# Evaluation of agricultural land resources in Benin by regionalisation of the marginality index using satellite data

**Dissertation**

zur

Erlangung des Doktorgrades (Dr. rer. nat.)

der

Mathematisch-Naturwissenschaftlichen Fakultät

der

Rheinischen Friedrich-Wilhelms-Universität Bonn

vorgelegt von

Julia Röhrig

aus

Waiblingen

Bonn, April 2008

Angefertigt mit der Genehmigung der Mathematisch-Naturwissenschaftlichen
Fakultät der Rheinischen Friedrich-Wilhelms-Universität Bonn.

1. Referent: Prof. Dr. G. Menz
2. Referent: Prof. Dr. M. Janssens

Tag der Promotion: 15.07.2008

Erscheinungsjahr: 2008

# Contents

# List of figures

# List of tables

# List of abbreviations

ABE: Agence Béninoise pour l'Environnement

AGEDREN: Association pour la GEstion Durable des REssources Naturelles du Benin

ASPRS: American Society of Photogrammetry and Remote Sensing

CARDER: Centre d`Action Régionale pour le Développent Rurale (recent name: CePRA)

CCD: Convention to Combat Desertification

CENAP: Centre National d’Agro-Pédologie

CENATEL: Centre National de Télédétection et de Surveillance du Couvert Forestier

CeRPA: Centre régional de promotion agricole (former: CARDER)

CPCS: Commission de Pédologie et de Cartographie des Sols

DED: German Development Service

GIMMS: Global Inventory Monitoring and Modelling Study

GTZ: German Technical Cooperation

EVI: Enhanced Vegetation Index

FAO: Food and Agriculture Organization of the United Nations

IFPRI: International Food Policy Research Institute

IGN: Institut Géographique National

IIASA: International Institute for Applied Systems Analysis

IPCC: Intergovernmental Panel on Climate Change

INRAB: Institut National des Recherches Agricoles du Bénin

MAEP: Ministère de l'Agriculture de l'Elevage et de la Pêche (former: MDR)

MEPN: Ministre de l'Environnement et de la Protection de la Nature (now: MEHU)

MODIS: Moderate Resolution Imaging Spectroradiometer

MDR: Ministère du Développement Rural (now: MAEP)

NDVI: Normalized Difference Vegetation Index

ORSTOM: Office de la Recherche Scientifique et Technique Outre-Mer

PAL: Pathfinder AVHRR Land

PRoCGRN: Programme de Conservation et de Gestion des Ressources Naturelles

QAG: Querschnittsgruppe Steuerung und Transformation im Förderschwerpunkt Sozial-ökologische Forschung des Bundesministeriums für Bildung und Forschung (BMBF)

SAVI: Soil Adjusted Vegetation Index

SONAPRA: Société Nationale pour la Promotion Agricole
SRES: Special Report on Emission Scenarios
SRTM: Shuttle Radar Topography Mission
UAC: University Abomey- Calavi
UNFPA: United Nations Fund for Population Activities

# Acknowledgements

Many people contributed to this study in different ways. My sincere thanks go to all of them, also those not mentioned explicitly.

I am grateful for the support I have received from Prof. Dr. Gunter Menz, who supervised the research leading to this PhD thesis. I want to thank him for fruitful discussions and prosperous ideas. Particular thanks also to Prof. Dr. Marc Janssens for accepting the second referee and his valuable support and most interesting discussions.

Particular thanks to Dr. Martin Cassel-Gintz for constructive discussions, and valuable comments on the manuscript. In addition, special thanks to Dr. Attanda Mouinou Igué for good cooperation, and helpful discussions about land evaluation in Benin.

Thanks to all members of the remote sensing working group, for a good working environment. In particular, I want to thank Doris Klein for most constructive discussion, technical advices and continuous motivation. I would also like to thank Dr. Kerstin Voß for interesting discussions on diverse aspects, valuable comments on the manuscript, and support in various ways. Furthermore, thanks to Tomasz Dobrzeniecki, Konstanze Kleinod, and Torsten Welle for their support.

Furthermore, I want to thank my colleagues Zhinxin Deng, Malte Diederich, Dr. Thomas Gaiser, Dr. Simone Giertz, Dr. Ina Gruber, Moritz Heldmann, Claudia Hiepe, Dr. Valens Mulindabigwi, Dr. Bettina Orthmann, Gero Steup, Alexandra Uesbeck, and many others, for constructive discussions, providing data, valuable comments on the manuscript, and common fieldworks in Benin. My warm thanks go additionally to colleagues and friends in Benin for supporting my fieldworks and stays in Benin, particularly Dr. Vincent Orekan, Andreas Preu, Dr. Elisabeth van den Akker, and Gabi Zink. In addition, I would like to thank Loukman Demba Diallo, Norbert Agoinon and Jean Bosco Vodounou for common fieldwork and lively discussions.

I want to thank the investigators of the study of Dr. Dave Frank, Christine Hermes, and Stefanie Tholen for prompt lecture and helpful comments.

Warm thanks to my parents, my sister Christine Koril with family, and my friends for continuous motivation and support. Finally, I would like to thank my husband Jörg for patience, motivation, and support, particular during the final stage.

This study was carried out in the framework of IMPETUS-project, funded by the German Federal Ministry of Education and Research (BMBF), grant ID 01 LW 0301A, and by the Ministry for Science and Research of North Rhine-Westphalia, project ID 223-21200200.

# Abstract

In the present work, the marginality index for agricultural land use was utilized to evaluate current and future biophysical resources for agricultural land use of Benin (West Africa) at a 1 km spatial resolution. The marginality index is an innovative capability evaluation approach that incorporates the main environmental factors, which limit agricultural production under low capital input. Furthermore, this index enables the detection of marginal sites, that is, sites prone to land degradation. In using this index, the feasibility of a global approach on a national scale was examined. Therefore, the same constraints, derived from input data at a higher spatial resolution, and adapted fuzzy logic based algorithms were used to determine the index for Benin. For the regionalisation, remote sensing data such as MODIS or SRTM were successfully applied to determine biophysical constraints. The outcome indicates that natural conditions are generally moderate suitable for agricultural land use in Benin, whereby most favoured regions are located in the south and centre of the country. Marginal sites can be found all over the country but in particular in northern regions. Currently, poor soils, limited length of growing period, and high rainfall variability are the crucial biophysical constraints on the national scale. Scenario analyses based on IPCC SRES scenarios A1B and B1 suggest that climate change will aggravate the natural suitability across Benin by 2025. Particularly temperature and the length of growing season will most likely impede future agricultural land use.

In the context of this thesis, direct and indirect validation methods were conducted by applying GIS analyses and statistical tests. The direct methods are based on empirical knowledge and ground truth data recorded during field campaigns. For the indirect methods auxiliary data, namely disaggregated data of population density and trends of land degradation derived from NDVI data, were used. Both the direct and the indirect validation approach indicate the accuracy of the regionalisation outcome. Thus, the constraints considered herein on a global scale describing and defining marginal sites are, in an initial examination useful indicators on a national scale.

Finally, based on biophysical constraints, population density, and trends of land degradation fields of investigations and corresponding location for national decision makers aiming a sustainable use of land resources were defined.

# Zusammenfassung

In der vorliegenden Arbeit werden naturräumliche Ressourcen für eine landwirtschaftliche Nutzung in Benin (Westafrika) bewertet. Für die Bewertung wurde der Marginalitätsindex gewählt. Der Index ermöglicht die Identifizierung naturräumlich bedingter marginaler agrarischer Standorte sowie die Quantifizierung spezifischer Beschränkungsfaktoren. Damit stellt der Marginalitätsindex vor allem in Gebieten, wo traditionelle, wenig kapitalintensive, Anbaumethoden, weit verbreitet sind, ein interessante und innovative Möglichkeit dar, Landressourcen zu bewerten. Mit der Wahl des Marginalitätsindexes ist eine wesentliche Forschungsfrage dieser Arbeit verbunden: Kann der Ansatz, der auf globaler Ebene entwickelt wurde, auf die nationale Ebene übertragen werden? Um dieser Frage nachzugehen, wurde der Index aus räumlich höher aufgelösten Inputdaten und einem modifizierten Berechnungsalgorithmus für Benin in einer Auflösung von 1km x 1km berechnet. Fernerkundungsdaten, wie MODIS und SRTM-Datenprodukte, bieten dabei gute Möglichkeiten, aktuelle naturräumliche Beschränkungsfaktoren zu bestimmen. Das Ergebnis der Regionalisierung (MI) ermittelt für Benin durchschnittlich eine moderate naturräumliche Eignung für eine agrarische Nutzung. Gunstgebiete befinden sich überwiegend im Süden und Zentrum Benins. Marginale Flächen kommen dagegen landesweit vor, großflächig vor allem im Norden. Gegenwärtig bestimmt vor allem eine geringe Bodenfruchtbarkeit, zu kurze Vegetationsperioden und eine hohe Niederschlagsvariabilität die naturräumliche Gesamtmarginalität. Szenarienanalysen dieser Arbeit, basierend auf den IPCC SRES Klimaszenarien A1B und B1, deuten darauf hin, dass sich bis zum Jahr 2025 die naturräumlichen Produktionsgrundlagen deutlich verschlechtern werden. Insbesondere Temperaturanstieg und Verkürzungen der Anbauperiode bei gleichzeitig höherer Variabilität von Begin und Ende der Regenzeit werden landwirtschaftliche Aktivitäten erschweren.

Zur Überprüfung der Ergebnisse von MI wurden direkte als auch indirekte Validierungsmethoden angewandt, die auf GIS-Analysen und statistischen Tests basieren. Die direkte Validierung bestand aus einem Vergleich mit eigenen Geländeaufnahmen sowie Überprüfung von Literaturangaben. Für die indirekte Validierung wurden zwei weitere Datensätze aufbereitet, die der Bevölkerungsdichte und Trends der gegenwärtigen Landdegradation. Ersteres wurde aus Zensusdaten disaggregiert und letzte-

res aus einer Zeitreihenanalyse unter Verwendung von NDVI-Daten abgeleitet. Sowohl die direkte als auch die indirekte Validierung bestätigen das Ergebnis der Regionalisierung. Die gewählten globalen naturräumlichen Beschränkungsfaktoren entsprechen damit den wesentlichen Faktoren auf der nationalen Ebene.

Eine nachhaltige Nutzung agrarischer Produktionsstandorte ist für die Gewährleistung der Ernährungssicherheit in stark landwirtschaftlich geprägten Ländern wie Benin von entscheidender Bedeutung. Aus diesem Grunde wurden auf der Basis der im Rahmen dieser Arbeit erzeugten Datensätze (MI, Bevölkerungsdichte und Trends der Landdegradation) zusätzlich Hauptinvestitionsfelder für eine nachhaltige Landnutzung ausgewiesen und eine entsprechende Karte erstellt.

# Résumé

Dans le présent travail, l’indice de marginalité agricole des sols a été employé, avec une résolution de 1 km, pour évaluer les ressources biophysiques actuelles et futures dans le but d’une exploitation agricole des terres au Bénin (Afrique de l’Ouest). L'indice de marginalité agricole des sols est une approche intéressante et innovatrice d'évaluation des potentialités des sols. Son calcul fait intervenir les principaux facteurs environnementaux limitant la production agricole en cas de faibles apports en inputs agricoles. En outre, il permet l’identification et la localisation des sites marginaux, c’est-á-dire des sites susceptibles à la dégradation. En employant cet indice, la praticabilité d'une approche globale sur une échelle nationale a été examinée. Par conséquent, certains facteurs, dérivés des données de base d’une résolution spatiale plus élevée et les algorithmes de la logique floue adaptés ont été employés pour déterminer cet indice pour le Bénin. Pour la régionalisation, les données dérivées de la télédétection, notamment de MODIS ou SRTM, sont intéressantes et facilitent la détermination des contraintes biophysiques. Les résultats indiquent que les conditions naturelles pour la production agricole au Bénin sont généralement modérées, mais plus favorables au sud et au centre du pays. Les sites marginaux sont localisés dans tout le pays mais les grandes étendues marginales se trouvent au nord. Sur l’échelle nationale, les sols pauvres, la durée de la période de croissance végétative et la variabilité des précipitations constituent actuellement les contraintes biophysiques cruciales. Les analyses des scénarios A1B et B1 d'IPCC SRES montrent que d’ici 2025 le changement climatique détériora les aptitudes naturelles dans toutes les régions du Bénin. En particulier, la température et la durée de la saison de croissance des plantes entraveront l’exploitation agricole. Dans le contexte de cette thèse, des méthodes directes et indirectes de validation ont été effectuées en appliquant des analyses de SIG et des tests statistiques. Les méthodes directes sont basées sur la connaissance empirique et sur les données collectées sur terrain. Pour les méthodes indirectes, des données ont été auxiliairement employées, à savoir la densité démographique et les tendances de la dégradation des terres dérivées des données de NDVI. L’approche de validation directe et indirecte indique l'exactitude des résultats de régionalisation. Ainsi, les six contraintes décrivant et définissant les sites marginaux à l’échelle globale sont également applicables à l’échelle nationale. En conclusion, basé sur des

contraintes biophysiques, la densité de la population et les tendances de la dégradation des terres, l’étude a permis de mettre en place un outil indispensable pour les décideurs nationaux visant une utilisation durable des terres ont été définies.

# 1 Introduction

## 1.1 Problem

In many parts of the world, land resources suitable for cultivation are becoming scarce. Main reasons are increasing space requirements due to growing population numbers and expanding land consumption. Climate change will additionally affect agro-ecological conditions and thus, directly influence food production (see for instance IPCC 2007). Indirectly, climate change will affect economies and population distribution. Consequently, the future demand for agricultural products will change.

Worldwide, it can be observed that the increasing scarcity of agricultural land resources leads to corresponding pressure on existing land resources causing conflicts and further environmental degradation. The degradation of the natural resources itself damages the biophysical production basis, decreases yield, and leads to further impoverishment stimulating by expansion on marginal areas (LÜDEKE et al. 1999, PETSCHEL-HELD et al. 1999). Naturally based marginal sites, however, are characterised by various environmental constraints, which limit agricultural productivity. Furthermore, marginal sites are particularly prone to land degradation, which means that under cultivation yields decline rapidly (CASSEL-GINTZ et al. 1997, LÜDEKE et al. 1999). Consequently, they can make only a limited contribution to improving food security, unless adequate measures to compensate natural constraints are applied. Case studies in developing countries analysing peasant agro-ecosystems indicate that many people there are caught in this typical socio-ecological trap (e.g. BILLINGS et al. 1989, LEONARD 1989, REENBERG & PAARUP-LAURSEN 1997, YOUNG 1998, BLUM & ESWARAN 2004). Thus, a main future challenge will be to guarantee food security without degrading land and water resources under expecting transformations of man-nature agrarian systems (ESWARAN et al. 1999). This study aims to support sustainable land use in Benin by evaluating the agricultural land resources.

## 1.2 Objective

In Benin, agriculture has a great economic and social meaning. Cultivation is still based mainly on traditional farming systems (e.g. shifting cultivation), in which subsistence with low capital inputs, like traditional tools and little use of fertilizers or irrigation, is predominant (BOHLINGER 1998, IGUÉ et al. 2004, MULINDABIGWI 2006). Thus, yields depend strongly on the biophysical conditions.

For the country, future projections suggest that more people will have to be fed under worsening natural conditions. Adapted IPCC (Intergovernmental Panel on Climate Change) SRES climate change scenarios for 2025 indicate rising temperatures and declining rainfall as well as altering patterns of the growing season (IPCC 2007, PAETH & THAMM 2007). Furthermore, national studies (e.g. CENATEL 2002, MEHU 2003) foresee further spatial extension and intensification of soil degradation. This outlook is especially alarming as beginning scarcity of land and water resources have already resulted in land degradation and ethnic conflicts (BOHLINGER 1998, AKAPI 2002, DOEVENSPECK 2004, MULINDABIGWI 2006). According to several authors, neither a large-scale return to extensive forms of land use with long periods of fallow nor permanent cultivation under high capital input seems a realistic or sustainable opportunity to realise future needs for food (BOHLINGER 1998, JUNGE 2004, MULINDABIGWI 2006). This estimation stresses the importance of an efficient and sustainable use of available potentials.

From the agrarian geographical perspective, an essential first step therefore is to obtain a better spatial knowledge of the national man-nature agrarian system including quality of land resources and population-supporting capacity, and dynamics of the system (MANSHARD 1997, SHEN 2004, QAG 2004). By setting up a land evaluation scheme for Benin, this study focuses on the first issue, quality of land resources. Land evaluation supports rational land-use planning and sustainable use of natural and human resources (LANDON 1994, ROSSITER 1996, ESWARAN et al. 1999, DORRONSORO 2002). In the thesis at hand, predominantly biophysical features are analysed within the evaluation scheme.

The focus on natural resources is motivated by the following two aspects. First, the inventory of natural resources and an improved resource management is still a main topic for agro-geographical studies in developing countries MANSHARD (1983, 1997). In poor countries, like Benin, the biophysical environment is still determining potentials and limitations of recent agricultural land use. Second, as the study area increases, the physical factors become more evident in agricultural land-use patterns than personal and management ones (ILBERY 1985). On a large scale, spatial agricultural variations can be explained by broad environmental differences. At the micro scale, in contrast, differences are likely to be caused by farm management and decision behaviour. Therefore, it seems acceptable to focus on predominately natural resources if analysing agricultural land resources of Benin, as it the aim of this study. The key objectives of the thesis at hand will be now considered in more detail.

### 1. Setting up a national land evaluation scheme based on biophysical conditions for Benin

An essential aim of this thesis is to set up a land evaluation scheme for agricultural land use based on the biophysical conditions of Benin. For Benin, several land evaluation schemes and corresponding suitability maps already exist. These maps contain suitability estimations for the main crops. Thus, a capability approach was chosen for this study, which is a novelty for the country. Capability approaches focus more on the general suitability for agricultural land use and on environmental sustainability of agricultural production systems. Therefore, the marginality index of agricultural land use was chosen to evaluate the biophysical resources. The marginality index is adequate as it incorporates main environmental factors, which limit agricultural production under low capital input. Furthermore, it enables the detection of marginal and thus, vulnerable sites, within the agrarian system. Another major objective of this study is to derive main biophysical constraints and their spatial distribution. Knowledge about key limitations is important for the planning of amelioration or compensating measures.

### 2. Analysing the feasibility of a global evaluation approach on a national scale

CASSEL-GINTZ et al. (1997) introduced the marginality index on a global scale. In other words, the feasibility of a global approach on a national scale is examined in this study. For Western Africa, the assessment of the index leads to very encouraging results in a spatial resolution of 0.05° (RÖHRIG 2002, RÖHRIG & MENZ 2005). For Benin, the index is determined in a spatial resolution of 1 km x 1 km (MI). Until now, aside from the author’s investigations in Western Africa, in no other region has the marginality index been used to evaluate biophysical resources. Thus, the regionalisation as well as the validation approach is challenging and unique.

### 3. Analysing the potential in order to incorporate satellite data in the evaluation scheme

For agrarian studies remote sensing has been broadly applied to obtain information about yields or the performance of crops on different spatial scales (e.g. FERENCZ et al. 2004, VOß 2005, SALAZAR et al. 2007). Land evaluation approaches, however, are still dominated by the terminology and methods of soil science (see chap. 3.2.1). Remote sensing data are used mainly to acquire information about land cover and land use (e.g. GRAEF 1999, WELLER 2002). Recent studies have demonstrated, however, the potential of newer sensors, like MODIS, and methods, respectively to derive relevant biophysical features (e.g. RICHTERS 2005). Thus, one main task of this research was to investigate the potential use of input data derived from remote sensing.

### 4. Determine future biophysical conditions under climate change

Scenario analyses are carried out assessing future biophysical conditions under climate change up to the year 2025. In doing so, two IPCC climate scenarios are incorporated within the determination algorithm of MI (A1B and B1). The knowledge about future alterations of biophysical constraints and especially about vulnerable sites are essential for the development of national adaptation and precautionary strategies in time.

### 5. Investigating the spatial patterns of risk and occurrence of human induced land degradation

The marginality index identifies regions, which are particularly prone to land degradation, if agriculturally used. In other words, the index contains information about the potential risk of land degradation. To derive the degree of actual risk of land degradation, the index must be overlaid with information about agricultural land use. On such marginal sites under cultivation, the set up of precautionary and conservation measures are necessary to maintain natural resources for food production. Due to the high degree of subsistence in Benin, spatial pattern of agricultural land use is closely linked with those of settlements. Hence, population density was used to derive information about areas, which are under cultivation. Therefore, necessary demographic data are disaggregated from census data using GIS-functionalities. Furthermore, recent trends of land degradation are derived from remote sensing data. This information is used to identify regions where agricultural activities are about to cause environmental degradation. These spatially explicit quantitative analyses about natural constraints, population density and land degradation are a new and interesting extension of the global approach.

## *1.3 Project framework of the study: the IMPETUS project*

This study is embedded in the IMPETUS-project. IMPETUS (Integrated approach to the efficient management of scarce water resources in West Africa) is part of GLOWA (Global Change and the Hydrological Cycle), a research programme of the German Federal Ministry of Education and Research (BMBF). GLOWA aims to analyse the impact of global change on the water cycle in catchments in different climate zones. The focus of IMPETUS is on two catchments in West Africa: the Wadi Drâa in South-East of Morocco and the Ouémé River in Benin. Especially in West Africa, fresh water availability could become problematic, as long periods of drought have been observed since the 1970s. IMPETUS aims to recommend concrete ways of translating scientific results about the hydrological cycle into action through scientifically based strategies (SPETH et al. 2005). Therefore, a cooperative, interdisciplinary and integrative approach is followed including three project phases with different main focuses:

- 1st project phase (2000-2003): Data acquisition and modelling
- 2nd project phase (2003-2006): Development of scenarios and problem clusters
- 3rd project phase (2006-2009): Transfer and application: Capacity building and Spatial Decision Support Systems (SDSS)

In this context, the present thesis is embedded in the problem cluster '*Conservation of the natural resources for the agricultural production in Benin under global change*' (PK Be-E.6). The problem cluster is located within the subject area of *Food Security*.

A problem cluster analyses meta-problems, which require a multi-disciplinary analysis in order to allow conclusions to be drawn with respect to possible future developments. Fields of investigations of PK Be-E.6 are, for instance, to determine current and future key biophysical constraints to derive compensation as well as precautionary strategies for national land use planning. In the context of this problem cluster, *AGROLAND*, a spatial decision support system (SDSS) has been developed (see LAUDIEN et al. 2007). In IMPETUS, a SDSS is defined as a computer based system that allows the user to solve semi-structural processes by using comprehensive datasets with a spatial context and analytical models. With the computer-based SDSS, the user is able to visualise and analyse (geo-)data and models.

## *1.4 Structural composition of this study*

**Chapter 2** follows this introduction by Benin, the study area of this research. Therein, the following aspects are focused: features of the physical geography, demographical aspects, characteristics of the predominant agricultural systems and land degradation forms and distribution. At the end, a short outlook of expected future developments is given. In **Chapter 3**, the theoretical setting of this study is examined. The chapter contains three main parts. The first part considers the objective of this thesis from the disciplinary side, agricultural geography. In presenting contents and a historical overview of the discipline, it will be demonstrated that the thesis at hand is an example of recent scientific research of agricultural geography in developing countries. The second part comprises an introduction into the terminology and concepts of land evaluation. Furthermore, existing schemes realised for Benin are considered. Finally, the third subsection comprehends the scientific framework, the *Syndromes of Global Change* and the original assessment of the marginality index.

In **Chapter 4**, the methodological set-up of the regionalisation approach is examined. First, theoretical aspects of the data choice are described. Then, the fundamentals to set up an adapted determination algorithm are illustrated. In this context, the author’s conducted field campaigns are examined. The last part of this chapter contains some theoretical considerations about validation of national data products and explains the validation methods used in this study. Afterwards in **Chapter 5**, used data and their pre-processing are examined. First, all biophysical data used for the assessment of current and future MI are illustrated. Second, data and methods used to determine population density and land degradation are considered. **Chapter 6** contains the evaluation of the biophysical resources and the determinations of MI. In doing so, necessary modifications of the global approach are presented. Additionally, the future changes of the biophysical constraints are addressed. In **Chapter 7** the question as to whether the approach is suitable to evaluate biophysical land resources of agricultural land use in Benin is answered. Therefore, marginal sites and the major biophysical constraints calculated with the MI are considered in more detail. Furthermore, outcomes of the validation are presented. Finally, **Chapter 8** summarises the main findings of this study and gives an outlook for future fields of research.

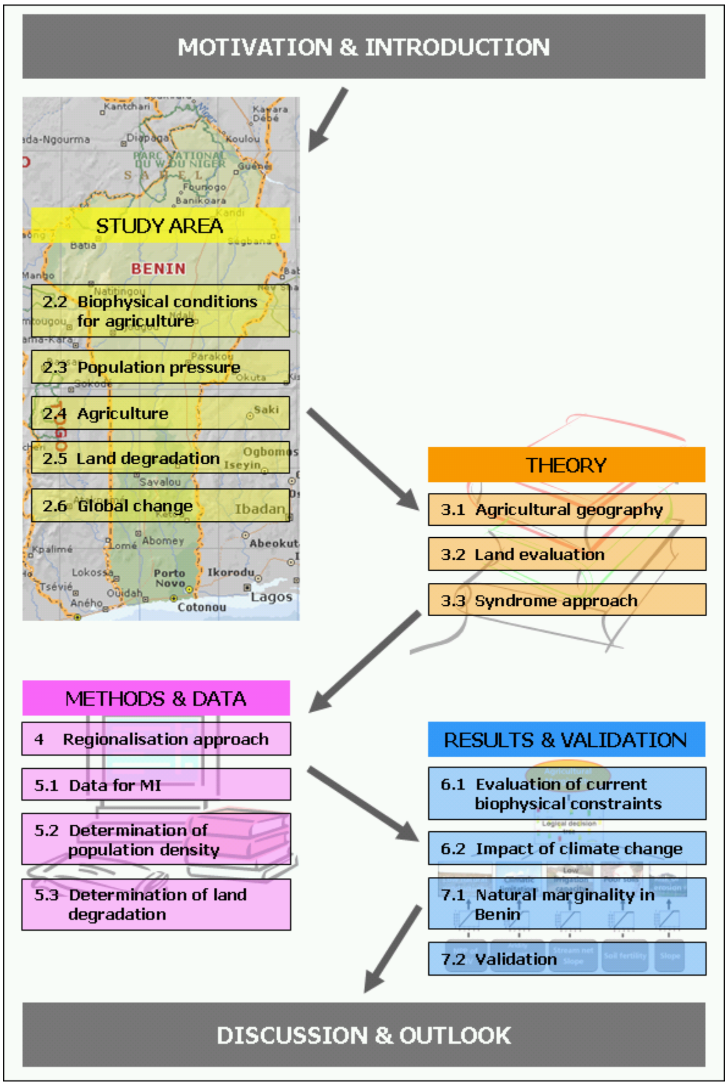


**Fig. 1: Structural composition of this study**

# 2 Framework for agricultural land use in Benin

This chapter will introduce Benin, the study area of this research. In the context of this study, factors affecting recent and future agricultural land use are important. In the first two subchapters, the natural conditions for agricultural land use in Benin are illustrated determining naturally based potentials and constraints. Population pressure that mainly drives the intenseness of agricultural activities and thus, the risk of agricultural overuse and land degradation, is presented in 2.3. In subchapter 2.4, agricultural land use in Benin itself is considered focusing on recent changes in the farming and social system. Due to their importance for this work, the consequences of agricultural activities for the environment in form of land degradation are presented in an extra subchapter (2.5). Finally, a brief outlook on future challenges is given.

