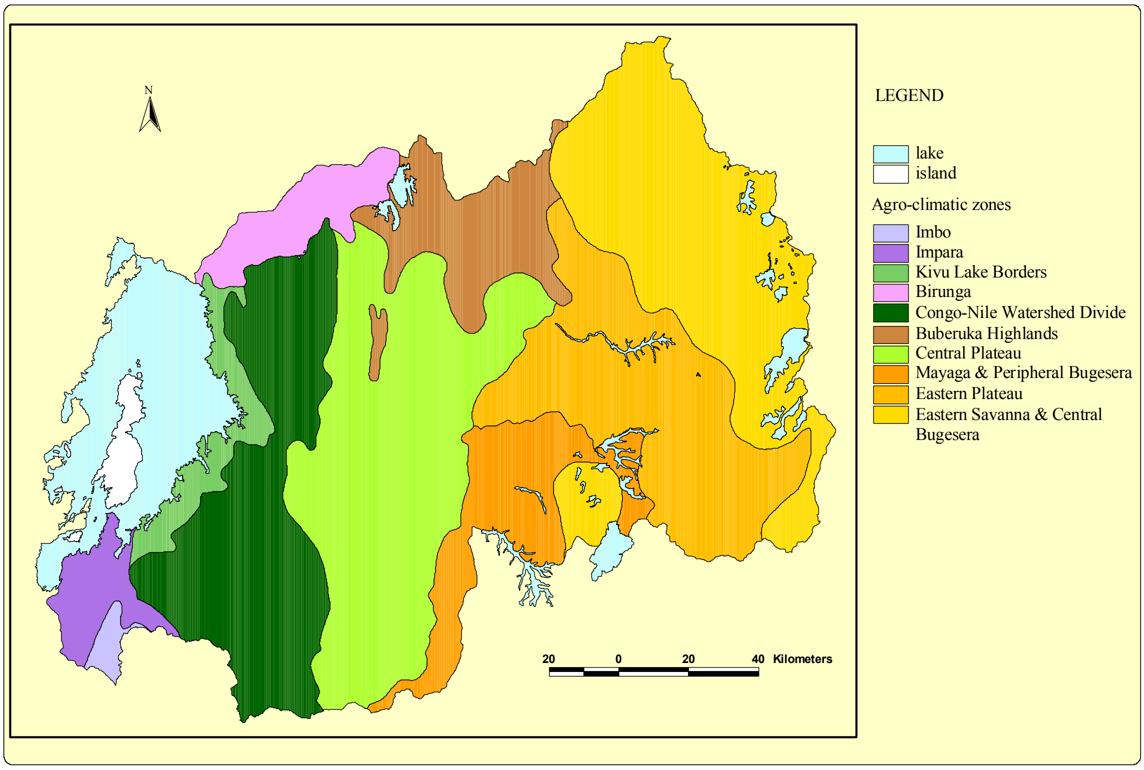
Characterisation of agro-climatic zones

The average length of the dry, intermediate and humid period in each of the meteorological stations was calculated from the available monthly data on temperature, rainfall and humidity following the procedure described by Papadakis (1970). According to this procedure, the water supply from rainfall during dry months is insufficient to meet the water demands and the crop has to rely on soil water reserves. In humid months, the water supply exceeds the demands, and the surplus of water is stored in the soil. Months with a water supply more or less equal to the water demand have been referred to as intermediate periods. The growing period has been defined as the period of the year during which agricultural production is possible thanks to a sufficient water supply and the absence of temperature limitations. In Rwanda, all intermediate and humid months belong to the growing period.

Integration of the knowledge on temperature, rainfall, soil temperature and moisture regime and the length of the growing period with the expert knowledge of the soil surveyors, resulted in the delineation of 10 agro-climatic zones (Map 4.4), which correspond very well to the agricultural regions identified by Delepierre (1974).

The agricultural regions of the Imbo, Impara, Kivu Lake Borders, Birunga, Congo-Nile Watershed Divide, Buberuka Highlands, and the Eastern Plateau have been retained in the agro-climatic map. One agro-climatic region, referred to as the Central Plateau, has been made up by the Central Plateau and the Granitic Ridge agricultural zones, having similar agro-climatic conditions. The Bugesera agricultural zone has been split in the central and peripheral Bugesera.

The Mayaga and Peripheral Bugesera constitute the ninth agro-climatic region; the Eastern Savanna and Central Bugesera is the tenth and driest agro-climatic region of Rwanda. Table 4.1 gives an overview of the number of stations representing the climate in each of the agro-climatic zones together with the average, maximum and minimum values for altitude, annual temperature, annual rainfall and length of the dry season. The high variability in climatic parameters recorded in all agro-climatic zones is striking and should be taken into account when performing the land suitability classification.



Map 4.4: Agro-climatic zones in Rwanda

Table 4.1: Characterisation of the agro-climatic zones in Rwanda

ACZ[a]	*stations*	*altitude (m)*			*mean temperature (°C)*			*total rainfall (mm year^{-1})*			*dry period (days)*		
(-)	*(n°)*	*mean*	*max*	*min*	*mean*	*max*	*min*	*mean*	*max*	*min*	*mean*	*max*	*min*
1	1	**<1,000**	-	-	**24**	-	-	**1,154**	-	-	**122**	-	-
2	16	**1,666**	2,100	1,400	**19**	21	17	**1,710**	2,360	1,203	**56**	62	31
3	13	**1,638**	1,890	1,465	**20**	21	18	**1,225**	1,420	1,087	**66**	92	31
4	17	**1,960**	2,500	1,460	**17**	20	14	**1,317**	1,678	1,110	**15**	62	0
5	23	**2,058**	2,550	1,450	**17**	21	13	**1,542**	2,276	970	**27**	92	0
6	16	**1,957**	2,312	1,500	**17**	21	15	**1,267**	1,553	1,033	**41**	152	0
7	44	**1,749**	2,110	1,400	**19**	22	17	**1,298**	1,993	1,025	**59**	123	0
8	16	**1,403**	1,500	1,325	**21**	21	20	**1,101**	1,310	901	**109**	153	62
9	33	**1,575**	2,200	1,370	**20**	21	18	**1,038**	1,255	891	**86**	123	31
10	16	**1,386**	1,485	1,280	**21**	25	20	**902**	1,258	632	**126**	153	92

[a] agro-climatic zone: 1 = Imbo; 2 = Impara; 3 = Kivu Lake Borders; 4 = Birunga; 5 = Congo-Nile Watershed Divide; 6 = Buberuka Highlands; 7 = Central Plateau; 8 = Mayaga and Peripheral Bugesera; 9 = Eastern Plateau; 10 = Eastern Savanna and Central Bugesera

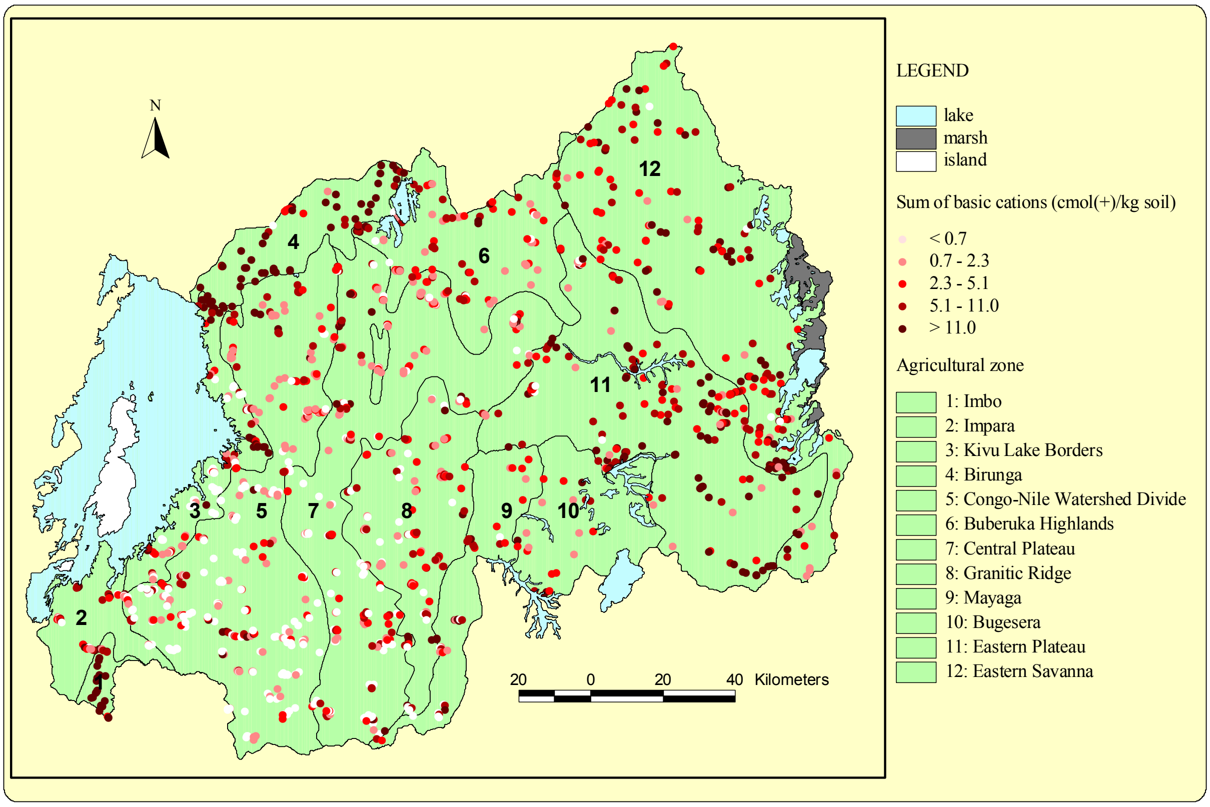
4.2.2. Agro-edaphic zones

In the chapter on the land capability classification, the topographical, morphological and physical characteristics of the soil units at scale 1:250,000 have been described in detail. With respect to the chemical properties, the ACEC and BS were estimated from the available data on soil profile development stage, reflecting the intensity of weathering, and the agricultural zone, reflecting the impact of the parent material and the leaching strength of the climate. Originally, both parameters have been introduced in the land evaluation methodology because they were easily available or derivable from recorded morphological characteristics or from the soil classification name. In Rwanda however, the interpretation of these properties is not evident when variable charged minerals dominate the clay fraction, which is the case in the volcanic region and eastern peneplains. The sum of the basic cations Ca, Mg and K, recorded in the upper 0.25 m of the soil surface, is therefore a more reliable indicator of the availability of nutrients.

Map 4.5 illustrates the spatial distribution of the weighted average sum of basic cations (SBC) in the upper 0.25 m of the soil surface recorded in 1,378 profiles. The class limits were determined by a quantile classification procedure, assigning the same number of records to each class. The SBC clearly increases from West to East, except for the soil profiles located in the Birunga and the Imbo which are characterised by a SBC exceeding 11 cmol(+) kg^{-1} soil. As such, climate and parent material clearly influence the level of this chemical parameter.

Further analysis of the soil profile database was conducted towards a grouping of the profiles according to parent material, agricultural zone and development stage. A considerable variability in SBC due to differences in land use and topographical position remained unresolved in most groups. Nevertheless, a classification key for the estimation of this chemical parameter in each soil unit could be designed (Table 4.2). Definition of the SBC classes was based on the crop requirements designed by Sys *et al*. (1993).

The alluvial, volcanic, and calcareous soils are characterised by a SBC exceeding 5 cmol(+) kg^{-1} soil. Also the soils derived from basic parent material or soils characterised by vertic properties have an equally high SBC. The availability of nutrients in soils developing on shales and schists depends on the leaching strength of the climate and the development stage. The SBC is clearly higher in the lowlands than in the highlands where the nutrient level strongly decreases with an increase in weathering intensity. Soils developing on quartzitic material generally have a SBC ranging between 2.0 and 3.5 cmol(+) kg^{-1} soil, except in the eastern lowlands where the SBC exceeds 5 cmol(+) kg^{-1} soil. Soils derived from granitic material have been identified at three different locations. Those in the agricultural zones of the Kivu Lake Borders and the Congo-Nile Watershed Divide are characterised by a SBC ranging between 2.0 and 3.5 cmol(+) kg^{-1} soil, independent on the development stage. The same applies to the soils derived from granites in the agricultural zones of the Eastern Plateau and the Eastern Savanna. In the Central Plateau, Granitic Ridge and Mayaga agricultural zones, the lowest SBC has been reported in soils with an intergrade argillic-oxic horizon. Soils with a cambic or argillic horizon have an intermediate fertility level, while those with an entic development stage are the richest.

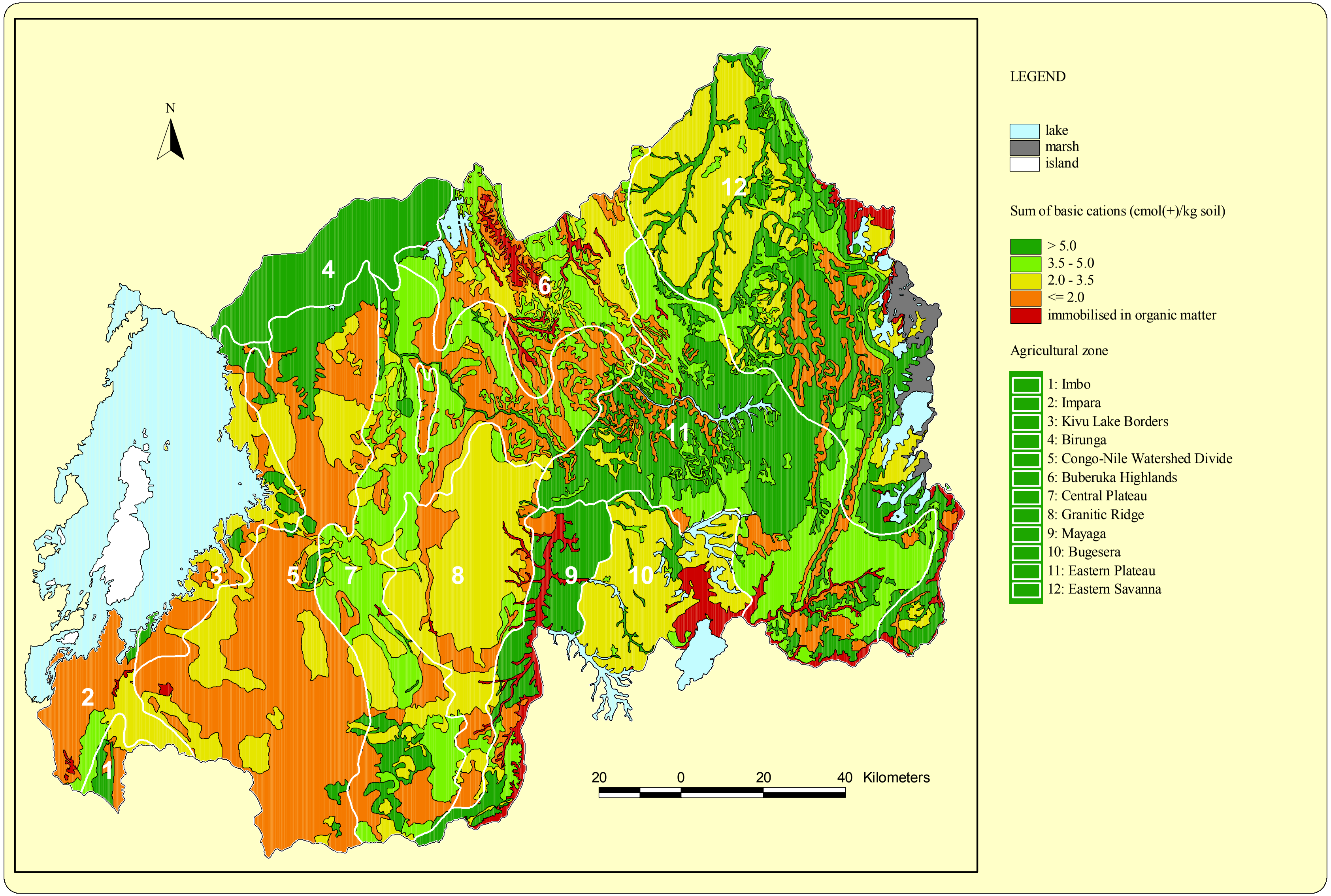


Map 4.5: Weighted average sum of basic cations (Ca, Mg, K) in the upper 0.25 m of the soil surface of the profiles in the soil database of Rwanda

Table 4.2: Key for estimating the SBC of the soil units at scale 1:250,000

parent material (-)	*agricultural zone* (-)	*development stage* (-)	*SBC* (cmol(+) kg^{-1} soil)
alluvium	any	any	> 5.0
colluvium	any	any	2.0 – 3.5
calcareous rocks	any	any	> 5.0
basic rocks	any	any	> 5.0
basalt	any	C, A	> 5.0
		K	≤ 2.0
granite	3, 5	any	2.0 – 3.5
	6, 11, 12	any	2.0 – 3.5
	7, 8, 9	E	3.5 – 5.0
		C, A	2.0 – 3.5
		K	≤ 2.0
schists	1, 2	C	3.5 – 5.0
		A	2.0 – 3.5
		K	≤ 2.0
	3, 5	any	≤ 2.0
	6, 7, 8	E, C, K	≤ 2.0
		A	3.5 – 5.0
	9	any	> 5.0
	10	E	≤ 2.0
		K, O	2.0 – 3.5
		C, A	3.5 – 5.0
	11, 12	E	≤ 2.0
		C, A, K	> 5.0
		O	3.5 – 5.0
quartzite-schists	1 to 9	any	2.0 – 3.5
	10, 11, 12	any	3.5 – 5.0
quartzite	any	any	2.0 – 3.5
volcanic material	any	any	> 5.0
any	any	V	> 5.0

The spatial distribution of these SBC classes has been illustrated in Map 4.6, while their areal extent has been summarised in Table 4.3.



Map 4.6: Estimated sum of basic cations (Ca, Mg, K) of the dominant soil units in Rwanda (derived from soil map at scale 1:250,000)

Table 4.3: Areal extent of the SBC classes of the dominant soil units at scale 1:250,000

sum of basic cations		*area*	
symbol (-)	*description (cmol(+) kg^{-1} soil)*	*(km²)*	*(%)*
1	> 5.0	5,969	25
2	3.5 – 5.0	4,489	19
3	2.0 – 3.5	6,150	26
4	≤ 2.0	6,072	26
	immobilised in organic matter	807	3
total		*23,487*	*100*

Half of the Rwandan territory is characterised by soils with a low SBC, being less than 3.5 cmol(+) kg^{-1} soil. The poorest soils are found in the Impara where the originally rich basaltic material is leached out completely. Also the deep soils of the Congo-Nile Watershed Divide lost most of their nutrients. In the middle altitude regions and in the lowlands, the lowest SBC values have been reported in the degraded, shallow and steep soils developing on shales and schists. A low SBC is also characteristic for the soils derived from granite and for the strongly weathered soils of the Bugesera. An intermediate level of SBC has been recorded in the deeper soils having an argillic horizon in the Buberuka Highlands, Central Plateau and Eastern Plateau. The highest nutrient levels are found in the alluvial valleys, in the volcanic plain and in the soils derived from shales and schists in the agricultural zone of the Mayaga. In the agricultural regions of the Eastern Plateau and Eastern Savanna, the highest nutrient levels are found in the soils developing on shales and schists and having an advanced development stage. In these latter two regions, also the soils with an intergrade argillic-oxic or oxic horizon thus are characterised by favourable nutrient levels.

4.3. Crop requirements

The land suitability at scale 1:250,000 has been assessed for 12 important crops of the Rwandan agriculture: common bean, maize, sorghum, pea, sweet potato, potato, cassava, groundnut, soybean, banana, arabica coffee and tea. The specific requirements of each of these crops have been summarised in Tables 4.4 to 4.15.

4.3.1. Suitability classes

The guidelines for the definition of the suitability classes offered by the FAO (1976) have been followed. Two suitability orders and five suitability classes have been distinguished. Suitable land is land on which the sustained use is expected to yield benefits that will justify required recurrent inputs without unacceptable risk to land resources on the site and in adjacent areas. Within this order, 3 suitability classes have been distinguished: S1, very suitable; S2, moderately suitable; and S3, marginally suitable. No firm criteria have been given for defining the classes, which permits complete freedom in the choice of the criteria determining the class limits. Unsuitable land is land having characteristics which appear to preclude its sustained use for the defined land utilisation type or which would create production, upkeep and/or conservation problems requiring a level of recurrent inputs unacceptable at the time of interpretation. Two different suitability classes can be distinguished within this suitability order: N1, actually unsuitable but potentially suitable and N2, actually and potentially unsuitable.

4.3.2. Agro-climatic requirements

In tropical Africa, the main climatic determinant for crop production is rainfall. Nevertheless, low temperatures hamper the successful cultivation of tropical crops in the high altitude regions where temperate crops or high-altitude tropical crops are more adapted to the climatic conditions. The temperature regime is strongly correlated with altitude, varies only slightly annually but is characterised by important diurnal variations. Rainfall, as well as temperature, is spatially and temporally strongly variable and both are thus determining the suitability for a whole range of crops. Several experts of the Rwandan climate, pedology and agriculture determined the crop-specific climatic demands (Birasa *et al*., 1992).

Altitude and temperature

With respect to the temperature requirements, the selected crops have been grouped into 5 classes. Potato is a typical crop of high-altitude tropical regions and requires temperatures below 22 °C. Taking into consideration the diurnal variations, marginal conditions have been found at an altitude between 1,500 and 1,800 m. Higher temperatures at lower altitudes are unsuitable for the production of this crop. The opposite is true for groundnut and cassava, both requiring warm and sunny conditions with a mean annual temperature exceeding 17 °C. Unsuitable temperatures have been reported at altitudes exceeding 1,900 m. The temperature requirements of banana are much less severe, but the low temperatures at 2,000 m or higher are unsuitable. Arabica coffee requires moderate temperatures without large differences in daily minima and maxima. Consequently, the production of this crop is only feasible at an average altitude ranging between 1,300 and 1,900 m. The high altitude areas are marginally suitable to unsuitable for the production of sweet potato, sorghum and soybean, which are quite well adapted to warm and dry tropical regions. Tea, pea, common bean and maize pose the lowest demands to temperature.

Rainfall

Also with respect to the rainfall demands, a high variability among the selected crops has been reported. The annual rainfall totals recorded in Rwanda are very suitable or moderately suitable for the production of groundnut, cassava, soybean, common bean and sorghum. Rainfall totals below 900 mm are marginal for the production of maize, sweet potato and banana, but very suitable conditions have been reported where the annual rainfall is at least 1,000 mm. For the successful production of arabica coffee, the rainfall totals have to attain at least 1,100 mm. With decreasing rainfall, the suitability becomes moderate or marginal. Rainfall totals below 900 mm annually are unsuitable. Regularly distributed rainfall is important for the growth of the high altitude crops pea and potato. No additional rainfall requirements have been defined for potato as the increased water demands are also reflected in the altitude requirements. With respect to pea, at least 1,300 mm of annual rainfall is very suitable, while the water supply is marginal when total rainfall drops below 1,200 mm annually. The cash crop tea poses comparable requirements, but its cultivation becomes unfeasible where annual rainfall is less than 1,100 mm.

Length of the dry season

Additional requirements have been defined with respect to the duration of the dry season for the cultivation sorghum and tea. Sorghum prefers areas with a dry season length of maximally 4 months. A moderate suitability has been reported if the dry season lasts longer. Under these conditions, tea production is unfeasible. A dry season of 3 to 4 months is marginally suitable, while very suitable environments are characterised by a dry season of maximum 2 months.

4.3.3. Agro-edaphic requirements

Important edaphic parameters affecting the land suitability for agricultural production are risk for flooding and internal drainage, texture and structure, soil depth and sum of basic cations. They affect the workability and the availability of oxygen, water and nutrients. Additionally, the slope gradient affects the workability and sustainability of the selected land use.

Reference documents for the design of landscape and soil requirements were the requirement tables designed by Sys *et al*. (1993). These general guidelines were adapted to the specific environmental conditions of Rwanda.

Slope gradient

The slope gradient determines not only the possibilities for mechanised agriculture, it also sets production limits to small-scale farmers. Crop independent suitability classes based on the slope gradient classes: 0–8 %, 8–16 %, 16–30 %, 30–50 %, and over 50 %, have been defined by Sys *et al*. (1993). In Rwanda, the cartographic landscape legend distinguished slope classes with slightly different class boundaries and the evaluation of slope gradient thus had to be adapted to the available data. Very suitable for crop production is a gradient equal to or smaller than 6 %. A slope gradient between 6 and 13 % is moderately suitable, while a gradient between 13 and 25 % is only marginally suitable. Actually unsuitable, but potentially suitable are the units with a gradient exceeding 25 %, but being lower or equal to 50 %. Units with a degree of inclination exceeding 55 % are both actually and potentially unsuitable for crop growth. This classification key is valid for all crops, except for tea. In Rwanda, the cultivation of tea is especially concentrated in the hilly areas around the Congo-Nile Watershed Divide, and thus it was decided to design a tea-specific suitability classification key for slope gradient. A slope gradient of 13 % or less is very suitable; a degree of inclination ranging from 13 to 25 % is moderately suitable. Gradients between 25 and 55 % are marginally suitable, while the cultivation of any crop is excluded if the gradient exceeds 55 %.

Flooding and drainage

Wetness limitations are related to risk for flooding and internal drainage. In Rwanda, flooding can be expected in soil units characterised by very poorly drained, organic soils. Although it is known that some crops can stand flooding for some time, while others cannot tolerate water logging at all, a crop independent evaluation had to be designed because data on frequency and depth of flooding were not available. All soils without any risk for flooding thus are optimal for crop growth. The management requirements in order to make the soils that are regularly subjected to flooding suitable for the selected crops run beyond the possibilities of the farmers. Consequently any risk for flooding is actually and potentially unsuitable.

When designing the crop requirements regarding internal drainage, the crop specific tolerance for impeded drainage has been taken into account. According to the requirements developed by Sys *et al*. (1993), two different crop groups have been distinguished. Groundnut, cassava, and arabica coffee are very sensitive to waterlogging. The other crops stand waterlogging for some time. In the cartographic legend, three drainage classes have been distinguished: excessive to well, moderate to imperfect, and poor to very poor. When designing new requirements, the preference of groundnut, cassava and coffee for well-drained soils has been respected. A well to excessive internal drainage is very suitable for the production of these crops. If the internal drainage is moderate or imperfect, the suitability is moderate to marginal. Poorly drained and very poorly drained soils are actually unsuitable but they can be properly managed to remove the wetness problems. The suitability classification for drainage designed for the other crops is quite similar, except for the moderately and imperfectly drained soils, which have been classified as very suitable to moderately suitable, and for the poorly to very poorly drained soils that are marginally suitable to actually unsuitable.

Texture and structure

The evaluation of these parameters has been adapted to the limited data that were available through the cartographic legend. Four different texture classes had been distinguished based on clay content, while the requirements developed by Sys *et al*. (1993) are based on all texture classes of the USDA textural triangle together with an assessment of structure. Fine textured soils with vertic properties (v) are usually classified one level lower than the soils with a well-developed, blocky structure (s).

All texture classes are very suitable for the production of sweet potato, except where a clay content exceeding 60 % is associated with vertic properties. These soils have been classified as moderately suitable. Groundnut, potato and cassava should be preferably cultivated on coarse textured soils, facilitating the harvest of the pods and tubers. Arabica coffee and banana clearly prefer fine textured soils, while tea production is best on soils with an intermediate clay percentage. Soils with vertic properties, however, are unsuitable for the production of arabica coffee and tea. All other crops don’t have a strongly expressed preference for a certain texture class.

Organic soils have a high pore volume (low bulk density) that causes considerable problems for the reclamation. The removal of water through drainage is necessarily associated with shrinkage and compaction of the loose organic matter and subsequent considerable subsidence of the land surface. After removal of the plant cover, the low thermal conductivity of the organic material allows very high temperatures to build up in the upper few centimetres of Histosols exposed to direct solar radiation. This causes irreversible transformation of organic colloids and makes the organic material crumble to a dry "powder" which is very susceptible to wind erosion. The lower parts of the solum, in contrary, heat up slowly which can be unfavourable for plant development in colder environments (FAO, 2000). The very different physical properties of organic soils compared to mineral soils thus seriously limit their suitability for the cultivation of the selected crops. Consequently, they have been classified as actually and potentially unsuitable.

Soil depth

Also the evaluation of soil depth was strongly limited to the three depth classes used by the soil surveyors: shallow soils from 0 to 0.50 m, moderately deep soils from 0.50 to 1.00 m and deep soils of more than 1.00 m depth. Nevertheless, the classification was designed to reflect the crop specific preferences. Very shallow soils, being less than 0.25 m deep have not been taken into consideration. They should not be cultivated but well managed to avoid further degradation. Soil depth is one of the most important parameters when determining the suitability for the production of arabica coffee. This perennial crop requires very deep soils for an optimal growth. The soil depth class exceeding 1.00 m has therefore been classified as very suitable to moderately suitable. Marginal conditions are found in moderately deep soils, while shallower soils are unsuitable for arabica coffee. Also cassava requires deep to moderately deep soils. Sorghum can be grown successfully on shallow soils. A soil depth of 0.50 m or less is moderately suitable; a greater soil depth is very suitable. All other crops are moderately demanding with respect to soil depth. Deep soils are very suitable, moderately deep soils are very suitable to moderately suitable while shallow soils are marginally suitable.

Sum of basic cations

According to the suitability classification designed by Sys *et al*. (1993), the selected crops can be classified into 3 groups. Maize, pea, and arabica coffee are the most demanding crops. A SBC exceeding 5.0 cmol(+) kg^{-1} soil is very suitable. With decreasing nutrient level, the suitability becomes moderate or marginal. The soil is actually unsuitable if the SBC drops below 2.0 cmol(+) kg^{-1} soil. Common bean, soybean, banana, groundnut, sweet potato, potato and sorghum are moderately demanding. A SBC exceeding 3.5 cmol(+) kg^{-1} soil is very suitable, while a SBC of 2.0 cmol(+) kg^{-1} soil or less is marginally suitable for the production of these crops. Cassava and tea can be grown successfully on strongly leached soils with a SBC of maximally 2.0 cmol(+) kg^{-1} soil. Additionally, a low BS is essential for the optimal growth of tea.

Table 4.4: Requirements for the cultivation of common bean in Rwanda

parameters	*suitability class*				
	S1	*S2*	*S3*	*N1*	*N2*
Climate					
altitude (m)	≤ 2,500	-	-	-	> 2,500
annual rainfall (mm)	≥ 1,000	< 1,000	-	-	-
Landscape					
slope gradient (%)	≤ 6	6 - 13	13 - 25	25 - 55	> 55
Soil					
flooding	no risk	-	-	-	any risk
drainage	excessive to moderate	imperfect	poor	very poor	-
clay (%) & structure	20 – 60, > 60 blocky	≤ 20, > 60 vertic	-	-	organic soils
depth (m)	≥ 0.75	0.75 – 0.50	< 0.50	-	-
SBC (cmol(+) kg^{-1})	> 3.5	3.5 – 2.0	≤ 2.0	-	-

Table 4.5: Requirements for the cultivation of maize in Rwanda

parameters	*suitability class*				
	S1	*S2*	*S3*	*N1*	*N2*
Climate					
altitude (m)	≤ 2,000	2,000 – 2,200	2,200 – 2,300	-	> 2,300
annual rainfall (mm)	≥ 1,000	1,000 – 900	< 900	-	-
Landscape					
slope gradient (%)	≤ 6	6 – 13	13 - 25	25 - 55	> 55
Soil					
flooding	no risk	-	-		any risk
drainage	excessive to moderate	imperfect	poor	very poor	-
clay (%) & structure	20 – 60, > 60 blocky	≤ 20, > 60 vertic	-	-	organic soils
depth (m)	≥ 0.75	0.75 – 0.50	< 0.50	-	-
SBC (cmol(+) kg^{-1})	> 5.0	5.0 – 3.5	3.5 – 2.0	≤ 2.0	-

Table 4.6: *Requirements for the cultivation of sorghum in Rwanda*

parameters	*suitability class*				
	S1	*S2*	*S3*	*N1*	*N2*
Climate					
altitude (m)	≤ 1,800	1,800 – 2,000	2,000 – 2,300	-	> 2,300
annual rainfall (mm)	≥ 900	< 900	-	-	-
Landscape					
slope gradient (%)	≤ 6	6 - 13	13 - 25	25 - 55	> 55
Soil					
flooding	no risk	-	-	-	any risk
drainage	excessive to moderate	imperfect	poor	very poor	-
clay (%) & structure	20 – 60, > 60 blocky	≤ 20, > 60 vertic	-	-	organic soils
depth (m)	≥ 0.50	< 0.50	-	-	-
SBC (cmol(+) kg^{-1})	> 3.5	3.5 – 2.0	≤ 2.0	-	-

Table 4.7: Requirements for the cultivation of pea in Rwanda

parameters	*suitability class*				
	S1	*S2*	*S3*	*N1*	*N2*
Climate					
altitude (m)	≥ 2,000	< 2,000	-	-	-
annual rainfall (mm)	≥ 1,300	1,300 – 1,200	< 1,200	-	-
Landscape					
slope gradient (%)	≤ 6	6 - 13	13 - 25	25 - 55	> 55
Soil					
flooding	no risk	-	-	-	any risk
drainage	excessive to moderate	imperfect	poor	very poor	-
clay (%) & structure	20 – 60, > 60 blocky	≤ 20, > 60 vertic	-	-	organic soils
depth (m)	≥ 0.75	0.75 – 0.50	< 0.50	-	-
SBC (cmol(+) kg^{-1})	> 5.0	5.0 – 3.5	3.5 – 2.0	≤ 2.0	-

Table 4.8: Requirements for the cultivation of sweet potato in Rwanda

parameters	*suitability class*				
	S1	*S2*	*S3*	*N1*	*N2*
Climate					
altitude (m)	≤ 1,800	1,800 – 2,000	2,000 – 2,200	-	> 2,200
annual rainfall (mm)	≥ 1,000	1,000 - 900	< 900	-	-
Landscape					
slope gradient (%)	≤ 6	6 - 13	13 - 25	25 - 55	> 55
Soil					
flooding	no risk	-	-	-	any risk
drainage	excessive to moderate	imperfect	poor	very poor	-
clay (%) & structure	≤ 60, > 60 blocky	> 60 vertic	-	-	organic soils
depth (m)	≥ 0.75	0.75 – 0.50	< 0.50	-	-
SBC[b] (cmol(+) kg^{-1})	> 3.5	3.5 – 2.0	≤ 2.0	-	-

Table 4.9: Requirements for the cultivation of white potato in Rwanda

parameters	*suitability class*				
	S1	*S2*	*S3*	*N1*	*N2*
Climate					
altitude (m)	≥ 2,000	2,000 – 1,800	1,800 – 1,500	-	< 1,500
annual temperature (°C)	≤ 18	18 - 20	20 - 22	-	> 22
Landscape					
slope gradient (%)	≤ 6	6 - 13	13 - 25	25 - 55	> 55
Soil					
flooding	no risk	-	-	-	any risk
drainage	excessive to moderate	imperfect	poor	very poor	-
clay (%) & structure	≤ 35	35 – 60 blocky	35 – 60 vertic, > 60	-	organic soils
depth (m)	≥ 0.75	0.75 – 0.50	< 0.50	-	-
SBC (cmol(+) kg^{-1})	> 3.5	3.5 – 2.0	≤ 2.0	-	-

Table 4.10: Requirements for the cultivation of cassava in Rwanda

parameters	*suitability class*				
	S1	*S2*	*S3*	*N1*	*N2*
Climate					
altitude (m)	≤ 1,500	1,500 – 1,700	1,700 – 1,900	-	> 1,900
annual temperature (°C)	≥ 21	21 - 18	18 - 17	-	< 17
annual rainfall (mm)	≥ 1,000	< 1,000	-	-	-
Landscape					
slope gradient (%)	≤ 6	6 - 13	13 - 25	25 - 55	> 55
Soil					
flooding	no risk	-	-	-	any risk
drainage	excessive to well	moderate	imperfect	poor to very poor	-
clay (%) & structure	≤ 35, 35 – 60 blocky	35 – 60 vertic, > 60 blocky	> 60 vertic	-	organic soils
depth (m)	≥ 1.00	1.00 – 0.75	0.75 – 0.50	-	< 0.50
SBC (cmol(+) kg^{-1})	> 2.0	≤ 2.0	-	-	-

Table 4.11: Requirements for the cultivation of groundnut in Rwanda

parameters	*suitability class*				
	S1	*S2*	*S3*	*N1*	*N2*
Climate					
altitude (m)	≤ 1,500	1,500 - 1,800	1,800 - 1,900	-	> 1,900
mean temperature (°C)	≥ 20	20 - 18	18 - 17	-	< 17
Landscape					
slope gradient (%)	≤ 6	6 - 13	13 - 25	25 - 55	> 55
Soil					
flooding	no risk	-	-	-	any risk
drainage	excessive to well	moderate	imperfect	poor to very poor	-
clay (%) & structure	≤ 35	35 – 60 blocky	35 – 60 vertic, > 60	-	organic soils
depth (m)	≥ 0.75	0.75 – 0.50	< 0.50	-	-
SBC (cmol(+) kg^{-1})	> 3.5	3.5 – 2.0	≤ 2.0	-	-

Table 4.12: Requirements for the cultivation of soybean in Rwanda

parameters	*suitability class*				
	S1	*S2*	*S3*	*N1*	*N2*
Climate					
altitude (m)	≤ 1,700	1,700 - 2,000	2,000 - 2,300	-	> 2,300
annual rainfall (mm)	≥ 1,000	< 1,000	-	-	-
Landscape					
slope gradient (%)	≤ 6	6 - 13	13 - 25	25 - 55	> 55
Soil					
flooding	no risk	-	-	-	any risk
drainage	excessive to moderate	imperfect	poor	very poor	-
clay (%) & structure	20 – 60, > 60 blocky	≤ 20, > 60 vertic	-	-	organic soils
depth (m)	≥ 0.75	0.75 – 0.50	< 0.50	-	-
SBC (cmol(+) kg^{-1})	> 3.5	3.5 – 2.0	≤ 2.0	-	-

Table 4.13: Requirements for the cultivation of banana in Rwanda

parameters	*suitability class*				
	S1	*S2*	*S3*	*N1*	*N2*
Climate					
altitude (m)	≤ 1,500	1,500 – 1,900	1,900 – 2,000	-	> 2,000
annual rainfall (mm)	≥ 1,000	1,000 – 900	< 900	-	-
Landscape					
slope gradient (%)	≤ 6	6 - 13	13 - 25	25 - 55	> 55
Soil					
flooding	no risk	-	-	-	any risk
drainage	excessive to moderate	imperfect	poor	very poor	-
clay (%) & structure	> 60 blocky, 35 – 60	> 60 vertic, 20 - 35	≤ 20	-	organic soils
depth (m)	≥ 0.75	0.75 – 0.50	< 0.50	-	-
SBC (cmol(+) kg^{-1})	> 3.5	3.5 – 2.0	≤ 2.0	-	-

Table 4.14: Requirements for the cultivation of arabica coffee in Rwanda

parameters	*suitability class*				
	S1	*S2*	*S3*	*N1*	*N2*
Climate					
altitude (m)	1,900 – 1,300	-	-	-	< 1,300 & ≥ 1,900
annual rainfall (mm)	≥ 1,100	1,100 – 1,000	1,000 - 900	-	< 900
Landscape					
slope gradient (%)	≤ 6	6 - 13	13 - 25	25 - 55	> 55
Soil					
flooding	no risk	-	-	-	any risk
drainage	excessive to well	moderate	imperfect	poor to very poor	-
clay (%) & structure	35 – 60 blocky, > 60 blocky	20 - 35	≤ 20	-	35 – 60 vertic, > 60 vertic, organic soils
depth (m)	≥ 2.00	2.00 – 1.00	1.00 – 0.50	-	< 0.50
SBC (cmol(+) kg^{-1})	> 5.0	5.0 – 3.5	3.5 – 2.0	≤ 2.0	-

Table 4.15: Requirements for the cultivation of tea in Rwanda

parameters	*suitability class*				
	S1	*S2*	*S3*	*N1*	*N2*
Climate					
annual rainfall (mm)	≥ 1,300	1,300 – 1,200	1,200 – 1,100	-	< 1,100
dry season (days)	≤ 60	60 - 90	90 - 120	-	> 120
Landscape					
slope gradient (%)	≤ 13	13 - 25	25 - 55	-	> 55
Soil					
flooding	no risk	-	-	-	any risk
drainage	excessive to moderate	imperfect	poor	very poor	-
clay (%) & structure	35 – 60 blocky, 20 - 35	> 60 blocky, ≤ 20	-	-	35 – 60 vertic, > 60 vertic, organic soils
depth (m)	≥ 1.00	1.00 – 0.50	< 0.50	-	-
SBC[b] (cmol(+) kg^{-1})	> 2.0	≤ 2.0	-	-	-
base saturation (%)	≤ 20	20 - 35	35 - 50	-	> 50

4.4. Land suitability classification procedure

4.4.1. Agro-climatic suitability

Comparison of the crop requirements with respect to altitude, rainfall and length of the dry period, with the actual characteristics of each agro-climatic zone, resulted in the assignment of a suitability class for these three parameters. Because of the large variability in most of the agro-climatic zones, very different suitability classes were calculated depending on whether the average, maximum and minimum recorded values were inserted in the evaluation. Based on these results the evaluator estimated the average suitability of the climatic parameters in all agro-climatic zones. The suitability class of the most limiting climatic parameter determined the overall climatic suitability of the agro-climatic zone. Limitations due to temperature or rainfall were indicated with a suffix "a" (altitude) or "p" (precipitation).

4.4.2. Agro-edaphic suitability

Comparison of the cartographic data with the parameter values in the requirement tables resulted in the assignment of a suitability class for each individual landscape and soil parameter.

4.4.3. Actual and potential land suitability

The final overall actual and potential land suitability of each land unit was attributed by the maximum limitation method: the resulting suitability classes for climate and those for the individual landscape and soil parameters were compared, and the most limiting one defined the overall land suitability. The suitability classes for climate, slope gradient, flooding, drainage, texture and structure, soil depth, SBC and eventually BS defined the actual suitability. The potential suitability has been determined by an evaluation of the suitability of climate, flooding, soil texture and structure and soil depth, provided that the soil is deep enough to correct the slope gradient through terracing.

Subclasses were added referring to the kind of production limitation. Different subclasses taken into consideration were (1) climatic constraints, indicated by a suffix "c"; (2) topographical problems, indicated by a suffix "t"; (3) wetness problems, indicated by a suffix "w"; (4) physical soil limitations, indicated by a suffix "s"; and (5) soil fertility problems, indicated by a suffix "f". High erosion risk, excessive wetness and nutrient mining can be corrected using appropriate management strategies, such as terracing, drainage, fertilisation, or liming of the soil surface up to a pH of 5.5.

4.5. National land suitability

The suitability of the climatic conditions in the 10 agro-climatic zones has been assessed for the cultivation of the 12 selected crops. Next, the actual and potential suitability of the dominant land units has been calculated. In order to illustrate the importance of the land suitability for the cultivation of common bean on the associated units, their actual and potential suitability has been discussed as well.

4.5.1. Common bean (*Phaseolus vulgaris* L.)

Climatic suitability

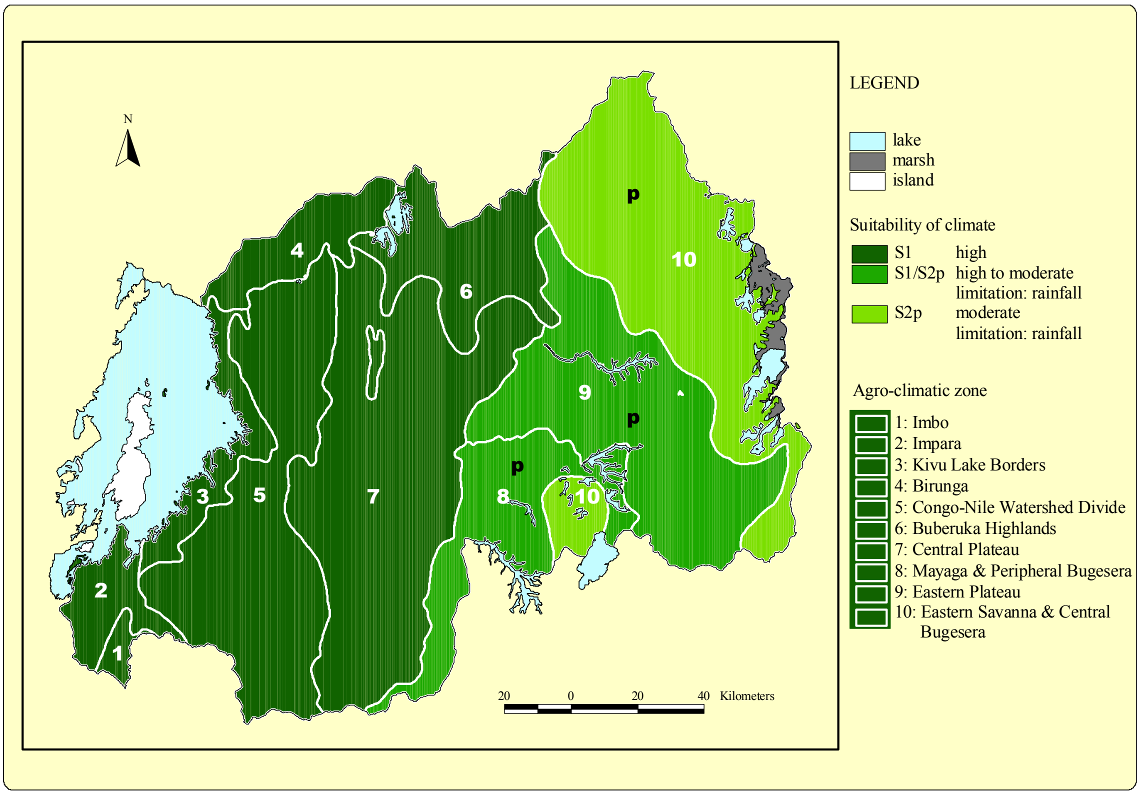
The tropical climate tempered by the high altitude of Rwanda is ideal for the cultivation of common bean. Map 4.7 illustrates the spatial distribution of the climatic suitability. In the agro–climatic region of the Eastern Savanna and Central Bugesera, the annual rainfall drops frequently below 1,000 mm, and consequently its suitability is moderate. A high to moderate suitability has been recorded in the other lowland agro–climatic regions of the Mayaga and Peripheral Bugesera, and the Eastern Plateau. In the agro–climatic regions of the middle and high altitudes, temperature and rainfall are optimal for the cultivation of common bean.

Actual suitability of dominant land units

According to the suitability classification designed for Rwanda, the actual suitability for the production of common bean generally increases from the West to the East (Map 4.8). In the agricultural regions of the Imbo, Impara, Kivu Lake Borders, Congo–Nile Watershed Divide, Buberuka Highlands and Central Plateau, the main limiting factor for the cultivation of this crop is the rough topography characterised by steeply sloping hillsides. The high degree of inclination associated to deep soils resulted in the assignment of the “actually unsuitable, but potentially suitable” – class. After terracing of the arable land, the restoration of the cation balance through fertilisation and liming is of great importance.

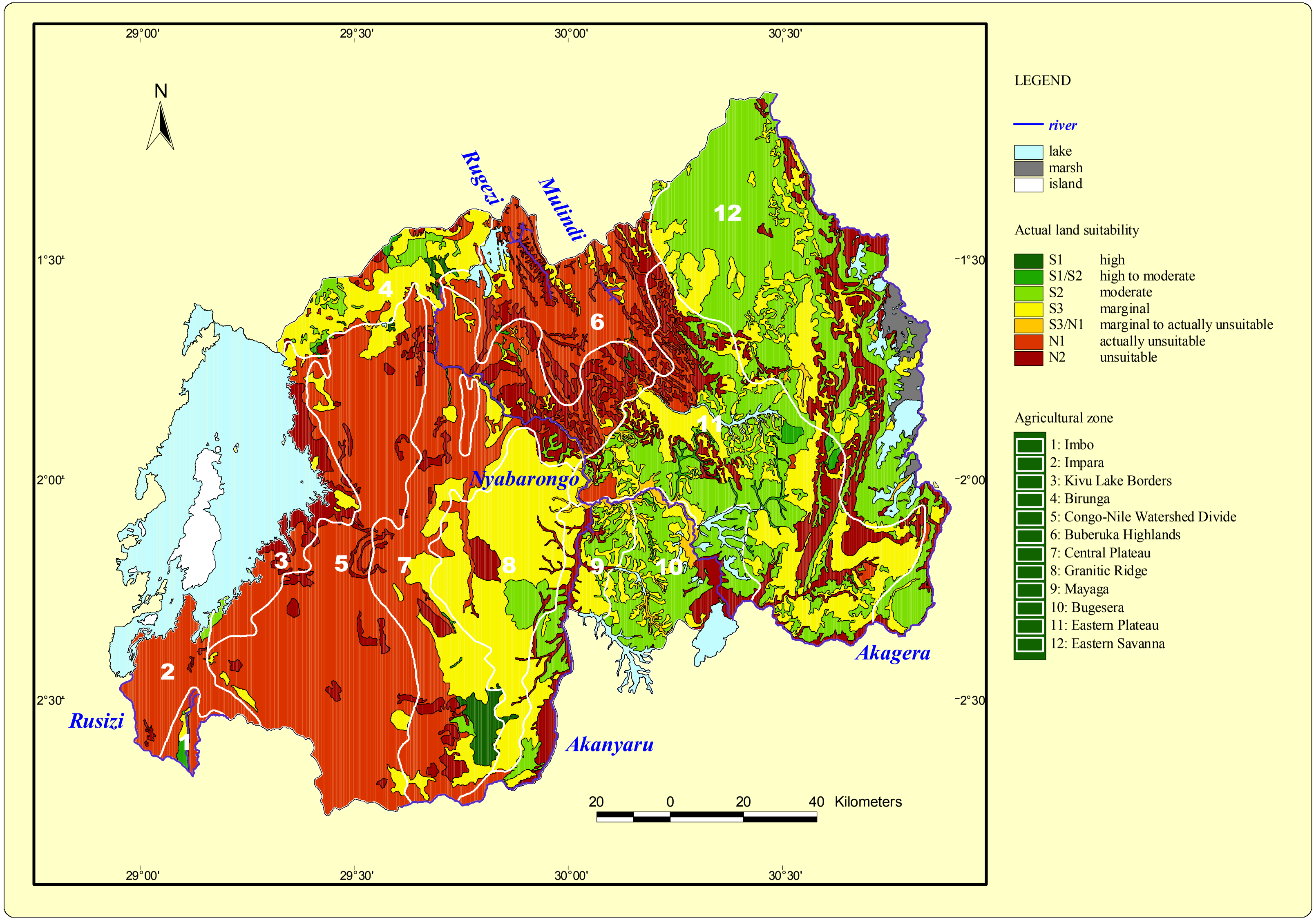
High soil fertility has been recorded in the Birunga. Its suitability ranges from very suitable to actually and potentially unsuitable. In the volcanic plain, soil depth is generally limiting the suitability to a marginal level. Where soils are deep, a very high suitability has been recorded.

The volcano slopes are generally too steep to allow an optimal production. Their suitability depends on the slope gradient. At middle altitude, slope steepness is also dominating the suitability classification for the cultivation of common bean in the agricultural zone of the Granitic Ridge and the Eastern Plateau, resulting in a marginal and moderate suitability, respectively.



Map 4.7: Suitability of climate for the cultivation of common bean in the agro-climatic zones in Rwanda

Shallow soils with a slope gradient exceeding 25 % can't be terraced and have been classified as actually and potentially unsuitable. These land units are particularly abundant in the East and Southeast and South of the Buberuka Highlands. The well-drained lowlands, on the contrary, have been classified as moderately suitable. The rolling hills are moderately suitable for their gentle slopes. On the peneplains in the Northeast and South, the low fertility level limits bean productivity. In the Bugesera, also the high subsoil stoniness often restricts the suitability of the units developing on granite to a marginal level. A very fine texture, shrink and swell properties or drainage problems limit the suitability of the lowland valleys. The Vertisols of the Northeast have been classified as moderately suitable. The suitability of the mineral soils in the valleys of the Akagera, Nyabarongo and Akanyaru valleys varies between moderately suitable and actually unsuitable, depending on the severity of the wetness problems. The valley of the Imbo received the most favourable suitability class: very suitable for the moderately drained units and moderately suitable for the imperfectly drained units. In the Eastern Savanna, the suitability of the best soil units is limited to a moderate level because of the dry weather.

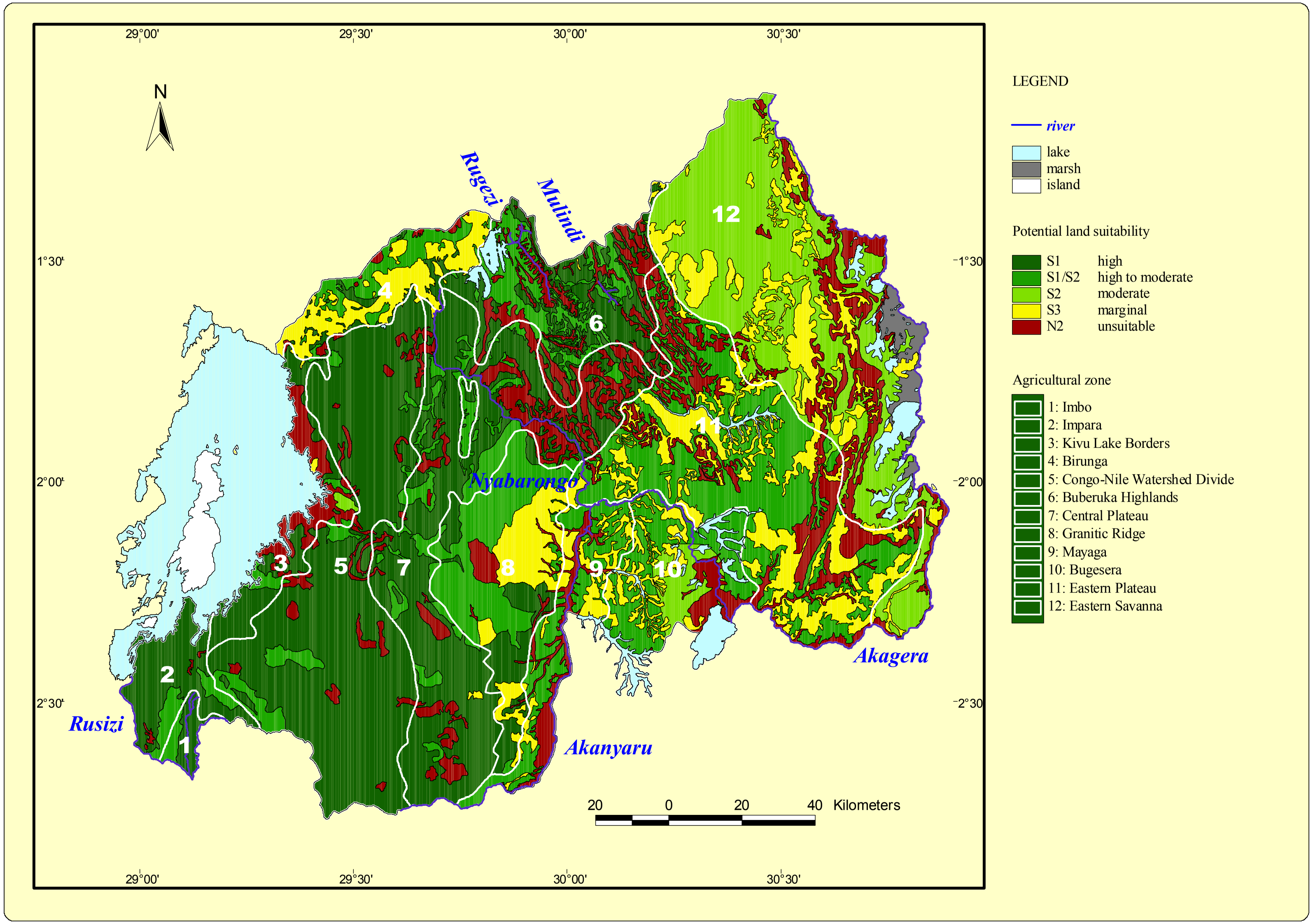


Map 4.8: Actual suitability of the dominant land units for the cultivation of common bean in Rwanda (derived from agro-climatic zones map and soil map at scale 1:250,000)

Potential suitability of dominant land units

Serious investments in terracing and fertilisation will increase the suitability of the western highlands considerably (Map 4.9). As such, the potential suitability in western Rwanda is varying between very suitable and marginally suitable, depending on the effective soil depth. Low annual rainfall and shallow soils further restrict the potential suitability in eastern Rwanda. Consequently, the suitability ranges from very suitable to marginally suitable. Nevertheless, additional attention should be given to the low nutrient content and retention of the most strongly weathered soils and the fragility of the land units on quartzite ridges.