## *2.1 Location*

The country of Benin is located in Western Africa at the Guinea Coast (see Fig. 2). It has frontiers with Togo in the east, Burkina Faso and Niger in the north and Nigeria in the west. Benin covers about 112,622 km², whereby the distance between north and south extends 650 km (6°-12°30N) and about maximal 120 km from east to west (0°30-4°E), respectively.

## *2.2 Biophysical conditions for agricultural land use*

### 2.2.1 Topography and hydrography

Generally, the topography of Benin is flat with heights ranging from some meters height above sea level to 650 m within the north-western Atacora region. Topography can be subdivided into five regions (cf. MAMA et al. 1998).

Starting in the south, first, a plain coastal zone and secondly, two series of sandy plateaus follow in northern direction with sediments of the Tertiary and Cretaceous periods.

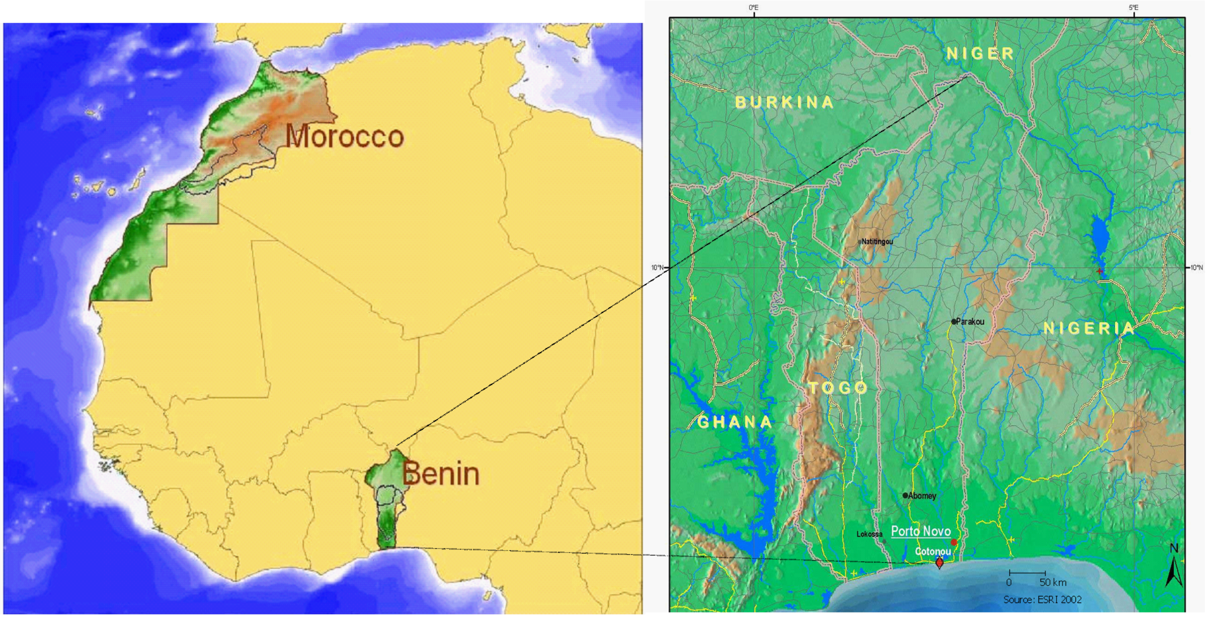


**Fig. 2: Location and topography of Benin**

The plateaus are divided by the WE oriented 'Lama Depression' into a southern and a northern series. In addition, the series are crossed by three rivers (Mono, Couffo and Ouémé) which flow towards the ocean (Faure & Volkhoff 1998, Weller 2002). Further north third, on the Precambrian crystalline basement, known as 'basement complex' (Igué 2000, Weller 2002) or 'Dahomeyan basement' (Faure & Volkhoff 1998) a wide area of peneplains with scattered inselbergs and more or less hilly sites has been developed. The basement covers 82% of the surface of Benin. In this region several different plateaus are differentiated (see Berding & Van Diepen 1982, Faure & Volkhoff 1998). Within the basement, a quartzitic long crest, the Kandi-Bembéréké alignment, is oriented from NE to SW.

**Fig. 3: Inselberg nearby Ouari Maro in central Benin (Photo: J. Röhrig, 2005)**

Fourth, in the Northwest the mountain range of Atacora occur with heights of more then 650 meters. Towards northern frontiers finally, on the Kandi and the Volta basins sedimentary plains and river plateaus nearby the Niger and the Volta River are characteristic.

Slopes are generally low. Steep slopes occur within the Atacora mountain range, at fringes of inselbergs, and in the south, at the borders between the sedimentary plateaus and the crystalline basement. Nevertheless, even slight slopes are prone to erosion due to intense and erosive rainfall (GRAEF 1999, CENATEL 2002).

Three main drainage orientations are observed on the basement complex: rivers which flow southwards to the Atlantic, which discharge into the Niger in the North or into the Pendjari in the Northwest. Only within the large rivers of Niger, Mono and the southern parts of Ouémé until Zangnanondo (GIERTZ 2007, personal communication) water discharges the whole year. All other rivers run periodically dry during the dry season. The sedimentary basins are erosion-plain and on its materials, the river network is widely spaced, but well-marked (BERDING & VAN DIEPEN 1982).

For agricultural land use, lowlands, sinks and valley are preferred locations (own observations). On the latter sites, water is conserved beyond the end of rainy season and thus, allows longer growing cycles. Furthermore, flooding regions along the river of Niger and Ouémé are used intensively for agricultural production, in particular for rice.

### 2.2.2 Climate

The study area is part of the West African Monsoon region (FINK 2006). Benin is emblematic of an alternating sub-humid climate of the outer tropics ranging from the Guinean Coast to the Sahel (SPETH et al. 2005).

Within the tropics, climate is largely controlled by the annual migration of the Inter-Tropical Convergence Zone (ITCZ). Along the ITCZ, dry dusty winds from the Sahara called 'Harmattan' come in contact with humid equatorial air masses. The dominant wind systems are the south-west monsoon in the south and the dry Harmattan in the north. Thus, climatic conditions in Benin are often subdivided coarsely into two homogeneous zones (e.g. BOHLINGER 1998, IGUÉ 2000, and FINK 2006). Other authors, however, distinguish three zones (see AUBRÉVILLE 1949, MAMA et al. 1998, CENATEL 2002). All classification schemes are thereby based on the rainfall regime. Below, the bio-climatic zones of AUBRÉVILLE (1949) will be described as it is the most detailed and consistent classification scheme. Thereby, information about rainfall and temperature given in Berding & Van Diepen (1982), Mama et al. (1998), Cenatel (2002) and MEHU (2003) are added.

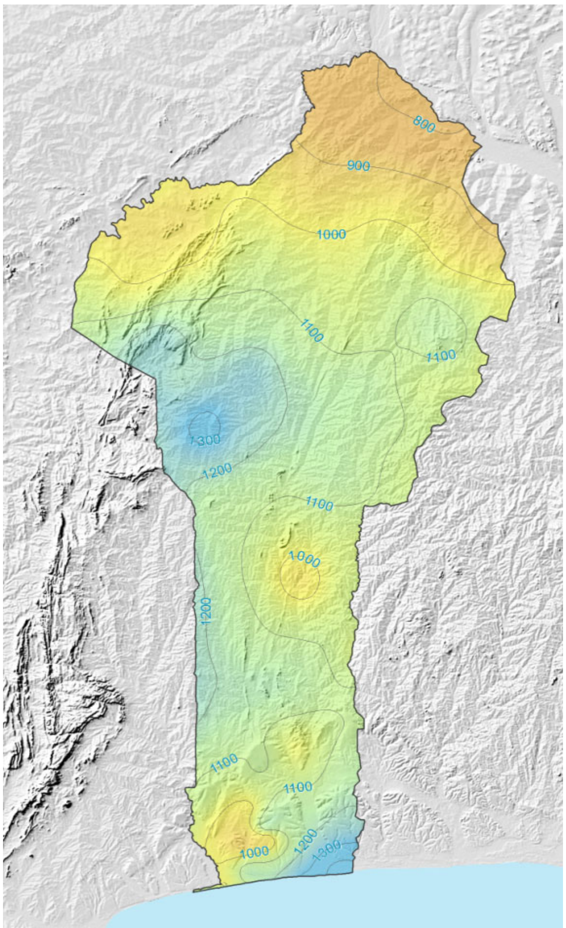


**Fig. 4: Mean annual rainfall in Benin over the period of 1961-1990 (Thamm et al. 2005a: BE-B-01)**

Within the **Guinean Zone**, from the coast up to about 8° north, the climate is tropically wet with usually two rainy seasons, a longer one from May to July and a shorter one from September to November with about 250 rainy days altogether. Yearly rain sums along the coastline show a clear decline from the East with about 1400 mm to the West with average values of about 900 mm. This region belongs to a climatically dry corridor disrupting the West African rain forest into the Upper and Lower Guinean forest blocks: the so-called 'Dahomey Gap' (White 1983, Fink 2006). Vollmert et al. (2003) proved that beside the atmospheric coastal divergence known as Ekman divergence, cooler sea surface temperatures are the reason for this precipitation anomaly. Annual mean temperature is about 27°C with maxima up to 40°C. Mean temperature pattern show low fluctuations over the year and daytime. Then, from 8° up to 11° north, the **Soudanian-Guinean Zone** follows as a transition zone with semi-humid tropical climate and a weak tri- or bi-modal rainfall distribution (Thamm et al. 2005a). Here, the rainy season lasts approximately from April to October. In southern areas, even with a less strongly developed bimodal rainfall distribution two crops per year can be cultivated here (Igué 2000). Annual precipitation is about 1000 mm with declining sums in a northward direction, but with regionally higher sums in the northwest due to the Atacora mountain range (Fig. 4). Mean annual temperature and its variations are comparable to those of the Guinean Zone. During the dry season, however differences of about up to 30°C between daytime and nighttime temperature occur.

North of 11° latitude follows the semi-arid **Sahel-Soudanian** climate with one rainy season lasting from Mai to September counting about 130 rainy days per year. In this zone, rainfall decreases further north down to an average of 850 mm per year, which fall within four months of the rainy season. Mean annual temperature and its fluctuation over the year are slightly higher than within the Soudanian-Guinean Zone. During cool nights, temperature can sink below 15°C. Differences between daytime temperature and night-time temperature increase northwards, particularly during dry seasons.

In tropical regions, the availability of water is the most essential factor for agricultural land use as it determines the agricultural calendar (BERDING & VAN DIEPEN 1982, MDR & INRAB 1995). CENATEL (2002) named the 1000 mm isohyets as frontier line of climatically favoured agricultural areas. Thus, in south-western and the northern regions the occurring rainfall sums are crucial for rainfed agricultural land use. In addition, high rainfall variability limits agricultural activities and cause insecurity for farmers on a large-scale (CENATEL 2002). In recent years, decadal variability of rainfall has been far larger in tropical West Africa than in other regions (FINK et al. 2006). Sea surface temperature (SST) of the oceans has been proven to have thereby a vast influence for all of Western Africa (PAETH & HENSE 2004). In addition, rainfall variations are caused by interactions with land cover and soil humidity (BRÜCHER et al. 2005). Concerning temperature requirements of the common crops, IGUÉ (2000) and WELLER (2002) detected minor constraints due to high temperature for all crops in southern and central Benin. According to the climatic gradient higher constraints can be assumed in northern Benin.

Taken all climate features together, conditions along the 10°N latitude are suitable for the majority of crops (BERDING & VAN DIEPEN 1982). There, the probability of rainfall is rather stable and the duration of rainy season adequate. In the south, the subdivision of precipitation into two rainy seasons is problematic for some cultures (BERDING & VAN DIEPEN 1982).

### 2.2.3 Geology and Soils

In Benin, a great variety of sols and thus, a wide range of physical and chemical conditions for plants exist. Nevertheless, five categories of dominant soils can be distinguished: 'Sols minéraux bruts et peu évolués', 'Vertisols', 'Sols ferralitiques or Terre de barre', 'Sols ferrugineux tropicaux', and 'Sols hydromorphes' (CENATEL 2002, MEHU 2003). This terminology of soils is taken from the French system of 'Classification des Sols' (CdS) (CPCS 1967), which have been used in modified forms within many francophone countries of West Africa (BERDING & VAN DIEPEN 1982, JUNGE 2004). As it is still common in literature about soils in Benin, this terminology has been chosen to examine the soils in this chapter.

The spatial differentiation of soil cover is mainly a product of geology and geomorphic units (FAURE & VOLKHOFF 1998). Geologically, the south refers to the West African Continental Terminal with sedimentary rock (Coastal basin), whereas the northern section (from 7-7°30N northwards) belongs to the Precambrian Shield (ADOMOU 2005). The latter consists of Precambrian crystalline and metamorphic rocks that form the 'basement complex' (IGUÉ 2000, WELLER 2002) and the Volta basin. Granito-gneissic rocks can be found as outcrops (inselbergs) on the basement. The Kandi basin along the northern border contains a Cambrian base-conglomerate, clays and mainly sand-

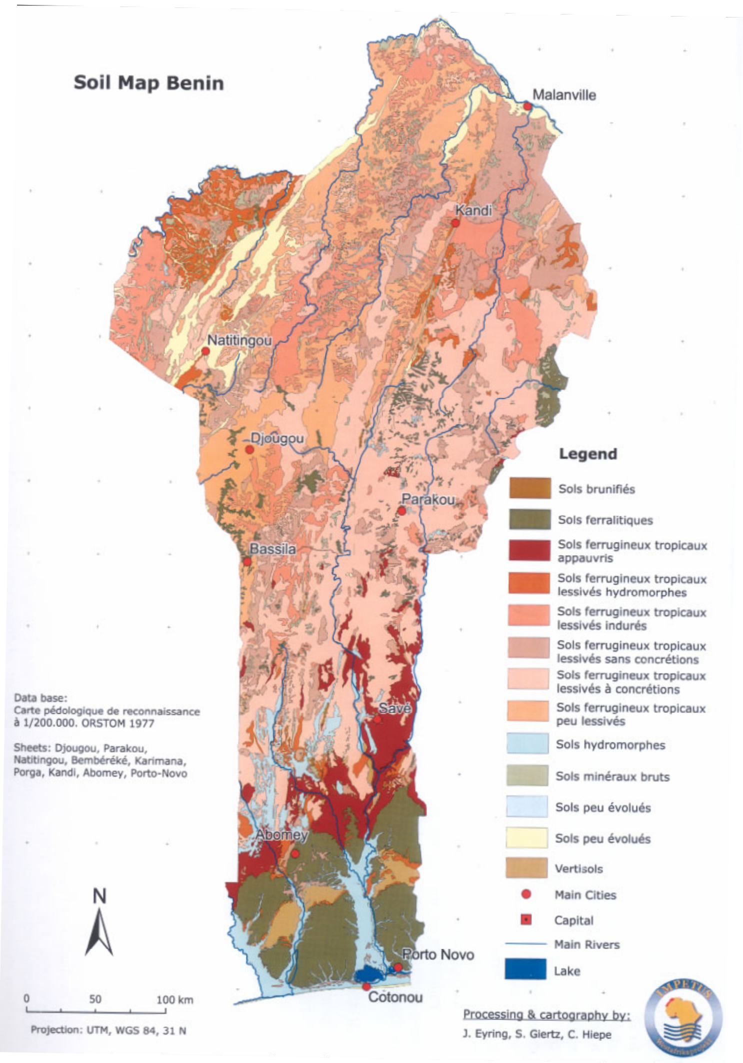


**Fig. 5: Soil map of Benin based on the Carte pédologique de reconnaissance by ORSTOM (THAMM et al. 2005A: BE-C-01)**

stones from different periods (ALIDOU et al. 1991, FAURE & VOLKHOFF 1998).

In the following, the spatial distribution of soil cover and soil characteristics is demonstrated in more detail from south to north based on studies of MDR & INRAB (1995), FAURE & VOLKHOFF (1998), and CENATEL (2002).

Within swamps and lagoons of the coastal sedimentary basin 'Sols minéraux bruts et peu évolués' (here: Sols sableux des cordons littoraux) and 'Sols hydromorphes' have been developed. Further north, on sandy plateaus the commonly named as 'Terre de Barre' or 'Sols ferralitiques' are widespread. Many of these soils are shallow and underlain by ferricretes. In the 'Lama depression', consisting mainly of smectitic-kaolinitic clay- and marlstone, 'Vertisols' are dominant. Where plateaus and depression are crossed by rivers, 'Sols hydromorphes' can be observed.

On the basement, most of the soils have developed on a thick kaolinitic mantle. The upper horizon is clay-poor and either partly or totally gravely. It contains quartz gravel and iron nodules overlying soft or hard ferricretes in the subjacent kaolinitic mantle. There, mainly 'Sols ferrugineux tropicaux' and 'Sols ferrugineux lessivés' have been developed. On some parts ferralitic soils and 'Sols minéraux bruts' are observed. Towards north, there are more concretions and ferricretes.

Towards the river of Niger, on the top of terraces, 'Sols ferrugineux' and on a filled basin with conglomerates, sand and clay stones 'Sols hydromorphes' have been formed. In the north-western Atacora region, 'Sols ferralitiques' and 'Sols minéraux bruts' are widespread. Uiquitary characteristics are a clear textural altering with a coarse textured surface horizon, a clay fraction consisting of kaolonite with differing proportions of smectite and illite, and a neutral soil reaction. Residual iron nodules are observed within a 'stone-line' together with quartz gravel or the top layer. Furthermore, secondary pedogenic ironstone is found in many forms, depths and with various thicknesses.

Beyond favourable climatic conditions, suitable soils are essential for agriculture. Due to the variety of soils, the suitability for agricultural land use is diverse. Considering fertility, most of the soils have rather medium chemical conditions. Thus, the use of nutrients or regularly periods of fallows are advised. Fertilizer use becomes essential when farmland is permanent exploited (BERDING & VAN DIEPEN 1982, BOHLINGER 1998, JUNGE 2004). This pedologic phenomenon and corresponding problems within the tropics is well-known (WEISCHET 1977, BOHLINGER 1998, ESWARAN et al. 2001, JUNGE 2004, MULINDABIGWI 2006). It will be picked up again in the context of agricultural overuse and land degradation in chapter 2.5. The main crucial nutrients are potassium, nitrogen and phosphorus, which depend directly on the proportion of organic matter as the major storage for nutrients (BOHLINGER 1998, IGUÉ et al. 2004).

Soils of rather good chemical fertility are 'Sols hydromorphes', 'Vertisols' or 'Sols ferrugineux tropicaux'. Whereas, 'Sols ferrugineux tropicaux' have also good physical conditions and are therefore suitable for various plants, the other soils have a rather poor physical suitability. Before the 'Sols hydromorphes' and 'Vertisols' can be agriculturally exploited, some efforts are needed. Until now, their potentials are not fully exploited because of missing irrigation systems and drainage, respectively (CENATEL 2002). The agricultural potential of 'Sols minéraux bruts et peu évolués' is very poor caused by shallowness of soils and coarse fragments. Thus, major soil types in Benin show either physical or chemical constraints for agricultural land use (BERDING & VAN DIEPEN 1982). Chemical limitations are thereby easier to compensate (with e.g. fertilizer), than most physical ones.

### 2.2.4 Vegetation

Western Africa is famous for its rain forests and its savannas. Savannah is a collective term for physiognomic similar, however, different developed vegetation forms with the common characteristic of dominant grasses and varying proportions of trees (CSA 1956, BOHLINGER 1998, REIFF 1998). Complex interactions of environmental parameters lead to coexistence of grasses and trees (for more details see ORTHMANN 2005). The most important ecological parameter is a periodical climate regime with distinctive rainy and dry seasons (NEUMANN et al. 2004). On the terrain, savannas are sometimes hardly separable with fluent transitions from forest to savannas which led, amongst other things, to terminological confusion and a variety of definitions (BOHLINGER 1998, NEUMANN et al. 2004, ORTHMANN 2005). Most classifications of vegetation in West Africa are based on the scheme set up during the Yangambi conference (CSA

1956), which has been extended by several authors (see ORTHMANN 2005).

In Benin, the vegetation cover follows predominately precipitation patterns. Thus, similar to the climatic zones, the three vegetation zones of Guinea, Sudan and Sahel are often differentiated, although the terminology is often modified (e.g. WHITE 1983). Other authors made more detailed differentiations (e.g. ADJAKIDJE 1984 cited in BOHLINGER 1998, ADJANOUHOUN et al. 1989, WEZEL et al. 1999).

In the following, the seven zones found in BOHLINGER (1998), WEZEL et al. (1999) as well as in WEZEL & BÖCKER (2000), are presented which is based on the zoning by ADJANOUHOUN et al. (1989) modified by investigations of the authors (see WEZEL et al. 1999).

Within the **Coastal** or **Littoral Zone** a narrow band of coastal vegetation like swamps and magroons exist along the shore. Further north, within the Guinea-Congolian zone a mixture of semi-deciduous forests and savannas, mainly tree savannas, is characteristic. The rather small extend of rain forest is due to relative small rainfall amounts within the Dahamey Gap explained in 2.2.2. Further north, in the **Southern Guinea Zone** moister types of woodland and savannas are dominant.

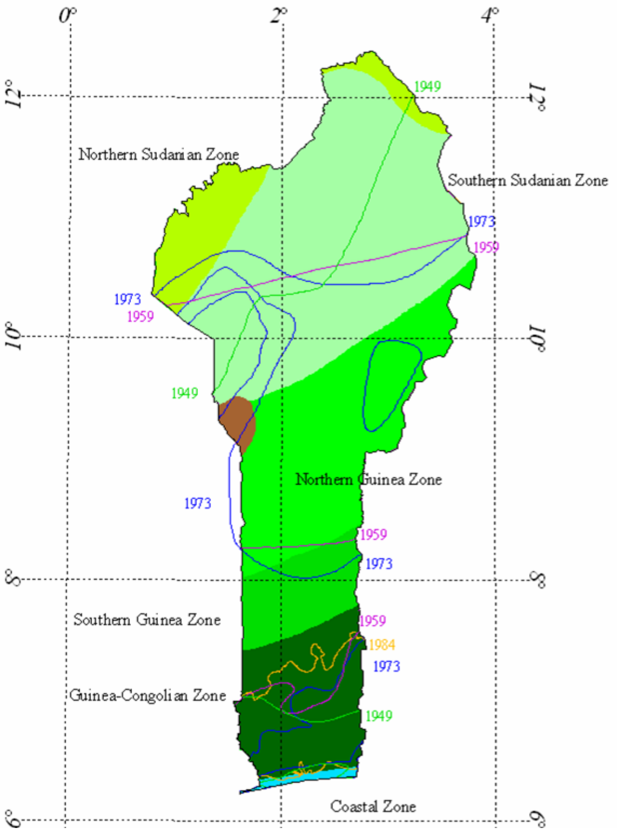


**Fig. 6: Vegetation zones in Benin derived from different authors (green: AUBREVILLE 1949, magenta: AÉTFAT 1959, blue: KNAPP 1973, and yellow: ADJAKIDJI 1989) summarized by WEZEL et al. 1999**

In the drier **Northern Guinea Zone**, tree and shrub savannas with abundant *Isoberlinia doka*, become more and more dominant. There, the grass layer of the savannas is not very tall, because of regular bush fires passes through. In both Guinea Zones, inselbergs with their typical vegetation are characteristic landscape features. The transition from the Southern to the Northern Guinea Zone corresponds with the northern boundary of bimodal rainfall (WEZEL & BÖCKER 2000).

Southern Sudanian Zone covers nearly the complete northern Benin. In this zone woodlands and tree savannas coexist. Furthermore, different types of gallery forests occur along rivers. Westwards from the town of Bassila, a hydrophile enclave, between the Northern Guinean and the Southern Sudanian Zone is mapped. There, vegetation of the **Guinea-Congolian Zone** is found: dry deciduous forest, forests in valleys and forms of woodland on hilltops. Finally, in the **Northern Sudanian Zone** with annual precipitation of 600 to 900 mm, savannas and woodlands are widespread vegetation types.

**Fig. 7: Sacred forest of Serou in western Benin (Photo: J. RÖHRIG, 2005)**

What is the potential natural vegetation of Benin? This question was discussed controversially over several years by many authors (e.g. ANHUF & FRANKENBERG 1991, BOHLINGER 1998 or NEUMANN et al. 2004). One of the key questions of this debate is if current savannahs in Western Africa are found due to natural conditions or if they are degraded forms of former forests, being a result of human activities. For Sudanian Zones in southern Niger and northern Benin, the vegetation analyses of NEUMANN et al. (2004) substantiated that recent forms of savannas are modifications of a natural woodland-savanna mosaic and mainly no degraded forests. They proofed that savannas were widely found already in the early and middle Holocene and therefore, appeared before first human activities. Hence, woodland-savanna mosaics would have been developed also without human beings. Concerning biomass or primary productivity a slightly environmental gradient of the primary vegetations is assumed as a consequence of climatic conditions.

Increasing human activities like selective logging, fire, grazing, and agricultural land use has changed vegetation cover on a large-scale (ADJANOHOUN et al. 1989, CENATEL 2002, IGUÉ et al. 2004). Actual proportion of woodland and savannah has been shifted in favour of latter, which have become the dominant vegetation form. Primary vegetation has remained only within protected forests (state or religion) and marginal areas (e.g. inselbergs or sites with ironstone) (BOHLINGER 1998, NEUMANN et al. 2004, REIFF 1998, ADJANOHOUN et al. 1989). According to CENATEL (2002) foret dense (dense forests), sémi-décidue and décidue (semi deciduous and deciduous) make up barely 1% of Benin's surface. Additionally, nowadays proportion of species and physiognomy of savannas overall in Benin has altered mainly by human activities (REIFF 1998, BOHLINGER 1998, NEUMANN et al. 2004, ORTHMANN 2005).

## *2.3 Population*

In 2002, 6.75 million people lived in Benin according to the last census results (INSAE 2003). If not quoted differently, the numbers in the following are taken from this reference. Population density is around 60 inhabitants per km² on average. Spatial distribution however exhibits enormous differences between the densely populated south (> 700 inh./km²) and the sparsely populated northern regions (<10 inh./km²).

Since the census from 1992, the average annual population growth has been around 3.25% p.a. showing a slight rise compared to 2.8% p.a. between polls from 1979 and 1992 (DOEVENSPECK 2004, THAMM et al. 2005A). These growing rates are similar to those of West Africa where the average population growth is about 3.3% (AKAPI 2002). Fig. 8 illustrates the spatial disparities and the wide range of this parameter. The highest growing rates are in Abomey-Calavi with more than 6.5%. In addition, growing rates with up to 6.5% are reached within several communes in the north and the centre due to migration from denser populated regions in the south and northwest. One of the important features considering population growth is migration. Beside inland migration which dominates, Benin has become a target country for transboundary migration (DOEVENSPECK 2004).

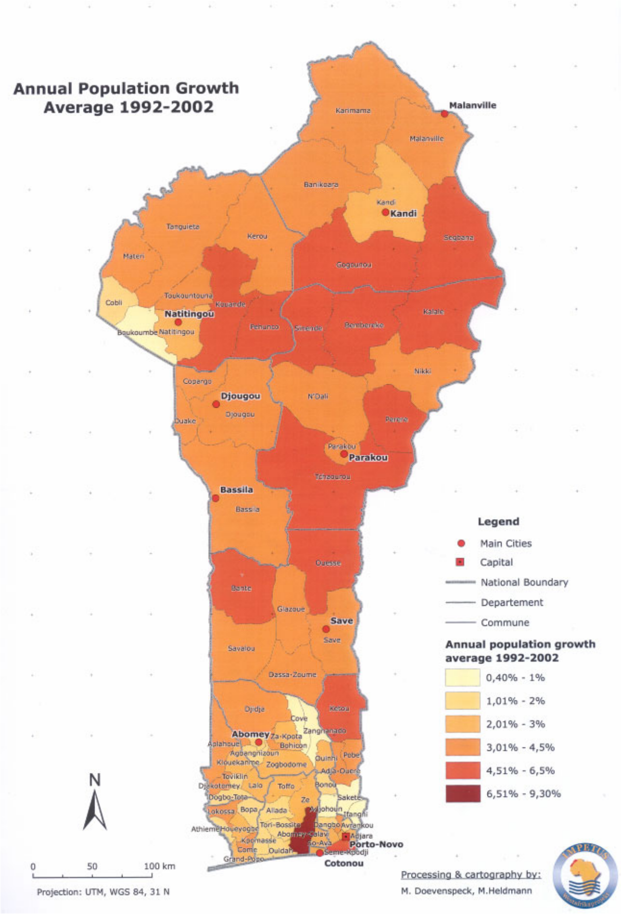


**Fig. 8: Annual population growth average 1992-2002 (THAMM et al. 2005A: BE-F-02)**

Both population density and growth are often used to define population pressure. According to SINDIGA (1984, cited in AMOS 2003), it is a relative term, relevant merely when related to other variables such as biophysical parameters, which should be measurable (PEDEN 1987).

The concept of population pressure is often used to address patterns and processes of land use change or land degradation (e.g. LAMBIN 1997, AMOS 2003). Population pressure is often named as one primary reason for changes of land use in Benin such as agricultural expansion, alteration of farming systems and environmental degradation (e.g. IGUÉ 2000, AKAPI 2002, AMOS 2003, NEUMANN et al. 2004).

In the next two subchapters consequences of population pressure on farming system and land resources will discussed in more detail.

## *2.4 Importance and characteristics of agricultural land use*

Benin is a developing country and belongs to one of the poorest countries in the world with a per capita income of around 370 US$ (UNDP 2003). One common characteristic of less developed countries is the elementary economic and social meaning of agriculture. Agriculture accounted with 37% for the second largest part of the gross domestic product in 2000 (DOEVENSPECK 2004). Whereby, cotton realised 82% of the exports. Other common cash crops are oil palm, groundnuts, cashew, or pineapple. Directly and indirectly, agriculture gives work and income for the majority (around 80%) of the population (IGUÉ 2000, MUNZIGER–ARCHIV 2002). Nearly 20% of the area of Benin is cultivated (CENATEL 2002).

In Benin, traditional farming systems are still dominant and generate the majority of agricultural products (IGUÉ 2000). Subsistence smallholders usually cultivate crops with low capital inputs (traditional tools and seldom use of fertilizers or irrigation) and with little mechanisation, predominantly for their own consumption (BOHLINGER 1998, IGUÉ 2000, CENATEL 2002, MULINDABIGWI 2006). Common crops for the own consumption are maize, yam, sorghum, beans, millet, or cassava. Others, like rice, mango, groundnut or cashew are for their own consumption as well as for markets. Fields of food crops made at least 60% of cropland (IGUÉ 2000). In such traditional systems, yields depend strongly on the biophysical conditions because of lacking input to compensate natural constraints. For instance, in Benin only 6,000 ha are irrigated (CENATEL 2002).

Yields are generally low as soil fertility declines rapidly after some years of cultivation and sustainable technology is lacking (IGUÉ 2000, MULINDABIGWI 2006). In the north, fields can be cultivated three to four years and in the centre and in the south up to nine years, respectively before soil fertility declines (IGUÉ 2000, MULINDABIGWI 2006). Traditionally, bush fires, altering crop and fallow systems are used to increase soil fertility causing small impact on natural resources (BOHLINGER 1998, IGUÉ 2000, MULINDABIGWI 2006). In addition, cropping phases are rather short compared to a long fallow period with a minimum of ten years. Such farming systems are called shifting cultivation or long fallow rotation depending on the ratio between period of cultivation and total rotation period (cf. RUTHENBERG 1980). Such extensive land use is, however, space consuming, in particular, as farmers minimise risk. Generally, farmers have several small fields (1-5 ha) within a specific area to cope with rainfall variability and low levels of yield (AKAPI 2002, MULINDABIGWI 2006). NEUMANN et al. (2004) stated that nearly all areas of Benin are included within a crop-fallow-cycle and only marginal sites like steep slopes are absolutely not agriculturally used. In the terrain, fallows can be distinguished from natural savannas as they contain often trees of shea or locust bean which are the same age. These trees are remained on the fields as they can be used in several ways, such as to gain oil or food.

**Fig. 9: Trees of shea (left photo) and of locust bean (right photo) (Photos: J. Röhrig, 2005)**

Increasing population pressure has led to typical changes in the traditional farming system in Benin. Rising population pressure together with access to market are driving forces that determine intensification processes of agricultural activities if other economic alternatives are lacking (Igué 2000). The latter can be observed mainly in the south and on sites where cash crops, in particular cotton and rice are cultivated. Examples of intensification forms are the increasing usage of plough in central and northern Benin, and usage of fertilizers for cotton. Population-driven intensification, however can be observed nearly overall (Wezel & Böcker 2000, Cenatel 2002, Mulindabigwi 2006). Thereby, ‘phases of expansion’ are followed normally by ‘phases of intensification’ (Bohlinger 1998, Igué 2000, Mulindabigwi 2006).

During the ‘**phase of expansion**’ agricultural activities are spatially extended to raise the general food production transferring natural vegetation cover into fields. This process is predominant as long as forests and woodland are available for transformation into fields. In Benin, 11% of woodland and forest were cleared between 1984 and 1994 (World Resource Institute 1998, cited in Wezel & Böcker 2000), whereas mosaics of cultivation and bush fallow increased between 1978 and 1997 by 223% (Igué 2000). Recently, this process is noticeable widespread in the middle and northern parts of Benin, where population pressure is still low. When suitable land resource becomes scarce, agricultural activities are expanded onto marginal sites, which is observable in southern areas (WELLER 2002, IGUÉ et al. 2004, MULINDABIGWI 2006).

The following '**phase of intensification**' is characterised by decreasing years of fallow up to permanent cultivation. During this phase productivity of land and labour decreases progressively (IGUÉ 2000). This can be observed in all regions with increasing population pressure. Where agricultural activities are intensified without improvements of technologies or adaptation of the farming systems, productivity declines and land degradation begins. Latter will be described in more detail in the next subchapter. The problematic consequences of rising scarcity of land resources on social systems, which have been noticed within several regions, are described in detail by AKAPI (2002) DOEVENSPECK (2005), or SINGER (2006).

## 2.5 Land degradation

In the following, land degradation caused by agricultural activities in the broadest sense will be examined.

**Fig. 10: Extend of erosion processes on the 'terre de barre' examined in the village of Oudeme-Peda in southern Benin (Photo: J. RÖHRIG, 2006)**

Land degradation is a diminution up to loss of the biological or economic productivity and complexity of land processes caused by human activities (ESWARAN et al. 1999, GRAEF 1999, STOCKING & MURNAGHAN 2001). The main reasons for land degradation caused by agricultural activities are unadjusted technologies and agricultural overuse (Blum & Eswaran 2004, IGUÉ et al. 2004, MULINDABIGWI 2006). In the following, the six types of land degradation in Benin described in MEHU (2003) are examined.

**Degradation of vegetation** is largely caused by slash and burn which is set up to explore new fields (French: feux de brousse). Each year about 100,000 ha are transformed into new fields (according to estimations by DOUREAU & SYLLA 1989, cited in MEHU 2003). The spatial focus of this transformation is in middle Benin where still enough land is available. Other reasons for degradation are logging and overgrazing. Both are mainly found in north and middle Benin. As a consequence of the degradation of vegetation, forests are lost, and fertility as well as biodiversity is diminished. Another reason for the loss of biodiversity is the enforcement of fire-resistant species on costs of others.

**Water erosion** increases if natural vegetation cover has been diminished. It occurs primarily on sparsely covered fields and settlements or on hillsides. But under cultivation, even minor slopes are prone to erosion due to intense and erosive rainfall (GRAEF 1999, CENATEL 2002). The severity of water erosion depends also on the soil type. For example, agricultural activities on 'terre de barre' have resulted in a dramatic degradation (Fig. 10); whereas ferralitic soils are rather stable (Igué 2000). Another region with widespread water erosion is the lama depression.

**Wind erosion** is restricted to dry seasons and mostly to the north, in the Atacora region and in Alibori. It is strongly linked to the occurrence of the Harmattan.

The **loss of soil fertility** is partially natural and particularly widespread on sites under cultivation as they are used mainly without fertilizer. Species indicating a reduction of soil fertility, like *Imperata cylindrical* or *Striga hermonthica,* are known by the farmers and are taken as signs to introduce fallow (Fig. 11).

**Fig. 11: *Striga hermonthica*, an indicator of declining soil fertility near Thya in northern Benin (Photo: J. RÖHRIG, 2005)**

Due to population pressure mostly in north-western and in the southern areas, fields are longer under cultivation and shortened fallows have led to a severe degradation. Organic matter declines thereby as well as CEC, microbiotic activity or phosphorus (Junge 2004). Furthermore, clays and exchangeable basis are lost and acidity increases (MEHU 2003). These processes result in a decline of crop yield (CENATEL 2002, Junge 2004, Mulindabigwi 2006). Fertility loss is, however, not limited to fields under traditional use. Also pure cultivated cotton fields in the north, where fertilizer is used, are degraded as they are generally under permanent cultivation (own observation).

Recapitulatory, different forms of land degradation are found in Benin. Water erosion and fertility loss are probably the most widespread types and in particular severe in southern, north-western and northern areas (CENATEL 2002). According to own observations, however, severely degraded sites do not cover wide areas as a whole, but occur on scattered spots. Spatially restricted, degradation of vegetation is prevalent on middle to low populated regions with larger surfaces of forests and woodlands or on marginal sites which are cultivated with increasing population pressure. The demonstrations in this subsection stress the need of a national land-use scheme realising sustainable land use.

## *2.6 Future conditions for agricultural land use in Benin?*

The question mark symbolises the uncertainty, which is always part of assumptions concerning future developments, projections or scenarios. The complexity of natural and human systems and the interdependencies among their components make it a sophisticated scientific challenge to document changes, diagnose their causes and develop useful projections of how natural variability and human actions may affect the environment in the future on different spatial scales. Nevertheless, recent projections of relevant climatic and demographic features and their impact on the agricultural framework are illustrated below.

### 2.6.1 Climate change

Since the 70ths, declining amounts of rainfall and increasing rainfall variability have been observed in Western Africa (IPCC 2001, Speth et al. 2005, Fink 2006). In Benin, the extraordinary dry year of 1977 made politicians and Non-Governmental Organisations (NGOs) aware about environmental problems initiating several supporting programmes and projects on different spatial scales (MEHU 2003). Although in recent years some regions experienced high rainfall amounts (1999, 2003, and 2005), scientists (see FINK 2006) expect no return to above-average rainfalls. Worsening climatic conditions is one reason that forced a large number of people from the Sahel and Sudanian Zone to migrate southwards. The upper Ouémé catchment has been one target region for numerous migrants resulting in changes and conflicts (cf. AKAPI 2002, DOEVENSPECK 2004 or SINGER 2006).

In the following, projection results of climatic variables relevant for agricultural land use of Western Africa are summarized (cf. IPCC 2001, 2007). More information about scenarios will be given in chapter 5.1.4.1 and the consequences for Benin considered in more detail in chapters 5.1.4 and 6.2.

Median annual temperature is projected to increase about 3.3° in West Africa by 2080-2090 relative to 1980-1990 in scenario A1B, whereby a strong human impact is assumed (IPCC 2007). Due to rising mean temperatures, heat stress will increase for plants and greater amounts of water will evaporate. For precipitation, the projected patterns and amounts of future annual rainfall are much more heterogeneous and insecure than those of temperature. Generally, no change or slight rise in rainfall within the tropics and a decrease of precipitation within the subtropics are announced enlarging the rainfall gradient between the two zones. This is particularly severe for Benin as rainfed agriculture is predominant and water availability is already limiting agricultural activities (see 2.2.2). Besides reduced rainfall amounts, rainfall variability, and thus, insecurity for farmers will enlarge in Africa generally (IPCC 2007).

### 2.6.2 Demographic trends

In the framework of IMPETUS, population projections have been assessed for Benin until 2025. Population projections are helpful for various purposes, mostly as a basis for planning. Following results are generated mainly by MARTIN DOEVENSPECK within the IMPETUS-Project, whereby required demographic data were provided by the National Statistic Office INSAE (Institut National de la Statistique et de l'Analyse Economique). More information about their development is exhibited in DOEVENSPECK (2004) and THAMM et al. (2005A).

Regarding the total population of 2025 in Benin, the department of Atlantique in the South remains the department with the highest total population because of attractiveness for rural-urban migrants. The most important target region of rural-rural migration will be Borgou in the Centre of Benin. Population density will enhance further in southern communes, where they will be among the highest in West Africa (up to 950 inhabitants per km² in Cotonou). In northern and central parts, all communes will exceed 70 inhabitants per km². Growing rates are projected to remain in any scenario one of the highest in the world. They are modest (1-2.3%) in the south, excluding Abomey-Calavi, Benin's fastest growing district. In the north, however, growing rates will be up to 3.5% and an average doubling time for its population will be merely 21 years.

Regarding current and projected population density and growth, in particular rather sparse populated regions in northern and central Benin will be target region of further migrants and thus, intensification of agricultural land use. Rising population pressure could come out with a doubling of intensification within the departments of Atacora and Alibori as wide areas are under protection and not available for agricultural land use (DOEVENSPECK 2004). Within the upper Ouémé area, pressure on natural resources could be aggravated due to enhanced areas of cashew plantation, which are used as permanent fallows (MULINDABIGWI 2006). The same author fears that periodical famines, which are recently, occur in single villages could affect large-areas in the future.

The framework of agricultural land use in Benin has changed and will change further under global change. Future projections suggest that more people will have to be fed under worsening natural conditions. This outlook is even threatening as beginning scarcity of land and water resources have already resulted into land degradation and conflicts. Concerning land degradation, MEHU (2003) expects for all regions, which are already strongly degraded, further degradation up to extreme degradation. According to several authors, neither a large-scale return to extensive forms of land use with long periods of fallow nor permanent cultivation under high capital input seems a realistic or sustainable opportunity to realise future needs for food (BOHLINGER 1998, JUNGE 2004, MULINDABIGWI 2006). This estimation stresses the importance of an efficient and sustainable use of available potentials. All mentioned authors pronounced themselves in favour of improvements of traditional agricultural land use and technologies.

# 3 Theoretical setting

In this chapter, the thematic and theoretical setting of this study will be outlined. This chapter contains three main parts. Subsection 3.1 embeds the study in the framework of agricultural geography. In presenting general contents and a historical overview of the discipline, it will be demonstrated that the thesis at hand is an example of recent scientific research of agricultural geography in developing countries. Subsection 3.2 comprises an introduction into the terminology and concepts of land evaluation. Furthermore, existing schemes realised for Benin will be considered. Finally, the third subsection 3.3 contains the marginality index and the scientific framework, the *Syndromes of Global Change*, within which the index was originally defined.

## *3.1 This thesis in the context of agricultural geography*

In this subsection, the nature and development of agricultural geography will be illustrated. In doing so, some thoughts about agriculture itself are given first. Then, the agricultural geography, itself will be considered. In 3.1.1 the development of the discipline will be presented. The focus will be for both parts on the German agricultural geography. Finally in 3.1.2, the introduction of the approach of the study at hand within the framework of agricultural geography will be addressed.

**Agriculture** is the process of producing food for human consumption, feed for animals, fibre and fuel for industrial purposes, and other goods by systematically growing plants and animals (SICK 1983, ARNOLD 1997). Agricultural activities are one of the oldest economic acts of humankind. Its global economic and social significance is still enormous. It employs globally the largest amount of the world's economically active people and is the most essential contributor to the national earnings in numerous developing countries (ILBERY 1985, ARNOLD 1997). In industrial nations, however, a declining economic, social and spatial importance can be observed since several decades.

Agriculture has generally a strong relation to the biophysical environment and its processes. Certain crops require specific physical and biological conditions. Thus, natural margins of cultivation can be defined spatially (Ilbery 1985, Manshard 1997). Nowadays, nearly all constraints can be compensated by adequate measures. Such measures are, however, costly and thus, not widely spread within poor countries. A further attribute is that agricultural products are renewable resources, which can be, if the cultivation methods are sustainable, produced indefinite. Sustainable farming systems are "*capable of maintaining their productivity and usefulness to society indefinitely. Such systems [..] must be resource-conserving, socially supportive, commercially competitive, and environmentally sound*" (Ikerd, cited by Duesterhaus 1990:4).

Reports and scientific studies about agriculture have a long tradition because of the importance of agriculture itself and the mentioned specified characteristics. Agricultural geography as a one discipline comes up only in the last century (cf. 3.1.1). From the beginning, various **definitions** were set up **for agricultural geography**. This circumstance is caused by its intersection of socioeconomic and natural sciences. An often cited definition within agricultural geography in Germany is the one by Otremba (1976). He defined agricultural geography as „*Wissenschaft von der durch die Landwirtschaft gestalteten Erdoberfläche, sowohl als Ganzes als auch in ihren Teilen, in ihrem äußerlichen Bild, ihrem inneren Aufbau und in ihrer Verflechtung*" (Otremba 1976:62). This definition is focused on a man-made agrarian environment. Recently however, such definitions and concepts have been increasingly criticized as being too biased (cf. Ruppert 1984, Rother 1988). The detractors argue for a more open agricultural geography due to the fact that the relevance of agrarian landscapes and agricultural product processes declined globally during the last decades (Ruppert 1984, Rother 1988, Arnold 1997). Particularly in industrial countries, the changes have been gigantic. There, the differences between agricultural and non-agricultural elements decreased within the agrarian landscape, the importance of agriculture declined and the functions of rural areas altered. In Germany, these discussions have lead also to discussions about a merge up with rural geography (Arnold 1997, Nüsser et al. 2005).

Similar to the variety of definitions, numerous **tasks and aims** of agricultural geography exist. Here again, temporal but also spatial context plays an important role.

Generally main tasks are spatial analyses of agriculturally structured areas including natural, economic as well as social relationships and organisations and explanation of spatial variations (ANDREAE 1977, ILBERY 1983). Furthermore, agricultural geography shall produce helpful information for land evaluation schemes in analysing and evaluating different agricultural land use forms, which are caused by biophysical, social and economic features (SICK 1983, cited in ROTHER 1988). Additional to these general tasks, context based tasks were defined, such as for developing countries. For instance, MANSHARD (1983, 1997) named the inventory of natural resources and an improved resource management as main topics for studies in developing countries. There, the relevance of agriculture, itself, but also the importance of biophysical resources differs significantly from other countries. Commonly, capital and technologies to compensate natural limitations are sparse in subsistence economies, which result in a strong dependency on the biophysical environment.

### 3.1.1 Agricultural geography under change: historical overview of the discipline

Reports and scientific studies about agriculture have a long tradition because of the importance of agriculture itself and the above specified characteristics. First scientific studies about agriculture with a spatial context were set up, however, not by geographers, but by national economists, farmers and cultural historians in the 19th century (ARNOLD 1997, NÜSSER et al. 2005). Geographical studies at that time considering the distribution of useful plants, like those by ALEXANDER VON HUMBOLDT (1769-1859) had a clear botanical focus (BERNHARD 1973). German agricultural scientists with a spatial focus were JOHANN NEPOMUK VON SCHWERZ (1759-1844), who described agriculture of specific areas like Westphalia (SCHWERTZ 1836) or JOHANN HEINRICH VON THÜNEN (1783-1850) (ARNOLD 1997, NÜSSER et al. 2005). VON THÜNEN's agricultural location theory is still part of the standard scientific geographic education (VON THÜNEN 1826).

Beginning with World War I 'agricultural geography' was propagandised and established as an own discipline by agricultural scientists like RICHARD KRZYMOWSKI or HANS BERNHARD (BERNHARD 1973, ARNOLD 1997, NÜSSER et al. 2005). Between the two world wars, in the course of a general upturn of economic geography, the essential breakthrough of agricultural geography took place. It became the preferred branch of economic geography for several decades although it was influenced by other disciplines. ARNOLD (1997) distinguishes the development of agricultural geography into five 'moments'(see also NÜSSER et al. 2005), which will be briefly described in the following section. Although these moments show some chronologies, they cannot be clearly separated because none of them have ended yet. For the five moments the German terms are kept followed by an English interpretation within brackets.

1. **Lösung vom Naturdeterminismus** (Disengagement of environmental determinism): Since 1900 within regional analysis interactions between the environment and human activity were increasingly considered. The perspective emerge that agricultural decision-making is not controlled alone by the natural environment. Instead, an economic human being is influenced by the environment, which he alters in the meantime with his activities.
2. **Zentrale Stellung des Begriffs der Agrarlandschaft** (Central position of the term agrarian landscape): The term agrarian landscape transfers the idea of a man-made landscape from cultural geography and was formed around 1935. Analyses of such spatial agrarian units, which were mostly physiognomic characterised, became a main task in the German agricultural geography until the 70s. In the beginning, the approaches were mainly focused on the structure of a region itself. Later, interdependencies and temporal dynamics were additionally analysed.
3. **Neue Forschungsrichtungen durch Impulse der Sozialwissenschaften, die zu neuen Forschungsrichtungen führten** (New fields of interests given by the new impetus of social sciences): Since the 60s, new fields of research were followed due to the rising significance of social sciences. In doing so, agrarian landscapes were seen as areas of social and economic processes and developments.
4. **Modellhaft-theoretische Fragestellungen** (theoretical research based on quantitative models): In German-speaking regions, approaches coupling theoretical questions with mathematical models like the one by JOHANN HEINRICH VON THÜNEN (1982) revive in the 70s. Nevertheless, these approaches remained rare because data access is difficult and confidence in statistical data is low.

5. **Nachfrageinduzierte Praxisorientierung** (demand-pull applied research): Since the 80s, recent agro-geographical problems (e.g. structural changes in rural areas, resource management, sustainable agricultural production or carrying capacity) are increasingly integrated into super ordinate aspects (e.g. rural geography, developing geography, applied geoecology or human ecology) (MEURER 1997, NÜSSER 2003). Such studies aim to record and value the interactions of natural resources, land use systems and change of landscape (NÜSSER et al. 2005).

Until now, all five 'moments' are still existent. Thus, a wide range of agro-geographical research topics are found. This is particularly the case, as agriculture and rural landscapes has been changed drastically within industrial nations during the last decades. Consequently, recent fields of interest of agro-geographical studies differ enormously between developing and industrial countries. Agricultural geography cannot resolve this dilemma, but it can analyse and illustrate parameters characterizing the agrarian landscapes and resulting into spatial differences. This can help to overcome uneven developments (cf. ROTHER 1988). Integrative approaches are thereby often more helpful than solutions set up by single disciplines.

Nevertheless, agricultural geography as an own branch is questioned because its themes overlap with other geographical disciplines and agricultural science (see above). Researchers believing in the given potentials and specific opportunities of agricultural geography, such as RUPPERT (1984), ROTHER (1988) or NÜSSER et al. (2005) stress the importance to widen the definition and tasks of agricultural geography. Thus, the change of the discipline is probable to continue.

### 3.1.2 This study in the framework of agricultural geography

This thesis demonstrates several characteristics of recent research of agricultural geography, which will be summarised in the following.

First, the key aim of this study corresponds to the main objectives of agro-geographical studies in developing countries (cf. MANSHARD 1997). In developing countries basic spatial data about biophysical information is often sparse or missing totally. Thus, an essential task of agro-geographical studies there is often to analyse and evaluate biophysical conditions. Furthermore, the physical environment is still determining potentials and limitations of agricultural land use because self-sufficing production with a low capital input is dominant. In addition, investigating spatial variations of agricultural activities depends on spatial scale. Thus, natural features become evident in agricultural land-use patterns as the study area increases (ILBERY 1985). On a large scale, regional agricultural variations can be explained by broad environmental differences, whereas at the micro scale, differences are likely to be caused by differing farm management and decision behaviour.