Wetness control in the valley and terracing of the slopes make the Imbo very suitable for bean production. The organic soils in the valleys of the Rugezi, Mulindi, Akanyaru and Akagera are actually unsuitable. The very poorly drained units risk flooding, the soil depth might be limited by the presence of a shallow groundwater table, while the nutrients are immobilised by the organic matter. The special management strategies related to drainage and fertilisation, required to improve these units for arable land are actually beyond the reach of the farmers. These valleys are currently occupied by papyrus and rice, two crops that are much more suited to this specific environment. With respect to common bean, organic soils thus have been classified as actually and potentially unsuitable.



Map 4.9: Potential suitability of the dominant land units for the cultivation of common bean in Rwanda (derived from agro-climatic zones map and soil map at scale 1:250,000)

Actual suitability of associated land units

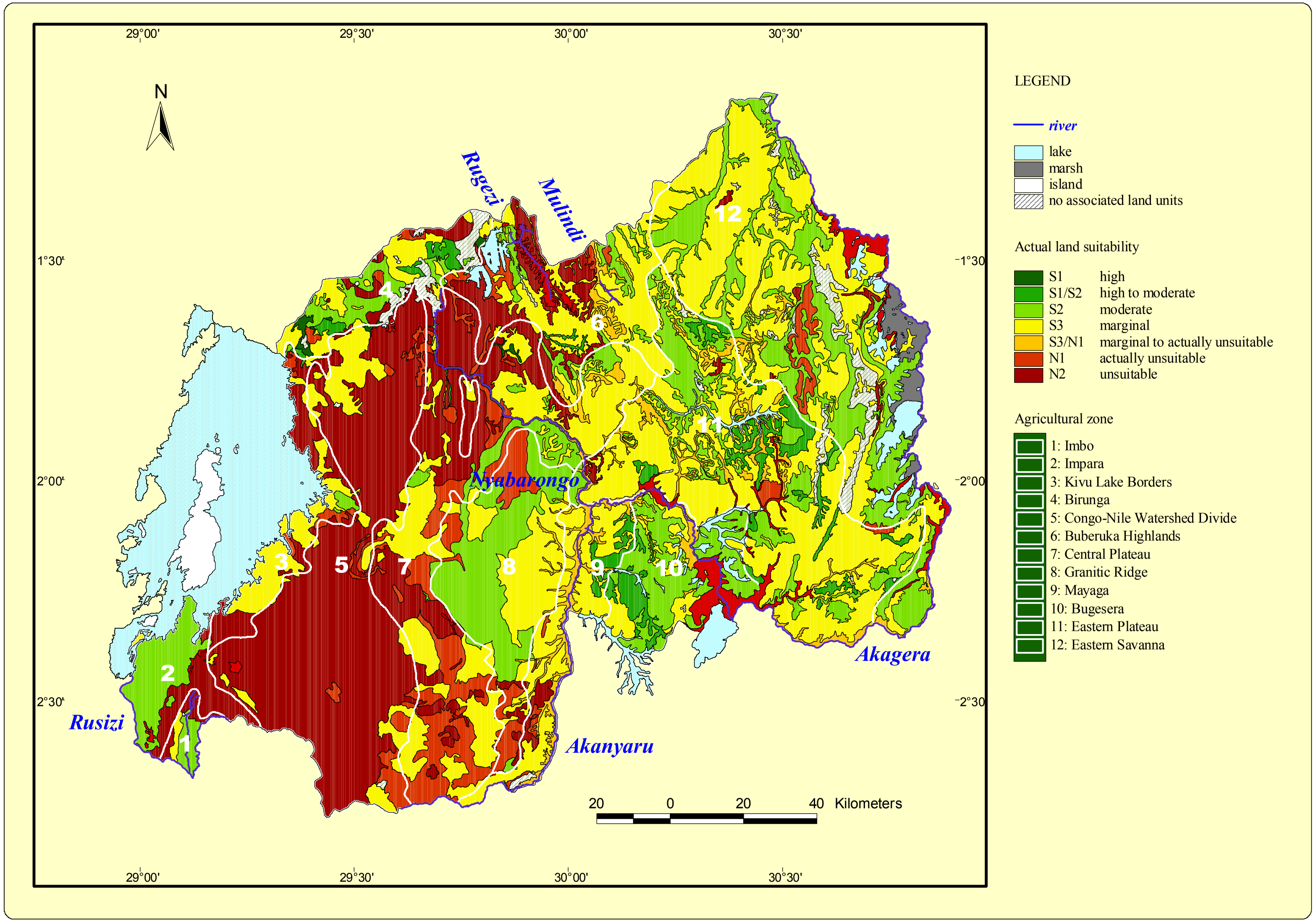
The actual suitability of the associated units reflects much more extremes than that of the dominant units, although the same general remarks remain valid (Map 4.10). Steep topography limits the suitability of the western soil units drastically, especially in the agricultural zones of the Congo–Nile Watershed Divide and the Central Plateau that are actually and potentially unsuitable or marginally suitable. Slope gradient, SBC and drainage restrict the suitability of the Buberuka Highlands, ranging from moderately suitable to actually and potentially unsuitable. The same applies to the agricultural zone of the Granitic Ridge with soils units that are moderately suitable to actually unsuitable, but potentially suitable with appropriate management. The suitability of the Birunga for bean production is also strongly variable and depends on soil depth and slope gradient. The slope gradient sets the suitability level in the Impara, while the other soil properties and the climatic conditions are very favourable. In the agricultural region of the Imbo, the steeply sloping soil units are actually and potentially unsuitable, while the relatively flat valley is occupied by fine clayey soils with vertic properties. The best conditions for the cultivation of common bean have been found in the East, beneath the Muhazi Lake, in small parts of the Mayaga and the Bugesera, where the rather low rainfall determines the high to moderate suitability. In the Mayaga, steep slopes limit the suitability of the soil units on the right bank of the Akanyaru, while the impeded drainage makes the valley marginally suitable to actually unsuitable, depending on whether the soils are moderately or imperfectly drained.

In the southeast of the Eastern Plateau, the steeply sloping, shallow soil units on the quartzite ridges are only marginally suitable. In the well-drained lowlands of the Bugesera and Eastern Savanna, the suitability is moderate to marginal. In these gently sloping areas, soil fertility, soil depth and annual rainfall are the main production constraints. The poorly drained valleys are moderately suitable, marginally suitable, or actually unsuitable, depending on the degree of wetness.

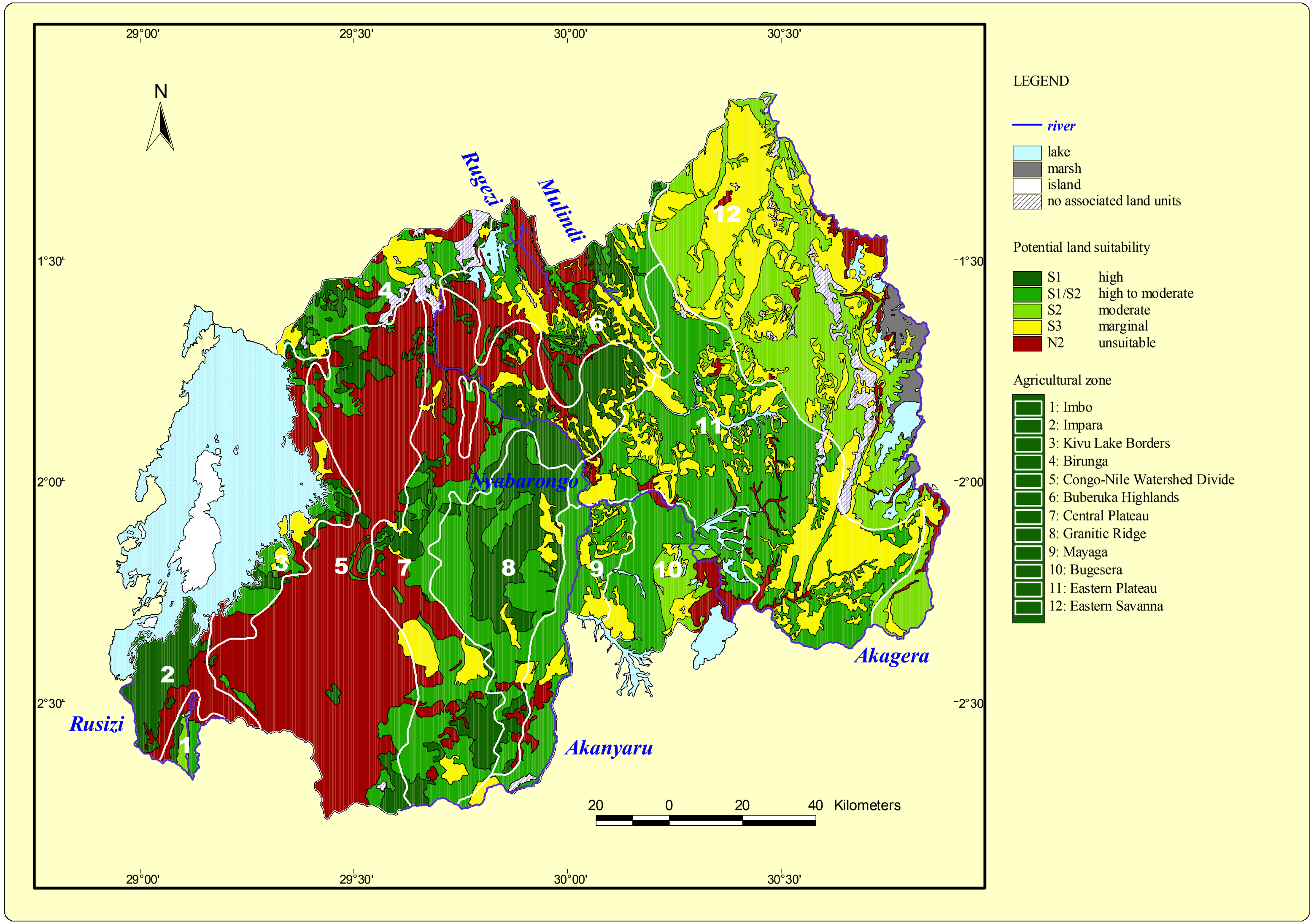
Potential suitability of associated land units

Map 4.11 illustrates the potential suitability of the associated land units. The very steep soil units of the Congo–Nile Watershed Divide and Central Plateau are actually and potentially unsuitable for the cultivation of common bean. Investments in terracing and fertilisation result in a serious increase of the suitability of all other land units, except for those in the dry and strongly weathered East. The Impara and a large part of the Central Plateau and the Granitic Ridge generally are potentially very suitable. The other land units of these agricultural zones are very suitable to moderately suitable, depending on the soil depth. In the Birunga, the Mayaga, the Bugesera and the Eastern Plateau, the land suitability ranges from very suitable to marginally suitable depending on soil depth and annual rainfall totals. Also in the Buberuka Highlands, appropriate management practices improve considerably the suitability of most units. The long dry period in the East restricts its suitability to a moderate level and the moderate suitability of the Imbo is due to the swell and shrink properties of the valley soils. Upon drainage or other management strategies reducing the wetness problems, the other valleys become very suitable to moderately suitable.

The soil units that, according to the capability classification, have been classified as non-arable land because of their slope gradient exceeding 55 % or because of the combination of a slope gradient exceeding 25 % and a soil depth of less than 0.50 m are also assigned to the “actually and potentially unsuitable” class in the suitability classification. They are especially abundant on the steeply sloping shores of the Kivu Lake and on the quartzite ridges in the North, East and Southeast. The same applies when classifying these land units for the cultivation of the other crops for which the suitability of the dominant land units has been discussed below.



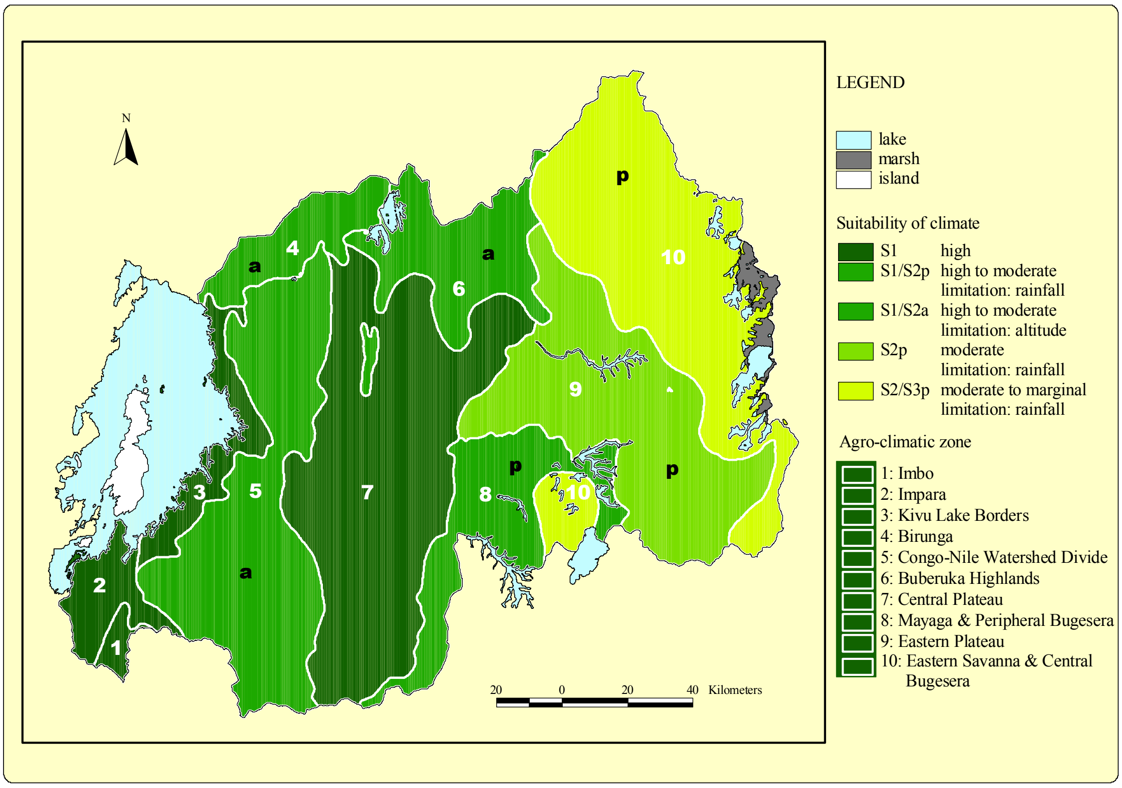
Map 4.10: Actual suitability of the associated land units for the cultivation of common bean in Rwanda (derived from agro-climatic zones map and soil map at scale 1:250,000)



Map 4.11: Potential suitability of the associated land units for the cultivation of common bean in Rwanda (derived from agro-climatic zones map and soil map at scale 1:250,000)

4.5.2. Maize (*Zea mays* L.)

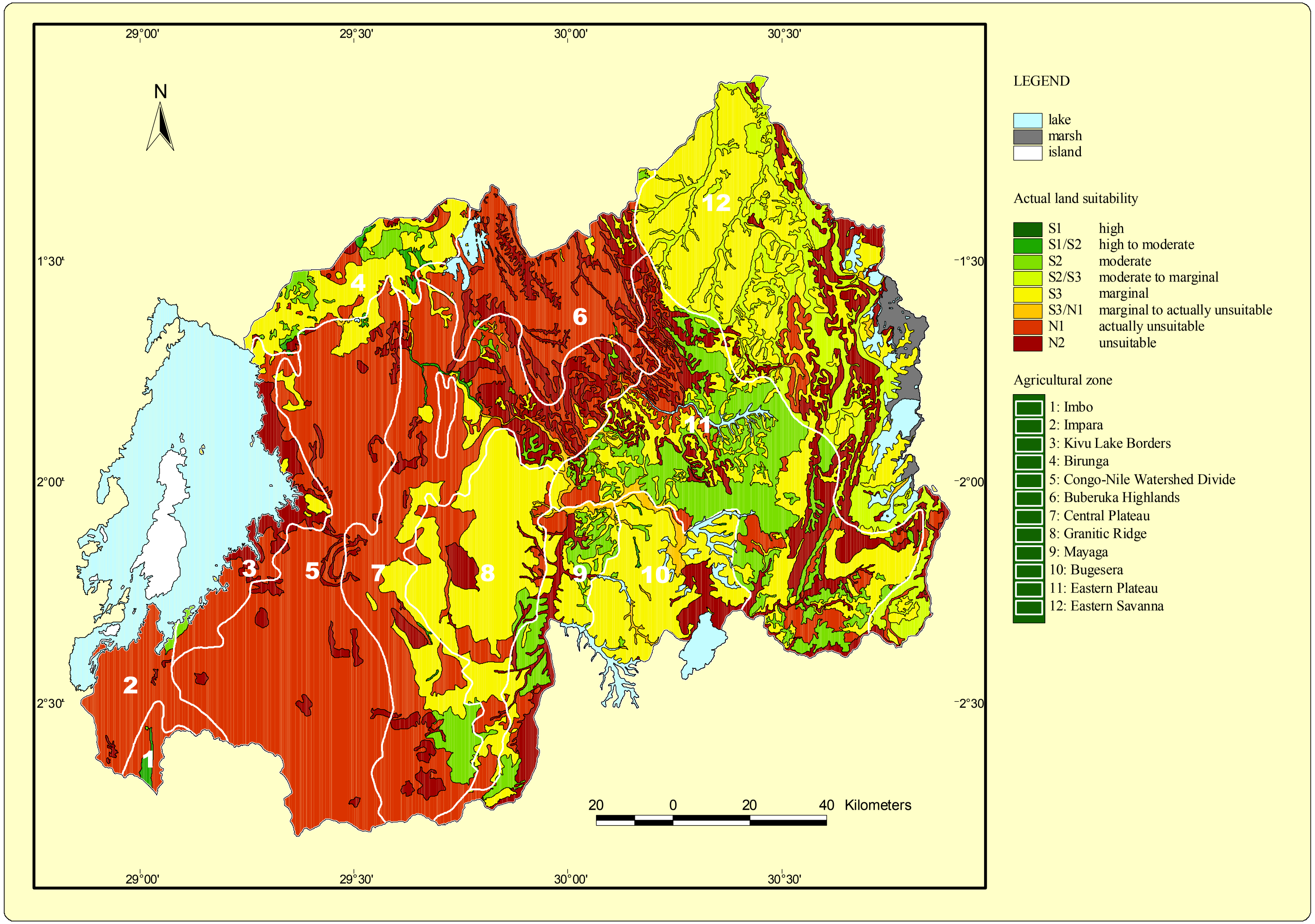
In Rwanda, common bean and maize are often grown together in a mixed cropping system. Both crops share several climatic, landscape and edaphic requirements, although maize is somewhat more demanding. From a climatic point of view, maize is more sensitive to water shortage or low temperature. Consequently, the cool, high altitude zones of the Congo–Nile Watershed Divide, the Birunga, and the Buberuka Highlands are very suitable at the lower altitudes, and moderately suitable at the highest elevations. The water and temperature regime are optimal in the agro-climatic zones of the Imbo, Impara, Kivu Lake Borders and Central Plateau. In the eastern lowlands, low rainfall limits maize production considerably, and a moderate suitability has therefore been assigned to the agro-climatic zone of the Eastern Plateau while the Eastern Savanna and Central Bugesera are characterised by a moderate to marginal suitability. An overview of this climatic suitability has been shown in Map 4.12.



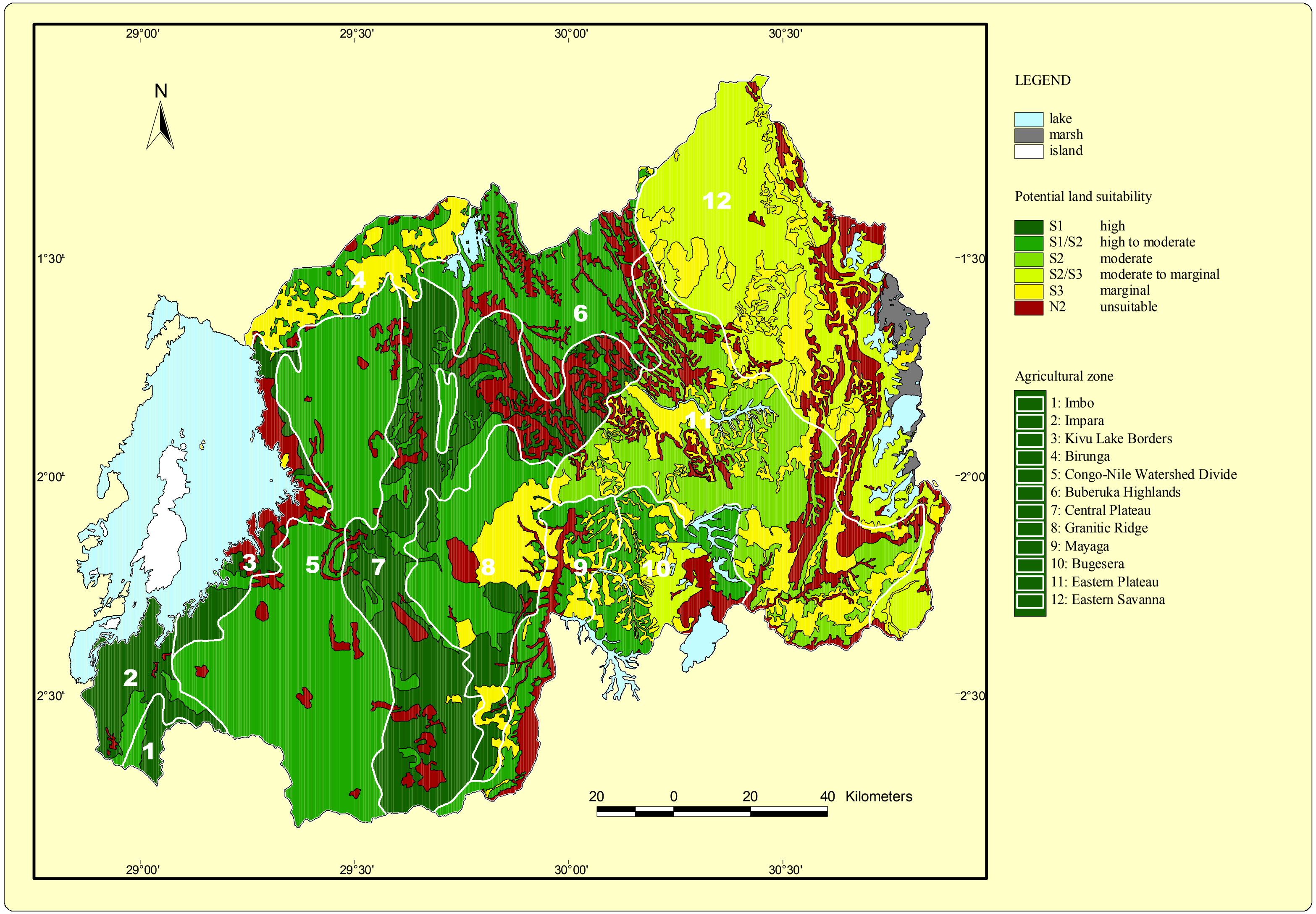
Map 4.12: Suitability of climate for the cultivation of maize in the agro-climatic zones in Rwanda

From an edaphic viewpoint, maize requires a higher chemical soil fertility level than common bean. Only those soils with a SBC exceeding 5.0 cmol(+) kg^{-1} soil fully meet the crop demands. However, most of the time other parameters determine the overall actual land suitability, such as the soil depth in the volcanic range, drainage in the Imbo, and low precipitation in East Rwanda. The actual suitability for maize is thus similar to that discussed for common bean, except for the different climatic requirements that have an impact on the suitability classification of the eastern lowlands and the higher fertility demands that resulted in a lower marginal suitability of the Bugesera.

Also the potential suitability for maize production equals that for bean, although somewhat higher investments in fertilisation are required, while the climate sets the production limit in the high altitude regions and in the low rainfall zones. The actual and potential suitability for the production of maize have been shown in Map 4.13 and 4.14, respectively.



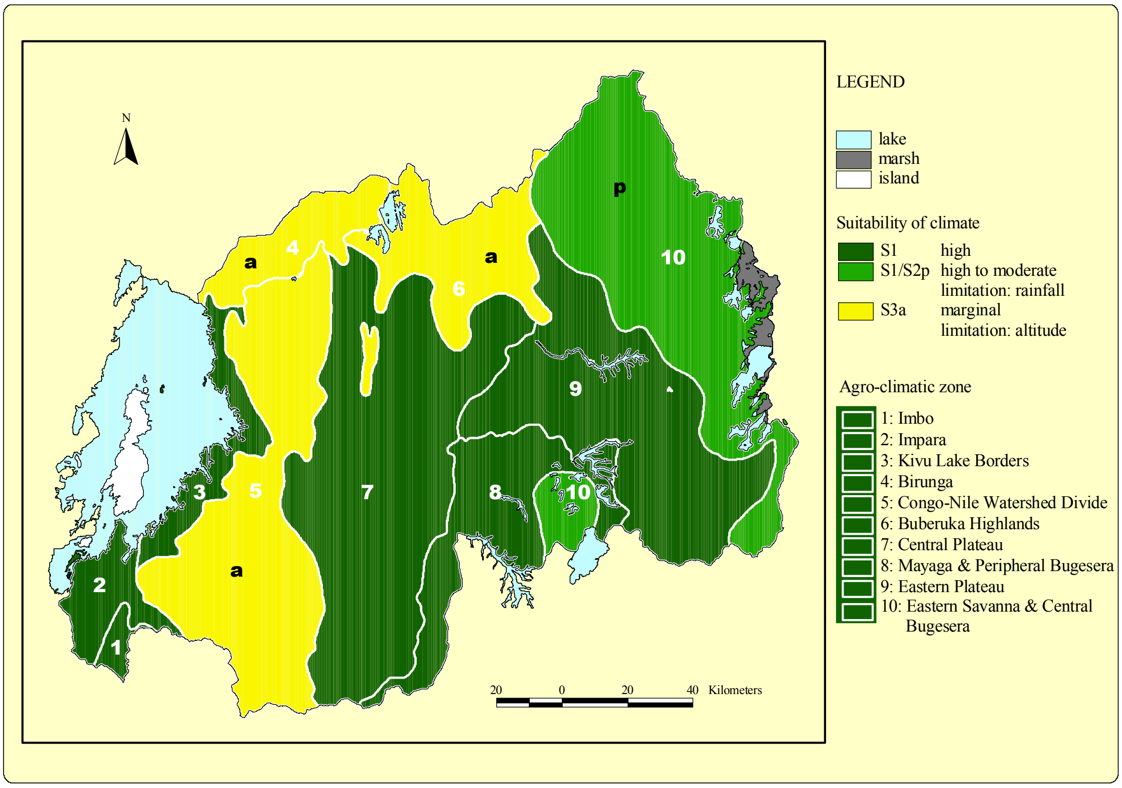
Map 4.13: Actual suitability of the dominant land units for the cultivation of maize in Rwanda (derived from agro-climatic zones map and soil map at scale 1:250,000)



Map 4.14: Potential suitability of the dominant land units for the cultivation of maize in Rwanda (derived from agro-climatic zones map and soil map at scale 1:250,000)

4.5.3. Sorghum (*Sorghum bicolor* (L.) Moench)

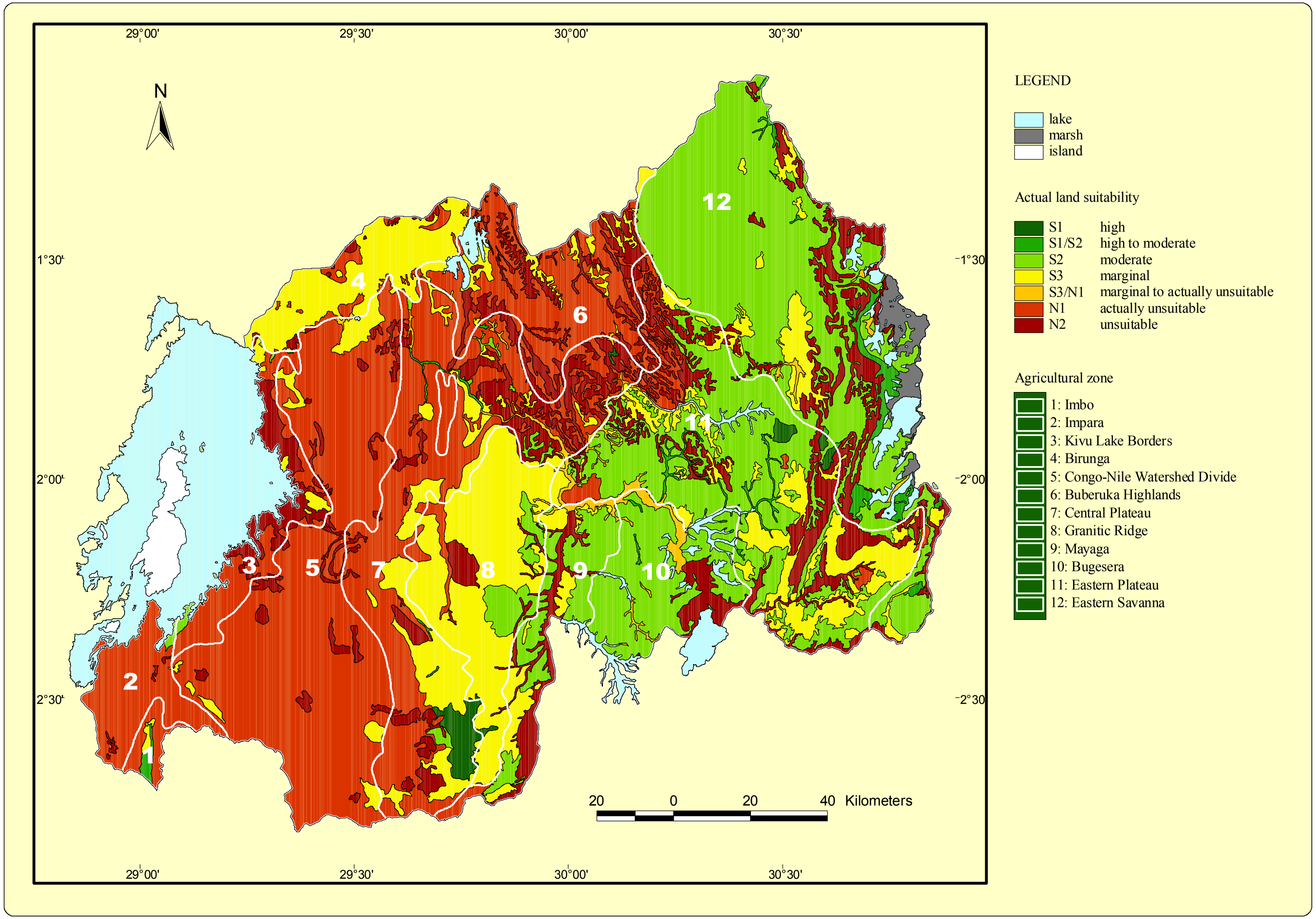
Another cereal that is frequently cultivated in Rwanda is sorghum. This crop is more drought tolerant than maize and also poses less severe demands to the soil. The suitability for the cultivation of sorghum in the different agro–climatic regions in Rwanda has been illustrated in Map 4.15. The middle altitude regions are very suitable for the cultivation of sorghum. The dry eastern lowlands are very suitable to moderately suitable, while the low temperatures recorded in the high altitude regions limit their suitability to marginal conditions.



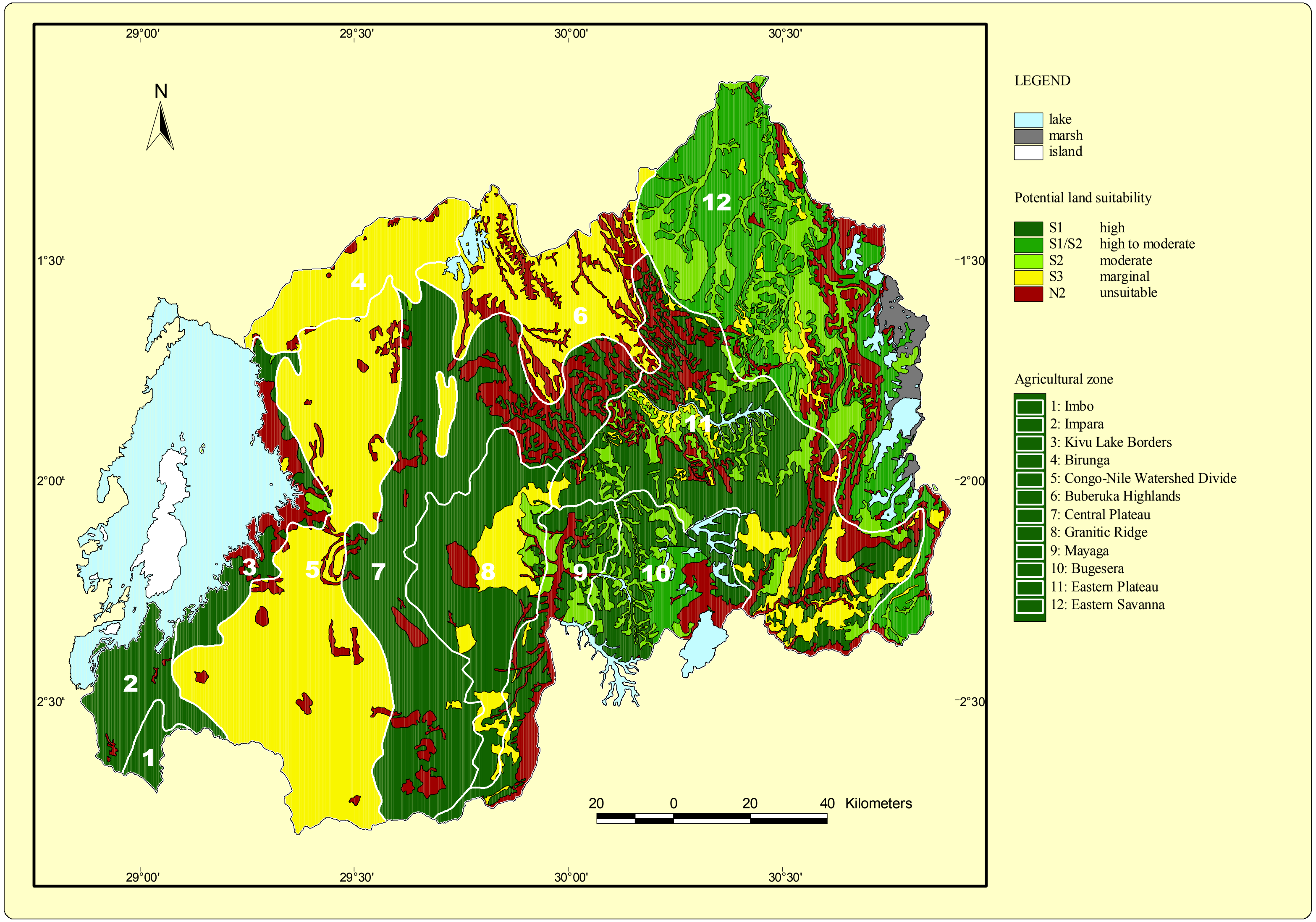
Map 4.15: Suitability of climate for the cultivation of sorghum in the agro-climatic zones in Rwanda

The suitability classification for slope gradient, flooding, internal drainage, soil texture and SBC is equal to that of common bean. With respect to soil depth, sorghum is one of the least demanding crops as the effective soil depth should be at least 0.50 m to allow optimal growth. The overall actual and potential suitability of the dominant soil units for the production of sorghum has been illustrated in Map 4.16 and 4.17. It largely corresponds to the suitability classification for common bean, except for some soil units in the agricultural zones of the Bugesera and the Eastern Plateau characterised by shallow soils that increased in suitability level, and the differences in climatic requirements that limit sorghum production seriously in the Birunga.

The potential suitability for sorghum production has been set by the climate for a large part of the country, showing no inherent landscape or soil properties related to the slope gradient, soil depth, soil texture and soil structure, that might limit sorghum development. Sorghum thus has a high production potential in all middle and low altitude regions of Rwanda.



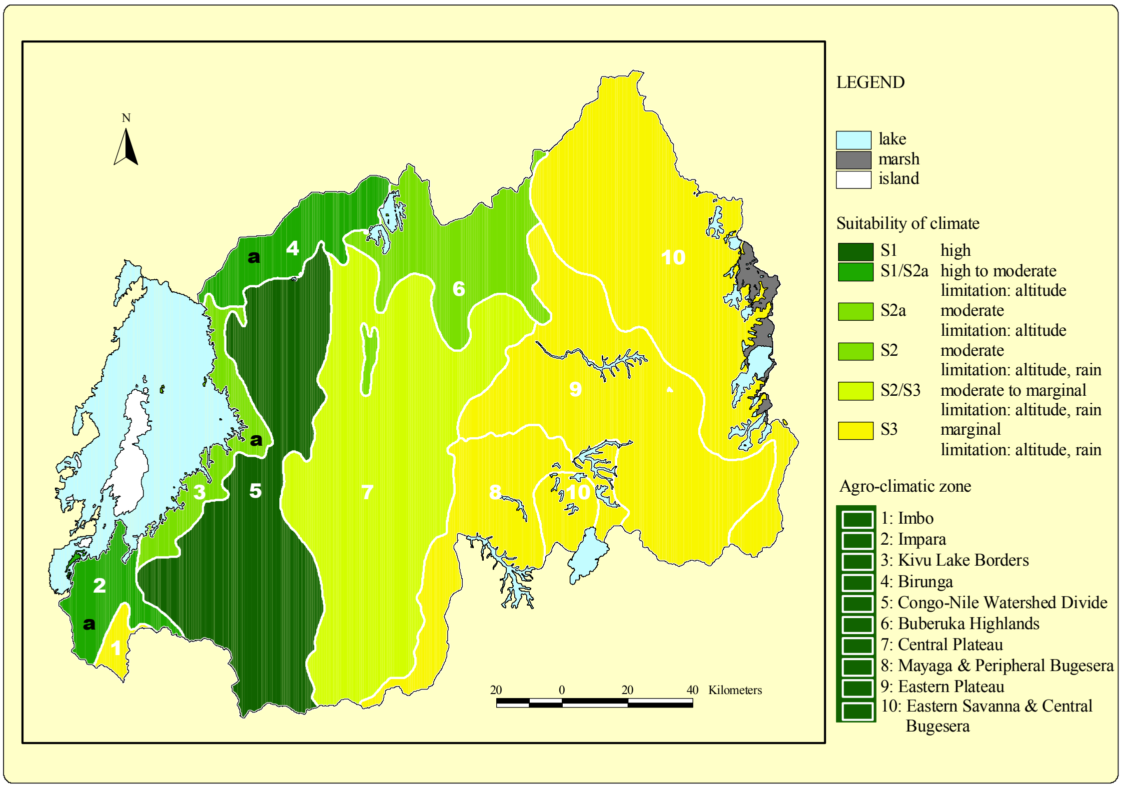
Map 4.16: Actual suitability of the dominant land units for the cultivation of sorghum in Rwanda (derived from agro-climatic zones map and soil map at scale 1:250,000)



Map 4.17: Potential suitability of the dominant land units for the cultivation of sorghum in Rwanda (derived from agro-climatic zones map and soil map at scale 1:250,000)

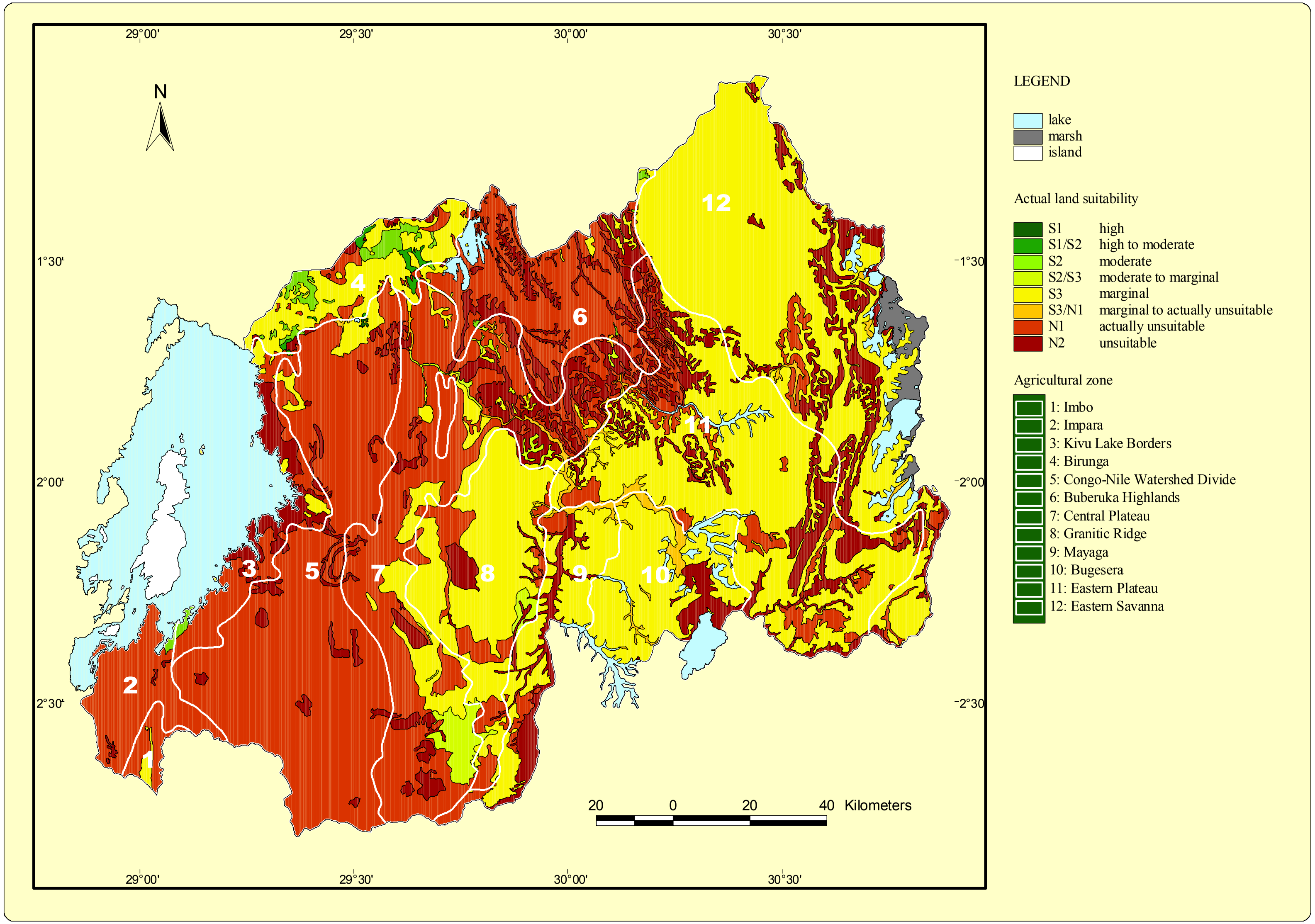
4.5.4. Pea (*Pisum sativum* L.)

Next to common bean, pea is a regularly cultivated legume in Rwanda. The climatic environment suited for the production of pea, however, is quite different. Pea requires relatively low temperatures and a well-distributed rainfall. As such, the climate of the Rwandan highlands is very suitable to moderately suitable. With increasing temperatures and decreasing rainfall amounts, the suitability of the climate decreases to marginal conditions reported in the eastern lowlands and in the agricultural zone of the Imbo (Map 4.18).

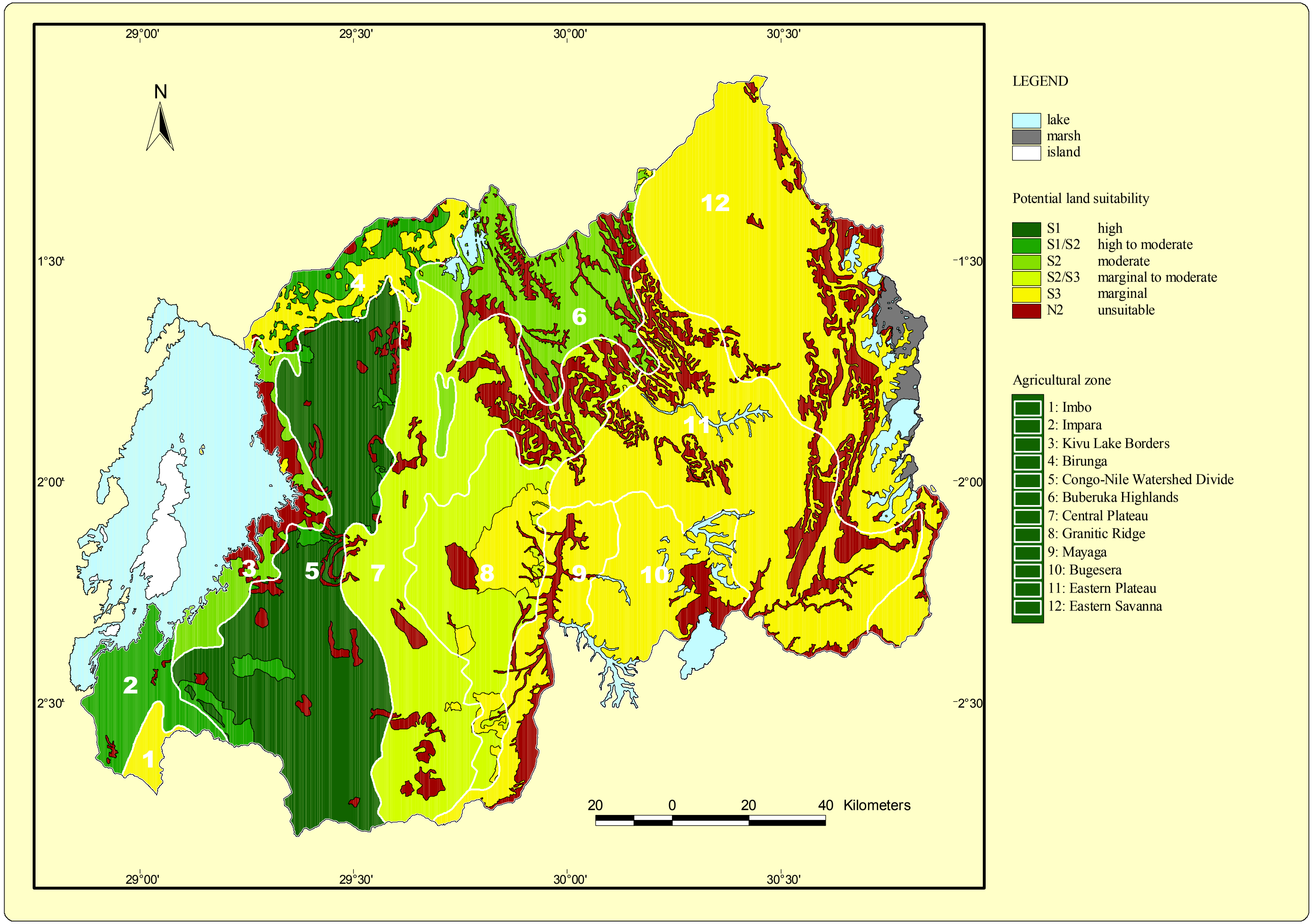


Map 4.18: Suitability of climate for the cultivation of pea in the agro-climatic zones in Rwanda

The edaphic requirements of this legume are similar to those needed for the successful cultivation of maize and thus their actual and potential land suitability classification are alike, except for important differences due to the preference of pea for the cool humid high altitude areas (Map 4.19 and 4.20). Marginal climatic conditions determine the actual and potential suitability of the East and South. Actually, the best land units have been reported on the deep soils of the volcano slopes. The steep topography limits the suitability in the other high altitude areas. After terracing and fertilization of the land units in the agricultural zones of the Congo-Nile Watershed Divide, Impara, Kivu Lake Borders and Buberuka Highlands they become very suitable to moderately suitable for the cultivation of this crop. In the volcanic plain, the limited soil depth restricts the production potential.



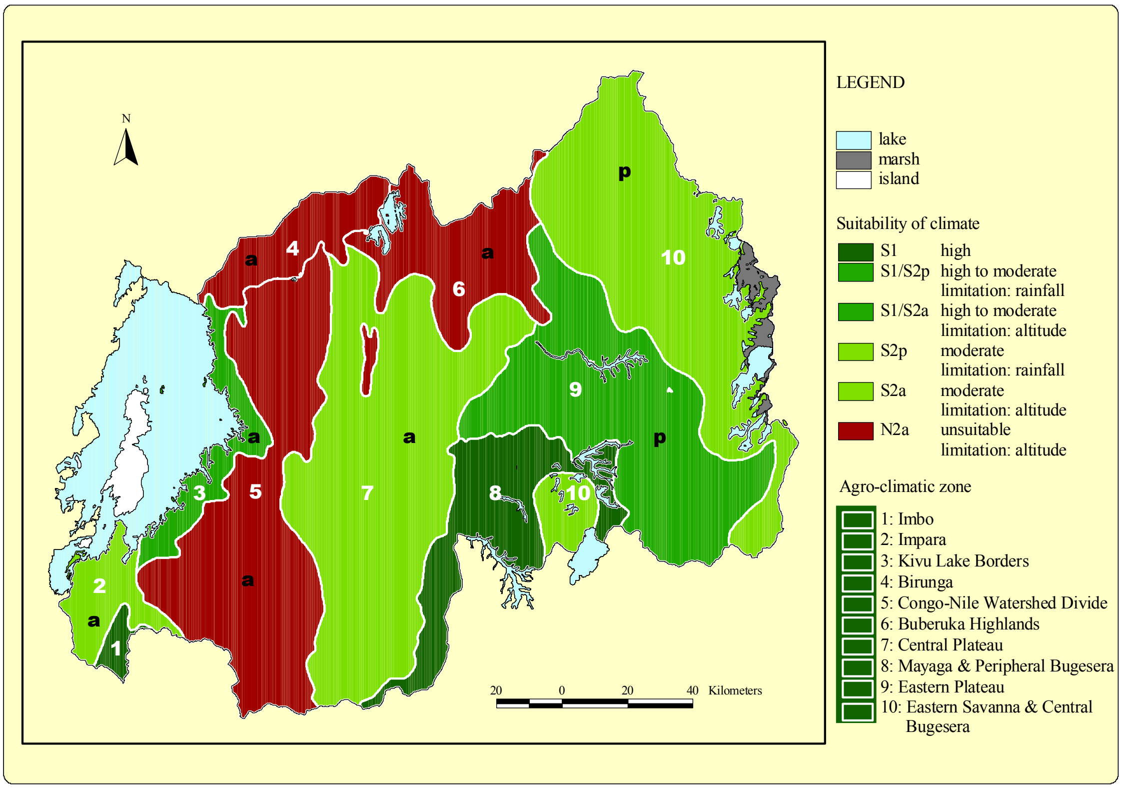
Map 4.19: Actual suitability of the dominant land units for the cultivation of pea in Rwanda (derived from agro-climatic zones map and soil map at scale 1:250,000)



Map 4.20: Potential suitability of the dominant land units for the cultivation of pea in Rwanda (derived from agro-climatic zones map and soil map at scale 1:250,000)

4.5.5. Cassava (*Manihot esculenta* Crantz)

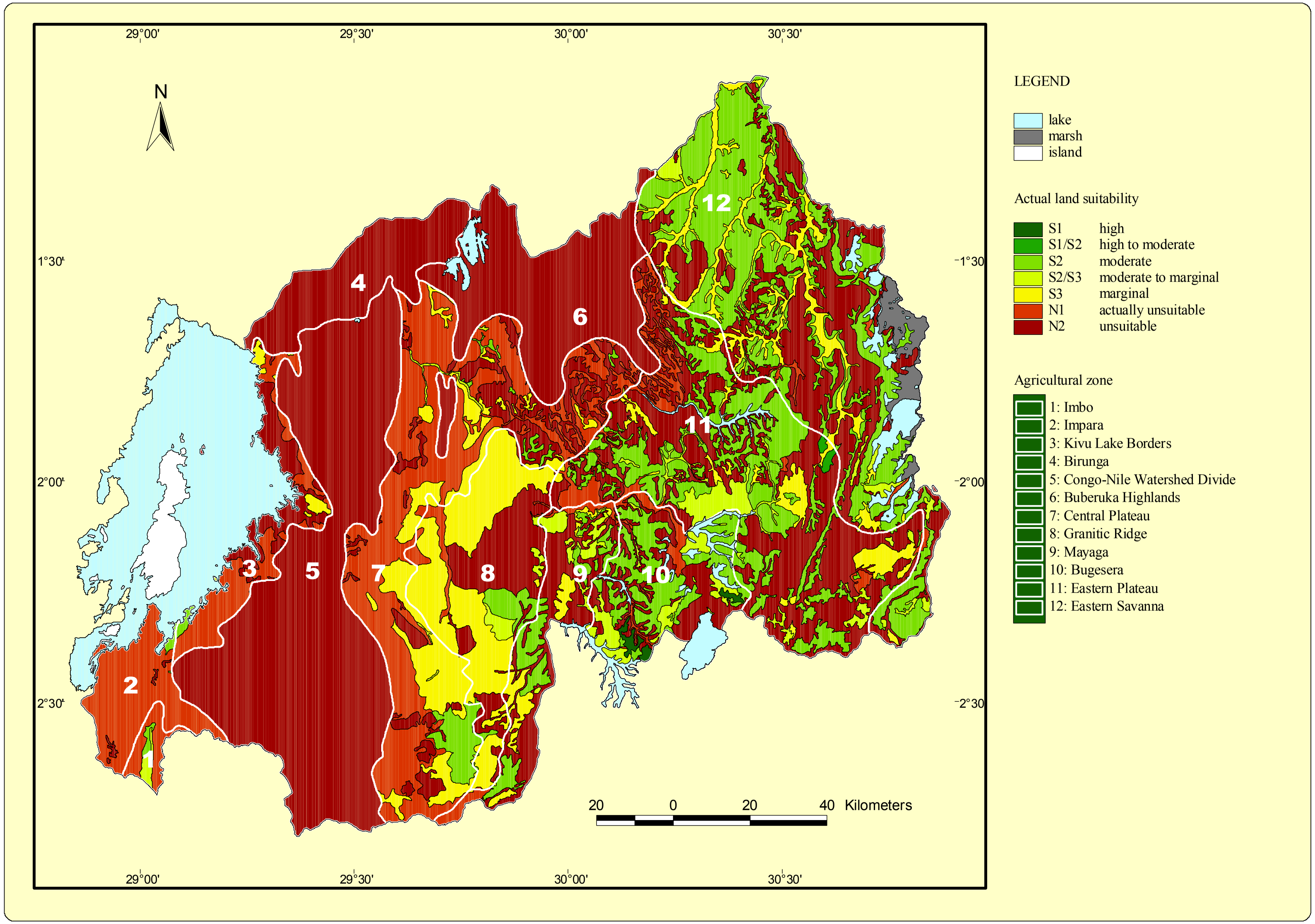
Cassava is the tuber crop of the lowland regions in Rwanda. When compared to sorghum, its temperature and rainfall demands are higher: cassava requires a warm, sunny environment and annual rainfall totals of at least 1,000 mm. The warm agro–climatic regions of the Imbo and the Mayaga and the Peripheral Bugesera, are optimally suited for the cultivation of this crop. Low and erratic rainfall limits the suitability of the other agro-climatic zones of the lowlands. The higher altitude and lower temperatures in the Impara, Kivu Lake Borders and Central Plateau slightly decrease cassava growth. Temperatures are too low in the high altitude regions. An overview of the climatic suitability for cassava has been given in Map 4.21.