Second, another essential aim of this approach is the identification of marginal agricultural production sites, which are particularly prone to land degradation (see for more detail 3.3.3). Thus, the thesis picks up another recent research question of agricultural geography: sustainable agricultural production and resource management (cf. fifth momentum).

The final aspect meets the recent attempts of repositioning agricultural geography. According to ROTHER (1988) agricultural geography tries to increase its importance by contributing knowledge on resources within interdisciplinary research projects. He stressed the specific potentials of agricultural geography studies on resource management in the context of sustainable land use, food security and carrying capacity due to its integrative approach and its knowledge about a wide-range of determinants. This thesis is embedded within IMPETUS, an interdisciplinary research project. Therein, this study is located in a *problem cluster* within the subject of ‘food security’ (see SPETH ET AL. 2005).

## *3.2 Land evaluation: Approaches and applications for Benin*

One aim of this study is to evaluate biophysical agrarian land resources and investigate the risk of land degradation. As many disciplines contribute to land evaluation in the broadest sense, a wide range of approaches with a variety of aims and focuses exist. This subsection provides an overview of common approaches, their aims, applications, and limitations in 3.2.1. In addition to a general overview, two approaches, the *Agro-Ecological Zones* (AEZ) and *the Parametric FAO/ITC-Ghent* evaluation are described in 3.2.3 and 3.2.4. Both approaches are implemented in Benin, will be illustrated in more detail in 3.2.5.

### 3.2.1 Concepts and definitions of land evaluation

In this subsection, terminology will be introduced first. Afterwards, objectives and concepts of land evaluation will be presented.

A widely used **definition of land evaluation** is that by the FAO, which defines the term as "*the assessment of land performance when used for a specified purpose*" (FAO 1996:13). In this context, the term 'land' describes both natural and manmade resources (VINK 1975, cited in SYS et al. 1991A:8). The term was introduced at the Amsterdam Congress of the International Society of Soil Science in 1950 (VAN DIEPEN et al. 1991). An overview of the historical development and early approaches are given by VAN DIEPEN et al. (1991) and LANDON (1994).

In the course of time, many other terms illustrating land evaluation evolved like 'soil evaluation', 'land (use) capability classification', or 'land suitability classification' (SYS et al. 1991A). These terms were used more or less as synonyms (VAN DIEPEN et al. 1991). However, nowadays with a longer history of land evaluation and new approaches confusion over existing terms is found. The variety of expressions occurs mainly due to the fact that land evaluation is a general term implying no particular methodology, classification, interpretation or land use in itself (VAN DIEPEN et al. 1991, LANDON 1994, GRAEF 1999).

Recent land evaluation terminology has been mainly 'pedocentric' and many terms defined within the FAO framework are transferred from soil science. Thus, a major confusion is caused by a poor distinction of 'soil' and 'land' evaluation considering terminology and conceptual approaches. Thus, several scientists, like DORRONSORO (2002), pronounced themselves in favour of a clear distinction of 'soil evaluation' and 'land evaluation'. SYS et al. (1991A) proposed thereby the most suitable division. According to them, soil evaluation approaches should contain solely pedological parameters, whereas approaches of land evaluation should encompass pedological properties as well as other biophysical or socio-economic ones. Therefore, interdisciplinary studies are most suitable.

The **aim** of land evaluation is to provide information on the potentials and limitations for making decisions about its use and management (SYS et al. 1991A, VAN DIEPEN et al. 1991). The essential importance of decision makers is also stressed by ROSSITER, who wrote that "*predictions of land performance, no matter how soundly based, are only useful if they will be used by decision makers […] to make better land-use decisions*" (ROSSITER 1996:187). The principal objective of land evaluation is to optimize land-use systems for a defined land unit and to conserve the environmental resource basis for a future use including natural and socio-economic considerations (SYS et al. 1991A).

In rural settings, land evaluation typically deals with the appraisal of potentials and constraints of land for agricultural land use. Therefore, (potential) crop yield estimates and productivity are traditionally key indicators for land evaluation. LANDON (1984), however, stated that potential yield is not a useful indicator for land evaluation within tropical regions, where shifting cultivation dominates. There, beyond crops, trees and their radix are part of the fields and thus, yields are generally lower. Since the 1990s, environmental sustainability of agricultural production systems and effects of land use have become a major issue within land evaluation research (VAN DIEPEN ET AL. 1991, GRAEF 1999, DORRONSORO 2002). Thus, intensive agriculture and its structural overproduction, pollution or declining soil fertility and erosion caused by overexploitation of the natural resources are often parts of recent land evaluation schemes. In addition, CORBETT (1996) stressed the cultural dimension of agriculture as he stated that societies chose crops not merely due to biophysical conditions but also due to socio-economic reasons. Thus, next to yields and optimal land use, other essential aspects are sustainability, cultural and socio-economic features.

### 3.2.2 Concepts and approaches

Land evaluation approaches can be distinguished according to their input data, focus and primary target. Table 1 gives an overview of existing methods with examples and their conceptual differences (cf. van Diepen et al. 1991, Sys et al. 1991b, Landon 1994, Rossiter 1996 and Dorronsoro 2002).

| **Two opposite concepts of land evaluation** | | |
|---|---|---|
| Suitability approach vs. **capability** approach | | |
| • Economic purposes are in focus, such as yields<br>• Focus on aptness of the land for specific crops or irrigation<br>• Examples: Agro-Ecological Zones (FAO 1996, FAO 2002), Land Index (Sys 1978, Sys et al. 1993) | vs. | • Environmental purposes are in focus, such as conserve natural resources<br>• Focus on general land use types such as farming, forest or pastures<br>• Examples: USDA Land Capability Classification (Klingebiel & Montgomery 1961), Fertility capability classification (FCC) (Sanchez et al. 1982) |
| soil vs. **land** evaluation | | |
| • Only soil properties are taken into account<br>• Analyses are made by soil scientists<br>• Examples: Fertility capability classification (FCC) (Sanchez et al. 1982) | vs. | • Several biophysical properties, such as climatic or topographic are taken into account<br>• Analyses are made by interdisciplinary teams<br>• Example: Agro-Ecological Zones (FAO 1996, 2002) |
| qualitative vs. **quantitative** approach | | |
| • Evaluation is descriptive mainly based on empirical and expert knowledge.<br>• Focus on the evaluation of broad zones. It is often the first attempt in land evaluation<br>• Example: Land quality classes (Eswaran et al. 1999) | vs. | • Evaluation is set up using numerical parameters in calculation procedures to produce numerical results<br>• Often based on detailed studies and data<br>• Example: Agro-Ecological Zones (FAO 1996, FAO 2002) |
| focus on fitness vs. **focus on limitations** | | |
| • Categorisation on the basis of feasibility based on multiplicative calculation methods<br>• Example: SOTER (UNEP et al. 1995) | vs. | • Categorisation based on constraints taking into account Liebig's law of the minimum (1855)<br>• Example: FCC (Sanchez et al. 1982) |
| actual vs. **potential** land evaluation | | |
| • Assessment of the present conditions without considering e.g. management factors<br>• Example: Storie Index (1933) | vs. | • Assessment of the possible prospective, which can be either without human impact or with feasible improvements<br>• Examples: Agro-Ecological Zones (FAO 1996), FCC (Sanchez et al. 1982) |

**Table 1: Summary of common approaches of land evaluation and their characteristics (based on van Diepen et al. 1991, Sys et al. 1991b, Landon 1994, Rossiter 1996, and Dorronsoro 2002)**

The key terms represent two contrasting approaches, which are described thereafter. Bold terms indicate that this approach, corresponding to the right column, is followed in this thesis. This table serves to introduce common terms and concepts and simultaneously embedding the current study in its theoretical framework.

In addition to this conceptual framework, approaches of land evaluation differ according to their level of generalization. At each level, interpretation varies according to precision, assumptions, requirements and objectives (SYS et al. 1991B). The level, which can be achieved, depends strongly on the available resources and data, and is thus often directly related to the spatial scale. A common assumption is that higher resoluted data produce results that are more accurate. VAN DIEPEN, however, relativises this assumption by writing "*there is always a point where the use of more detailed data does not produce more accurate results because of scale-specific variability in natural processes and also because of our limited understanding of the functioning of biological systems of which the soil forms a basic part*" (VAN DIEPEN et al. 1991:197). Consequently, the spatial resolution of an outcome should correspond with the actual information and existing knowledge of relationships and processes.

Processes of land evaluation remain to some extend subjective and arbitrary depending on several influencing factors, such as spatial scale, context and main target of a study (LANDON 1994). Decisions must be made about selection of data and indicators, evaluation, weighting and combining the chosen properties (VAN DIEPEN et al. 1991, ROSSITER 1996). In this context, land evaluation for agricultural purposes is extraordinarily complex. A wide range of regional varieties of each crop exists with altering requirements concerning natural resources or management measures. Additionally, the translation into operational or planning terms is embedded within a specific spatial and social framework. Therefore, empirical expert knowledge, while often qualitative, is still an essential basis for the various stages of land evaluation processes and a first attempt and approximation of a study (LANDON 1994).

### 3.2.3 Agro-Ecological Zones (AEZ)

In this subsection, the approach, methodology and applications of Agro-Ecological Zoning (AEZ) are presented and discussed. More information can be found in FAO &

IIASA (1991), Sys et al. (1991b) and FAO (1996, 2002). This approach is particularly relevant as it is a very widely used methodology on global and national scales and was also implemented in Benin. Corresponding results for Benin will be presented and compared later in chapter 3.2.5.1.

The methodology of AEZ originates from the 'Framework for Land Evaluation' (FAO 1976), the most essential reference of land evaluation research (van Diepen et al. 1991). FAO and IIASA developed the AEZ approach by the 1980s as part of a global study about land resources (FAO et al. 1982). *"An Agro-ecological Zone is a land resource mapping unit, defined in terms of climate, landform and soils, and/or land cover, and having a specific range of potentials and constraints for land use"* (FAO 1996:7). It focuses on land resource potentials and limitations for various crops considering different input and management levels. AEZ is an early quantitative suitability approach applicable at different spatial scales (from global to national scale). The general aim is to provide information about the adequacy of land resources to feed present and future populations based on zones with comparable limitations or advantages for agricultural production. Furthermore, the zones shall provide useful information for national and international policymaking (FAO 1986, FAO 2002). On a global scale this database was implemented at a spatial resolution of 0.5° x 0.5° (FAO 2002). Possible applications are various within the fields of agricultural land use planning, management and conservation of natural resources. In the course of time, several extensions were implemented and a wide range of activities is associated with this approach, which were often quite different in scope and objective (Fischer & Antoine 1994, FAO 2002).

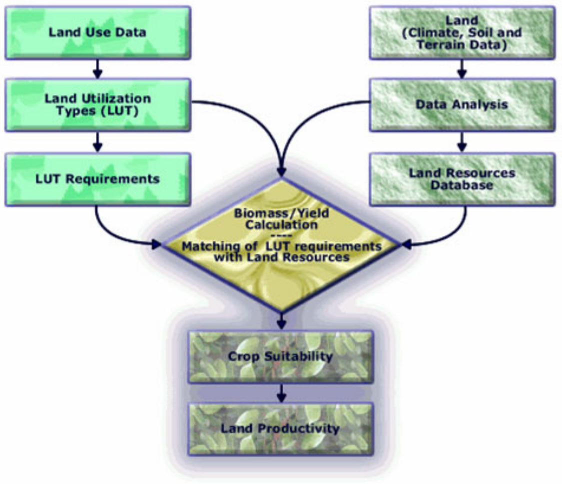


**Fig. 12: Conceptual framework of the AEZ methodology (FAO 2002:8, modified)**

In the simplest form, the framework consists of five basic elements (for more information see FAO 2002): Land Utilization Types (LUT), land resource database, crop yields and LUT requirements matching, assessments of crop suitability and land productivity (cf. Fig. 12).

First, **Land Use Types (LUT)** are chosen and defined. A LUT consists of technical specifications within a socioeconomic setting. LUT-specific attributes include crop information such as crop calendars or crop requirements. The crops are thereby classified according to their adaptation towards specific environmental conditions. Additionally, three levels of inputs and management are defined: high, intermediate and low.

Parallel, relevant and measurable data, *land characteristics* are set up for the **land resource database**. A land characteristic is "*a simple attribute of the land that can be directly measured or estimated in routine survey, including remote sensing and census as well as natural resource inventory*" (ROSSITER 1996:170). Land characteristics include climatic, soil and terrain features as well as data about land use and land cover.

In the third step, **crop yields and LUT requirements matching**, the crop adaptability inventory and the defined crop/LUT specific requirements are compiled and the optimal cropping calendar based on calculations of potential biomass and yield is determined. Matching for instance temperature requirements and prevailing temperature regime, crop/LUT-specific thermal constraints are calculated on the basis of reduction factors. Furthermore, irrigation requirements are assessed for each grid-cell.

The result of the matching process is combined in a further step with calculated potential biomass and agro-climatically attainable yields providing **crop suitability** classifications. The suitability classification of pedological features is mainly based on the experience documented by SYS and colleagues (cf. SYS ET AL. 1991A). In this scheme five classes are defined: very suitable, suitable, moderately suitable, marginally suitable, and not suitable. Finally, the climatic, soil, and terrain suitability and constraints are assessed and summed providing the overall **land productivity** for each crop at the three input levels.

Finally, a critical review of the AEZ approach will be carried out. The AEZ is one of the rare quantitative land evaluation approaches, which enables a detailed characterisation and assessment of land resources and crop-specific suitability and potentiality. These assessments in particular provide helpful information for decision makers. For the application of the approach, however, various climatic and edaphic data are needed to determine a crop specific suitability. For instance, 27 climate-related parameters are taken into account for each grid-cell. The variety of input data encloses the challenging issue how to weight and combine them deriving a suitability classification. Additionally, needed data may not always be available in good spatial resolution on a regional or national scale. Case studies contain often interpolated data of land characteristics or data in a low resolution (cf. BERDING & VAN DIEPEN 1982, FAO & IIASA 1991, FISCHER & ANTOINE 1994).

There is another critical aspect concerning the chosen climate indicators. The assessment is based only on average values neglecting temporal dynamic and variability. But "*it is the deviation from the average that interferes with farming practice*" (VAN DIEPEN et al. 1991:189). IGUE et al. (2004) showed exemplarily for central Benin that crop suitability varies enormously with the years due to significant year-by-year climatic differences. Thus, the determination of year-by-year conditions provides helpful information for farmers.

### 3.2.4 Parametric FAO/ITC-Ghent evaluation

The FAO/ITC-Ghent evaluation is a semi-quantitative approach for biophysical land evaluation without considering socioeconomic resources. It was developed at the International Training Centre for post-graduate soil scientists of the University of Ghent (ITC). The approach is described in detail in SYS et al. (1991A,B). Its terminology is similar to the terms used in the FAO Framework. Generally, this approach implements requirements of specific land utilisation types at different levels of generalisation; from high generalisation levels distinguishing annual crops, permanent crops, grassland, and forest, to low generalisation levels distinguishing different crops. Essentially, the method is based on some simple crop growth functions, various crop requirement tables, and a classification scheme (see SYS et al. 1991B, IGUÉ 2000).

The parametric method is based on the multiplicative *Storie Index* (STORIE 1933, 1978) enabling quantitative evaluation. The evaluation is derived thereby by numerical ratings of the diverse limitation levels ranging from a maximum value of 100 down to a minimum value of zero. A rating of 100 is applied to optimal development, rarely ratings above 100 can be seen if developments are particular favourable. An important feature is rated in a broader range (e.g. 100-20), than a less important one (e.g. 100-60). In doing so, weighting factors are incorporated. For a successful application of the parametric method, some rules must be minded. For example, the number of land characteristics (cf. 3.2.3) should be reduced to a minimum avoiding the repetition of related biophysical characteristics (for more details see SYS et al. 1991A: 66FF).

In the evaluation procedure, four biophysical groups are taken into account: climate, vegetation, landform and soil. For each group various *land characteristics* and *land qualities* are defined. *Land characteristics* correspond to the ones defined within the AEZ framework (cf. 3.2.3). *Land qualities* contain information about the attributes of a specific environment and thus, it's potential according to a certain land use (SYS et al. 1991A). Named examples are gross productivity, required recurrent (management) inputs or non-recurrent (improvement) inputs. The land characteristics and qualities of each group are evaluated by a limitation method regarding number and intensity of limitation. This process calculates *land classes* (S1-N2) for climate, vegetation, landform and soil. The *total land index* is the product of the individual ratings of each group. Alternatively, the index is calculated by the square root method according to KHIDDIR (1986, cited in SYS et al. 1991A).

The FAO/ITC-Ghent evaluation is a detailed evaluation scheme that is valuable to examine biophysical resources at different levels of generalisation. In particular, the summary of detailed crop requirements for 45 crops in SYS et al. (1993) is unique and valuable for land evaluation applications. According to IGUÉ (2000), this information is an improvement of the Framework for Land Evaluation and the AEZ. Several studies in Benin, for instance, used the listed crop requirements together with the SOTER approach (SOter and TERrain database) (see 3.2.5.2). Nevertheless, the FAO/ITC-Ghent evaluation is also based only on average climate data, which limit the magnitude of the approach (see 3.2.3). Furthermore, the crop requirements do not take into account the large variety of crops or the full span of conditions that these crops require. This limitation necessitates the examination of crop requirements for specific applications (GRAEF 1999, GAISER & GRAEF 2001). The incorporation of socioeconomic resources would improve the method (IGUÉ et al. 2004).

### 3.2.5 Land evaluation of Benin

In Benin, land evaluation schemes have been implemented on different spatial scales and at different levels of generalisation going beyond the 0.5° resolution of global products from FAO and others. On the national scale, Agro-Ecological Zones and suitability maps for several crops were realised (see 3.2.5.1). Additionally, a land evaluation scheme based on the FAO/ITC-Ghent evaluation and detailed soil evaluation studies using the SOTER method were set up for some regions in Benin (see 3.2.5.2).

#### 3.2.5.1 Land evaluation on national scale

On national scale, suitability maps for the main crops exist for Benin. The oldest maps are the 'Cartes d'aptitude des sols de la République Populaire du Bénin'. Later, different AEZ maps were produced.

The '**Cartes d'aptitude des sols de la République Populaire du Bénin**' were realised within the FAO 'Project d'Agro-Pédologie' in the 1980s. The work includes suitability maps for ten common crops (e.g. maize, rice, cotton, or sorghum) and a report with accompanying information published by Berding & Van Diepen in 1982. The maps are mainly based on the soil maps produced by ORSTOM between 1967 and 1971 and climate data interpolated from weather stations. The land evaluation is based on the method described in Sys (1978) - an early form of the parametric FAO/ITC-Ghent evaluation. Thus, the registered land characteristics as well as the rating schemes are similar to those described

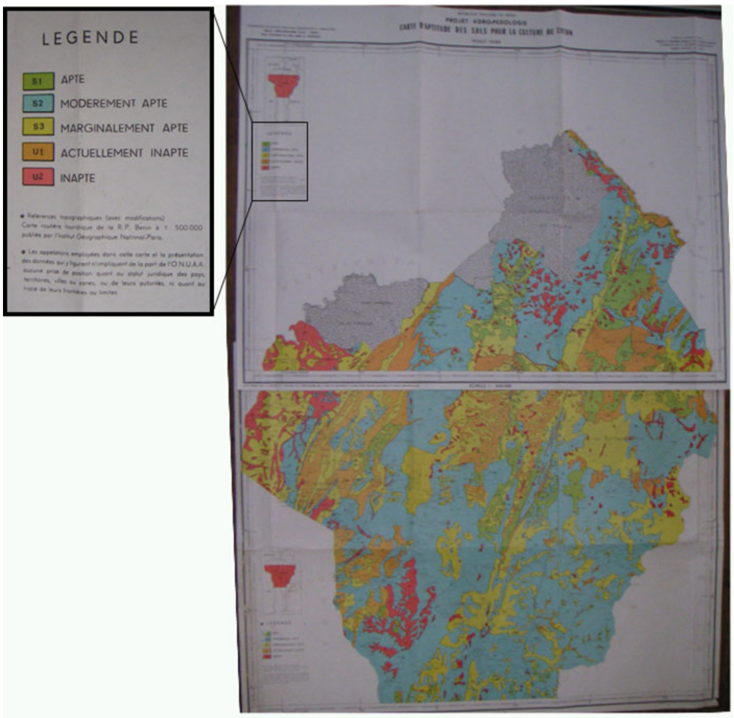


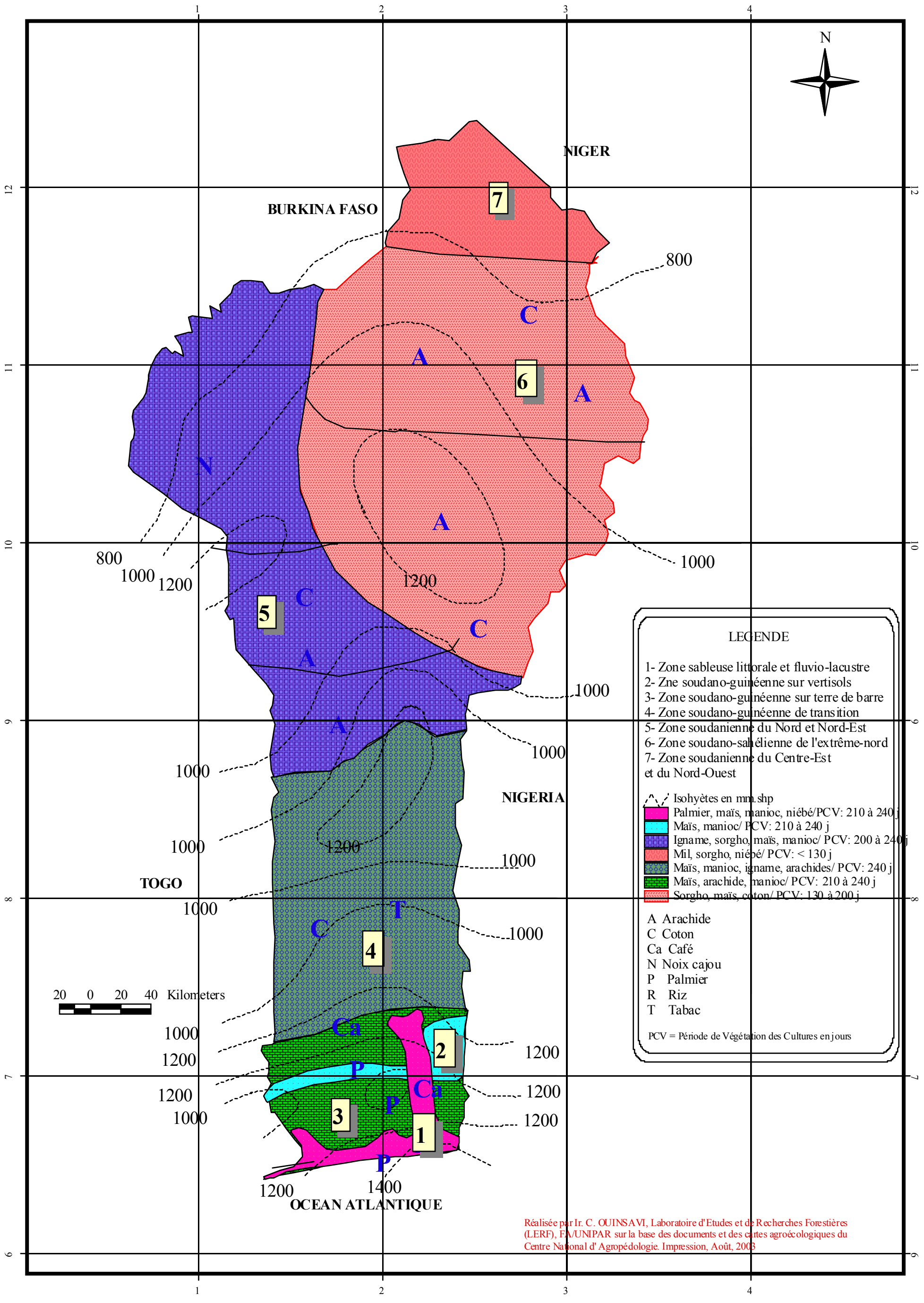
**Fig. 13: Suitability maps for cotton according to Berding & Van Diepen (1982)**

in chapter 3.2.4. Fig. 13 exemplifies the suitability for cotton within the northern part of Benin.

Within this FAO project, a database on soil characteristics was processed. This must be appreciated as soil is the most relevant feature determining the agricultural potentials and constraints in Benin. On national scale, the ORSTOM soil map contains the most detailed spatial information. However, according to IGUÉ (2000), the number of so-called reference profiles is too small for a national suitability approach given the heterogeneity of soil cover. Additionally, the spatial variability within mapping units is not considered. For both reasons, IGUÉ doubts the quality of the findings.

For Benin, three different versions of **Agro-Ecological Zones** were determined. The zone names contain information about predominant climatic and sometimes pedological characteristics. For each zone the following information is given: distribution, size, climate, soil, topography, vegetation cover, main crops and population density. The first version with eight zones was published by MDR & INRAB in 1995, the second with only five zones by MDR ET AL. in 1998, and the third, with seven zones by MEHU in 2003. The comparison of the different maps and description of zones shows that the AEZ from 1995 are very similar to the version of 2003. The reduction from eight zones to seven zones in the recent version results from the merging process of Zone 3 ('Zone soudanienne du nord-est') and Zone 2 ('Zone soudanienne du nord') into one zone, Zone 5 ('Zone soudanienne Nord et Nord-est'). Nevertheless, there are differences concerning the boundaries even though the zones are similarly named and described. The smaller number of zones in 1998 is explicable as some of them consisting of three or four distinguishing parts (cf. MDR et al. 1998).

Fig. 14 illustrates the most recent AEZ map of Benin from 2003. The determination of the zones is based on existing literature and reports from CENAP, CARDER, and MAEP (compare MEHU 2003). The legend contains basic information: name, length of growing period, and information about dominant and suitable crop.



Réalisée par Ir. C. OUINSAVI, Laboratoire d'Etudes et de Recherches Forestières (LERF), FA/UNIPAR sur la base des documents et des cartes agroécologiques du Centre National d' Agropédologie. Impression, Août, 2003

**Fig. 14: The agro-ecological zones of Benin (according to MEHU 2003:15)**

While providing a zoning used within several studies, a more detailed inspection reveals nonconformities, as some names, and description of the zones do not always correspond with the location on the map. For instance Zone 5, which is named 'Zone soudanienne Nord et Nord-est', is located in the west not in the east. The former name of Zone 5 was 'Zone soudanienne du Centre-est et du Nord-ouest', which is the name of Zone 7 in the recent version (cf. MDR & INRAB 1995 and MDR et al.