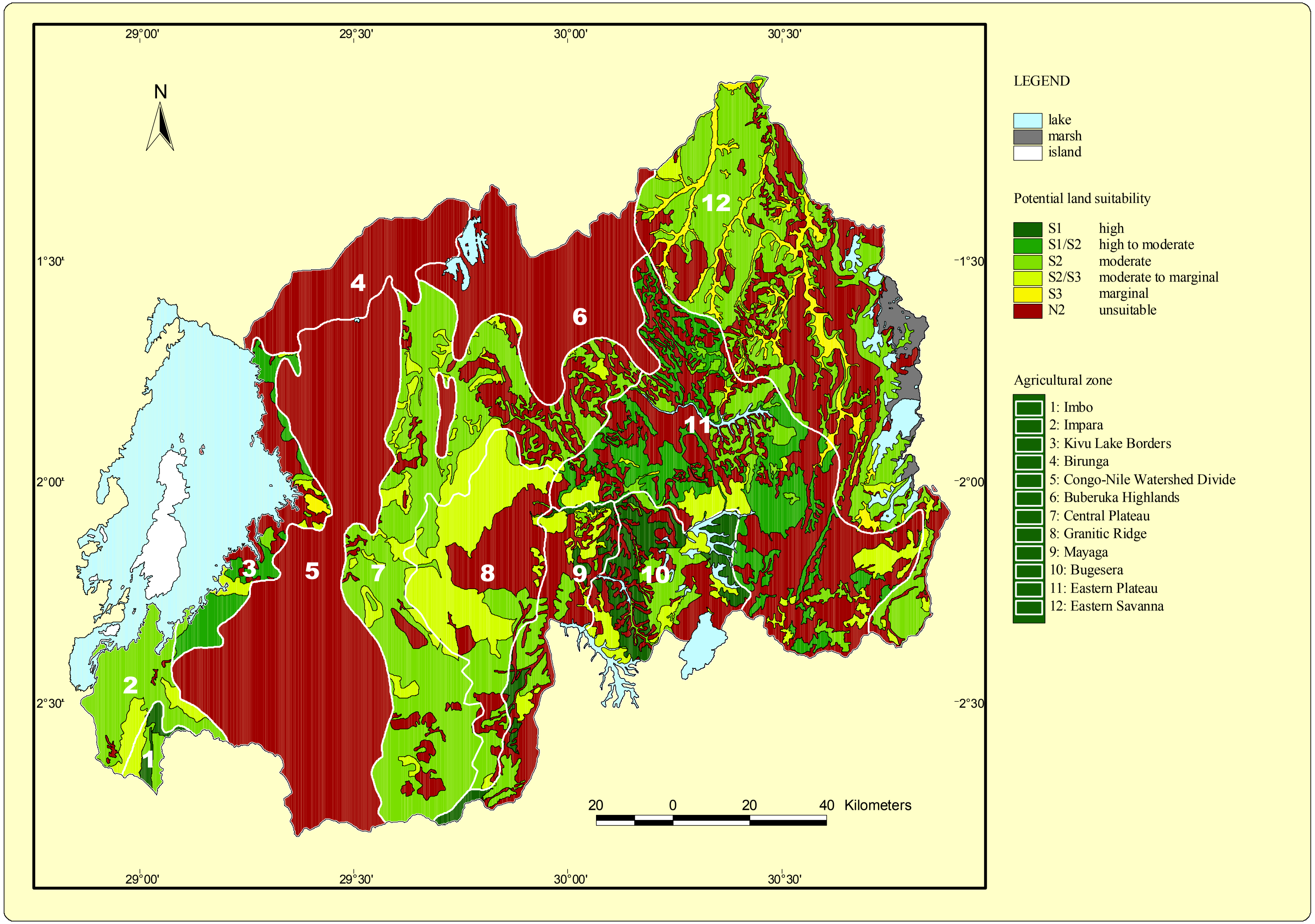
Map 4.21: Suitability of climate for the cultivation of cassava in the agro-climatic zones in Rwanda

From an edaphic viewpoint, tuber crops generally prefer deep, well drained, and coarse textured soils. On the well-drained land units the actual suitability for cassava production is determined by the slope gradient and the fine texture of the soils in the West, and the slope gradient and soil depth on the Central Plateau and Granitic Ridge (Map 4.22). The enclosed high altitude regions are climatically unsuitable. Climatic characteristics also set the suitability of the deep, well-drained and medium textured soils of the East. The limited soil depth due to the presence of granite or quartzite gravel and the low fertility level limit the soil suitability for cassava in the Bugesera and on the quartzite ridges. Poorly drained valley soils are actually unsuitable for cassava production, while a moderate to imperfect drainage limits the suitability of the soil unit from moderately to marginally suitable.

Drainage of the valleys and erosion control measures on the sloping hills and plateaus will increase the potential suitability of the Rwandan lowlands only slightly. More important changes upon relevant management can be expected in the Central Plateau and the western agro–climatic zones bordering the Kivu Lake. Consequently, a moderate suitability can be attained in most of the zones where the climatic conditions allow the production of cassava. Map 4.23 illustrates the spatial distribution of this potential suitability. The highest production potential has been assigned to the agricultural zones of the Imbo, the Mayaga and the Bugesera.



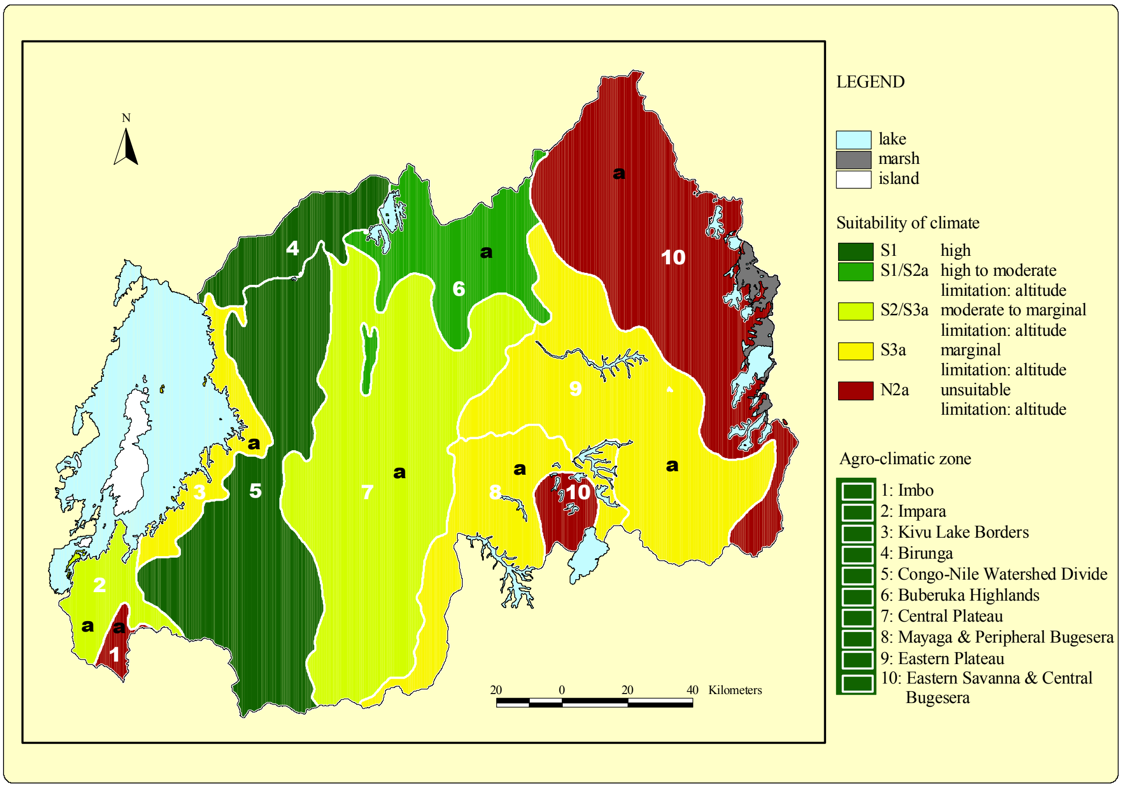
Map 4.22: Actual suitability of the dominant land units for the cultivation of cassava in Rwanda (derived from agro-climatic zones map and soil map at scale 1:250,000)



Map 4.23: Potential suitability of the dominant land units for the cultivation of cassava in Rwanda (derived from agro-climatic zones map and soil map at scale 1:250,000)

4.5.6. Potato (*Solanum tuberosum* L.)

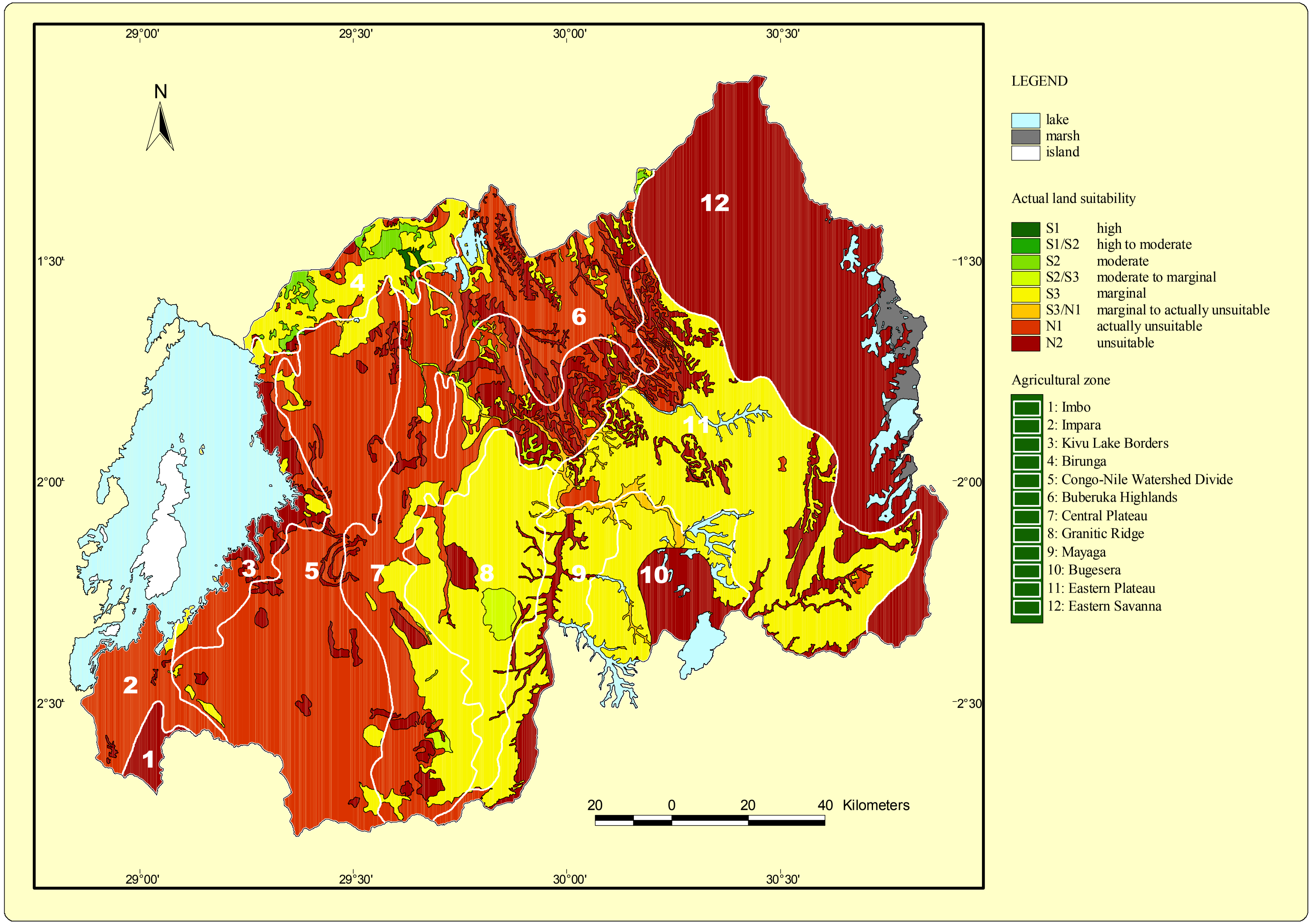
In the high altitude areas the main tuber crop is potato. Optimal climatic conditions are found in the cooler agro–climatic regions of the Congo–Nile Watershed Divide and the Birunga. Very suitable to moderately suitable temperatures have been registered in the Buberuka Highlands, while the Impara and the Central Plateau are moderately to marginally suitable. The temperatures near the Kivu Lake, in the Mayaga and the Peripheral Bugesera, and in the Eastern Plateau are too high, reducing the suitability for potato to a marginal level. Unsuitable temperatures have been registered in the East of the country and in the Imbo (Map 4.24).



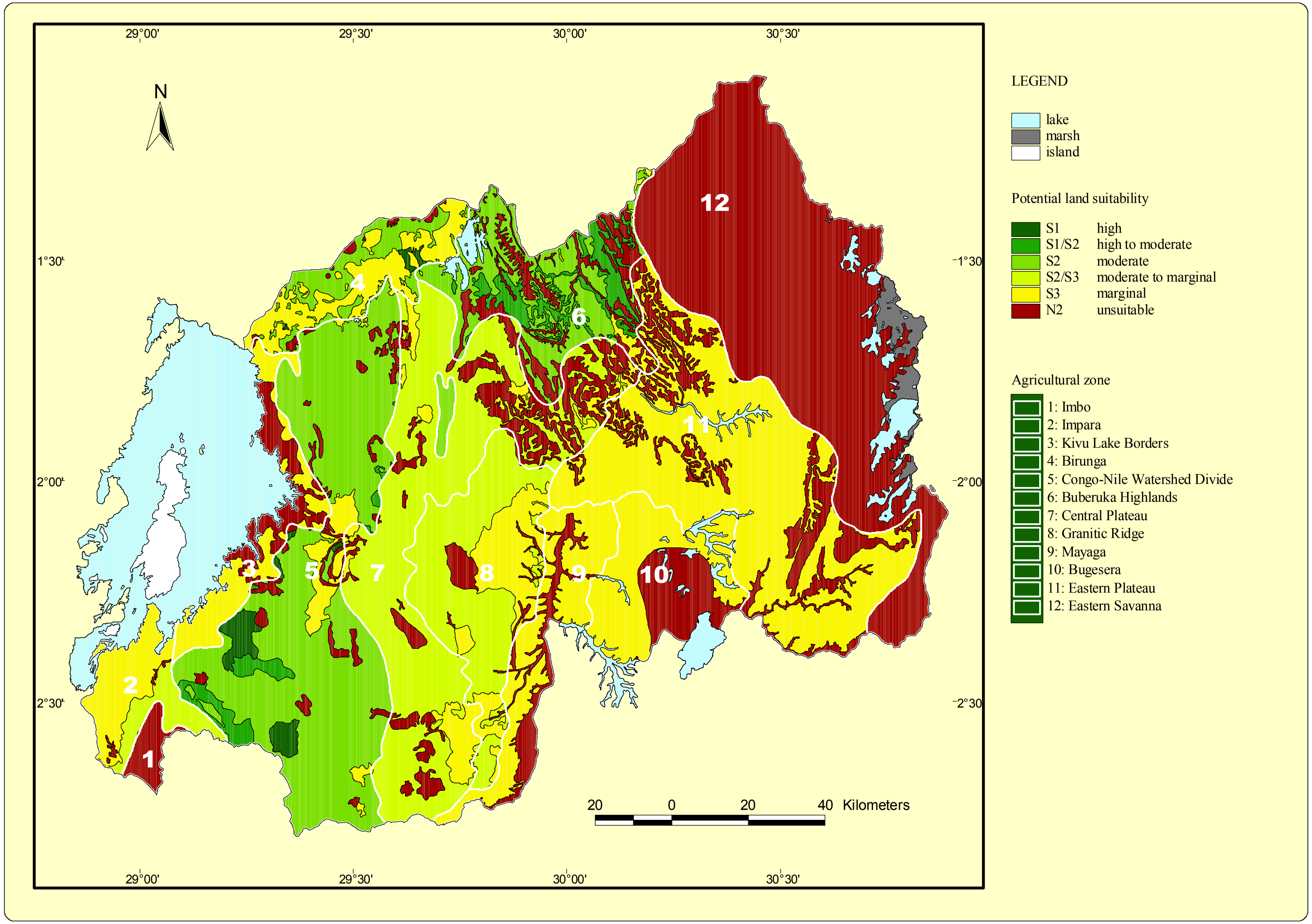
Map 4.24: Suitability of climate for the cultivation of potato in the agro-climatic zones in Rwanda

Compared to cassava, potato is clearly less demanding with regard to the physical soil properties, while it is slightly more demanding with respect to the chemical soil fertility. Potato is relatively tolerant to an imperfect drainage, while a soil depth of at least 0.75 m is sufficient for an optimal development of the tubers. This tuber clearly prefers coarse textured soils. Fine textured soils, and those with vertic properties, are only marginally suitable. The distinctly different climatic and edaphic requirements of cassava and potato, result in a quite different actual and potential suitability for potato. The actual suitability for the production of potato, shown in Map 4.25, is determined by climatic limitations in the lowlands, while slope gradient determines the actual suitability class in the western and central part of the country. On the gentle slopes of the volcanic plain, soil texture and soil depth are the most limiting parameters. Consequently, in these highlands, the actual suitability ranges from actually unsuitable to very suitable.

With erosion control and management options to restore or maintain the chemical soil fertility, the potential suitability of most land units in the high altitude regions is moderate, due to the medium texture. The very clayey soils of the Impara limit the suitability for potato production to a marginal level. In the other agricultural zones, the temperature regime limits the potential for potato production (Map 4.26).



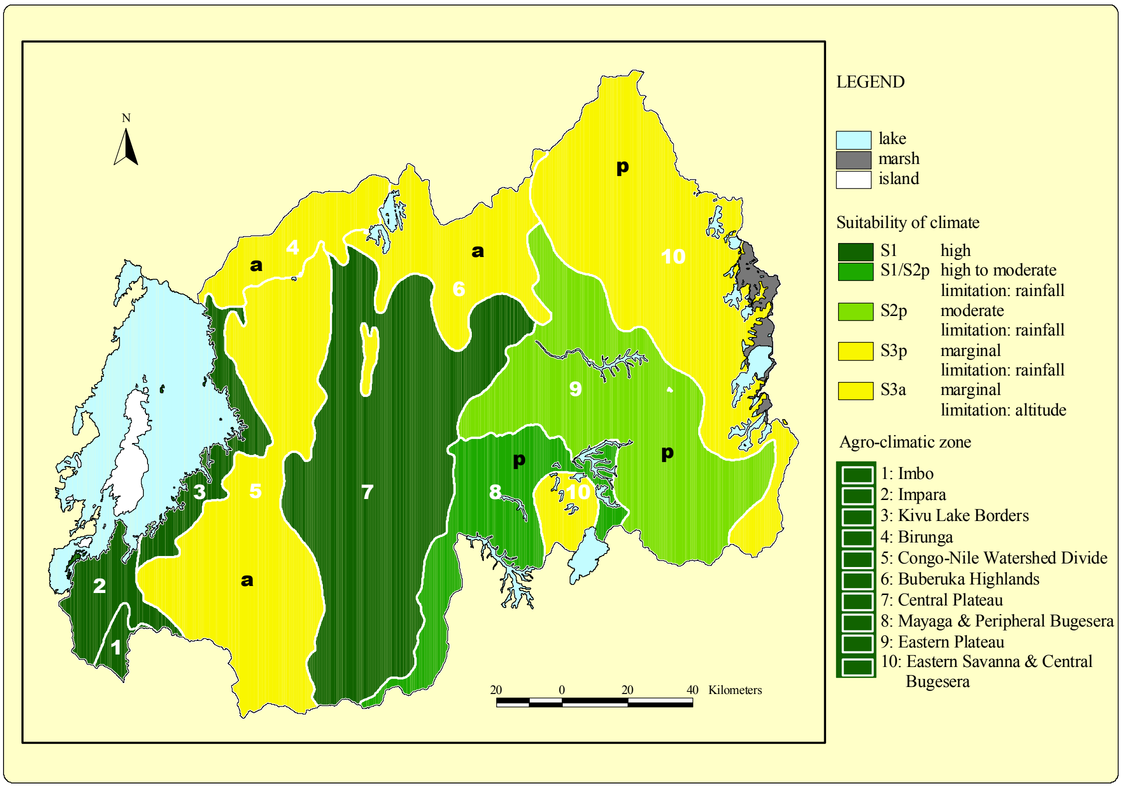
Map 4.25: Actual suitability of the dominant land units for the cultivation of potato in Rwanda (derived from agro-climatic zones map and soil map at scale 1:250,000)



Map 4.26: Potential suitability of the dominant land units for the cultivation of potato in Rwanda (derived from agro-climatic zones map and soil map at scale 1:250,000)

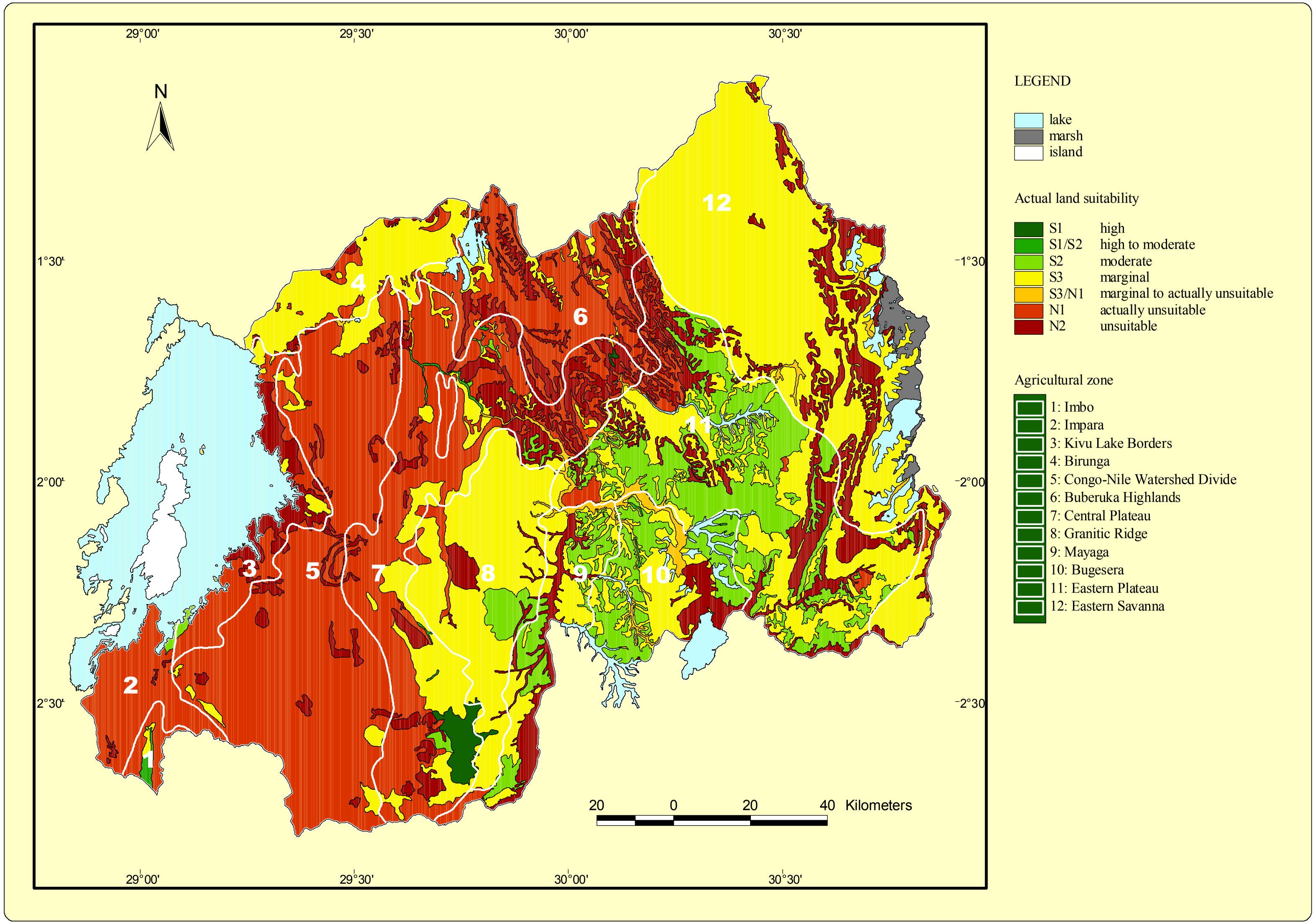
4.5.7. Sweet potato (*Ipomoea batatas* (L.) Lam.)

Cassava is the tuber of the lowlands, while potato is the tuber of the highlands. Most suited for the climatic conditions of the middle altitude regions is the tuber crop sweet potato. In the high altitude zones the low temperature is marginal. In the lowlands the water supply is insufficient resulting in marginal growing conditions too (Map 4.27).

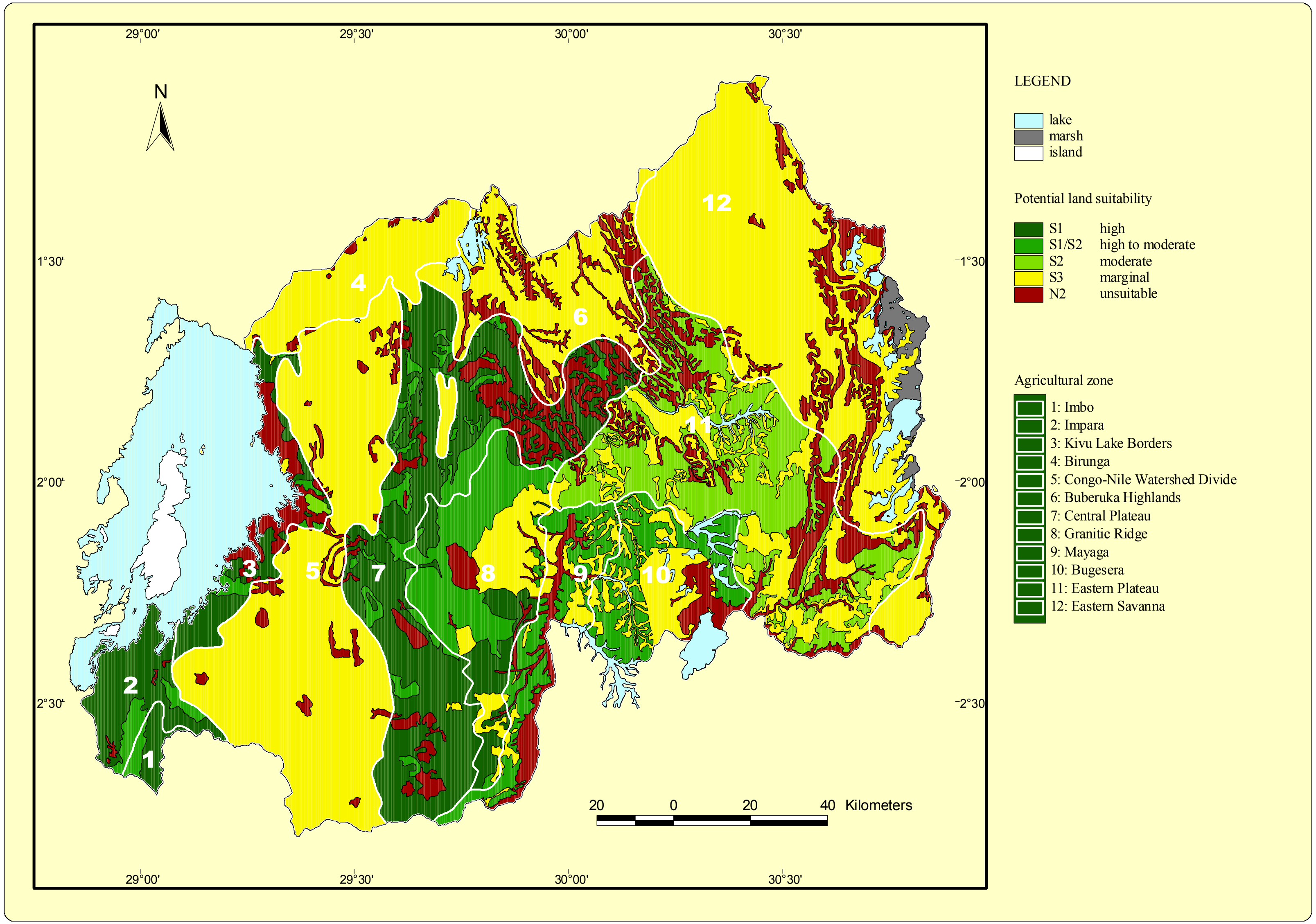


Map 4.27: Suitability of climate for the cultivation of sweet potato in the agro-climatic zones in Rwanda

Again, the specific climatic demands determine the production potential in the highlands and lowlands: they are actually and potentially marginally suitable (Map 4.28 and 4.29). The edaphic requirements for the cultivation of sweet potato are similar to these of common bean. In the high rainfall regions near the Kivu Lake and at the middle altitudes, where the climate is suitable for both crops, exactly the same actual and potential suitability has been found.



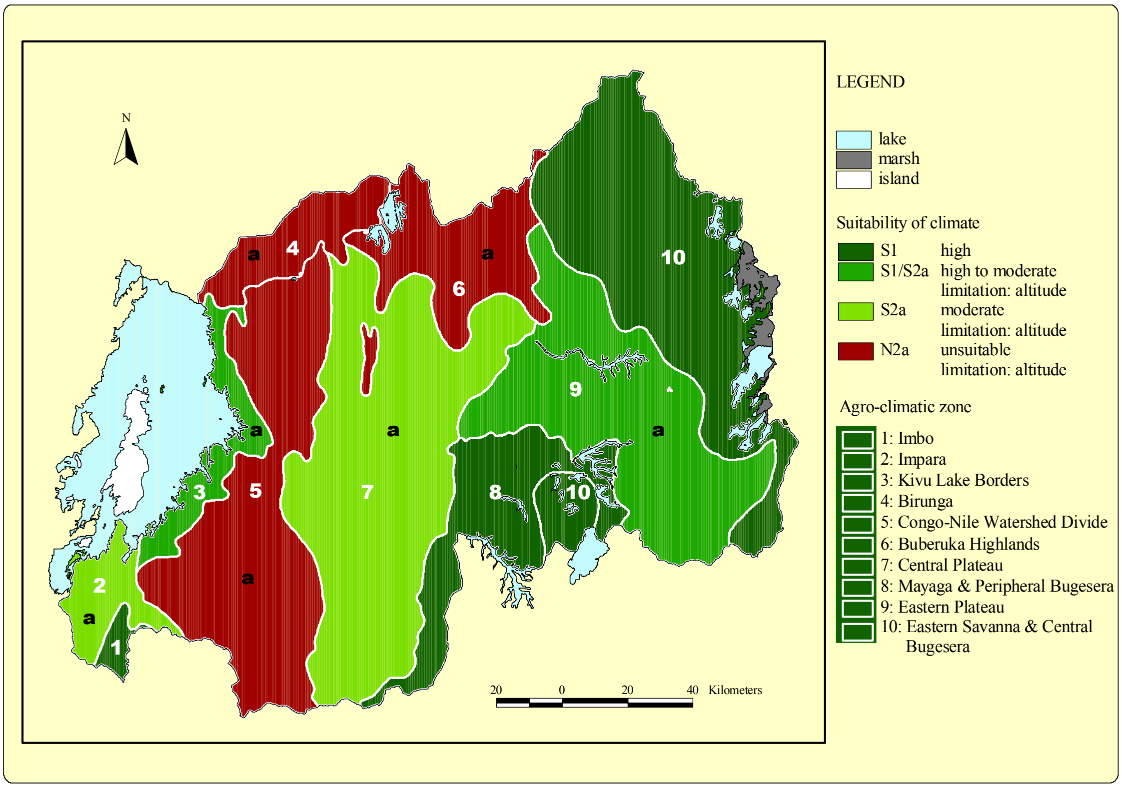
Map 4.28: Actual suitability of the dominant land units for the cultivation of sweet potato in Rwanda (derived from agro-climatic zones map and soil map at scale 1:250,000)



Map 4.29: Potential suitability of the dominant land units for the cultivation of sweet potato in Rwanda (derived from agro-climatic zones map and soil map at scale 1:250,000)

4.5.8. Groundnut (*Arachis hypogaea* L.)

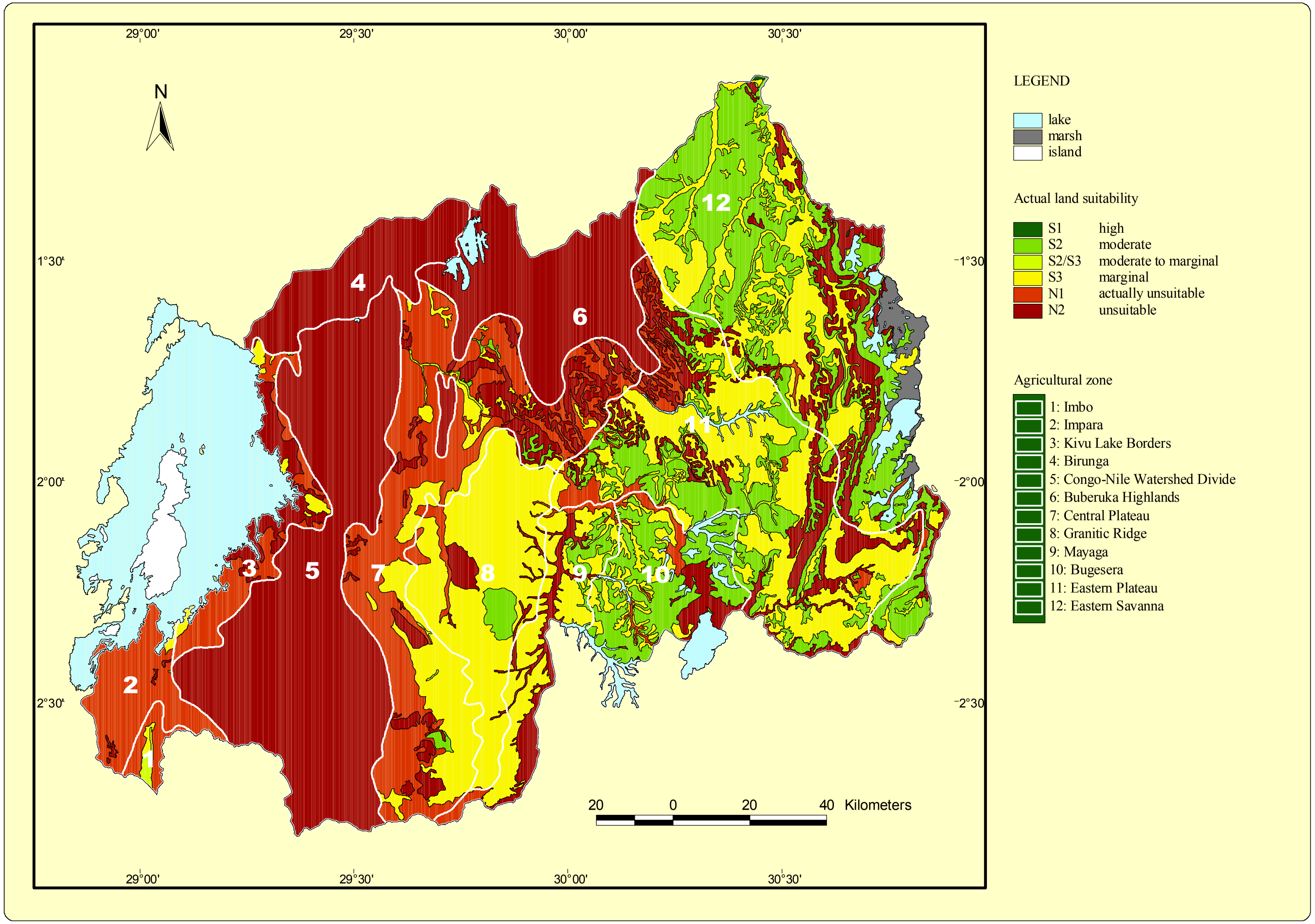
Groundnut, preferring warm tropical temperatures, without demanding too much water, is the crop most suited to the drier East. The suitability of the agro-climatic regions generally corresponds to that of cassava, except for the very suitable conditions found in the Eastern Savanna and Central Bugesera. Optimal climatic conditions have also been found in the agro–climatic zones of the Mayaga and the Peripheral Bugesera, and the Imbo. Near optimal conditions have been recorded in the Eastern Plateau and near the Kivu Lake, while a moderate suitability is to be expected in the middle altitude regions of the Central Plateau and the Impara. The high altitude regions are unsuitable for groundnut production (Map 4.30).



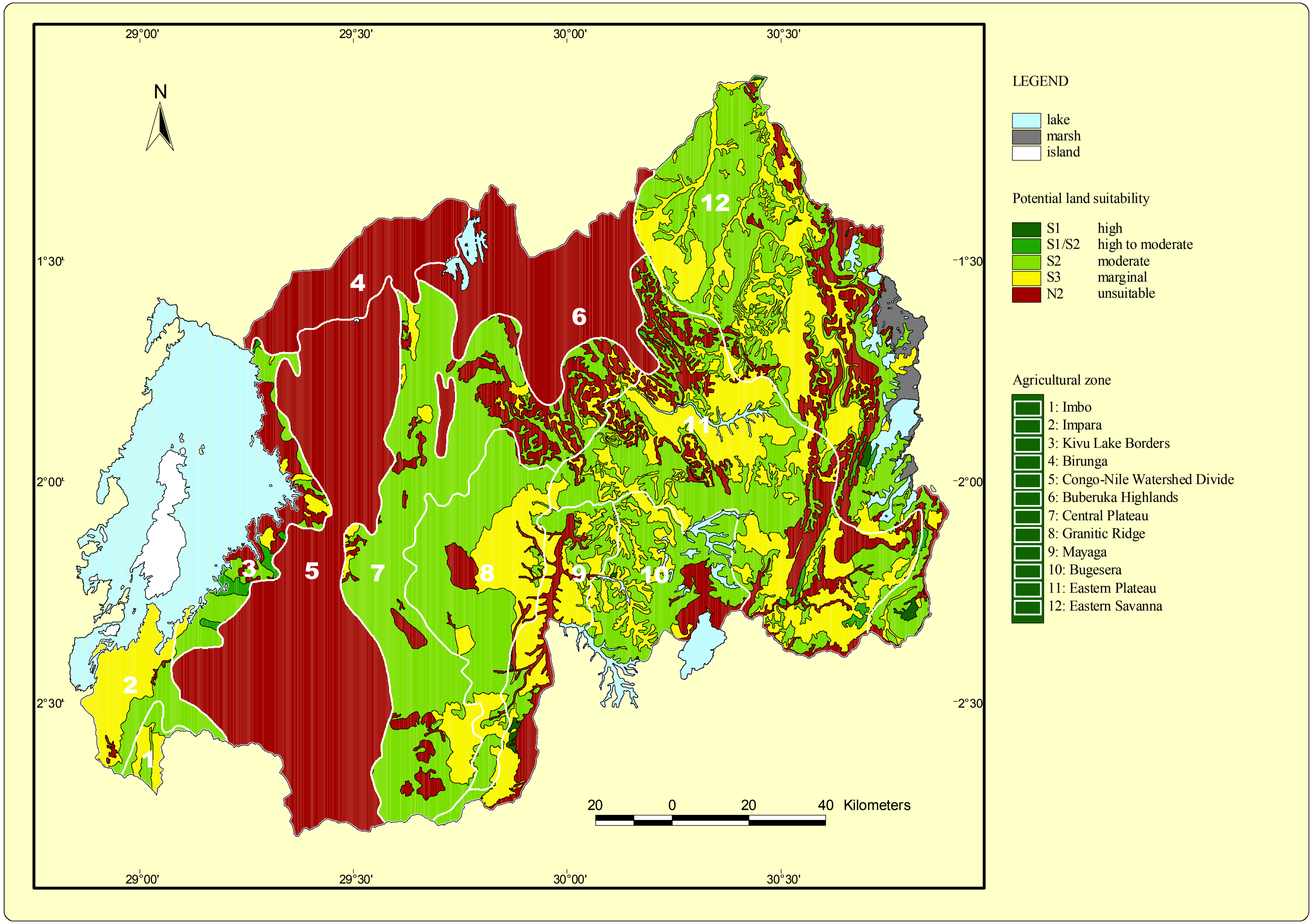
Map 4.30: Suitability of climate for the cultivation of groundnut in the agro-climatic zones in Rwanda

Also with respect to the edaphic requirements and the actual suitability for the production of groundnut, large similarities have been found with those of cassava. The small differences in the actual suitability of the soil units in the east and centre of the country are due to the decreased demands of groundnut with respect to soil depth. The cool climate limits the suitability of the high altitude regions; slope gradient and soil depth set the limits to the actual suitability in the middle altitude regions. The suitability of the lowlands varies between very suitable and actually unsuitable, depending on the soil texture, depth, drainage and SBC (Map 4.31).

Except for the drainage and chemical soil fertility, none of the soil parameters can be improved, and consequently, there are no management strategies to increase the suitability of the East. Soil depth and texture determine the inherent suitability of the soil units. The most important improvements in suitability for groundnut production can be expected in the agricultural regions of the Impara, Kivu Lake Borders and the Central Plateau. Soil erosion control and restoration and maintenance of the chemical soil fertility increase the suitability of the land units to a moderate level. The main limitation to the production of groundnut thus is the fine texture of most Rwandan soils (Map 4.32).



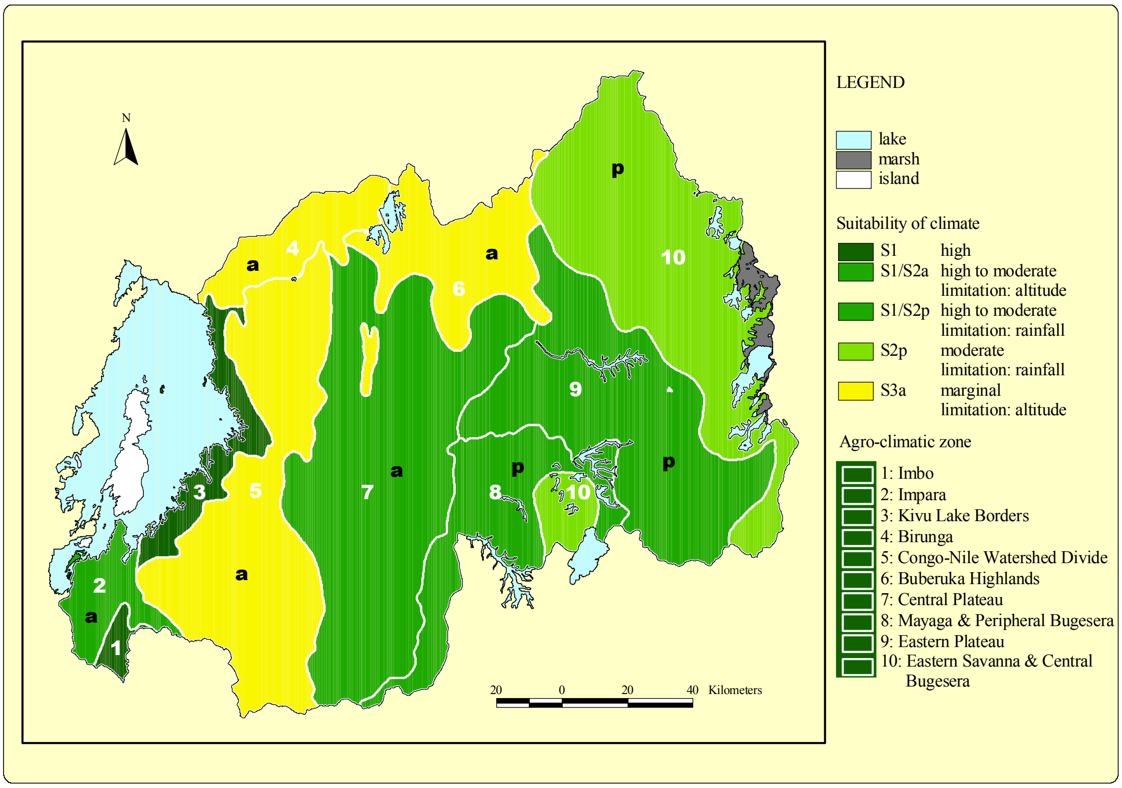
Map 4.31: Actual suitability of the dominant land units for the cultivation of groundnut in Rwanda (derived from agro-climatic zones map and soil map at scale 1:250,000)



Map 4.32: Potential suitability of the dominant land units for the cultivation of groundnut in Rwanda (derived from agro-climatic zones map and soil map at scale 1:250,000)

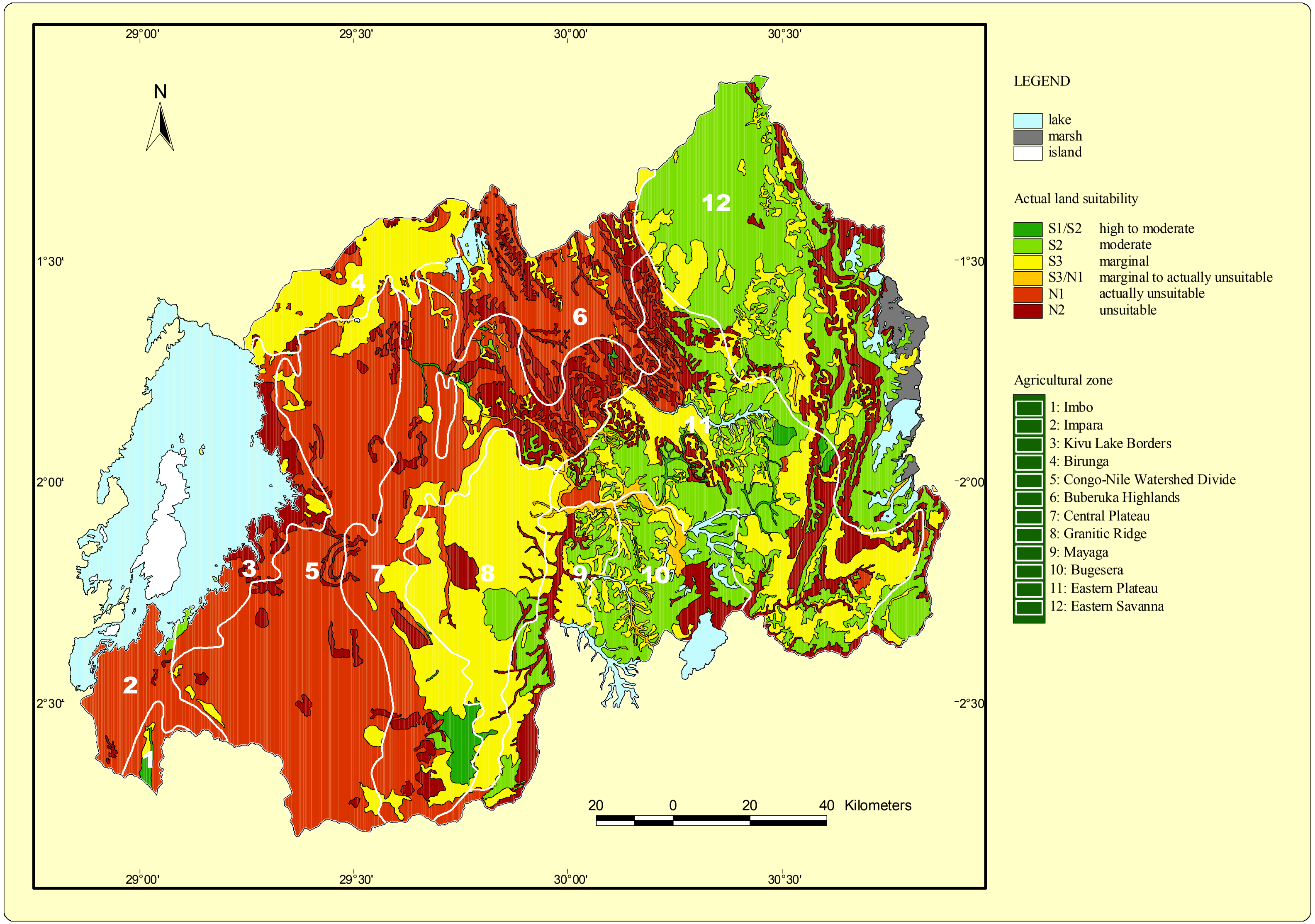
4.5.9. Soybean (*Glycine max* (L.) Merrill.)

Because of its higher energetic value, the cultivation of soybean results in higher nutritional returns that the cultivation of common bean. With respect to their edaphic requirements, both crops are identical. Also their water demands are comparable. Soybean, however, prefers slightly higher temperatures and gives only marginal returns when cultivated above 2,000 m altitude (Map 4.33).

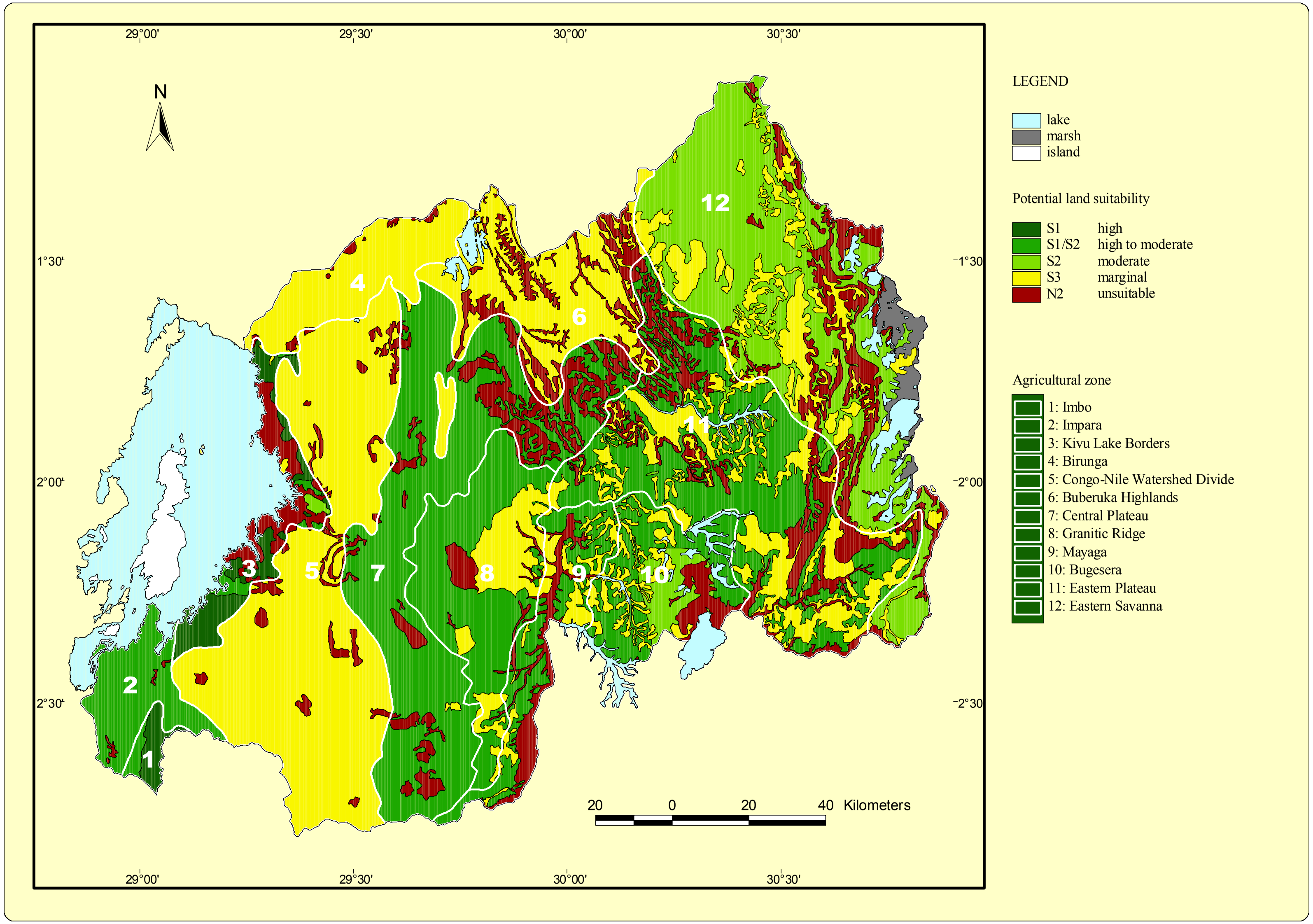


Map 4.33: Suitability of climate for the cultivation of soybean in the agro-climatic zones in Rwanda

This marginal suitability of the climate also determines the potential land suitability in the agricultural zones of the Congo-Nile Watershed Divide, the Birunga and the Buberuka Highlands. Actually, the deepest soils of the Eastern Savanna are best suited for the production of soybean. However, after terracing and restoring the cation balance, the highest returns to these investments are to be expected in the Imbo and along the Kivu Lake. The middle altitude regions and the Mayaga will become very suitable to moderately suitable. An overview of the spatial distribution of the actual and potential suitability for the cultivation of soybean has been illustrated in Map 4.34 and 4.35.