1998). The definitions of the zones are not always clear, as the zones, themselves are sometimes not that homogeneous. Zone 5 for instance, contains various agro-ecological conditions. The zone encompasses good pedological and climate conditions in southern areas, but also mountainous sites within the Atacora with shallow soils and steep landscapes and rather dry climatic conditions towards north-western regions. Furthermore, the zones and borders are spatially rather coarse (cf. Zone 2). Therefore, it must be assumed that the maps are products from inaccurate digitising or that underlying maps were already coarse. In this context, IGUÉ et al. wrote that *„the scale of the AEZ was by far too large to be applicable to the small structural units in Benin"* (2004:42).

### 3.2.5.2 Land evaluation on regional scale

The parametric FAO/ITC-Ghent evaluation was applied for the Ouémé catchment and small parts in the north in combination with detailed soil evaluations based on the SOTER method (GRAEF 1999, IGUÉ 2000, WELLER 2002, IGUÉ 2005). The principal goal of all studies was to set up a digital database of soil and terrain resources (SOTER) assessing soil potentials and erosion risk on a regional scale. All studies have a strong pedogenic focus as they were led by soil scientists.

Originally, a joint initiative of UNEP, IUSS (former ISSS), ISRIC, and FAO developed the SOTER approach (UNEP et al. 1995), a widely accepted soil evaluation approach. The fundamental concept is the identification of land areas, so-called SOTER units, characterised by a distinctive pattern of landform, surface form, slope, and various soil and geological features which respond comparatively evenly to management measures (IGUÉ et al. 2004). For that reason, a detailed soil survey is essential. The great advantage in contrast to the ORSTOM soil maps is that spatial heterogeneity of soil properties within units is taken into account. The method is based on the identification of three hierarchical land units (Terrain units (TU), Terrain components (TC), and Soil components (SC)) with distinctive patterns of soil and landscape parameters such as landform, surface form, slope, and lithology (for more details see GRAEF 1999, IGUÉ et al. 2004). Climate data are not directly related to the SOTER units, but treated independently and linked geographically with the SOTER units.

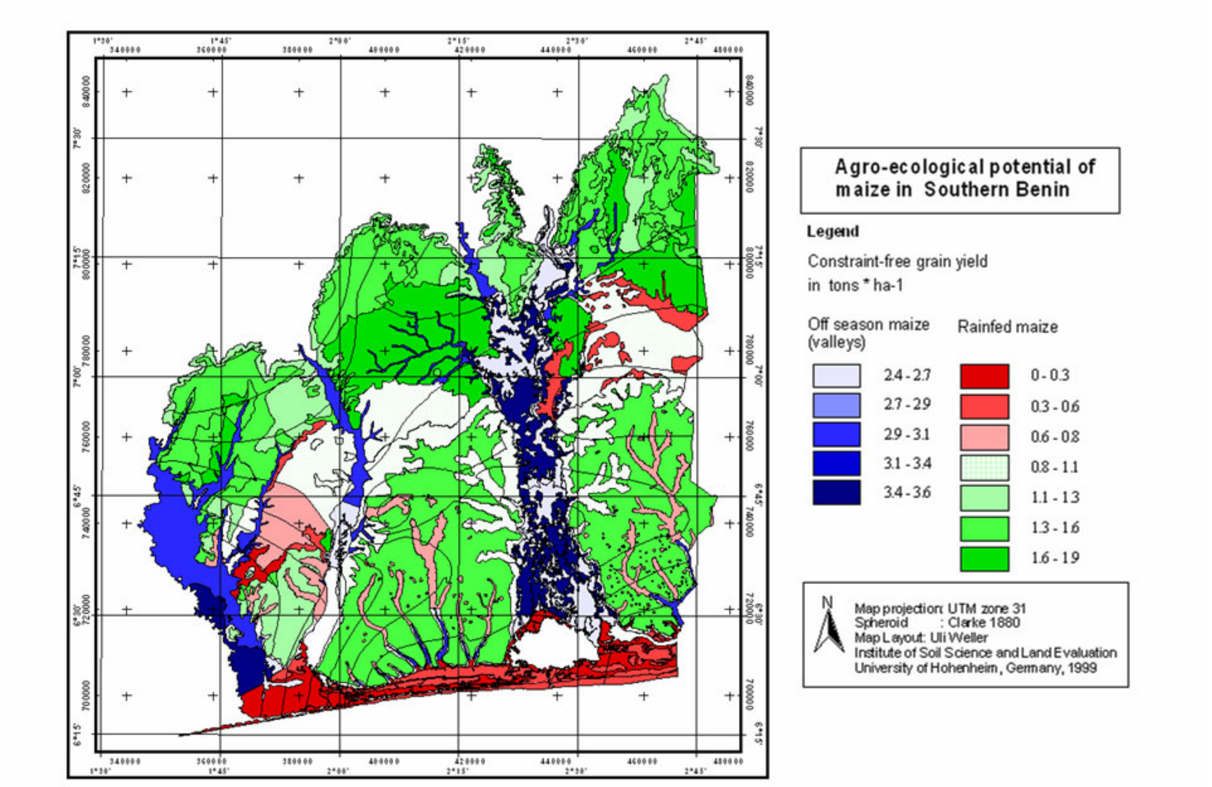


**Fig. 15: Agro-ecological potential of maize in southern Benin (according to Weller 1999)**

Together with the SOTER approach, the slightly modified parametric FAO/ITC-Ghent evaluation was used to determine biophysical features constraining yields for all studies in Benin (Sys et al. 1993, Graef 1999, Igué et al. 2004).

Main outcomes of the studies in Benin were detailed suitability maps applying the land index for several main crops (e.g. groundnut and maize). Furthermore, main biophysical constraints and potentials as well as degradation processes were analysed. Fig. 15 illustrates spatially detailed agro-ecological potential of maize according to Weller (1999). Theses studies produced the best available information on soils, including spatial variability, and topography. Used climate data are, however not that detailed. They were interpolated or taken from weather stations nearby. Furthermore, the presented studies considered only average climate which does not consider the immense interannual variation of climate and hence year-by-year changes in the suitability of crops (Igué et al. 2004). Unfortunately, the databases cover, only the Ouémé-catchment limiting their usefulness for countrywide policies and applications.

### 3.2.6 The need for another land evaluation scheme for Benin

Several land evaluation schemes and corresponding suitability maps already exist for Benin. Thus, why set up a new one, based on a capability approach?

A big disadvantage of all presented approaches is that the climate data are spatially and temporally coarse resoluted. Both, however is needed for land evaluation schemes in Benin, where temporal as well as spatial variability of the climatic conditions are enormous. Consequently, the maps must be used carefully. Furthermore, crop requirements are very different concerning climate features (GRAEF 1999), which mean that for a suitability approach relevant climate parameters must be available in an adequate spatial resolution.

Regional studies mapping SOTER units have significantly improved the spatial pattern and provided crop-specific information for some parts of Benin. Until now, however, nationwide maps are missing limiting their usefulness for countrywide policies and applications.

The evaluation schemes on national scale contain crop requirements based on the varieties cultivated in Benin. Thus, they can be considered as valuable information on land resources. Nevertheless, suitability approaches requires a wide range of input data, which are not available for Benin in an adequate spatial resolution. Thus, the maps are based on coarse resoluted maps containing no detailed information on spatial variability for specific crops. Consequently, on a national scale, the available databases, like the national soil map of ORSTOM, are likely inadequate to implement a suitability land evaluation approach but sufficient to realise a capability approach (IGUÉ 2005, personal communication). In addition, a capability approach is valuable for national decision makers who do not decide which crop to cultivate. National concerns should focus on food security, land degradation and escalating conflicts due to land scarcity and population growth. Furthermore, scenario analyses can be more easily carried out providing interesting information for decision makers.

In the following chapter, the chosen capability approach, the marginality index for agricultural land use will be described in detail.

## *3.3 The marginality index for agricultural land use: Scientific background and determination*

For the evaluation of the biophysical resources of Benin the marginality index of agricultural land use was chosen. Thus, the feasibility of a global approach on a national scale is analysed. The marginality index was defined within the German Global Change research framework, called *Syndromes of Global Change*. The index is therein the natural dimension of the Sahel-Syndrome. In this subsection, the syndrome approach will be introduced briefly in chapter 3.3.1. Then in 3.3.2, the Sahel-Syndrome will be presented. Finally, the determination of the marginality index is illustrated and discussed in 3.3.3.

### 3.3.1 Syndromes of Global Change

In the 90s, a novel transdisciplinary approach within the German Global Change research was set up to express and model global environmental change, the *Syndromes of Global Change* (WGBU 1996, SCHELLNHUBER et al. 1997, PETSCHEL-HELD et al. 1999, LÜDEKE et al. 2004). The approach was developed by the German Advisory Council on Global Change (WBGU) together with the Potsdam Institute for Climate Impact Research (PIK) (PILARDEAUX 1997).

One of the basic beliefs was that the phenomenon of global change should not be divided into sectors, regions or processes. Furthermore, it should be understood as a "*co-evolution of dynamic partial patterns of unmistakable character*" (SCHELLNHUBER et al. 1997:20). Hence, the principal aim of the approach was the decomposition of the essential dynamics of Global Change into patterns of problematic, which means unsustainable, civilization-nature interactions called *syndromes*. The term *syndrome* is used in a double sense (cf. SCHELLNHUBER et al. 1997). On the one hand neutrally, in the sense of the ancient Greek, meaning a coalescence of many factors. And on the other hand normative, in the sense of medical terminology as a complex clinical profile of the earth system. Another term is derived from medical context, the *symptoms*. Symptoms are interlinkages of the most relevant natural and human-induced trends and syndrome dynamics.

This approach intends to conceptualise the symptoms by a small number of qualitative functional models (SCHELLNHUBER et al. 1997, PETSCHEL-HELD et al. 1999, LÜDEKE 2001). These models express various intersectoral cause-effect complexes, which are defined globally on an aggregated and abstract level (LÜDEKE et al. 1999, PETSCHEL-HELD et al. 1999). The particular aim of the approach is to identify precautionary measures avoiding severe and irreversible damage to human societies and natural systems. Beyond, strategies to mitigate problems related to global change shall be set up. Therefore, the understanding of the earth system is aimed to be improved and the concept of sustainable development to be more clearly defined. The methodology of the approach includes fuzzy logic (see chapter 3.3.3.3) and qualitative differential equations. The latter, which is not further examined in this study, is described in detail by PETSCHEL-HELD et al. (1999) and PETSCHEL-HELD & LÜDEKE (2001). Both methods allow implementing qualitative knowledge as well as case studies, which were essential for the definition of the different syndromes and their global characteristics.

With the focus on man-nature relations, this approach contains one of the essential basic ideas of geography (see for more details CASSEL-GINTZ 2001). Consequently, the syndrome concept is incorporated in numerous recent scientific and scholar geographical education materials (HARENBERG 2004, HELLBERG-RODE 2004, NILLER 2004, GEBHARDT et al. 2006, DED SCHULPROGRAMM BERLIN et al. 2007).

### 3.3.2 Sahel-Syndrome– overuse of marginal land

The core characteristic or *kernel* of the Sahel-Syndrome consists of a downward spiral incorporating the symptoms impoverishment, intensification/expansion of agricultural activities and environmental degradation (PETSCHEL-HELD et al. 1999, PETSCHEL-HELD & REUSSWIG 2000, CASSEL-GINTZ 2001). Poor rural population are thereby forced to expand their agricultural activities onto marginal lands due to few or missing alternatives to ensure food security. Agricultural marginal sites, however, are characterised by various environmental constraints limiting agricultural productivity (cf. 3.3.3.1). Furthermore, marginal sites are particularly prone to agricultural overuse and thus, environmental degradation (CASSEL-GINTZ et al. 1997, LÜDEKE et al. 1999).

The degradation of the natural resources damage the biophysical production basis, decrease yield, and lead to further impoverishment stimulating an extension of the syndrome (LÜDEKE et al. 1999, PETSCHEL-HELD et al. 1999). Case studies in poor countries analysing peasant agro-ecosystems indicate that this core mechanism of the syndrome describes the situation of many people in developing countries caught in a typical socio-ecological trap (e. g. BILLINGS et al. 1989, LEONARD 1989, REENBERG & PAARUP-LAURSEN 1997, YOUNG 1998, BLUM & ESWARAN 2004). Fig. 16 illustrates the kernel of the syndrome (yellow ellipses) and further symptoms making up the characteristics of the overuse of agriculturally marginal land.

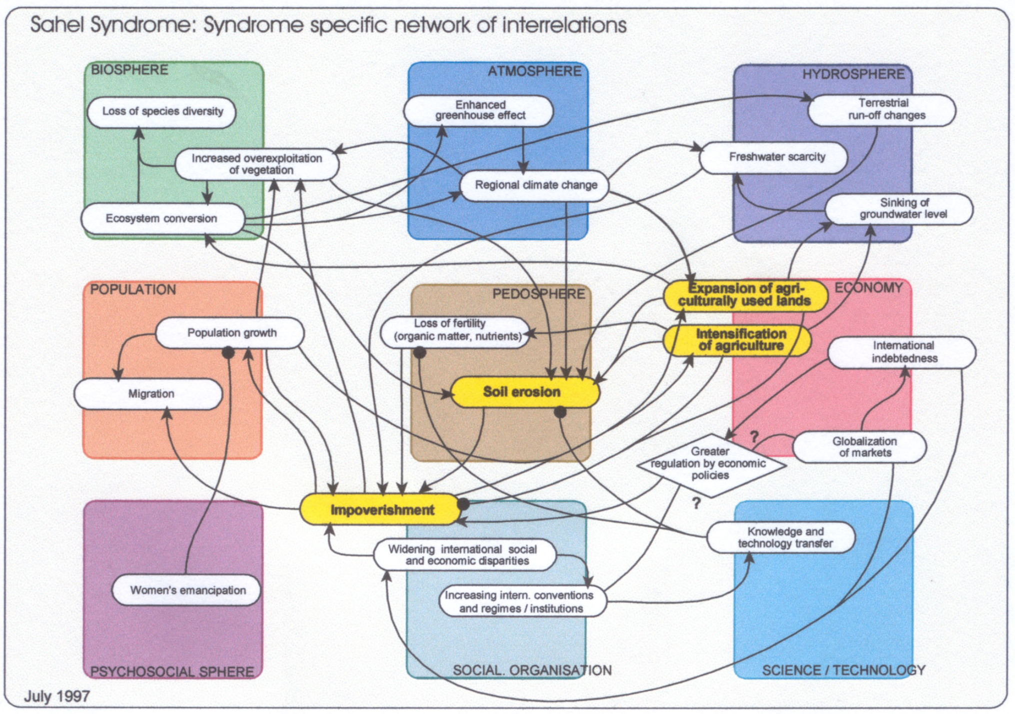


**Fig. 16: The Sahel-Syndrome specific network of interrelations with the core symptoms in yellow (PETSCHEL-HELD et al. 1999: 301)**

It is a primary task of the *syndrome diagnosis* to identify geographical patchworks that adequately typify syndromes on a global scale (PETSCHEL-HELD et al. 1999). The analysis must thereby on the one hand avoid getting lost in accidentals and details being coarse-grained enough. On the other hand, the chosen indicators and interactions between them must be detailed enough to achieve a sufficient overview on the dynamics of global change (PILARDEAUX 1997, PETSCHEL-HELD et al. 1999). The concept of syndrome diagnosis consists of three mutually consistent parts: *disposition*, *intensity*, and *exposition* (cf. SCHELLNHUBER et al. 1997, PETSCHEL-HELD et al. 1999).

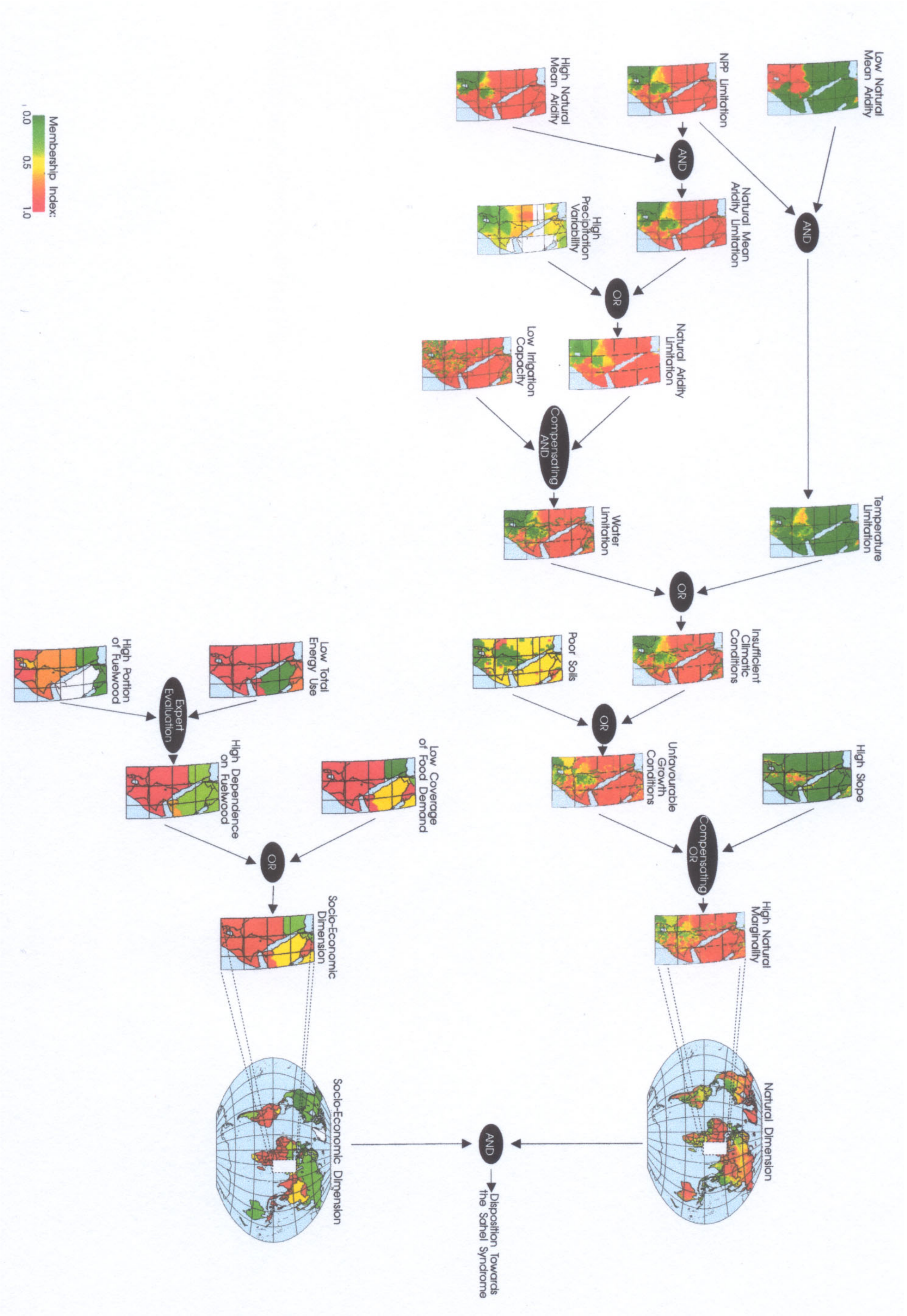


**Fig. 17: The decision tree for the socio-economic and natural dimension towards the Sahel Syndrome (SCHELLNHUBER et al. 1997:27)**

The **disposition** measures the proneness of regions to the kernel of a syndrome.

The determinants of the disposition change slowly in time and can thus, be considered as early warning indicators. The disposition consists of a natural and a socio-economic component. For the Sahel-Syndrome, the marginality index for agricultural land use was developed as a complex indicator for natural marginality evaluating the biophysical resources (CASSEL-GINTZ et al. 1997, LÜDEKE et al. 1999). The socio-economic proneness of a society depends on its reliance on agricultural production and the proportion of subsistence farming (cf. Fig. 17).

The **intensity** determines whether a syndrome is active in a specific region (cf. SCHELLNHUBER et al. 1997, CASSEL-GINTZ 2001). Meaning it is analysed, in which regions the syndrome-specific interactions of the kernel can be found and hence, a breakout of this syndrome is likely. For the Sahel-Syndrome, data on poverty, intensity of agricultural land use and soil degradation were chosen and a mathematical model set up (cf. PETSCHEL-HELD et al. 1999, CASSEL-GINTZ 2001).

The transition from a prone to an actually affected region is triggered by the **exposition** factors. Exposition factors were divided into endogenous and exogenous factors, respectively. Endogenous ones are captured within the syndrome approach whereas syndromes or symptoms do not examine latter factors, such as natural catastrophes.

## 3.3.3 The marginality index for agricultural land use

### 3.3.3.1 Natural agricultural marginality

The term *marginal site* is very widely used by different disciplines working in the context of land evaluation, land degradation or food security and, thus causes altering associations (e.g. SYS et al. 1991A, GRAEF 1999, DORRONSORO 2002, DAVIS 2003). Beyond, the term is often used without definition and interchangeable with other terms such as resource poor, low potential, fragile or vulnerable (CGIAR TAC 1999). Therefore, some introductive considerations about marginal sites will be given.

One problem to define such less-favoured areas stems from the heterogeneity and variety of encountered reasons for that (LIPPER et al. 2006). Thus, the definition of marginal sites can be based on numerous altering characteristics. Consequently, there exists no universally accepted definition to express marginal areas. Existing

definitions are often very general. The FAO (1996) describes marginal sites as low-potential land and fragile environments. PENDER & HAZELL (2000:3) support this definition by defining marginal areas as "*less favoured either by nature or by man*".
Within the Syndrome approach, a marginality index of agricultural land use was defined similarly general at a first glance. Hence, naturally based marginal agricultural sites are defined as fragile regions of a low natural agricultural productivity (see CASSEL-GINTZ et al. 1997, LÜDEKE et al. 1999). On a second glance however, incorporating its determination, the idea of marginal sites becomes clearer. Therein, marginal sites are quantified by a comprehensible selection of determinants based on a clearly defined logical decision tree (see also 3.3.3.2.). The index evaluates the biophysical resources with respect to marginality. In doing so, it can be seen as a capability approach for land evaluation.

### 3.3.3.2 Indicators and data sets

The marginality index of agricultural land use was developed by the Potsdam Institute for Climate Impact Research (PIK) and the Max Planck Institute for Meteorology (CASSEL-GINTZ et al. 1997). For its evaluation, several natural constraints limiting agriculture under low capital input on the global scale were quantified and summed into one integrative index: low natural plant production, restrictions due to temperature or light, high aridity, precipitation uncertainty, poor soils and the risk of erosion caused by the steepness of slopes. Beyond these constraints, the compensation of natural aridity by irrigation near inshore waters is taken into account as it can be implemented even with low capital input. CASSEL-GINTZ et al. (1997) chose the following six indicators incorporating the named compensation opportunities and constraints (see also Fig. 17):

1. Net primary productivity of potential natural vegetation (*NPP*)
2. Aridity coefficient (*Alpha*)
3. Internal variability of the seasonal precipitation pattern (*PV*)
4. Potential irrigation capacity (*IC*)
5. Soil fertility (*SF*)
6. Slope (*SL*)

In the following, the data sets, from which these indicators were derived, will be demonstrated. Additionally, the relations of these indicators according to the logical decision tree of the assessment algorithm will be outlined. For more details and background information see CASSEL-GINTZ et al. (1997), LÜDEKE et al. (1999), CASSEL-GINTZ (2001) or RÖHRIG (2002) as well as the reference quoted.

The **net primary productivity of potential natural vegetation (*NPP*)** is the elementary indicator within the determination of the marginality index (cf. Fig. 17). Sites with low NPP were considered as potential marginal sites. Regions of high vegetation productivity are, however, not automatically favourable for agricultural land use. For its estimation, the average of five different global models was used, as no single universally accepted model exists (cf. CASSEL-GINTZ et al. 1997). The indicator NPP was later modified by LÜDEKE et al. (1999) analysing the sensitivity of regional proneness towards the syndrome with respect to climate (see also CASSEL-GINTZ 2001). They used the Neural Net based Npp model (NNN) that is driven by climatic parameters from CLIMATE 2.1 estimating the annual equilibrium NPP of the current climate (see for more details MOLDENHAUER & LÜDEKE 2000). One advantage for the scenario analyses was that in doing so, all climate parameters implemented within the determination algorithm are interlinked.

The **aridity coefficient *alpha (Alpha)*** is a common indictor for drought (see e.g. LANDSBERG 1986, NISHIDA et al. 2003). In the syndrome context it is used twofold (*alpha low* and *alpha high*). Alpha high enables the detection of regions where low natural vegetation productivity is caused by aridity. Instead, alpha low is used to identify all areas, where climatic constraints are caused not by aridity (CASSEL-GINTZ 2007, personal communication). These results are named as limitations due to temperature and light within the determination algorithm. Alpha is assessed from the ratio of annual sums of daily actual and potential evapotranspiration (cf. PRENTICE et al. 1992 and LEEMANS & VAN DEN BORN 1994).

The impact of aridity on water availability is decreased by water storage capacity of soils as long as droughts occur only for a short time period. Hence, the indicator of **internal variability of the seasonal precipitation pattern *(PV)*** was defined to take into account uncertainties of agricultural productivity up to a total loss due to rainfall variations. PV is based on anomalies of monthly precipitation data within the growing season based on the standard deviation. For PV, only negative anomalies were considered believing that only less rainfall than normal would be problematic. As data, the monthly rainfall data from the World Meteorological Organisation (WMO) member stations were chosen.

Even with low capital input, aridity can be reduced near inshore waters. Thus, the **potential irrigation capacity (*IC*)** was set up to implement this compensation opportunity. The compensation effect works double. First, sites near rivers or lakes are characterised by a higher groundwater level. Second, irrigation can be realised rather simple close to waterbodies. The potential irrigation capacity or compensation degree depends on the severity of the drought on the one hand and on available amount of available water on the other hand. Furthermore, within plain landscapes, irrigation is easier to realise. Hence, IC was calculated from the inshore water density and slope. For the assessment of the water the hierarchically structured inshore water network from ARC/WORLD$^{TM}$ by ESRI was used (ESRI 1992). Recently, a more dynamic data set given by the MEGARUS model was chosen (cf. LÜDEKE et al. 1999). The model takes lateral and vertical fluxes of surface runoff into account. The slope data set was derived from the global digital elevation model ETOPO5 provided by the U.S. National Geophysical Data Center (1988).