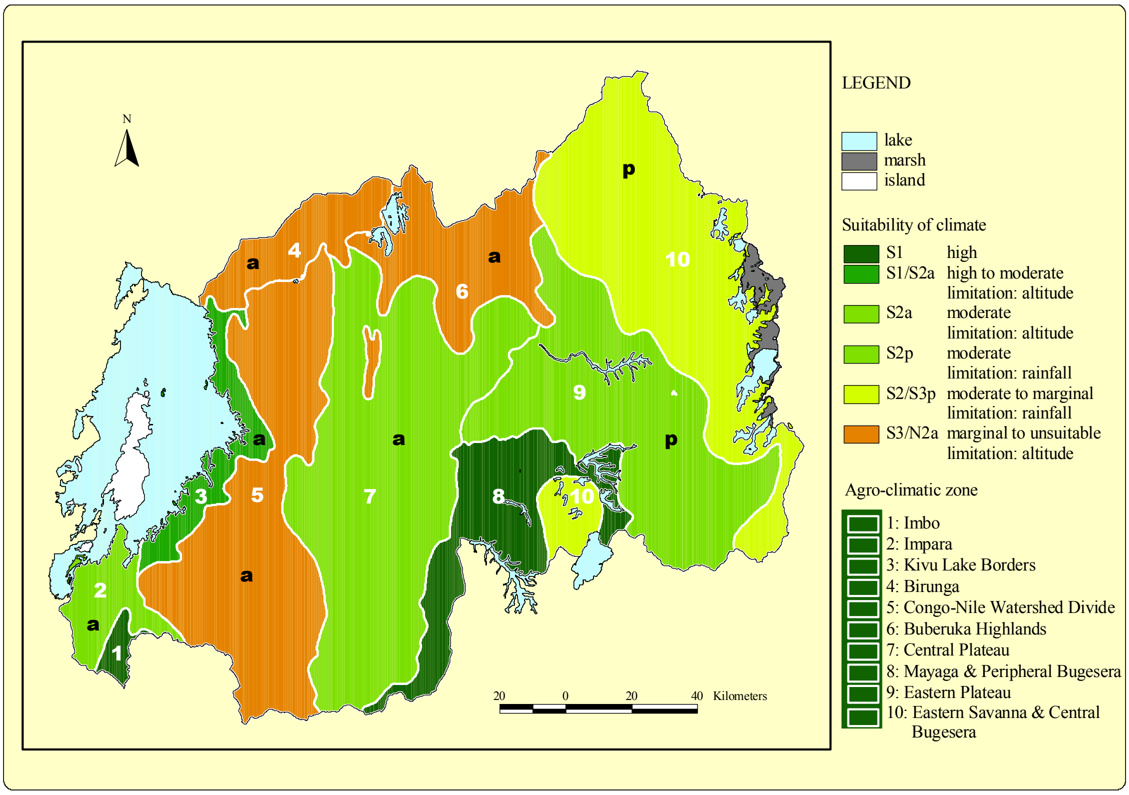
Map 4.34: Actual suitability of the dominant land units for the cultivation of soybean in Rwanda (derived from agro-climatic zones map and soil map at scale 1:250,000)



Map 4.35: Potential suitability of the dominant land units for the cultivation of soybean in Rwanda (derived from agro-climatic zones map and soil map at scale 1:250,000)

4.5.10. Banana (*Musa* L.)

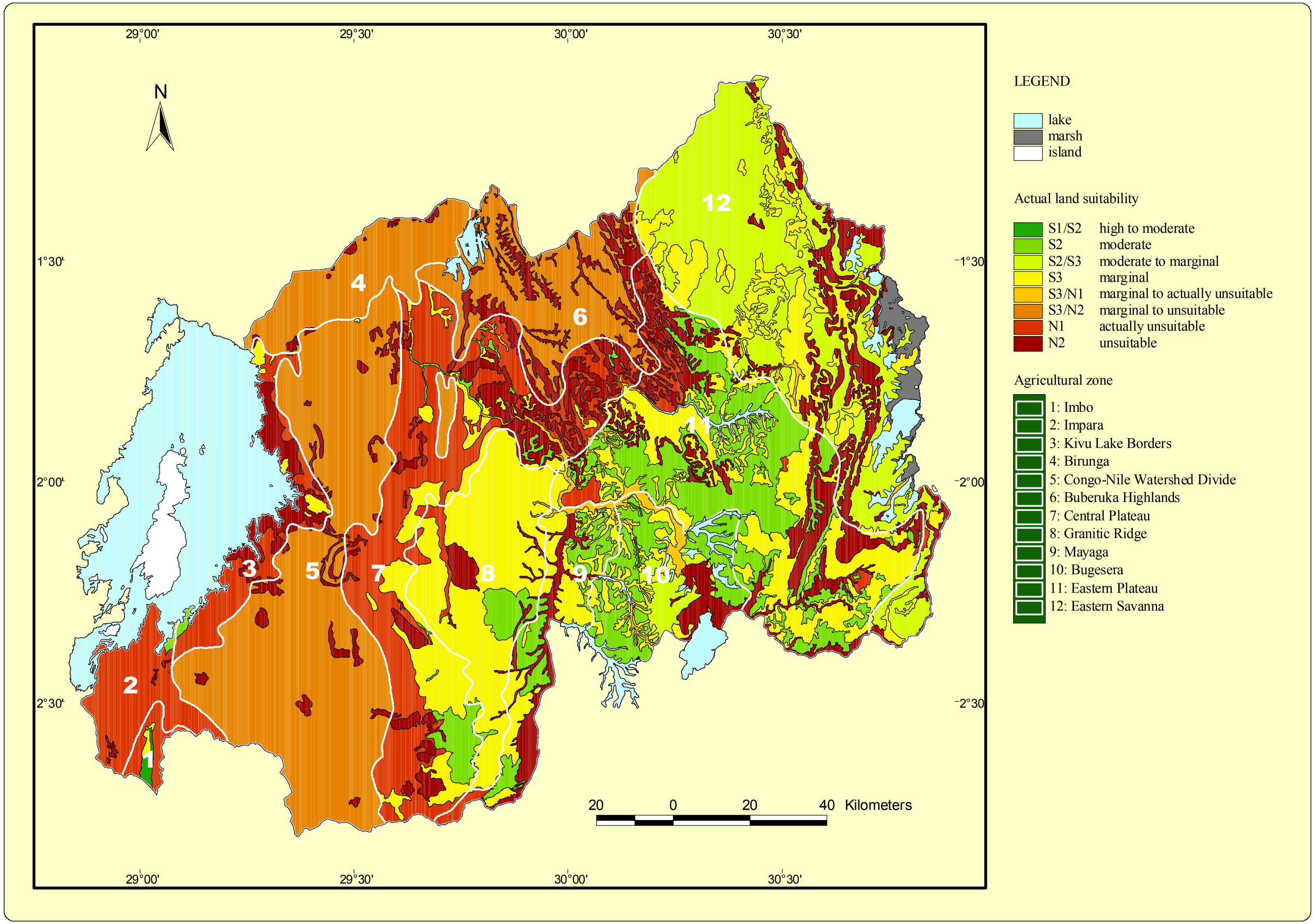
Banana prefers the average Rwandan climate (Map 4.36). The best growing conditions have been recorded in the warm and sub-humid agro-climatic regions of the Imbo and the Mayaga and the Peripheral Bugesera. Also along the Kivu Lake near optimal climatic conditions have been recorded. The lower temperatures of the Impara and Central Plateau are moderately suitable, while at the lower altitudes of the Birunga, Congo-Nile Watershed Divide and the Buberuka Highlands marginal temperatures have been reported. The cool highlands gradually become unsuitable for the cultivation of banana. In the East, low rainfall reduces the suitability of the Eastern Plateau to a moderate level and that of the Eastern Savanna to a marginal level.



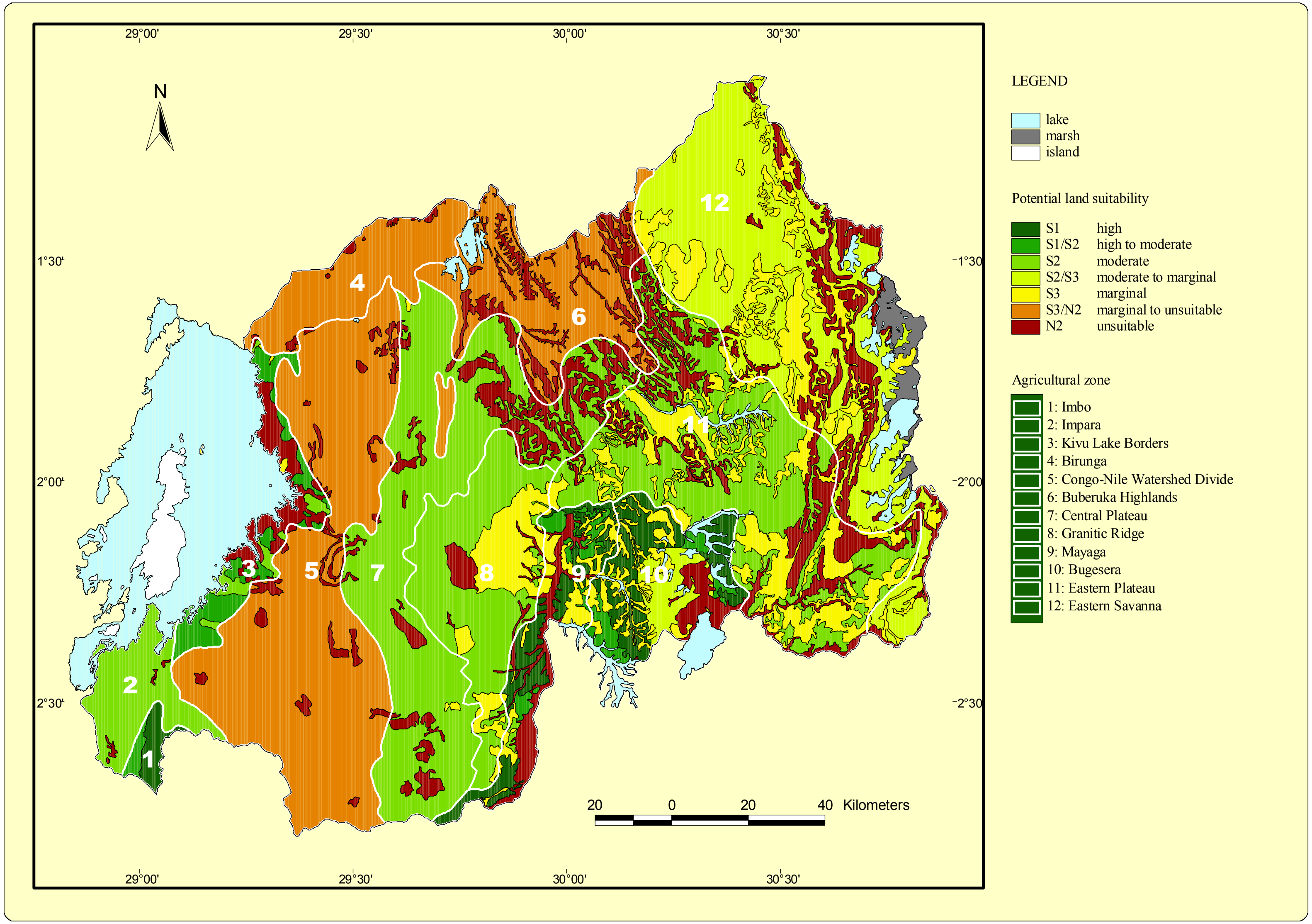
Map 4.36: Suitability of climate for the cultivation of banana in the agro-climatic zones in Rwanda

The edaphic requirements of banana largely correspond to those of bean and maize. The actual and potential suitability maps (Map 4.37 and 4.38) however, change considerably due to the different climatic requirements. Actually, the most suited soil units are found in the agricultural zones of the Eastern Plateau between the Muhazi and Mugesera lakes, the Mayaga, the Bugesera and the Imbo. Their suitability varies from very suitable to moderately suitable. Low temperatures, low rainfall, steep slopes or shallow soils limit the actual suitability in the other agricultural zones.

Appropriate management increases the suitability of the Imbo, the Mayaga and a large part of the Bugesera to very suitable. The potential suitability of the soil units in the Eastern Plateau, Central Plateau, Impara and the southern shores of the Kivu Lake generally is moderate. As such, banana grows well in a large part of the country.



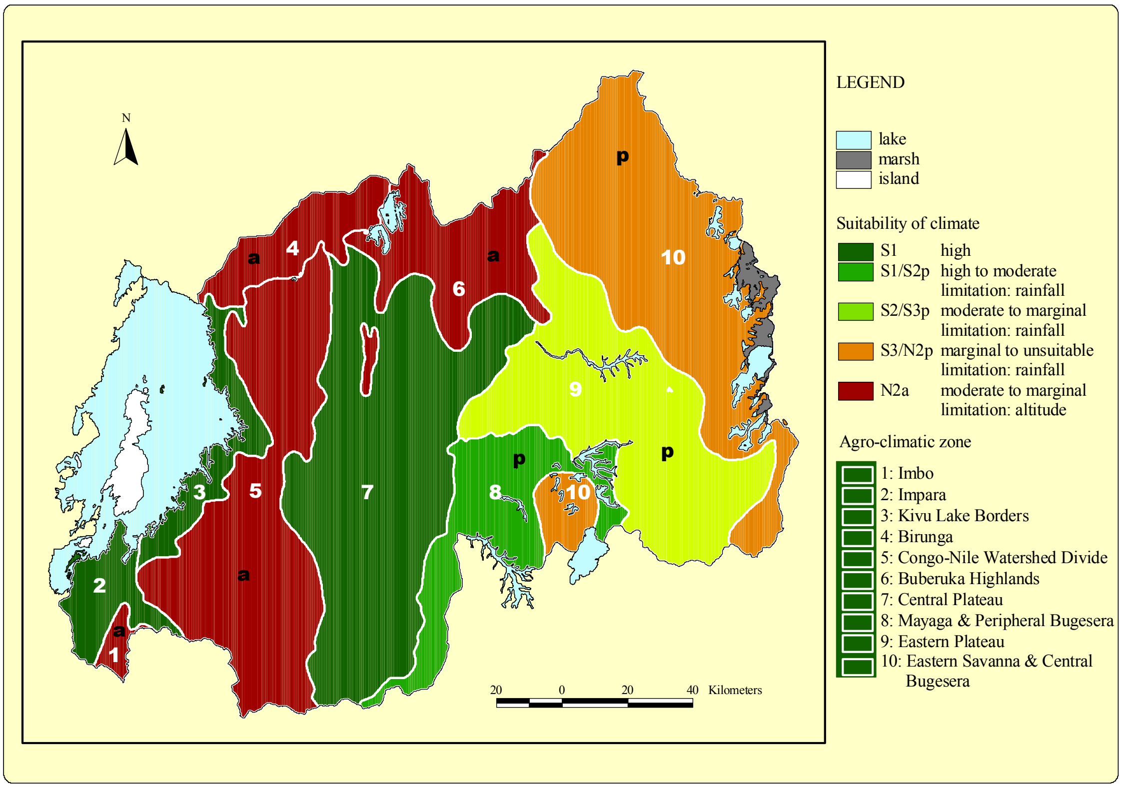
Map 4.37: Actual suitability of the dominant land units for the cultivation of banana in Rwanda (derived from agro-climatic zones map and soil map at scale 1:250,000)



Map 4.38: Potential suitability of the dominant land units for the cultivation of banana in Rwanda (derived from agro-climatic zones map and soil map at scale 1:250,000)

4.5.11. Arabica coffee (*Coffea arabica* L.)

In Rwanda, arabica coffee is a crop of the middle altitude regions that are well supplied by rain (Map 4.39). Optimal growing conditions have been registered on the shores of the Kivu Lake, in the Impara and in the Central Plateau agricultural regions. The Mayaga and the Peripheral Bugesera are characterised by a very suitable to moderately suitable climate, with the relatively low rainfall slightly limiting the optimal development of coffee.

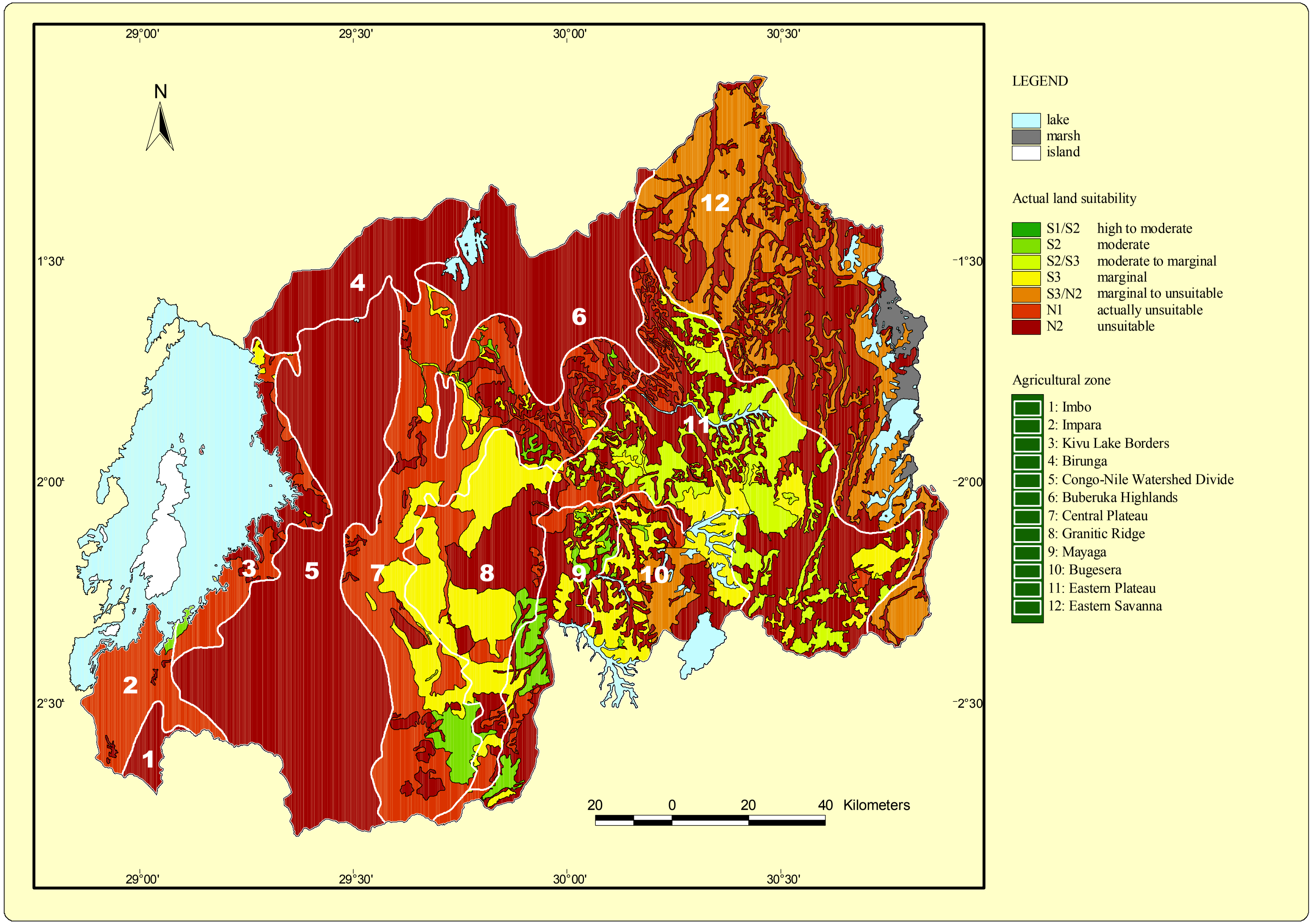


Map 4.39: Suitability of climate for the cultivation of arabica coffee in the agro-climatic zones in Rwanda

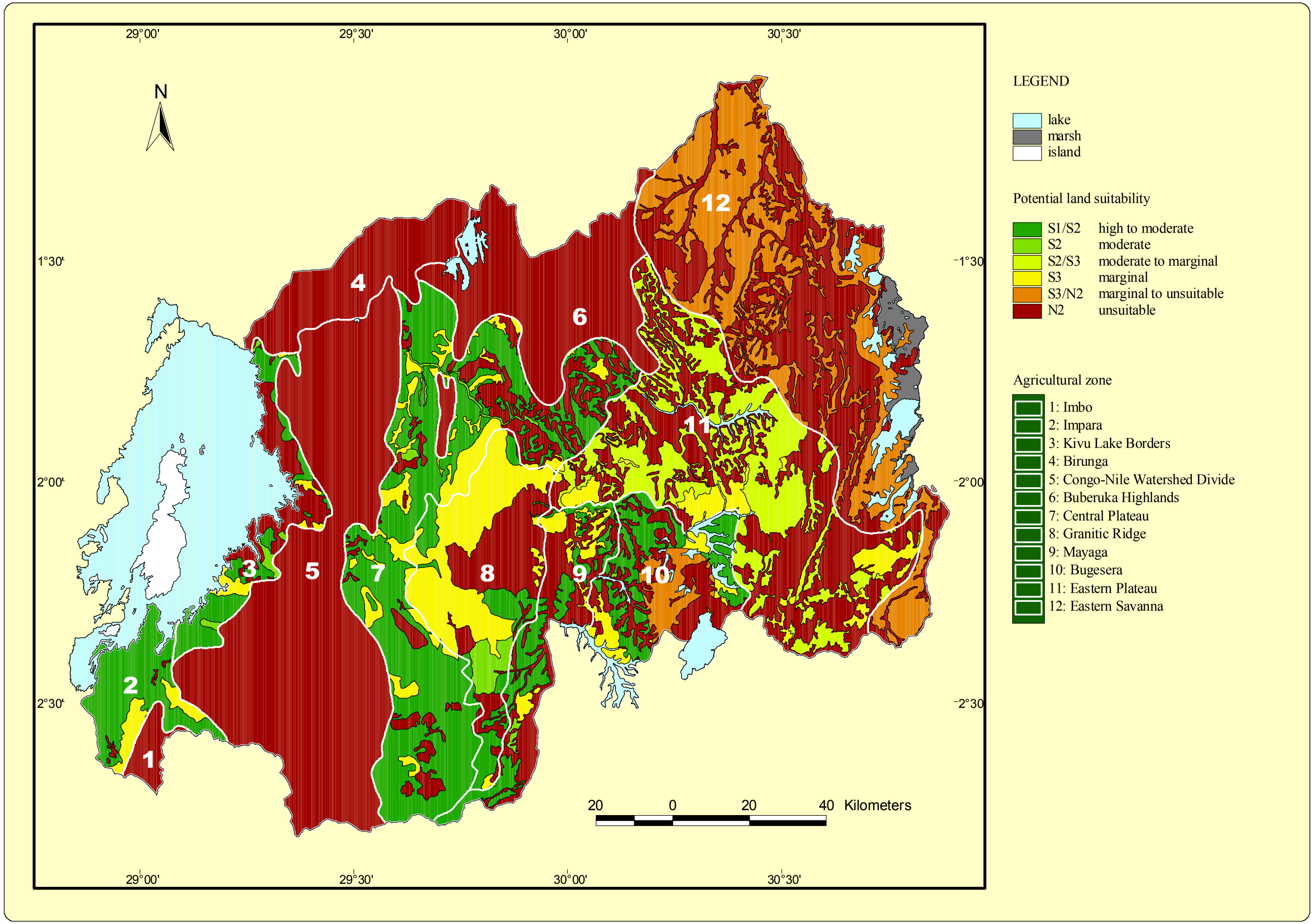
A further decrease in rainfall towards the east, gives a further reduction in suitability, with the Eastern Plateau being moderately to marginally suitable, while the climate is marginal or too dry for coffee in the Eastern Savanna and Central Bugesera. Unsuitable climatic conditions have also been recorded in the cool high altitude regions.

Apart from the high climatic requirements, arabica coffee also poses severe edaphic demands. The fine textured soils of Rwanda fulfil the textural requirements perfectly, as long as they don't have vertic properties. The great soil depth and the high sum of basic cations are much more difficult to attain, and often they limit the actual suitability for the production of the crop. Again, the best production environment has been recorded in the Mayaga, and around the Muhazi and Mugesera Lakes of the Eastern Plateau where the erratic rainfall limits the development of the cash crop (Map 4.40).

Terracing and fertilisation considerably increase the suitability of the soil units in the Impara, and of the deepest soils on the Borders of the Kivu Lake and the Central Plateau (Map 4.41).



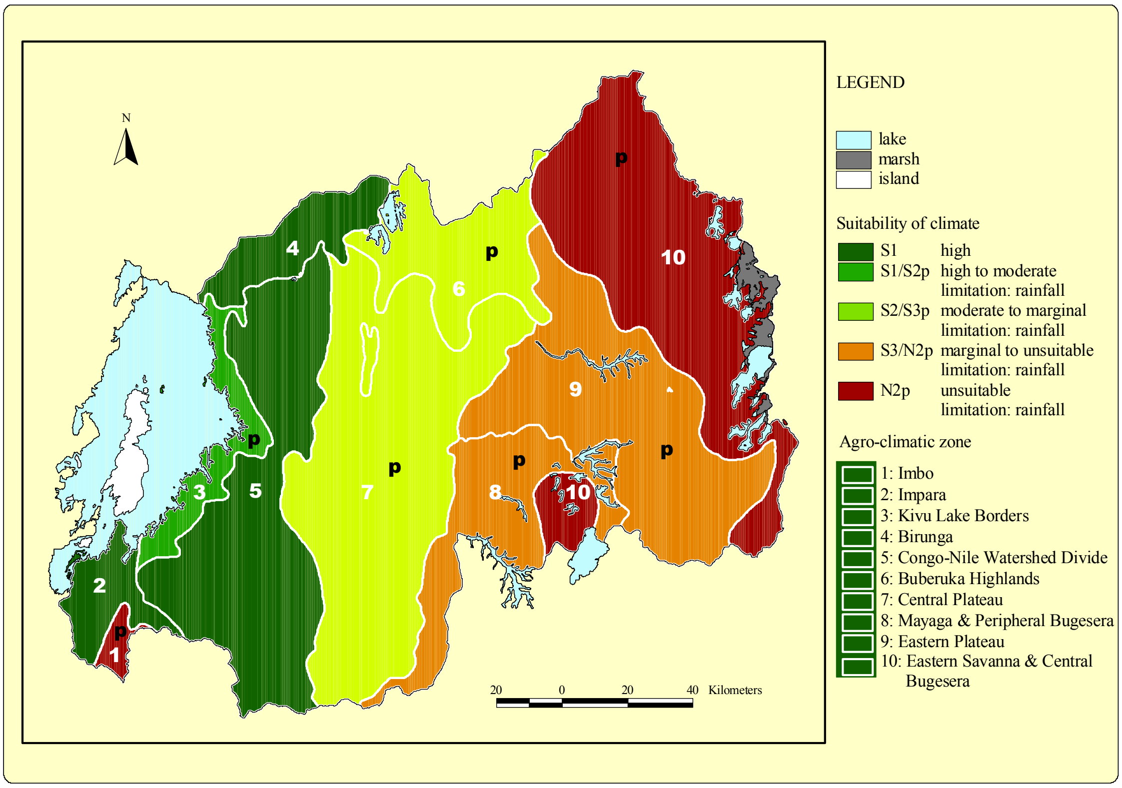
Map 4.40: Actual suitability of the dominant land units for the cultivation of arabica coffee in Rwanda (derived from agro-climatic zones map and soil map at scale 1:250,000)



Map 4.41: Potential suitability of the dominant land units for the cultivation of arabica coffee in Rwanda (derived from agro-climatic zones map and soil map at scale 1:250,000)

4.5.12. Tea (*Camellia sinensis* (L.) O. Kuntze)

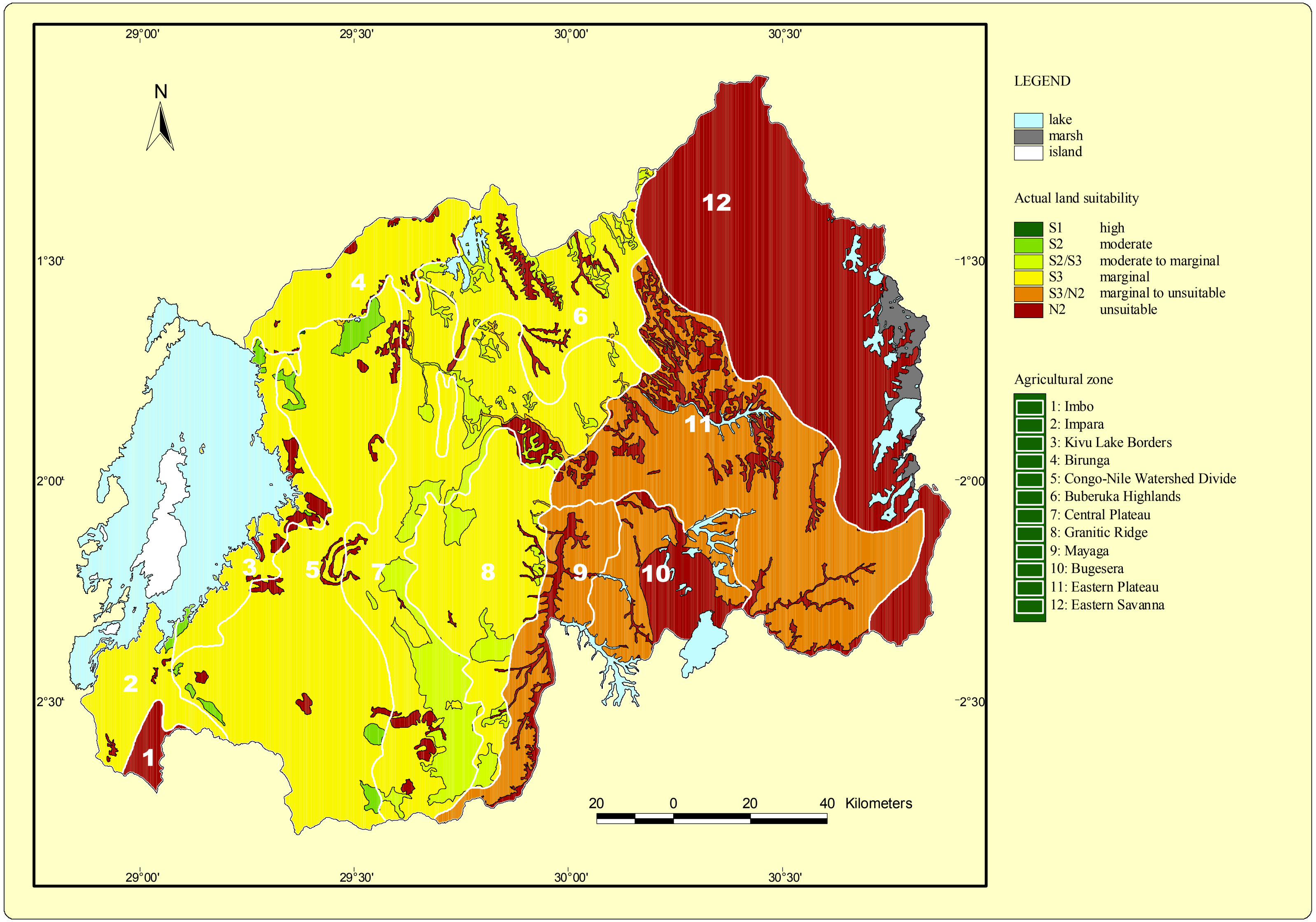
The high rainfall agro-climatic regions of the Impara, the Congo–Nile Watershed Divide, the Birunga and the Kivu Lake Borders are characterised by optimal climatic conditions for the growth of tea. The Rwandan lowlands are too dry and are unsuitable from the climatic viewpoint. All other agro–climatic regions are moderately to marginally suitable, as shown in Map 4.42.



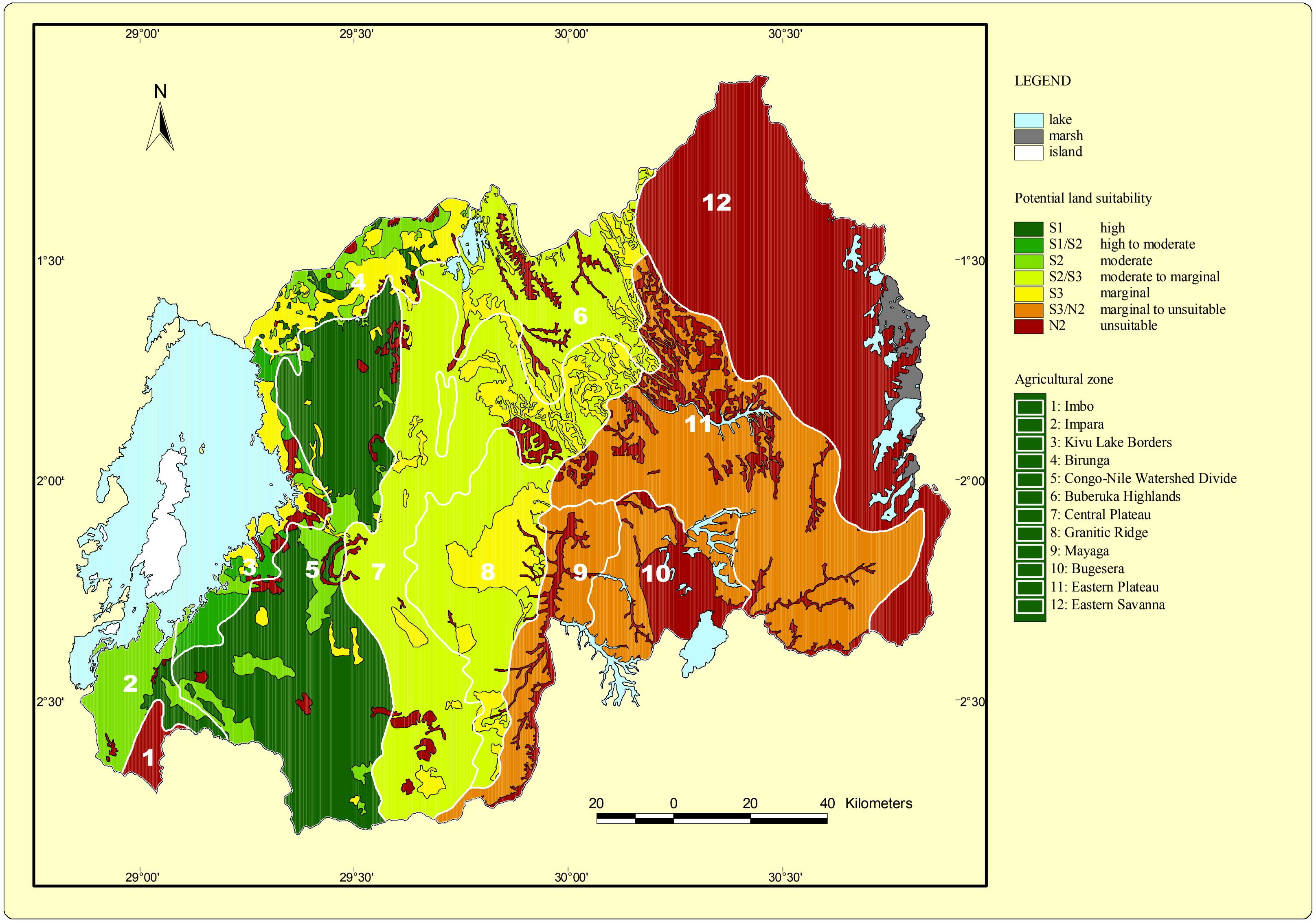
Map 4.42: Suitability of climate for the cultivation of tea in the agro-climatic zones in Rwanda

From an edaphic viewpoint, tea requires poor soils for an optimal development. The slope gradient requirements have been weakened, as tea is commonly grown very well in relatively steep environments. Also regarding soil depth, this crop doesn't require much and shallow soils are marginally suitable. The textural requirements correspond very well to the prevailing dominant medium to fine textures in Rwanda, but soils with vertic properties should be avoided. The requirements of this crop related to the soil nutrient status are remarkable. The BS should be lower than 20 % to give optimal yields. The actual suitability of the Rwandan soil units has been shown in Map 4.43. Tea is a crop of acid soils, and therefore is very well suited for the leached soils of the high altitude regions, once the erosion risk has been lowered. The actual suitability for tea is dominated by the slope gradient resulting in a marginal suitability in the climatically adapted regions.

Management techniques aimed at reducing soil loss through erosion considerably increase the suitability of the Impara, Kivu Lake Borders and Congo–Nile Watershed Divide, which are potentially very suitable for the production of tea (Map 4.44).



Map 4.43: Actual suitability of the dominant land units for the cultivation of tea in Rwanda (derived from agro-climatic zones map and soil map at scale 1:250,000)



Map 4.44: Potential suitability of the dominant land units for the cultivation of tea in Rwanda (derived from agro-climatic zones map and soil map at scale 1:250,000)

4.6. Discussion

4.6.1. Suitability classification versus capability classification

The most important edaphic limitations to crop production in Rwanda are the slope gradient, soil depth and SBC. Where climatic conditions are optimal or near optimal, these soil properties will determine the spatial distribution of the final suitability. Important deviations from this general rule have been reported for crops that are very demanding (arabica coffee), or for those that pose extremely low requirements to the soil (groundnut). Also with respect to the land units that are unsuitable for the cultivation of crops similar results have been reported when applying the land capability and land suitability classification procedures. Consequently, the capability classification that was designed for Rwanda and that takes into account the extreme importance of erosion risks, effective soil depth and nutrient availability, performs very well with regard to climatologically adapted and moderately demanding crops.

4.6.2. Actual suitability versus potential suitability

Reducing the risk of erosion and increasing or maintaining soil fertility, being two major management techniques of extreme importance in Rwanda, are generally much more responsive on the deep soils of the West, than on the old, strongly weathered or stony soils of the East, where inherent soil properties such as stoniness and low cation exchange capacity set a limit to the production level. This doesn't mean that these soils have not at all the potential of producing well. However, for maintaining the same chemical fertility level, much higher investments will be required, while a smaller range of crops will be suited for production.

4.6.3. Suitability classification versus yield data

The performance of the suitability classification system has been evaluated using data from the national agricultural interviews of the agricultural year 1984 (MINAGRI, 1985). This document provides information per agricultural zone on the land surface occupied by several crops as well as their production. Table 4.16 summarises the land surface occupied by common bean, maize, sorghum, potato, sweet potato and groundnut during the two agricultural seasons. Common bean and maize are very important crops in all agricultural zones, especially during the first agricultural season from September to January. Sorghum is a typical crop during the second season, from February to June. With respect to the other three crops, the spatial variability in land surface is much more important than the temporal changes. The cultivation of potato is generally restricted to the high altitude zones, especially in the Birunga. It also occupies a relatively large land surface in the Granitic Ridge. Sweet potato is clearly the crop of the middle altitude regions while its importance decreases in favour of groundnut in the warmer lowlands.

The average annual yield of these crops has been summarised in Table 4.17. Together with the crop information reported in the agricultural calendar published by MINAGRI (2003), these data were used to verify the results of the land suitability classification.

Common bean

According to the yield data of the agricultural year 1984, common bean is cultivated in all agricultural regions. The national average yield is 1.0 t ha^{-1}. The highest yields have been reported in the Mayaga, Eastern Savanna and Granitic Ridge. Also the yields recorded in the Eastern Plateau, Central Plateau, and Buberuka Highlands exceed the national average.

According to Baudoin *et al*. (2001), the yield in traditional cropping systems generally ranges between 0.2 and 0.5 t ha^{-1}, while in modern cropping systems or research stations yields can rise up to 3.0 to 6.0 t ha^{-1}, depending on the variety. According to MINAGRI (2003), the optimal yields recorded in Rwanda amount to 2 t ha^{-1} and common bean is mostly cultivated in the agricultural zones of the Imbo, the Impara, the Mayaga and the Eastern Plateau. With respect to the land suitability classification of the dominant land units, this latter agricultural zone has also been identified as moderately suitable for the production of common bean, together with some parts of the Imbo and Mayaga. The drier Eastern Savanna and the Bugesera have been reported as moderately suitable too. The land suitability classification of the associated land units reveals a high potential for the cultivation of bean in the Imbo, the Impara and the Granitic Ridge. The land suitability classification for bean thus is performing well.

Table 4.16: Land surface (%) per agricultural zone occupied by 6 important crops during the agricultural year 1984 (Aug-83 to Jul-84)

agricultural	crop					
zone	bean	maize	sorghum	potato	sweet potato	groundnut
season A (Sep-Dec)						
1	51	44	1	0	4	0
2	55	41	0	1	1	2
3	53	30	7	1	0	9
4	27	39	10	22	0	2
5	37	34	5	6	0	18
6	45	19	2	1	0	33
7	59	17	4	1	0	19
8	56	14	0	10	3	17
9	50	33	0	3	5	9
10	57	27	2	0	7	6
11	57	26	3	3	6	5
12	33	38	24	1	4	1
season B (Jan-Jun)						
1	46	44	0	0	8	2
2	69	5	14	0	3	9
3	42	12	22	0	0	24
4	30	33	5	29	0	2
5	21	17	24	11	0	27
6	29	13	32	2	0	24
7	26	12	33	1	1	27
8	29	13	36	1	5	16
9	13	27	47	2	4	7
10	23	28	38	1	3	7
11	38	15	33	1	1	11
12	35	30	20	2	8	4

Table 4.17: Average yield per agricultural zone of 6 important crops recorded during the agricultural year 1984. Bold = yields equalling or exceeding the national average; underlined = outliers

agricultural zone	*average yield (t ha^{-1})*					
	bean	*maize*	*sorghum*	*potato*	*sweet potato*	*groundnut*
Imbo	**1.0**	0.3	**<u>9.6</u>**	**<u>43.5</u>**	**5.4**	**0.7**
Impara	0.7	**0.6**	0.4	**11.0**	**7.2**	0.5
Kivu Lake Borders	0.9	0.4	0.4	1.3	4.3	**0.8**
Birunga	0.6	**0.8**	0.6	**4.4**	3.1	-
Congo-Nile Watershed Divide	**1.0**	**1.7**	0.4	**5.1**	3.8	-
Buberuka Highlands	**1.1**	**0.9**	**0.8**	**5.5**	3.8	-
Central Plateau	**1.2**	0.4	0.7	2.8	4.1	**0.6**
Granitic Ridge	**1.3**	0.2	**0.9**	1.2	**4.7**	0.5
Mayaga	**1.4**	0.1	**0.8**	2.5	**4.8**	**0.6**
Bugesera	0.8	0.1	**0.8**	**5.5**	4.4	0.4
Eastern Plateau	**1.2**	0.2	**1.1**	1.9	**4.6**	**0.8**
Eastern Savanna	**1.3**	0.2	**1.7**	**5.0**	**<u>9.1</u>**	0.5
Rwanda	*1.0*	*0.5*	*0.8*	*4.2*	*4.6*	0.6

Maize

Also maize is cultivated all over Rwanda, although with a varying degree of success. The national average yield amounts only to 0.5 t ha^{-1} and is very low compared to the optimal yield of 3.5 t ha^{-1} reported by MINAGRI (2003). According to Ristanovic (2001) however, maize yields in Eastern and Southern Africa are generally below 1.0 t ha^{-1}. The most important maize producing regions are the Imbo, Impara, Birunga, Congo-Nile Watershed Divide and the Buberuka Highlands. The actual suitability classification on the other hand identified the valley of the Imbo and the deepest soils of the Mayaga and Eastern Plateau as very suitable to moderately suitable. Potentially, very favourable conditions have been reported in all agricultural zones, except for the dry Eastern Savanna and for the central part of the Bugesera.

According to the yield data of the agricultural year 1984, the highest yields have also been recorded in the Impara and the three high altitude regions.

Sorghum

While maize is the crop of the rainy West, sorghum clearly is yielding best in central and eastern Rwanda. In all agricultural zones of the lowlands and middle altitudes located at the western side of the Congo-Nile mountain chain, yields equalling or exceeding the national average of 0.8 t ha^{-1} have been reported. Extremely high yields have been recorded in the Imbo. According to Murty and Renard (2001), sorghum has a yield potential over 10 t ha^{-1}, but generally grain yields in Africa vary from 0.5 to 0.9 t ha^{-1} and 2 t ha^{-1} can be obtained with local cultivars and improved practices. MINAGRI reported optimal yields of 3 to 4 t ha^{-1}. The main sorghum producing regions are the Granitic Ridge, Central Plateau, Mayaga, Bugesera, Eastern Plateau and Eastern Savanna. The results of the land suitability classification generally correspond to this actual distribution. The agricultural zones of the Impara and Kivu Lake Borders have been identified as potentially very suitable regions, but apparently in reality they don't yield as much as in the agricultural zones of the East.

Pea

The cultivation of pea is mainly limited to the high altitude areas of the Birunga, Congo-Nile Watershed Divide and the Buberuka Highlands (MINAGRI, 2003). This corresponds very well to the results of the potential land suitability classification. Additionally, the agricultural zones of the Impara and Kivu Lake Borders have been identified as potentially very to moderately suitable.

Cassava

Both the potential land suitability classification and the agricultural calendar by MINAGRI (2003) report that cassava can be cultivated in all lowlands and at the middle altitudes of Rwanda. In the western agricultural zones of the Impara and Kivu Lake Borders, additional management related to erosion control and chemical fertility might be required to improve the yields.

Potato

Optimal climatic conditions for the cultivation of potato have been reported in the high altitude regions of Rwanda, and especially in the volcanic range. Under normal growing conditions, potato yields about 40 to 60 t ha^{-1}. In tropical Africa however, the national averages are only about 10 t ha^{-1} (Rolot, 2001). The national average yield during the agricultural year of 1984, reported by MINAGRI (1985) however, is much lower, attaining only 4.2 t ha^{-1}. Very high yields have been recorded in the Imbo, while also the production potential of the Impara approaches the averages reported in the literature. Potato yields are relatively low in the highlands areas. Comparable yields have been reported in the Bugesera and Eastern Savanna, while according to the suitability classification of climate temperatures are too high for the successful cultivation of this tuber. While the yield data are clearly erroneous, consistent results have been reported between the potential suitability classification and the actual distribution of potato. According to MINAGRI (2003), potato is the tuber of the Birunga, Congo-Nile Watershed Divide and Buberuka Highlands. In the Birunga, the crop needs to be cultivated on ridges in order to increase the effective soil depth.

Sweet potato

In Rwanda, under intensive cultivation, sweet potato yields about 20 to 30 t ha^{-1}. The reported yields however, range between 3 and 9 t ha^{-1}. This corresponds with the yield range of sweet potatoes cultivated in village gardens in tropical Africa, reported by Janssens (2001). The highest yields have been reported in the Eastern Savanna, Impara and Imbo. According to the suitability classification, however, the Eastern Savanna is only marginally suited for the production of sweet potato because of the erratic rainfall. The Imbo and Impara have a high potential suitability, but they have not been reported by MINAGRI (2003) as being important regions for the cultivation of this crop. Other regions with yields exceeding the national average are the Granitic Ridge, the Mayaga and the Eastern Plateau. According to the agricultural calendar of MINAGRI (2003), sweet potato is mainly cultivated in the agricultural zones of the Kivu Lake Borders, Granitic Ridge, Central Plateau, Mayaga and Eastern Plateau. These regions have also been identified by the land suitability classification.

Groundnut

Groundnut is cultivated mainly in the Imbo, the Mayaga, the Bugesera, the Eastern Plateau and the Eastern Savanna. Under optimal conditions, the crop attains a yield of 1.5 t ha^{-1} (MINAGRI, 2003). The yields reported during the agricultural year 1984 are clearly lower, but the differences between the agricultural zones are relatively limited. Groundnut is not cultivated in the highlands. The distribution of the crop reported by MINAGRI corresponds with the land units that have been identified as moderately suitable. With the correct management practices, the crop can also be cultivated successfully in the agricultural regions of the Central Plateau and Granitic Ridge.

Soybean

Soybean is cultivated in all agricultural zones with an altitude below 1,900 m. According to the suitability classification, only large parts of the Eastern Savanna, Eastern Plateau, Birunga and Mayaga are moderately suitable, but with the correct management, the crop can be cultivated on most land units of the lowlands and middle altitudes.

Banana

The main cultivation regions of banana, reported by MINAGRI (2003) are the Imbo, Impara, Kivu Lake Borders, Eastern Plateau and Eastern Savanna. According to the land suitability classification however, the suitability of the East ranges between moderate and marginal because of the low rainfall. On the other hand, the Mayaga and the peripheral part of the Bugesera have been indicated as actually moderately suitable, while they were not reported by MINAGRI (2003). The land units near the Kivu Lake are potentially suitable.

Coffee arabica

In the agricultural calendar reported by MINAGRI (2003) the following regions have been identified as zones where the cultivation of coffee needs to be intensified: the Southwest, the shores of the Kivu Lake, the Central Plateau, Granitic Ridge, Eastern Plateau, Mayaga and the peripheral part of the Bugesera. This generally corresponds to the results of the suitability classification. Nevertheless, the Imbo has been classified as unsuitable because of the high temperatures, while the Plateaus of the East are only moderately to marginally suitable because of the low rainfall. In the Granitic Ridge, most soil units are too shallow to allow an optimal development of the deep root system of the coffee shrubs. Apparently, the crop requirements related to climate and soil depth need some corrections. On the other hand, coffee is abundantly cultivated in the Mayaga, while this region has not been reported by MINAGRI (2003) as being an important production zone.

Tea

The main tea producing regions in Rwanda, the Impara, Kivu Lake Borders, Birunga, Congo-Nile Watershed Divide and Buberuka Highlands have also been identified by the land suitability classification.

4.6.4. Final conclusion

Apart from some minor adaptations, the suitability classification developed for application in Rwanda performs very well. It is an interesting tool for the analysis and description of important climatic and edaphic properties affecting agricultural production. The crop–specific suitability classification succeeds in giving a sound overview of the suitability of the agro–climatic zones and soil units at a scale of 1:250,000.

CHAPTER 5. CONCLUSIONS

5.1. Performance of the elaborated land evaluation tools

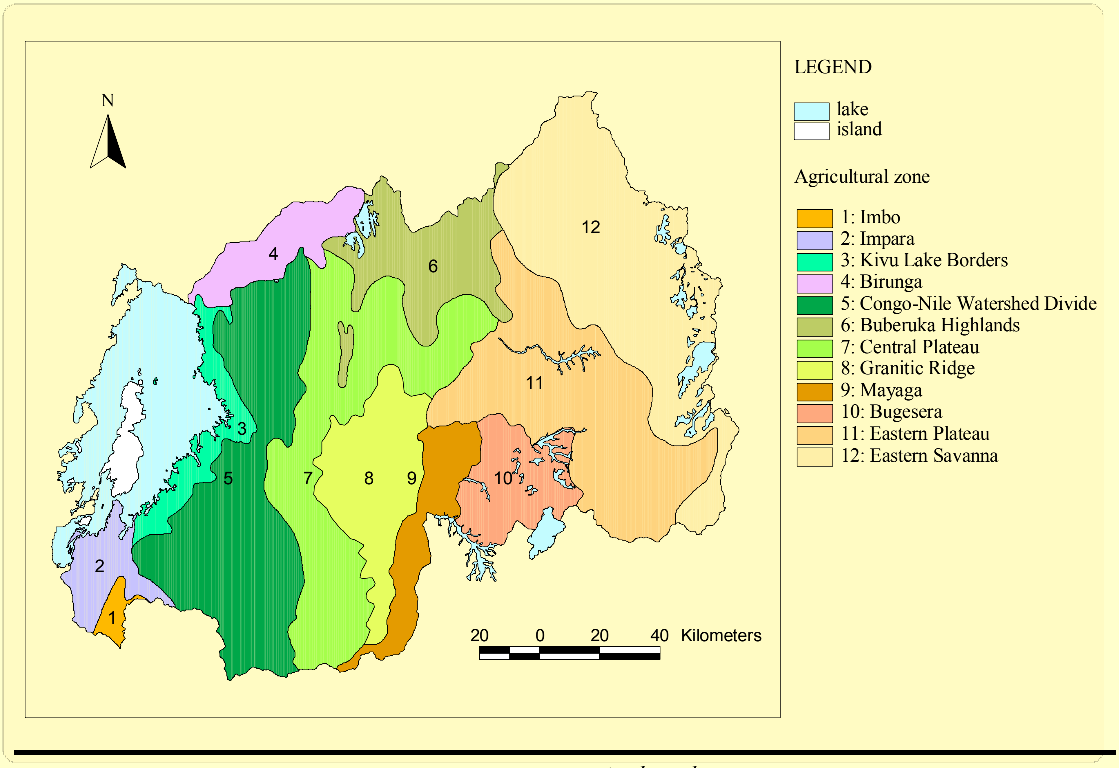
Information on the agricultural potential in Rwanda was gained through the development of a land capability and land suitability classification system, running on monthly climatic data and soil physical and morphological properties at scale 1:250,000. Development of these two land evaluation tools, adapted to the specific environmental conditions in Rwanda, resulted in new insights with respect to the impact of climate, topography, soil and management on the agricultural potential in Rwanda.

The land capability and suitability classification systems are especially interesting because of the framework they offer within which the land resources data can be explored and evaluated. Local agronomists are able to identify the limiting soil properties and interpret the soil maps with respect to their crop-specific suitability. Nevertheless, they don't know how to translate their expert knowledge in an evaluation procedure that can be integrated within a geographical information system. Both classification systems, adapted to the specific conditions in Rwanda, performed well when comparing with the actual land use.

5.2. Agricultural potential of the arable land in Rwanda

Without going into detail with respect to the land suitability for each of the 12 crops, it can be concluded that the land suitability classification resulted in identifying clear options for regionalisation (Map 5.1).

The main determinants for crop selection at scale 1:250,000 are the temperature and rainfall regimes. Erratic rainfall in East Rwanda limits the production potential of crops sensitive to water stress. In mountainous western Rwanda, abundant rainfall leached most soils developing on nutrient-poor parent materials. Nevertheless, important investments in terracing and fertilisation, required in the highlands, result in a serious increase of the agricultural production potential. In the lowlands, inherent physical or chemical properties often limit the potential suitability. Application of the land suitability classification at scale 1:50,000 however, will give more detailed results with respect to the regionalisation of crops, making a clear distinction between the land units of the hilltops, hillsides and valleys.



	agricultural zone											
crop	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*
banana	+[a]	+	+	+		+	+	+	+	+	+	
cassava	++	+	+	+				+	+	++	+	+
sweet potato	+	+	+	+		+	++	+	+	+	+	+
potato				++	+	+						
groundnut	+	+	+					+	+	+	+	+
soybean	+	+	++				+	+	+	+	+	+
common bean	+	+	+	+		+	+	+	+	+	+	+
pea		+		+	++	+						
sorghum		+	+	+		+	+	+	+	+	+	+
maize	+	+	+	+	+	+	+	+	+	+	+	+
coffee		+	++				+	+	++		+	
tea		++	+		++							

[a] + = reported by Delepierre (1974) but of no importance after crop regionalisation
+ = reported by Delepierre (1974) and regionally important after crop regionalisation
++ = reported by Delepierre (1974) and nationally important after crop regionalisation
+ = not reported by Delepierre (1974) but regionally important after crop regionalisation

Map 5.1: Selection of the most suitable crops in the agricultural zones in Rwanda

REFERENCES

Baudoin, J.-P., Vanderborght, T., Kimani, P.M. and Mwang'ombe, A.W. (2001). Common bean. In: Raemaeckers, R. (ed.) (2001). Crop Production in Tropical Africa. DGIC, Ministry of Foreign Affairs, External Trade and International Co-operation, Brussels.

Birasa, E.C., Bizimana, I., Bouckaert, W., Deflandre, A., Chapelle, J., Gallez, A., Maesschalck, G. and Vercruysse, J. (1990). Rwanda. Les sols du Rwanda: méthodologie, légende et classification. Carte Pédologique du Rwanda. CTB et MINAGRI, Kigali.

Birasa, E.C., Bizimana, I., Bouckaert, W., Gallez, A., Maesschalck, G. and Vercruysse, J. (1992). Carte d' aptitude des sols du Rwanda. Carte Pédologique du Rwanda. CTB et MINAGRI, Kigali.

Clay, D.C. (1996). Fighting an Uphill Battle: Population Pressure and Declining Land Productivity in Rwanda. MSU International Development Working Paper 58. Michigan State University, East Lansing.

Delepierre, G. (1974). Les Regions Agricoles du Rwanda. Note technique 13. ISAR, Butare.

FAO (1976). A framework for land evaluation. Soils Bulletin 32. FAO, Rome.

FAO (2000). ProSoil – Problem Soils Database. FAO, Rome.
<http://www.fao.org/ag/agl/agll/prosoil/default.htm>

Goemaere, S. (2000). Assessment and rehabilitation of the chemical fertility status of the soils in Rwanda using computer techniques. Thesis. International Training Centre for Postgraduate Soil Scientists, Ghent.

Imerzoukene, S. and Van Ranst, E. (2001). Une banque de données pédologiques et son S.I.G. pour une nouvelle politique agricole au Rwanda. Bull. Séanc. Acad. r. Sci. Outre-Mer 47 (3): 299-329.

Janssens, M. (2001). Sweet potato. In: Raemaeckers, R. (ed.) (2001). Crop Production in Tropical Africa. DGIC, Ministry of Foreign Affairs, External Trade and International Co-operation, Brussels.

Klingebiel, A. and Montgomery, P. (1966). Land Capability Classification. Agriculture Handbook 210. SCS-USDA, Washington D.C.

MINAGRI (1985). Résultats de l'enquête nationale agricole 1984. Vol I – Rapport 1. Service des Statistiques Agricoles, Kigali.

MINAGRI (2003). 2003. Agenda Agricole. Ajenda Y'Ubuhinzi. MINAGRI-UE, Kigali.

Murty, D.S. and Renard, C. (2001). Sorghum. In: Raemaeckers, R. (ed.) (2001). Crop Production in Tropical Africa. DGIC, Ministry of Foreign Affairs, External Trade and International Co-operation, Brussels.

Papadakis, J. (1970). Climates of the world. Their Classification, similitudes, differences and geographic distribution. Buenos Aires.

Ravelingien, B. (2001). Spatial and Temporal Variability of the Climate in Rwanda and the Consequences for Crop production. Thesis. International Training Centre for Postgraduate Soil Scientists, Ghent.

Ristanovic, D. (2001). Maize. In: Raemaeckers, R. (ed.) (2001). Crop Production in Tropical Africa. DGIC, Ministry of Foreign Affairs, External Trade and International Co-operation, Brussels.

Rolot, J.-L. (2001). Potato. In: Raemaeckers, R. (ed.) (2001). Crop Production in Tropical Africa. DGIC, Ministry of Foreign Affairs, External Trade and International Co-operation, Brussels.

Soil Survey Staff (1975). Soil Taxonomy. Agricultural Handbook 436. SCS-USDA, Washington DC.

Sys, C., Van Ranst, E. and Debaveye, J. (1991). Land Evaluation. Part II: Methods in land evaluation. Agricultural Publications 7. General Administration for Development Cooperation, Brussels.

Sys, C., Van Ranst, E., Debaveye, J. and Beernaert, F. (1993). Land Evaluation. Part III: Crop requirements. Agricultural Publications 7. General Administration for Development Cooperation, Brussels.

Van Ranst, E. and Imerzoukene, S. (2001). Carte du Relief du Rwanda. Planchettes 1 – 43. Université de Gand, Département de Geologie et Science du Sol, Laboratoire de la Science du Sol, Gand.

Van Ranst, E., Imerzoukene, S. and Verdoodt, A. (2002). The Digital Land Resources Inventory of Rwanda and its Applications. Transactions of the 17th World Congress of Soil Science "Soil Science: Confronting New Realities in the 21st Century, 14-21 August, 2002, Thailand.