Besides climate conditions, **Soil fertility (*$S_F$*)** is an elementary basis for the agricultural productivity. LEEMANS & VAN DEN BORN (1994) have developed a database with soil properties based on the soil classification of the global soil map by ZOBLER (1986). This map is based on the FAO Soil Map of the World from 1974 (FAO 1974). From this classification scheme, the fertility factor $S_f$ was chosen to incorporate soil fertility.

**Slope (*SL*)** is used to incorporate constraints due to topography. In doing so, the risk of erosion caused by the steepness of slopes was implemented. Again ETOPO5 was used as described above.

#### 3.3.3.3 The fuzzy-logic based determination of the marginality index

The calculation of the marginality index is based on fuzzy logic. In the following, a short introduction into the fuzzy set theory and its terminology are given first. Then, the processing of the input data and the outcome are presented.

The term **fuzzy logic** was introduced by Lotfi Zadeh in 1965 developing the theory of fuzzy sets (Kruse 1993). Fuzzy logic is an extension of conventional Boolean logic set up to handle the concept of partial truth meaning allocating continuous truth values. Boolean logic instead, divides only 'true' and 'false' working with true values of 1, which means true, and 0, which means false ($\mu \in \{0;1\}$). For many clauses based on personal judgement, however, there is no reasonable way to assign Boolean truth values. For example, the clause 'population growth is low' is true (=1) if it is below 2% per year and false (=0) if it is higher would not be appropriate. Nevertheless, one would be inclined to agree with the statement to a lower or higher extent. In such cases, fuzzy logic has been proofed helpful as it allows allocating continuous truth values to qualitative indicators, such as 'low' or 'high' (Zimmermann 1991, Kruse 1993). Using fuzzy logic, the possibility of partial membership of elements to a fuzzy set is calculated by evaluating infinite truth values between 0 and 1 ($\mu \in [0;1]$). This procedure of normalisation and evaluation is called *fuzzification*. Fuzzification means that for each value of the input data set a degree of membership of linguistic categories (low, high etc.) is set up in relation to its contribution to a fuzzy set (compare Fig. 18).

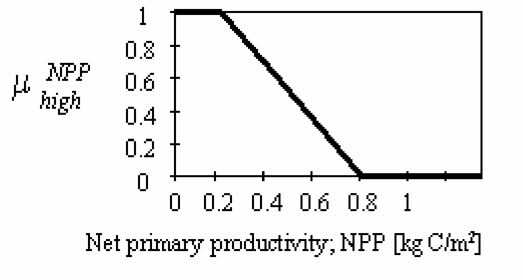


**Fig. 18: Fuzzification of NPP (according to Cassel-Gintz et al. 1997:139)**

In the **context of the marginality index**, all indicators are fuzzificated before they are summed up. In doing so, a degree of naturally based constraint and marginality, respectively is assessed for each indicator defining $\mu^{indicator}_{ling.category}$ ($0 \leq \mu \leq 1$) (Zimmermann 1991, Cassel-Gintz et al. 1997). A membership index of 0 indicates that on this site agriculture is not restricted by an indicator. Such sites have a high natural potential. Membership degrees nearby 1, though, implicate that on this site great efforts are required to achieve sustainable high yields. Between these minimum and maximum values, a linear fuzzy set membership equation was assumed for all indicators. The set up of the membership functions was done according to regional knowledge, empirical observations or measurements. Fig. 18 exemplifies the membership function for NPP.

In a further step, these fuzzificated variables were combined using a logical hierarchical decision tree (see in more detail CASSEL-GINTZ et al. 1997:137F). This step needs also an extension of the Boolean local operators as continuous truth values are combined and related. Within the decision tree all arguments for or against agricultural marginality are summed using fuzzy logic operators. The selection of operator is ruled by the question to what extent one clause can be compensated by the other. In doing so, parameters are weighted. In the course of time, numerous fuzzy logic operators have been defined (see e.g. KRUSE 1993). In most applications, however, non-compensatory *fuzzy AND* and *fuzzy OR* operators are used (ZIMMERMANN 1991). This is also true for the determination of the marginality index (cf. Fig. 17). If the fuzzy AND is used, a minimum operation is applied. This means that the high constraint of one feature diminish if the other constraint is low. In other words, both constraints must occur to come out with high limitations. Choosing the fuzzy OR operator the statement 'either or' is implemented and thus, the maximum value is taken. Hence, the final restriction can be caused by each of the feature; both are weighted in the same way. In doing so, the fuzzy AND Liebig's principle (1855) of the limiting factor was implemented.

Additionally, two compensatory fuzzy operators are used to assess the marginality index: the *compensatory AND* (*Lukasiewicz AND*) and *asymmetric-compensatory OR* (for more details see CASSEL-GINTZ et al. 1997:148). With the Lukasiewicz AND, the following statement was incorporated: without any irrigation capacities, natural aridity cannot be reduced to any degree, whereas middle irrigation availabilities can decrease high aridity to some extent and can totally compensate moderate aridity. The asymmetric-compensatory OR was taken to relate 'unfavourable growth conditions' and 'high slope'. In this context, extremely fertile sites under favourable climate conditions like in East Africa remain suitable for agricultural land use even as the slopes get steeper.

Finally, the combination of all natural constraints results into the marginality index. Fig. 19 shows the geographical distribution of natural agricultural marginality in a spatial resolution of 0.5° x 0.5° according to CASSEL-GINTZ et al. (1997). Red symbolises marginal areas and thus, regions of high natural disposition of the Sahel-Syndrome. Most parts of the world have biophysical conditions, which limit agricultural land use to some, often to a high extend. Marginal areas contain primarily deserts, mountainous regions or sites covered by ice. Larger favourable regions are found in Eastern America, in Southeast Asia and smaller ones in Western Europe, Western Africa and Eastern South America.

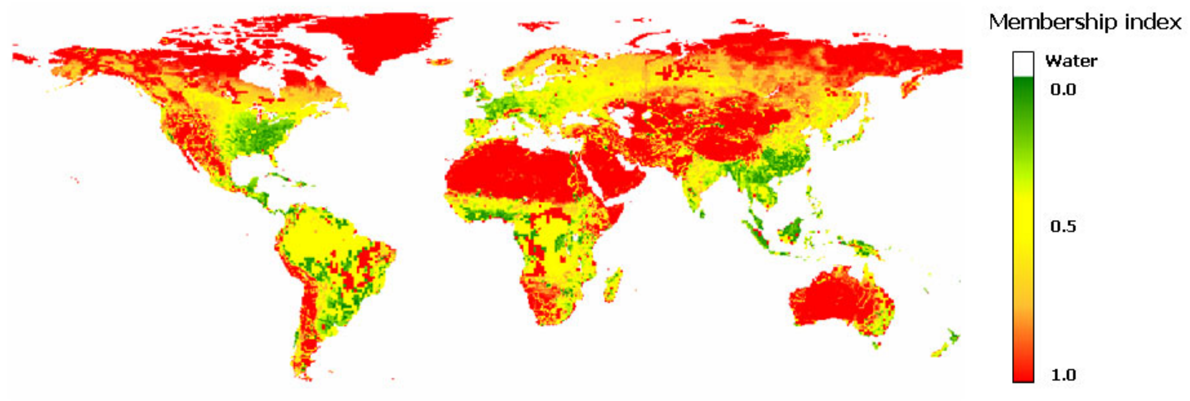


**Fig. 19: The global distribution of the marginality index (spatial resolution: 0.5° x 0.5°) (according to Cassel-Gintz et al. 1997:143, modified)**

Comparisons with recent land use patterns defined by WARNANT et al. (1995) indicate that the majority of farmers select favourable sites for cultivation. 30% of agricultural used areas show marginality values of more than 0.6 (cf. CASSEL-GINTZ et al. 1997). The majority of these sites are named as 'vulnerable' or fragile in the literature. Some of them are already affected by problems of land degradation such as Northern India. This was considered as an indirect proof of the correctness of the outcome.

### 3.3.4 Potentials and limitations of the approach

In the framework of the Sahel-Syndrome, naturally based agricultural marginality is defined on a global scale. The marginality index of agricultural land use comes out with very encouraging results as it corresponds with recent land use patterns. The restricted number of indicators is sufficient to reflect the natural constraints and its placement within the assessment algorithm is largely formulated clearly. That makes the assessment more transparent and comprehensible than the AEZ from the FAO, for instance, and thus attractive for decision support systems (cf. Laudien et al. 2007). The index is an early warning indicator to identify endangered regions. Furthermore, regions with a naturally high agricultural potential, meaning sites of low natural agricultural marginality, can be identified. Such high potential areas, concerning biophysical resources, are of specific interest for regions facing problems of growing population, poverty and scarce land resources like many of the less developed countries, such as Benin. The significance of such sites becomes even more valuable, if the sites aren't yet under agricultural use.

Beyond these advantages, the global approach contains some weaknesses. This includes the selection of the data sets and the derivations of the indicators, which are often subjective and sometimes vague. In particular, the essential indicator of fertility factor $S_f$ introduced by Leemans & van den Born (1994) is unconvincing. First, the explanation about its progress is not comprehensible and second, only five different values between 0.5 and 1.0 are distinguished (cf. Leemans & van den Born 1994:140). This range is certainly too little to reflect the variety of soil fertility adequately. Furthermore, it must be questioned whether a linear membership function is always suitable evaluating natural constraints, such as slopes for instance.

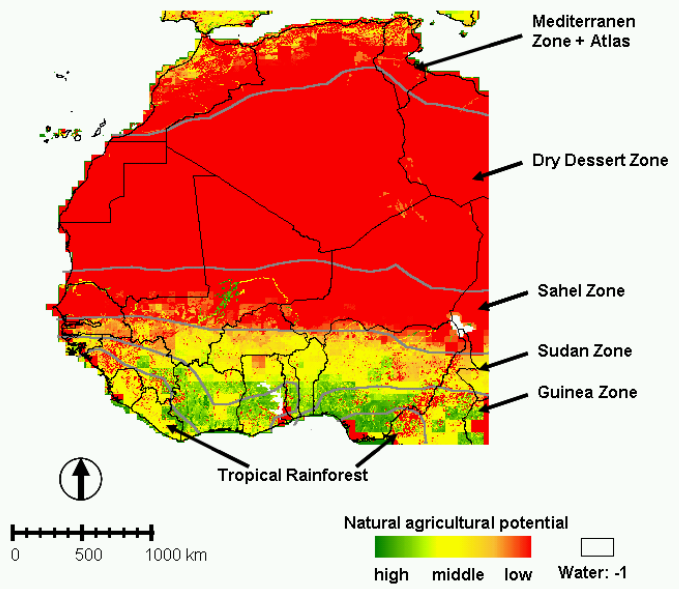


**Fig. 20: Naturally based marginality in Western Africa according to Röhrig & Menz (1995)**

Nevertheless, the potential of the approach in general and particularly its advantage for decision makers warrant further investigations about the feasibility of the approach for smaller study areas. Thus, global data, however, with a spatial resolution of 0.5°, can give only a very general idea about the risk of degradation caused by agricultural activities, and provides little information for national decision makers. Thus, successful investigations have already been undertaken to calculate the index for Western Africa at a spatial resolution of 0.05° x 0.05°

using influencing factors in a higher spatial resolution and an adapted fuzzy logic based algorithm (cf. RÖHRIG 2002, RÖHRIG & MENZ 2005). The outcome reflects well the biophysical conditions of the region.

# 4 Methodical set-up of the regionalisation approach

The marginality index for agricultural land use is utilized to evaluate the agricultural land resources of Benin. In using this index, the feasibility of a global approach on a national scale was examined. This section elucidates the methodological set-up of the regionalisation approach (see also Fig. 21). First in 4.1, theoretical aspects about the data choice and the fundamentals to implement an adapted determination algorithm will be illustrated. In doing so, results from field campaigns will be examined. In 4.2, theoretical aspects of an accuracy assessment framework for this study will be discussed. This will be followed by a demonstration of the validation approach applied herein.

## *4.1 Conceptual design of the regionalisation approach*

One of the main aims of this study was to analyse the transferability of the globally defined marginality index by CASSEL-GINTZ et al. (1997) and LÜDEKE et al. (1999) on the national scale of Benin.

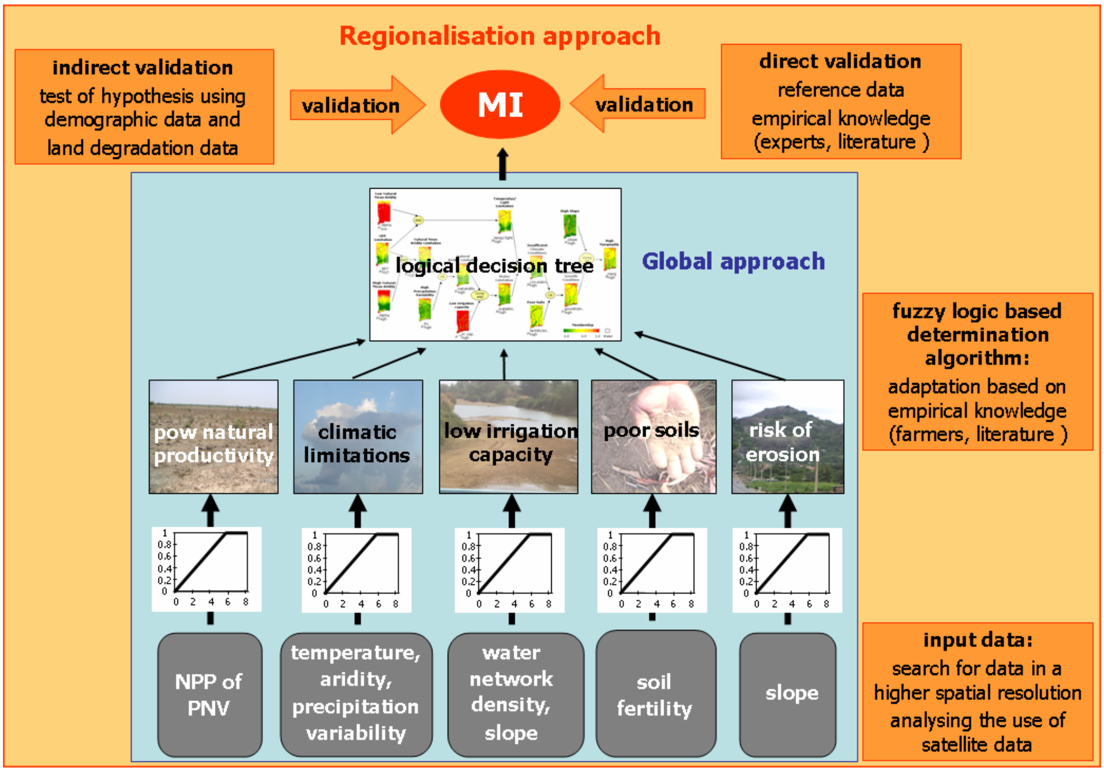


**Fig. 21: Concept of the regionalisation approach**

In practice, this means to determine whether the approach accurately reflects the biophysical constraints for agricultural land use in Benin and thus, enables to detect marginal sites. Therefore, investigations have been undertaken to regionalise this approach for Benin at a spatial resolution of 1 km x 1 km using influencing factors in a higher spatial resolution and an adapted fuzzy logic based algorithm. The outcome of the regionalisation will be labelled MI to distinguish it from the global result. The use of same or comparable input data, indicators and biophysical constraints are essential as the transferability of the approach was investigated.

Hence, one task was to assess the marginality index for Benin with adequate input data in a higher spatial resolution. Before, the relevance and meaning of the globally chosen indicators for the natural constraints were discussed with scientists from the IMPETUS project and national experts in Benin. For more information about the institutions and persons questioned in Benin see TableA 1. Then, input data sets analogous to those used in the global approach were searched (e.g. NPP, alpha, and slope), but at a higher spatial resolution. In doing so, the potential use of data derived from remote sensing was investigated. If the chosen data could not satisfy the needs on a national scale, comparable approaches and corresponding data were searched to determine the biophysical constraint. Essential information was derived by the literature review.

Beyond input data in an adequate spatial resolution, detailed regional knowledge is essential for a successful application of the approach for Benin. This is especially true as the evaluation algorithm is based on fuzzy logic. Fuzzy logic enables incorporating qualitative knowledge (see 3.3.5.3). In the context of the marginality index, empirical knowledge is essential to formulate membership functions and the logical decision tree. Original membership functions were assigned as a first approximation for assessing a natural constraint. If an original membership function did not calculate a natural constraint correctly, it was modified based literature review and interviews of farmers in Benin.

In **literature**, such as BERDING & VAN DIEPEN (1982), MDR & INRAB (1985), SYS ET AL. (1993) or ECOCROP of the FAO (2007) detailed crop-specific requirements are listed. Therein, for several crops optimal biophysical condition and sometimes graduation of the suitability of a feature are given. On the basis of this crop-specific information, general suitability graduations over major crops in Benin were defined. For ten of the most important crops in Benin (cotton, cowpea, groundnut, maize, millet, manioc, oil palms, rice, sorghum and yams) information about climatic and topographic indicators was summed. If the values varied between different sources due to different crop varieties, the ones specifically formulated for Benin (e.g. BERDING & VAN DIEPEN 1982 or MDR & INRAB 1995) were used.

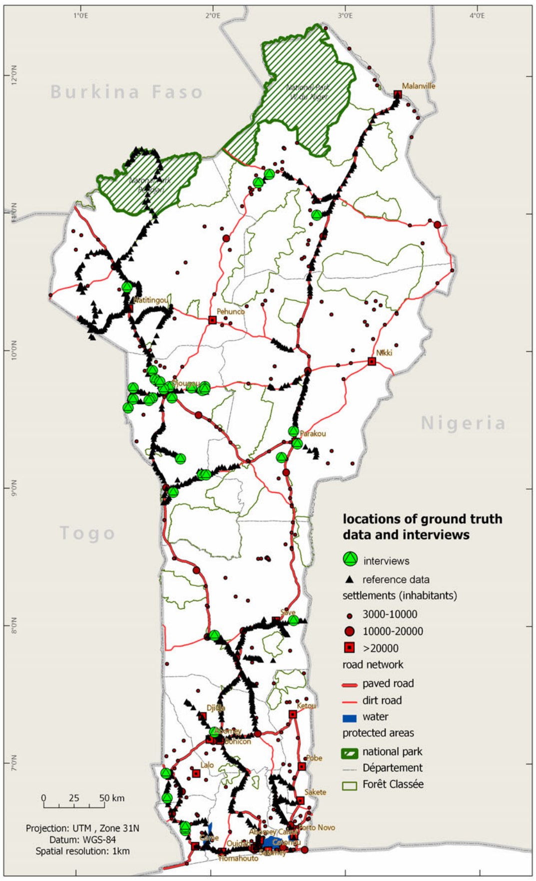


**Fig. 22: Locations of ground truth data and interviews recorded during 2005-2007**

Based on the number of crops for which a value fits well, suitability graduations were defined for each indicator. Thus, the term 'no constraints' (x0) expresses optimal conditions for all crops. Concerning some indicators, however, the requirements were controversial. In such cases an optimal range was defined based on the majority of crops. Requirements for the more common crops such as cotton, maize, millet, manioc, rice, sorghum and yams were thereby assigned higher weights. Accordingly, ranges with marginal conditions for all or the majority of crops express 'insufficient for agricultural land use' (x 1). In other words, none of the essential crops can be cultivated sustainably without certain compensation measurements.

During three field campaigns, **farmers** of 33 villages were **interviewed**. For the questioning, locations of different biophysical conditions for agricultural activities were chosen with a spatial focus in the Upper Ouémé catchment (see Fig. 22). In this area, starting in 1970, a dynamic small farming agricultural colonisation initiated by settlement activities of the state and Christian churches began (cf. DOEVENSPECK 2004). A spatial focus during one field campaign was thereby the surrounding of

Djougou and Ouakè in the west. Both regions are of particular interest for this study. Djougou is known for extended areas under cultivation; and the latter for severe degradation caused by overexploitation. In the north or southwest, detailed interviews were impeded due to linguistic problems.

The outcomes of the interviews were valuable for this study as they provided essential regional knowledge, although the number of interviews was too small to set up a statistically robust framework (cf. 4.2.2). To receive information about a larger spatial area and predominant features within this area, whenever possible a group of farmers were questioned (see TableA 2).

**Fig. 23: Interview with farmers from Manigri in central Benin (Photo: J. Röhrig, 2006)**

The key aim was to gain to obtain additional site-specific information about biophysical constraints. These statements were used to specify the thresholds of membership functions. This will be exemplified in subsection 6.1.7. Furthermore, common adaptation and conservation measurements were discussed. Therefore, semi-structured interviews were carried out based on an outline. Semi-structured interviews are interviews carried out by prepared questions and topics, but not by a universal standardised questionnaire. This technique is used to collect qualitative data by setting up a situation (the interview) that allows a respondent the time and scope to talk about their opinions on a particular subject. The advantage is that outcomes are more open-minded about aspects an interviewer is interesting in (Schnell et al. 1995).

## *4.2 Validation*

Beyond the regionalisation of the marginality index itself, the challenge of implementing a feasible validation approach on a national scale was undertaken. In this subsection, theoretical aspects of an accuracy assessment framework for this study will be discussed. Then, the chosen validation approach will be demonstrated.

### 4.2.1 Theoretical aspects setting up a validation framework

The theoretical considerations address characteristics of large-area data products in low spatial resolution as well as characteristics concerning the index itself. Both characteristics are important to keep in mind while setting up an adequate validation framework for this work. Thus, insecurities of research can be more easily identified, which is essential for accuracy assessment (SHI et al. 2005).

The marginality index is assessed on national scale in a spatial resolution of 1km. Thus, it is a **large-area product in a coarse resolution**. This fact entails some characteristics considering accuracy assessment. First, it is generally difficult to label 1km² of land adequately as landscapes are rarely homogeneous on this spatial scale (WULDER et al. 2006). Thus, the problem of mixed pixels is common. One consequence is that accurate geographical positions of pixels are more difficult to assign and prove. Second, the set up of a feasible accuracy assessment framework is more problematic than for smaller test sites and more highly resolved information. In praxis, it is often impossible to set up a statistically rigorous accuracy caused by sufficient numbers and sizes of reference data (MERCHANT et al. 1994, MUCHONEY et al. 1999, WULDER et al. 2006). The collection of adequate ground truth data often suffers due to logistical, financial or temporal compromises. Thus, validation matters themselves were for a long time neglected completely (ACHARD et al. 2001) and standardised frameworks for validation of large-area classification products, for instance, have only been addressed recently (e.g. FOODY 2002, WULDER et al. 2006).

A common way to validate coarse resolution classification products is to use higher resolution data products or additional data (ACHARD et al. 2001, BOSCHETTI et al. 2001, USGS 2006, WULDER et al. 2006). This is based on assumptions that higher resoluted data reflects reality, the time of recording is comparable, and that the classes are similar interpretable independent from different spatial resolutions. As these aspects are often not true, a consensus has developed that classification outcomes derived from high-resolution data cannot automatically be transferred onto coarse products although they are still valuable for validation (WULDER et al. 2006). Concerning the marginality index, a comparable approach exists neither in a similar nor in a higher spatial resolution for Benin. Until now, merely suitability land evaluation schemes exist in a comparable spatial resolution and extent (cf. chapter 3.2.5). Consequently, there was no opportunity for a direct comparison with already existing studies.

Furthermore, the **index as well as fuzzy logic** is problematic to validate the data product. Concerning the index, Cassel-Gintz et al. wrote, "*the defined marginality index does not have a directly measurable analog. For this reason a direct validation of the results of this assessment is not possible*" (Cassel-Gintz et al. 1997:144). Fuzzy logic contains many advantages as the method enables the incorporation of qualitative knowledge rather easily. The validation of its outcome implies, however, some difficulties. Instead of a binary decision, a continuous degree of membership underlies the evaluation algorithm. It is impossible to judge whether a membership degree of a site is indeed 0.34 or maybe only 0.29. Consequently, no error matrix, which is common for accuracy assessment of classification results, is feasible in this context. Fig. 24 summarizes essential characteristics of this study and corresponding problems and consequences for an accuracy assessment.

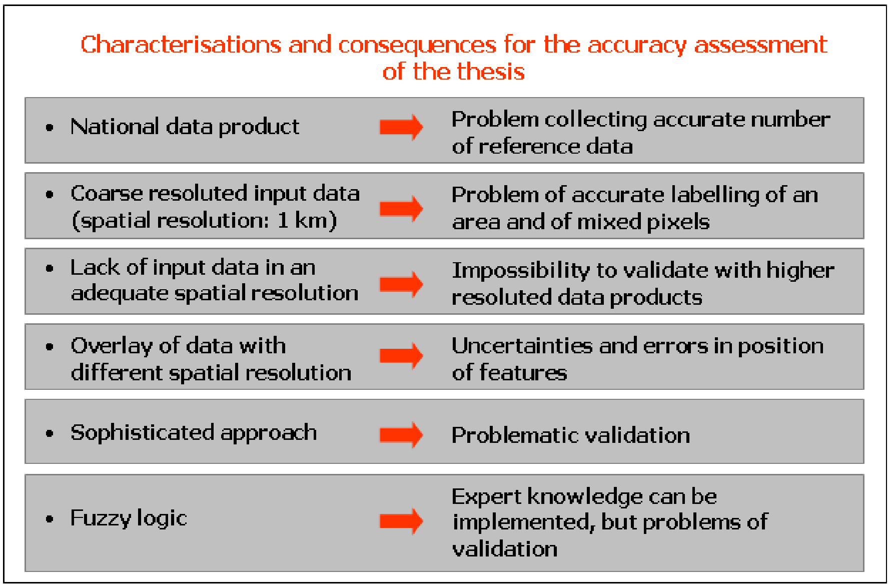


**Fig. 24: Summary of theoretical fundamentals for the validation framework**

### 4.2.2 Validation approach of this study

For the regionalisation, both a direct and an indirect validation approach were performed. The latter is based on ground truth data. The indirect validation approach was conducted also with reference data, but mainly with auxiliary data. For latter, demography and land degradation information were determined.

During the field campaigns ground truth data were gathered for **direct validation** reasons. In contrast to the global approach, at least 'high marginality' was measurable on the ground due to a more concrete definition of the term. Furthermore, the smaller extent of the study area and the higher spatial resolution promoted direct validation. Thus, the focus was on the recording of marginal sites and their specific constraints. For validation, a handheld with GPS functionalities was used, on which the software programme ArcPad was installed (ESRI 2002, see Fig. 25). ArcPad is a software for field mapping and mobile GIS applications. Two thirds of all recorded sites were topographically marginal sites, which were clearly observable in the field due to steep slopes. Additionally, farmers often showed marginal sites surrounding their village after discussing the subject during interviews. In such cases, poor soils or steep slopes caused the marginality. Altogether, information at about 100 ground truth locations could be collected.

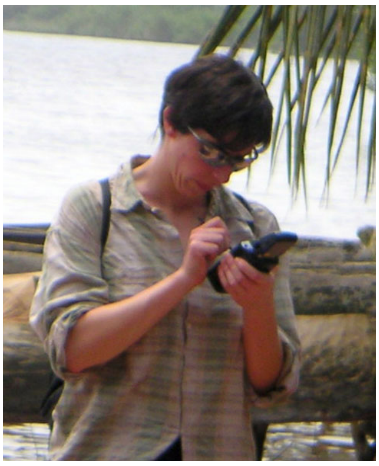


**Fig. 25: Record of reference data (Photo: V. OREKAN, 2006)**

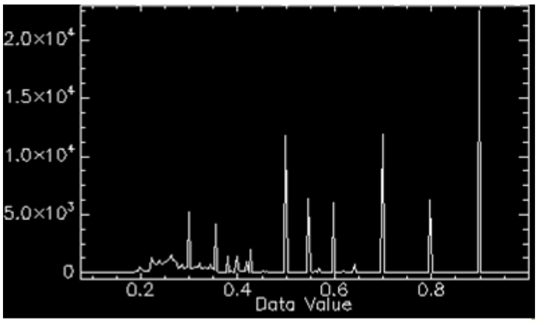


**Fig. 26: Histogram of MI for Benin**

Due to the specific characteristics of fuzzy logic (see 3.3.3.3), a statistical test was used to analyse whether marginal sites are reflected well by the marginality index. Therefore, it was tested whether marginal sites recorded in the field are significant higher than the mean MI-value of Benin. The Wilcoxon rank-sum test, also known as Mann-Whitney u-test, was applied for this analysis. This test is a nonparametric alternative to the t-test (see also 5.3) that is based only on the sequence in which the observations from the two samples occur. The test analyses the hypothesis that two sample populations have the same mean of distribution against the hypothesis that they differ. In the context of this work, a nonparametric test is necessary as the marginality index does not follow a normal distribution (cf. Fig. 26). The Wilcoxon rank-sum test is based on the nearly-normal test statistic (Z) (see WALPOLE & MYERS 1985). The test is incorporated in IDL-program by the *RS_TEST*-function (for more information about the function see RSI 2000). RS_TEST calculates the Mann-Whitney statistics (Ux and Uy), which is used to determine the test statistic (Z) and the one-tailed probability to obtain a value of Z or greater. If the computed probability is greater than the 0.05 significance level the hypothesis is confirmed that the two sample populations have the same distribution mean.

With the direct validation approach, only marginal sites are considered. Consequently, an **indirect approach** was additionally carried out. This validation approach is based on the assumption that farmers choose agricultural land selectively, at least in the long term. Furthermore, it is assumed, that marginal sites under cultivation are particularly prone to land degradation (cf. CASSEL-GINTZ et al. 1997). Consequently, additional data, in particular demographic and land degradation data were used for an indirect validation.

First, it was investigated how the biophysical conditions of the regions, where people in Benin live and cultivate, are characterised. Therefore, own reference data as well as population figures disaggregated from census data in Benin were compiled. Due to the high degree of subsistence in Benin, settlements are spatially closely linked with areas under cultivation. Methods used to disaggregate the recorded population figures will be examined in more detail in chapter 5.2. During own field campaigns, altogether 675 sites dominated by agricultural activities, were recorded. However, it has to be kept in mind that the average field size in Benin is small and hardly any area of a 1km² is entirely under cultivation. Nevertheless, most savanna areas show typical forms of former agricultural activities and thus, even larger areas are detectable as agriculturally used (cf. chapter 2.4).

Second, the hypothesis was tested that people cultivate generally favoured land. In other words, farmers avoid marginal sites. Thus, the relationship between degree of marginality and population density was investigated. The hypothesis is confirmed if the degree of marginality declines with increasing population density values. Therefore, the mean MI of different population density classes was statistically analysed. For this analysis, the statistical Wilcoxon Rank-Sum Test was applied again to test whether each mean differ significantly from the national mean (see description above). Additionally, the Kruskal-Wallis H-Test was performed to test the hypothesis that the sample populations have an equal mean of distribution against the hypothesis that they vary. Therefore, the IDL *KW_TEST* function was applied. This test is an extension of the Rank Sum Test (RSI 2000) based on the H-test statistic that approximates a Chi-square distribution with defined degrees of freedom (WALPOLE & MYERS 1985).

Finally, vulnerable sites, or more specifically, marginal sites under cultivation, were considered in more detail. Following the syndrome approach, these are particularly prone to land degradation. Thus, the locations of these sites were compared with areas, which are known to be affected by strong degradation (e.g. AKAPI 2002, CENATEL 2002, MEHU 2003, JUNGE 2004, MULINDABIGWI 2006).

# 5 Data for the evaluation of current and future agrarian land resources of Benin

In this chapter the indicators and data used for the evaluation of the agricultural land resources will be illustrated. Thus, input data used to determine the biophysical constraints and thus necessary to assess the marginality index, demographic data, as well as trends of land degradation will be examined. The latter two data types make it possible to derive real risk and recent spatial trends of land degradation. In 5.1 the indicators and data to assess the marginality index on a national scale will be examined. In doing so, modifications applied in this study will be discussed. Therein, the indicators will be demonstrated first in 5.1.1. Afterwards in 5.1.2, the data sources and their processing will be illustrated. The opportunity to implement data derived from remote sensing will be thereby addressed. The succession of the data descriptions (5.1.2.1-5.1.2.7) follows thereby the appearance of the related constraints in the logical decision tree. Then, in 5.1.4 the indicators and datasets used for the scenario analyses of MI will be described. In subsection 5.2, the spatial interpolation of population density from census data will be examined. Finally, the derivation of land degradation from remote sensing will be exhibited in detail in 5.3. Furthermore, recent trends of land degradation will be discussed and compared with own observations in the field.

## *5.1 Indicators and data to determine the current biophysical conditions for agricultural land use in Benin*

### 5.1.1 Definition of the indicators

Several natural biophysical constraints were incorporated for the evaluation of the marginality index on the global scale (cf. chapter 3.5.2). For each natural constraint, one adequate indicator was set up (see Table 2, left column).

In a first step of the regionalisation, it was analysed whether these six indicators sufficiently reflect the key natural constraints in Benin. The aim was to consider the issue of agricultural marginality with a sufficient level of complexity, while restricting the number of input data to the most crucial ones. The tangibility of the data amount is of particularly importance if an algorithm will be implemented within a decision support system, as scheduled within the IMPETUS framework. Besides literature review, this issue was discussed intensely with other scientists from the IMPETUS project and national experts in Benin. For more information about the institutions and persons questioned in Benin see appendix TableA 1. Nevertheless, it has to be mentioned, that no other capability approach exists for Benin thus, no direct comparison was possible (cf. 3.2.5). Hence, the chosen indicators are geared to available suitability approaches, like the Agro-Ecological Zones.

| **Indicators chosen in the global approach by CASSEL-GINTZ et al. (1997)** | **Indicators chosen for the regionalisation (MI)** |
|---|---|
| Net primary productivity of potential natural vegetation (NPP) | Potential natural vegetation cover (PVEG) |
|  | Temperature (TEMP) |
| Aridity coefficient *alpha* | Length of growing period (LGP) |
| Internal variability of the seasonal precipitation pattern | Rainfall variability (RV) |
| Potential irrigation capacity | Potential irrigation capacity (IC) |
| Soil fertility | Soil fertility (SOIL) |
| Slope | Slope (SL) |

**Table 2: Indicators of the global and of the regionalisation approach**

The gathered information approved the general adequacy of the chosen constraints and indicators on the national scale. The six indicator names were modified partly, if the input data set on the national scale changed significantly (PVEG, and LGP) or if the term was long and complicated (RV).

In addition to the already incorporated constraints, restrictions caused by temperature were added (see Table 2). CASSEL-GINTZ et al. (1997) used the aridity coefficient *alpha* to derive besides aridity, temperature and light limitations. For the national scale, however, a separate indicator of temperature was incorporated to detect directly regions with temperature limitations. Further explanation is given in 5.1.2.2.

The literature review and the discussion with several experts in Benin proved that the chosen constraints and indicators on a global scale are key biophysical limitations for agricultural land use in Benin (e.g. BERDING & VAN DIEPEN 1982, MEHU 2003, IGUÉ et al. 2004). Although the suitability approaches of BERDING & VAN DIEPEN (1982) or IGUÉ et al. (2004) use naturally more to derive crop specific information (cf. chapter 3.2). For instance, they implemented yearly rainfall amounts as a further aridity indicator. In addition, other features, such as humidity during the growing season or duration of daily sunlight are incorporated, but cause only slight constraints (cf. Igué 2000, WELLER 2002). Consequently, the approach is generally feasible to describe and define marginal sites on a national scale, too. Only temperature constraints were necessary to add as a separate indicator. In addition, the applied modifications of the indicators labelling were realised primarily to increase the tangibility for national decision makers.

### 5.1.2 Input data and assessment of the indicators

For every indicator implemented within the assessment of the index, adequate datasets free of charge were searched for the regionalisation. Therefore, the implementation of data derived from remote sensing was analysed. In the following subsections the chosen input data and their pre-processing will be illustrated. The input data were mainly processed with the software ENVI/IDL (RSI 2000). If other software was used, it is mentioned in the text.

#### 5.1.2.1 Potential natural vegetation cover (PVEG)

For the general detection of the upper boundary for agricultural plant production the indicator of **net primary productivity of potential natural vegetation (NPP)** was chosen as the base indicator within the original approach (CASSEL-GINTZ et al. 1997). In doing so, potential marginal sites that are sites, where the natural vegetation is limited due to biophysical constraints, should be detected (cf. 3.3.3.2). The potential natural vegetation is hypothetical vegetation which would be found due to climatic and pedological characteristics in the absence of human impact (THÜXEN 1956). It represents the optimal production of the vegetation without human influence (ESSER 1993). The net primary productivity is defined as "*the rate at which radiant energy is stored by photosynthetic and chemosynthetic activity of producer-organisms, chiefly green plants, in the form of organic substances which can be used* *as food materials"* (ODUM 1971, cited in AJTAY et al. 1979:1). Radiation and climatic features, particularly rainfall, temperature, and availability of nutrients, which control the absorption of the photosynthetic active radiation (PAR), and the transformation primarily drive NPP into organic matter (LANDSBERG et al. 1997, HIBBARD & SAHAGIAN 1998, RICHTERS 2005).

NPP is a significant feature in various studies analysing and modelling vegetation characteristics and cover or assessing the carbon dynamics of terrestrial ecosystems in the framework of global change (e.g. LIETH 1975, LANDSBERG et al. 1997, CRAMER et al. 1999, RUNNING et al. 2000, CLARK et al. 2001, NEMANI et al. 2003, RICHTERS 2005). Since the first simple regression model, the MIAMI model of LIETH (1975), a wide range of models have been developed to quantify NPP. They differ enormously according to complexity, necessary input data and region of interest. A good overview about existing approaches and models are given in HIBBARD & SAHAGIAN (1998) or RICHTERS (2005).

As climate information in an adequate spatial resolution are missing within several regions in the world, recent studies modelling NPP are increasingly based on data derived from remote sensing (cf. NEMANI et al. 2003, RICHTERS 2005). For the tropics in particular, information and data about NPP are sparse (CLARK et al. 2001). They are applied to gain information about the actual vegetation performance and have yielded encouraging results. The same is true for existing NPP-products, such as from SPOT VEGETATION or MODIS (Moderate Resolution Imaging Spectroradiometer). For Benin, however the actual vegetation conforms to the potential vegetation only within restricted regions of protected forests and marginal areas (e.g. inselbergs or sites with ironstone) (cf. 2.2.4). Hence, a model approach based on remote sensing data seems not helpful in the context of the marginality index. Furthermore, climatic data in an adequate spatial resolution are still missing for modelling NPP.

Thus, instead of NPP, the closely related feature, the one of **biomass** and the dataset of 'Maximum potential biomass density' (PBD) by (BROWN & GASTON 1996) was used as to derive potential marginal sites due to low natural plant production. Before the data set is described in more detail, some general information about biomass and its relationship to NPP will be given. Biomass is defined by Brown (1997) as "*the total* *amount of aboveground living organic matter in trees expressed as oven-dry tons per unit area*" (Brown 1997:4). The potential biomass density is the "*potential amount that the landscape can support under prevailing environmental conditions*" (Brown 1997:27). Hence, it corresponds with the concept of the potential vegetation. Generally, the correlation between NPP and biomass is loose, and is not broadly helpful for the estimation of productivity itself. Biomass is much affected by ages of the dominant plants, and these ages differ much in succession communities (Lieth 1975). Focusing, however on the potential natural vegetation, this restriction seems not that crucial. Additionally, Clark et al. (2001) found a significant relationship between biomass and biomass growth. As the tropics and hence Benin is characterised by a high productivity, biomass seems suitable to substitute the original indicator of NPP.

Brown et al. (1996) set up the '**maximum potential biomass density**' (PBD) data set as part of the numeric data package 'NDP-055' for tropical Africa in a spatial resolution of 5km x 5km. The database can be downloaded freely from the internet (Brown & Gaston 1996). The PBD was determined for the woody vegetation based on climatic, pedological and topographic data. Different biophysical information was summed into one climatic, one pedological, and one topographic image (for more details see Brown et al. 1996, Brown 1997). These three data classes were normalized in a further step, when data values were transformed within a range of 1-25. Afterwards, Brown et al. summed these values into one index, the PBD index. The climate layer accounted for 50% of the possible index value, and both the soil and the topographic layer accounted for 25%. From this index, they derived concrete biomass density values according to an intensive literature review (cf. Brown et al. 1996). They assumed thereby a logistic-shaped function between the PBD index and biomass. Fig. 27 illustrates the result for Africa.

For Benin, the values range from 7 Mg/ha in the north up to 250 Mg/ha in the south. The result comes out with the highest values in the transition zone of bimodal to unimodal rainfall patterns.

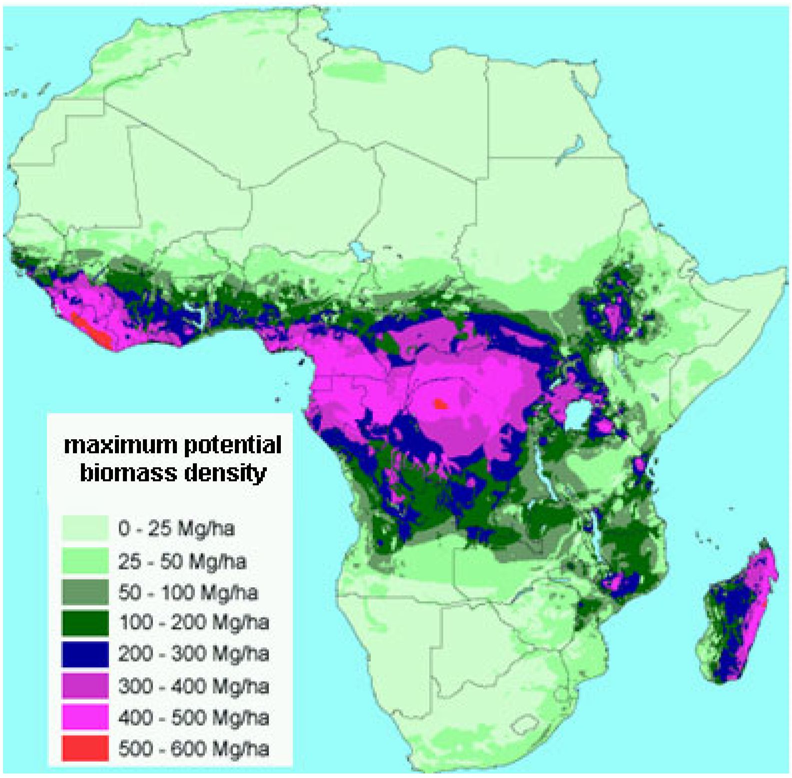


**Fig. 27: Outcome of the maximum potential biomass density for Africa according to (Brown & Gaston 1986)**

Although this data set seems to be the best base to detect potential marginal sites, it possesses several restrictions.

First, the approach considers the biomass above the surface and for woody vegetation only.

Additionally, the used input data are not very detailed. Climatic data were obtained from the FAO agro-meteorology database and then interpolated. In doing so, climate data were extrapolated into areas with little or no data. Information about soil characteristics were derived from the FAO soil map of the world which is not very detailed for Benin (cf. 5.1.2.6). Consequently, the result of PBP is not very detailed on a national scale. Although the spatial resolution of 5 km is acceptable, the vegetation of Benin is characterised by only six different values. Thus, Benin consists of several zones with sharp boundaries, which seems not to reflect the natural conditions.

Before the data set was implemented within the marginality index determination, some **pre-processing** was necessary. The original projection of normal cylindrical equal-area projection was converted into the UTM projection, Zone 31 North. Additionally, the image was resampled into 1km x 1km grid cells using cubic convolution for resampling. In doing so, the outcome consists of 335 samples and 682 rows. Finally, a low pass convolution filter with a kernel size of nine was applied to smooth the unnaturally sharp boundaries within the image.

#### 5.1.2.2 Temperature (TEMP)

The global approach contained no separate indicator of temperature constraints, although this limitation is named within the determination algorithm. This indirect incorporation is realized by alpha low, a second fuzzification outcome of the aridity index *alpha* (CASSEL-GINTZ et al. 1997, SCHELLNHUBER et al. 1997; cf. 3.3.5.2). For Benin, the implementation of the additional data set of temperature was decided to be able to detect regions with temperature constraints directly.

The most common way to receive temperature values is to measure them at climate stations. **Remotely sensed surface temperate** is of special interest in areas where climate stations are sparse or non-existent. In Benin, temperature is available at only six climate stations. Hence, remote sensing is very helpful to achieve spatially detailed temperature information for Benin. Therefore, the temperature data were taken from the MODIS MOD11A1-product ('Land Surface temperature'; LST) which is available in a spatial resolution of 1km x 1km on a global scale. Daily data for the years 2001-2006 were downloaded from EOS Data Gateway (USGS et al. 2007). The spatial extend of Benin consists of two HDF-data for each day, which resulted in a greater data amount. The LST product consists of 12 bands containing information about emissivity, day- and night-time surface temperature, times observations, quality control, view zenith angles, and clear sky coverage for both recordings. Due to the present version of the MODIS cloud-mask product land pixels are processed only in clear-sky conditions at a confidence level of 99% (WAN 2002).

The differences between the LST-products of MODIS and conventional temperature measured at climate stations are intrinsic. They vary with land-cover structures and materials, wind speed, solar zenith angle, and the viewing angle of the land-surface temperature (WAN 2002, MOSTOVOY et al. 2006). Additionally, the temporal resolution of the air temperature data is much higher, as thermometers 2 meters above the ground record measurements at regular time intervals (e.g. one hour). In contrast, satellite measures the thermal radiation at its specific overpass time which is twice a day for the MODIS LST-products (around: 10:30 am and pm local solar time). Consequently, direct comparisons seem to be inappropriate because of fundamental differences between data. Several studies although, demonstrated high correlations between them (e.g. Wan 2002, Mostovoy et al. 2005, Mostovoy et al. 2006, Colombi et al. 2007). Especially stratified approaches that subdivide areas according to land cover or altitude comes out with encouraging linear regression models between air temperature and MODIS LST-products (Mostovoy et al. 2005, Mostovoy et al. 2006, Colombi et al. 2007). Unfortunately, such approaches cannot be applied for Benin due to the restricted number of measured air temperature data of Benin (six weather stations). Hence, temperature and its constraints were derived directly from the LST-products.

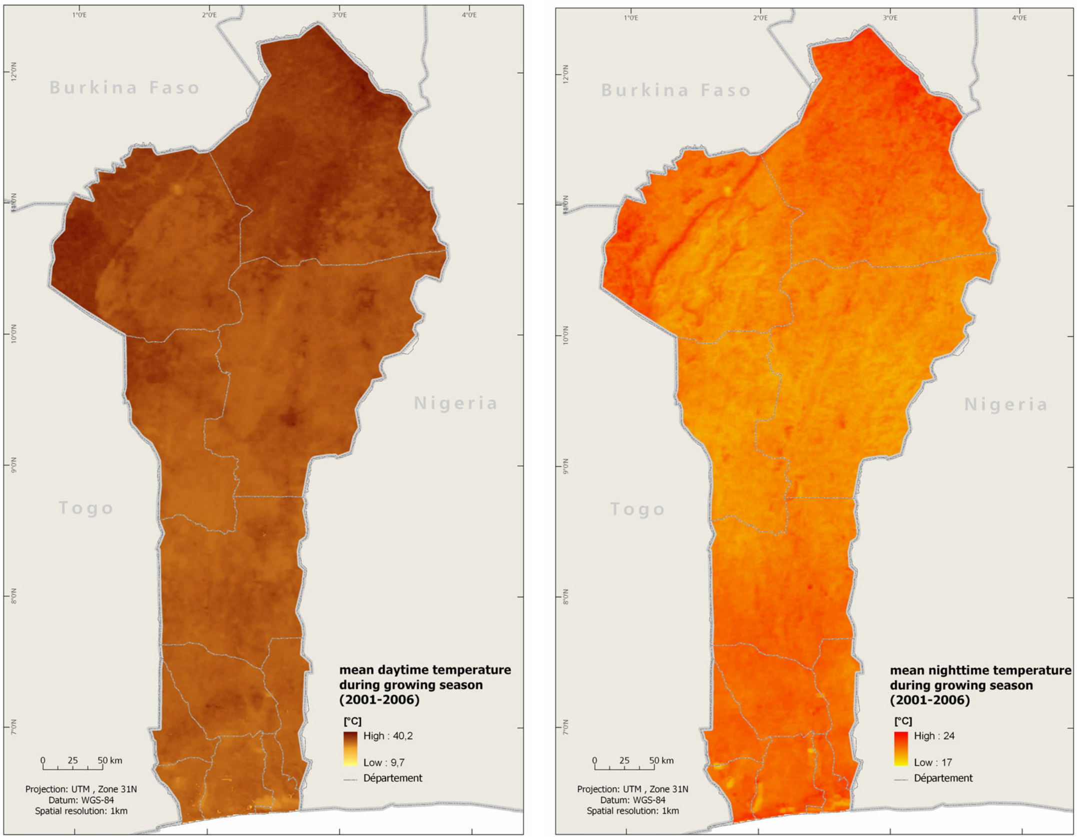


**Fig. 28: Mean daytime (left) and mean nighttime (right) temperatures during the growing season (2001-2006) based on daily LST-MODIS products**

Differences between the MODIS LST products and air temperature are generally small during night irrespective of land cover. Consequently, 'Daily nighttime 1km grid Land-surface Temperature' information over the growing period of 2001-2006 is more appropriate for this study. Fig. 28 illustrates, that the daytime-product shows a greater reliance on land cover. Thus, general land use patterns (forest, cities and fields) are clearly observable. In daytime, in addition, discrepancies can range between several degrees over crops up to 15°C over soils (WAN 2002). In contrast, within the mean nighttime temperature image, topographic structures are more dominant.

There was no specific **pre-processing** for the MODIS LST-product required as it is already validated by spectral BRDF measurements in the thermal infrared (WAN 2002, WAN 2006). For the determination of the real LST-values, the data must be only multiplied with the scale factor of 0.1 (WAN 2006). Thus, mosaics were built, the projection changed and resized according to the chosen region of interest (cf. 5.1.2.1). The assessment of the growing period will be examined in more detail in the following subsection.

### 5.1.2.3 Length of growing period (LGP)

For the determination of aridity constraints in Benin the mean length of growing period (LGP) as well as the variation of the mean length was used (see 5.1). In doing so, the former indicator alpha was replaced. The **replacement of alpha** was decided due to the following arguments:

First, evaporation data in a high spatial resolution over an adequate time period is missing. Actual and potential evapotranspiration are often calculated from climatic input data (e.g. PENMAN 1948, ALLEN et al. 1998). Until now, however both actual and potential evapotranspiration model outcomes have a spatial resolution of only 0.5° for Benin. This resolution is too coarse for the regionalisation approach. Although, remote sensing techniques cannot measure evapotranspiration (ET) directly, they provide two opportunities to estimate evapotranspiration. Simple methods are based on empirical relationships, such as proposed by PENMAN (1948) to extend point measurements to larger areas, including those regions where measured meteorological data may be sparse. Additionally, several studies use remotely sensed measurements to determine variables in the moisture and energy balance models of ET (cf. JIANG & ISLAM 1999, NISHIDA et al. 2002, RICHTERS 2005, WANG et al. 2006). In this context, however, both approaches were rejected. Sparse meteorological data for Benin make the use of empirical relationship impossible. Furthermore, the MODIS-products, on which latter approaches are based upon, cover only a rather short (2001-2007) time period. In Western Africa conversely, climatic variability is extremely high and thus longer time series are preferable to determine aridity constraints.

Second, alpha is a rather abstract feature and hence, not very concrete for national decision makers. The length of growing period, in contrast, is much more common and easier to grasp and communicate. Additionally, it is also very widely used as aridity indicator. The AEZ approach for instance uses the growing season to determine aridity constraints (i.e. FAO 1996$_A$, FAO 2002). In Benin, the rainy season is particularly important for agricultural activities as it determines the agricultural calendar (BERDING & VAN DIEPEN 1982, MDR & INRAB 1995).

**LGP** is defined as the "*period of the year in which agricultural production is possible from the viewpoint of moisture availability and absence of temperature limitations*" (FISCHER et al. 1995:2). In principal, two approaches exist for determining LGP: approaches based on meteorological data and approaches based on remote sensing data.

Studies, which derive **LGP from remote sensing data**, are mostly based on the phenology using time series analyses of vegetation indices (e.g. NDVI or EVI) (WHITE et al. 1997, MOULIN et al. 1997, SCHWARTZ & REED 1999, ZHANG et al. 2005, WHITE & NEMANI 2006, LINDERHOLM 2006). Rather simple approaches define a specific threshold for the definition of the growing season, which can be either a static index value (HENRICKSEN & DURKIN 1986, JUSTICE et al. 1986, LLOYD 1990, CHURKINA et al. 2005) or pixel-specific values depending on exemplary minimum and maximum values of a year (WHITE et al. 1997, RICHTERS 2004). Approaches that are more sophisticated analyse the course of the time-series to identify the onset and the end of the growing period due to their specific characteristics (REED et al. 1994, LÜDEKE et al. 1996, SCHWARZ & REED 1999, ZHANG et al. 2005).

However, the disadvantage of all phenological approaches is that the outcome relies significantly on the actual land cover. Own investigations with NOAA 10-day composite NDVI time series of Global Inventory Monitoring and Modelling Studies (GIMMS) (PINZON et al. 2004, TUCKER et al. 2005) confirmed this. For Western Africa, the more recent 1km SPOT VEGETATION NDVI product is less appropriate than the AVHRR data due to an insufficient cloud screening of SPOT suppressing rainy seasons (see

RÖHRIG et al. 2005, KLEIN & RÖHRIG 2006, FENSHOLD et al. 2007). For Benin, the two different approaches of WHITE et al. (1997) and REED et al. (1994) were applied. Both results did not reflect aridity constraints, but predominately actual land cover patterns. Hence, the longest lengths were estimated for the forest regions in central Benin, like for the area of Monts Kouffé. Aridity constraints in the southwest were not detectable.

In short, a phenological approach and thus, remote sensing data are not suitable to define the aridity indicator of LGP. The outcomes depend too much on the actual land cover. Thus, climatic data were used to derive the length of growing period. The advantage of using meteorological data is that purely climatic constraints are considered independently from vegetation cover and other biophysical parameters. Another benefit is, that existing climatic scenarios of the IMPETUS-project are usable to derive marginal sites of the future.

A common approach to determine **LGP with meteorological data** is the one from agro-ecological zoning approach of the FAO. The calculation of the growing season is based on temperature, precipitation, and potential evapotranspiration (FAO 1996). Due to the already mentioned lack of meteorological data in an adequate spatial resolution this approach could not be applied for this study. Instead, statements in AGRHYMET (1996) and of VANACKER et al. (2005) were assigned. The advantage is that only precipitation data are needed to assess LGP. Therefore, decadal rainfall sums from 1960 to 2000 were used, which were set up for Benin in a spatial resolution of 0.05° x 0.05° within the IMPETUS project by the meteorologist MALTE DIEDERICH (cf. THAMM et al. 2005A, SPETH et al. 2005). The decadal precipitation data are based on weather station observations and outcomes of the regional climate model REMO. REMO is driven by a Global Circulation Model (GCM), the ECHAM5 model (ROECKNER et al. 2003, cited in BRÜCHER et al. 2005). For more details about the REMO model see PAETH (2004) or PAETH & HENSE (2005). The model output was downscaled and disaggregated using satellite – mainly Meteosat Second Generation (MSG) – data. The received data set consisted of six ensemble simulations for the 1960-2050 period. For the assessment of the recent LGP, averaged decadal sums over all ensemble simulations were used between 1960 and 2000.

According to the information about onset in AGRHYMET (1996) and end of the growing season given by VANACKER et al. (2005) the length was determined for each year for Benin. AGRHYMET (1996) defines the onset of the growing period when the rainfall sum of the first decade (10 days) is at least 25 mm and the sum of the second and third decade achieves a minimum of 20 mm. The duration of the vegetation period lasts as long as the decadal rainfall sums exceeds 10 mm (cf. VANACKER et al. 2005). Based on the yearly length of the growing period the mean length as well as the standard deviation was assessed.

For the determination of the vegetation period needed for temperature and rainfall variability constraints, the growing season was defined in a broader sense. The high rainfall variability at the beginning of the season is particular crucial for the farmers why an extended vegetation period was taken into account. A decade was defined as being part of the growing season if in at least 20% of the 40 years (8 years) this decade was determined as growing season. This outcome of LGP values correspond well to the values given in the literature (cf. MDR & INRAB 1995, CENATEL 2002, MEHU 2003).

For the determination of the **mean length of growing period** a median filter with the kernel size of five was applied to the image (see Fig. 29). The spatial pattern reflects well the regions in Benin which are known for aridity problems; particularly the southwest and the north. Contrary to the general pattern, the mean length values are almost everywhere lower then named within the literature. According to MDR et al. (1998), CENATEL (2002) and MEHU (2003) LGP is with 24-25 decades longest in the southern area and with 13-14 decades shortest in the north. The calculated mean LGP is, in contrast, around four decades lower as it ranges from 19 to 10 decades. An explanation of these generally lower values may be the prolonged drought from the early 1970s that reached its first climax in the first half of the 1980s in the tropical West Africa (SPETH et al. 2006). This argument was strengthened by general higher mean lengths of the growing period between 1986 and 2000, the time period of existent NDVI data. For this period remotely sensed derived LGP and meteorological derived LGP show similar lengths of growing season although the patterns are different.

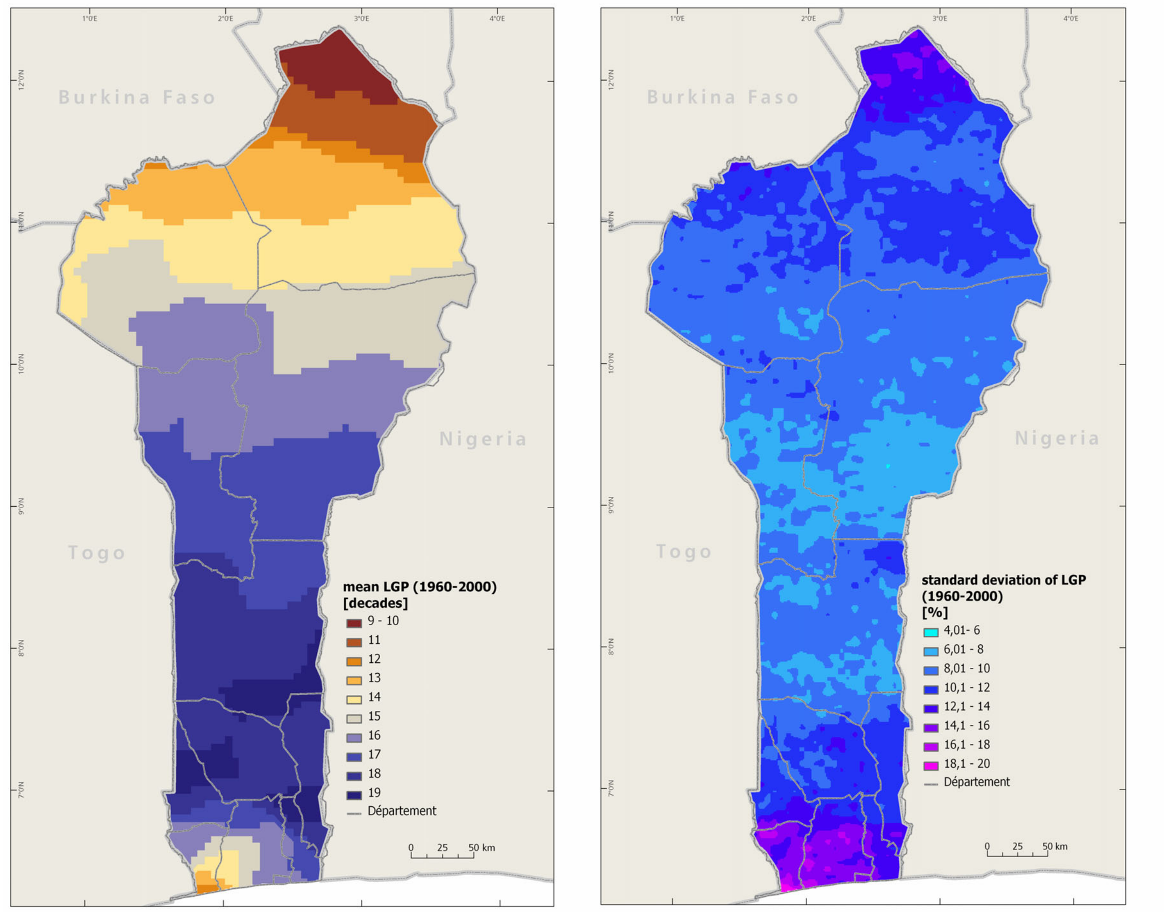


**Fig. 29: Mean length of growing period in decades (left) and variability of LGP (right) (1960-2000)**

The **standard deviation in percent** was used to receive information about the fluctuation of the length. As climatic variability is particularly high in Benin, the implementation of the variability of LGP is essential to reflect the biophysical conditions properly. Fig. 29 illustrates high variability values particularly in the south and the north.

### 5.1.2.4 Rainfall variability (RV)

With the indicator of rainfall variability, the uncertainty in agricultural planning and perturbations in yields are expressed. Therefore, rainfall variability within the growing season is considered (see 5.1.2.3).

For its assessment, the same decadal rainfall data, already described in 5.1.2.3, were used as input data. Thus, the temporal resolution of the input data could be increased compared with the monthly resolution of the climate variables in CASSEL-GINTZ et al. (1997) or LÜDEKE et al. (1999).

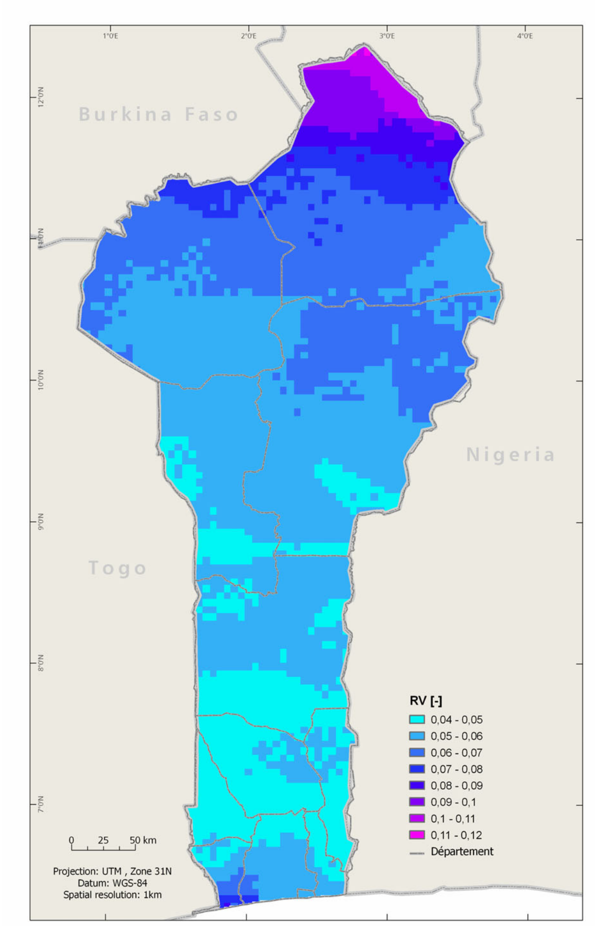


**Fig. 30: Rainfall variability in Benin**

In the original approach only negative anomalies of rainfall were taken into account. For Benin, however, interviews with farmers made it clear that rainfall sums not only below but also above average are problematic. Consequently, the equation of CASSEL-GINTZ et al. (1997) was corrected. First, *PD*, the standard deviation from the mean seasonal course divided by *P*, the mean rainfall sum of the vegetation period, was calculated for each year $j$ between 1960 and 2000:

$$PD_j = \frac{1}{P}\sqrt{\frac{\sum_{i=m}^{n}\left(P_{ij}-P_j\right)^2}{n-m+1}} \qquad \textbf{(1)}$$

Where $P_{ij}$ is the rainfall sum of the decade $i$ in the year $j$ and $P_j$ the mean precipitation sum of the decade $i$ over the entire time period. Parameter $m$ denotes the first and $n$ the last decade of the vegetation period.

Then, the rainfall variability (*RV*) was calculated, where $x$ is the amount of years considered (CASSEL-GINTZ et al. 1997:141).

$$RV = \sqrt{\frac{\sum_{J=1}^{x} PD_j^2}{x}} \qquad \textbf{(2)}$$

Fig. 30 presents the spatial distribution of RV in Benin with highest values in the north and in the southwest, where rainfall amounts are already low.

#### 5.1.2.5 Potential irrigation capacity (IC)

The potential irrigation capacity (IC) was set up incorporating the opportunity to compensate aridity near inshore water. The compensation effect works two-fold. On the one hand, sites near rivers or lakes are characterised by a higher groundwater level and thus water is more easily and longer available for the plants. This positive effect was named by several farmers which were interviewed. On the other hand, small irrigation systems can be realised easily nearby rivers and lakes, particularly within plain landscapes. Thus, the indicator consists of two input data sets: water network density and slope. Both features were derived from remote sensing data, namely the SRTM digital elevation model (DEM). In this subsection, the X-SAR SRTM data will be presented and the determination of the stream network examined in detail. The calculation of slope will however be described in subsection 5.1.2.7 where the indicator is considered in detail.

SRTM (Shuttle Radar Topography Mission) is an international project headed by the National Aeronautics and Space Administration (NASA) and the National Geospatial-Intelligence Agency (NGA) (for more details see FARR & KOBRICK 2000). SRTM consisted of an ad hoc modified radar system that flew onboard the Space Shuttle Endeavour for the period of 11-day in February of 2000 (FARR & KOBRICK 2000). The X-SAR SRTM products are an inventive way to gain highly accurate topographic information using space borne radar instruments. For Africa, the spatial resolution of the digital elevation model (DEM), which is freely available, is 3 arc seconds (approx. 90m x 90m). The digital elevation model is provided in tiles of 15' size in latitude and longitude which allows a rapid provision and distribution over the internet. The area of Benin consists of 23 such tiles which were firstly merged using the *mosaicking* function in ENVI. The general accuracy assessment proved the high quality of the data (FARR & KOBRICK 2000). Comparisons with topographic information from Russian topographic maps showed a good match of the SRTM data in Benin. For the assessments of the stream network the original data were used, without any preprocessing.

The software package ArcGIS 9.2 (ESRI 2007) provides hydrologic modelling functions in ArcGIS Spatial Analyst to derive stream networks and thus, the **water network density** from digital elevation models. The necessary processing is subdivided into several working steps, which will be presented in more detail now.

First, the sinks were filled using *Fill*. With this function small imperfections within the data are removed. Sinks are frequent errors caused by the rounding of elevations to the nearest integer value or resolution of the data. Hence, sinks should be filled to make certain correct delineation of basins and streams. Own analyses demonstrated that if the sinks are not filled, the derived network is discontinuous. Then, this output was used to determine the *flow direction* with the tool of same denominator. The flow direction results from the direction of the steepest decrement from each cell. More detailed information about this tool is given by GREENLEE (1987) and JENSON & DOMINGUE (1988). The flow direction raster is taken to derive the accumulated flow to each cell. Therefore, the *Flow Accumulation* tool was applied (see JENSEN et al. 1988, TARBOTON et al. 1991). In doing so, the number of upslope cells flowing to a location is calculated using the default weight of one for all cells. Afterwards, a threshold of 100 was specified on this raster, whereby the initial stage defines the stream network system. This step is necessary to define the level of detail of the stream network. Thus, all cells with more than 100 cells flowing into them will be part of the stream network. The outcome is comparable in spatial detail to that of the stream network, which was digitalised from a LANDSAT ETM+ scene for the upper Ouémé catchment (see THAMM et al. 2005A). Lower thresholds came out with a too widely ramified river network wherein nearly all sites are part of a river.

Then, the hierarchy of the stream network can be determined. However, before the *Stream Order* tool can be applied, all background values of this outcome were reclassified with the *Reclass* tool. In doing so, zero-values in the binary raster were converted into 'noData'. *Stream Order* assigns a numeric order to segments of a raster that represent branches of a linear network. The offered methods for ordering are the SHREVE and STRAHLER techniques. In this study the STRAHLER method (1957) was applied as it is the most common method. In this method, the stream order merely increases if streams of the same order intersect. Consequently, the intersection of a first-order and second-order link will stay a second-order link and not create a third-order link. In contrast, in the SHREVE method (1966) the orders are additive, which means that in this case a third-order link is created. With the *Stream to Feature* tool, a linear water network was calculated based on the raster data containing the stream order according to STRAHLER and the flow direction. *Stream to Feature* is a vectorisation function designed mainly for the vectorisation of raster data which represent a linear network for which directionality is known, like within river networks.

For the estimation of the capacity to compensate temporal dryness it is essential to distinguish the inshore water according to its availability in time and quantity. Therefore, CASSEL-GINTZ et al. (1997) incorporated the hierarchically stream network of the World Basemap from ESRI (1997, 1999) (see Table 3). The classification and weighting scheme was thus, applied on the determined river file. The differentiation between perennial and intermittent rivers and lakes was applied empirically as this characteristic depends mainly on the location of the waterbodies and to a minor extent on the size and order. In doing so, the perennial rivers of Niger, Mono and Ouémé up to Zangnanondo were selected manually using the attribute table. All perennial rivers were classified as major rivers. The same was needed for the major intermittent rivers as the order values alone came out with poor results. For the further classification the calculated order values were used, whereby class boarders were defined empirically based on discharge measurements of the IMPETUS-project (GIERTZ 2007, personal communication). The order of a link corresponds to the GRID_CODE within the attribute table of the vector layer.

| Type of waterbodies | Size of waterbodies | Order (Strahler method) | Weighting |
|---|---|---|---|
| perennial rivers | major | manual classification | 12 |
| intermittent rivers | major | manual classification | 4 |
| | additional major | 6-7 | 3 |
| | additional | 4-5 | 2 |
| | minor | greater than 3 | 1 |
| lakes | floodplains of rivers | | 12 |
| | perennial lakes | | 12 |
| | intermittent lakes | | 4 |

**Table 3: Classification and weighting scheme of the hierarchically structured inshore water network based on ESRI (1997) and Cassel-Gintz et al. (1997).**

The lakes were taken from the World Basemap from ESRI (1999) (see for more details Röhrig 2002). The surfaces were corrected with the aid of the analogue general map of Benin in a scale of 1:500.000 and the SRTM data set.

The weighting factor for each class was assigned to the layers through the Spatial Analyst tool *Reclassify*. Then, each vector file corresponding to the different types were transferred into raster data by *Feature to Raster*. Additionally, it is essential that *Output cell size* and the *Environment Settings* of *extend* are the same. As output cell size, the choice of the SRTM data was selected. Finally, all layers were added into one layer by addition of the values, thereby determining the water network density. In doing so, it is important that all background values have a value of zero and are not labelled as 'noData'.

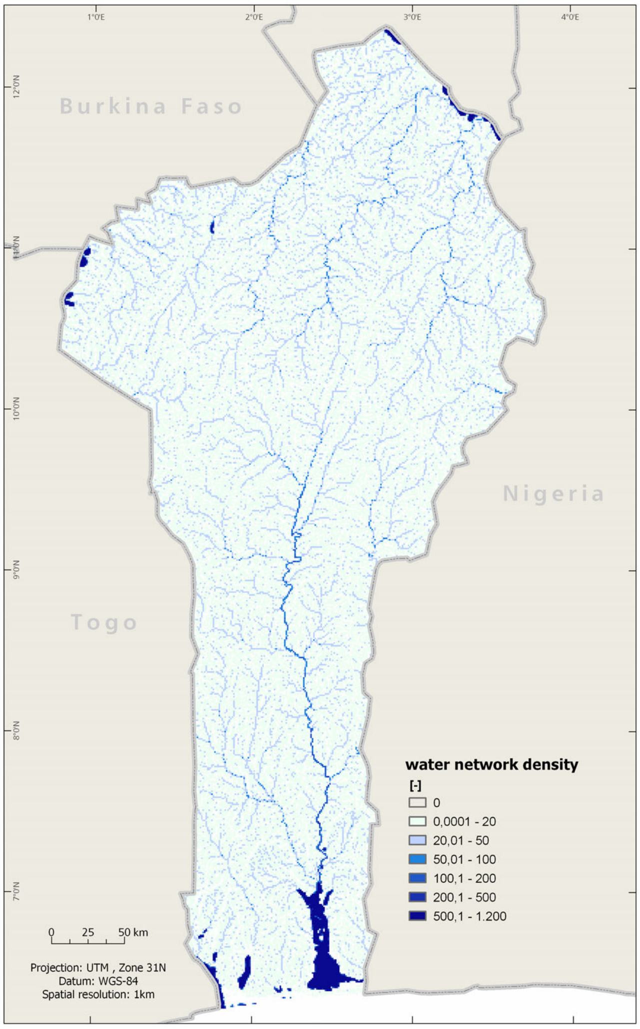


**Fig. 31: Water network density of Benin derived from SRTM digital elevation model**

Fig. 31 illustrates the water network density of Benin derived from SRTM in a spatial resolution of 1km. For the resampling, the resampling method pixel aggregate was used.

SRTM has a much higher level of detail and accuracy compared with the original one, which is based on the stream network of the World Basemap from ESRI (1999). This improvement is due to the higher spatial resolution of the input data but also due to the better definition of the hierarchical water network based on empirical knowledge. The ESRI data set comes out with a significantly higher number of permanent and major water bodies. Hence, the compensation effects are overestimated when the water network density is derived from this source.

#### 5.1.2.6 Soil fertility (SOIL)

Soil fertility is an elementary basis for agricultural land use in general. For the determination of the marginality index on the global scale, soil fertility was incorporated based on the soil properties database introduced by LEEMANS & VAN DEN BORN (1994). This database is related to the different soil classes of the ZOBLER's *World File for Global Climate Modeling* (ZOBLER 1986). This soil map consists of 106 soil types which are generated from the FAO Soil Map of the World (FAO 1974) and the vegetation map of MATTHEWS (1984). The soil properties database of LEEMANS & VAN DEN BORN (1994) contains beyond salinity, acidity level, drainage and rooting conditions, the soil fertility factor $S_f$. The values of $S_f$ range between 0.5 for poor soils and 1.0 for the most fertile soils in the world. Between these two extremes, only three further soil groups are distinguished. For the regionalisation of MI for Benin, this approach was not suitable for several reasons:

First of all, $S_f$ incorporates information only about the chemical fertility of soils. In Benin however, agricultural activities are limited by both low chemical and low physical fertility (cf. 2.2.3). The small opportunity to differentiate the soil fertility is moreover insufficient to examine the greatly heterogenic soil conditions in Benin. Additionally, no information about the way the soil properties were evaluated is given by LEEMANS & VAN DEN BORN (1994). This makes it impossible to apply the approach on input data sets other than ZOBLER's and FAO's. For Benin, however, the soil map of ORSTOM is much more detailed than the FAO soil map (IGUÉ, personal communication 2005; SKOVRONEK, personal communication 2006). Together with the Notice explicative corresponding to each of the ten soil sheets the ORSTOM soil map provides the most detailed information about soil cover and characteristics on a national scale. Within these sheets detailed information about soil properties and land use potential are stated. In this context, a conversion of the French soil classification scheme of ORSTOM into the American classification scheme of the FAO would be thereby problematic and additionally, connected with a considerable loss of specific information. Consequently, the approach used in CASSEL-GINTZ et al. 1997 was rejected for the determination of MI.

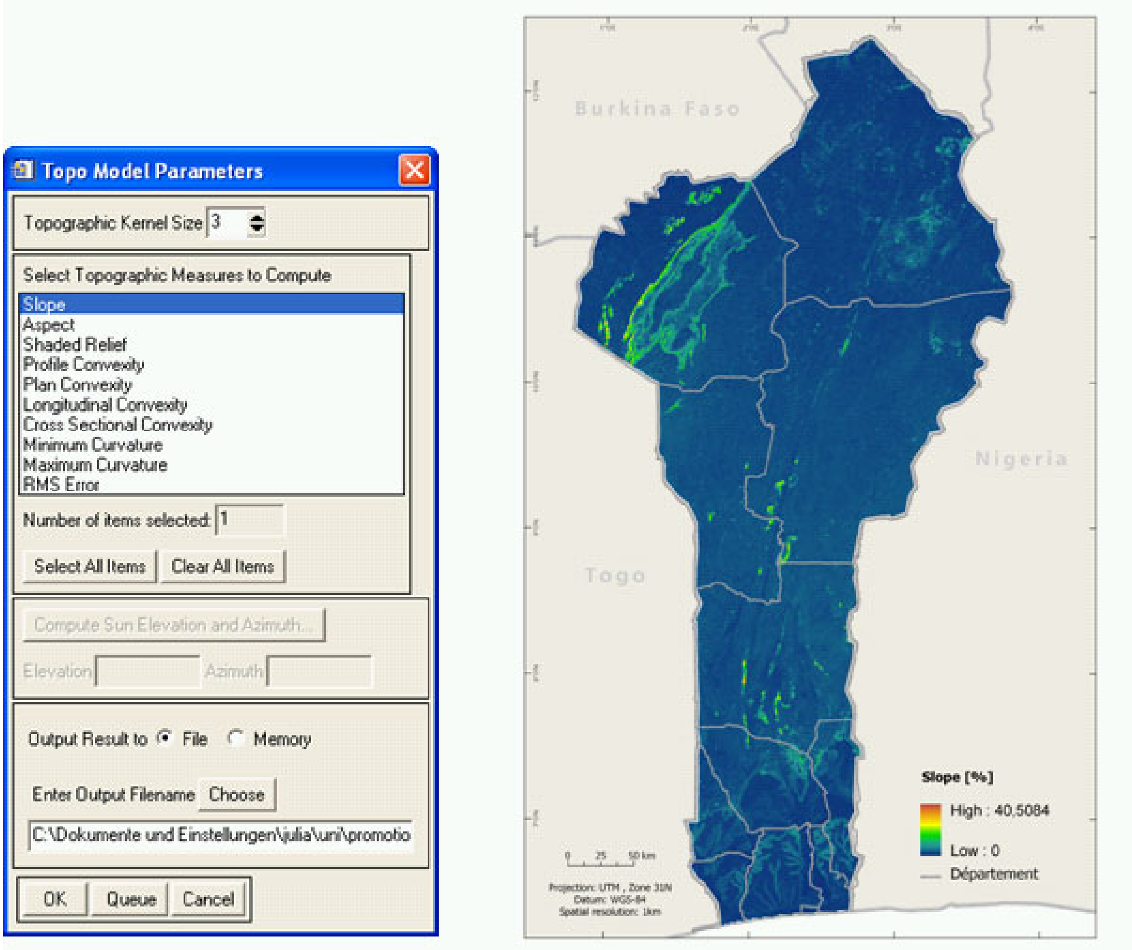
Approaches based on remote sensing deriving different soil properties seemed also not suitable due to lacking reference data and thus restricted possibilities to calibrate and validate the data. Due to the enormous advantage of this soil map and missing reference soil information on a national scale, it was decided in cooperation with CLAUDIA HIEPE to use a soil evaluation scheme derived directly from the ORSTOM map. Hence, all soil evaluation approaches based on the FAO soil classification, like the Fertility Capability Classification System (FCC) proposed by SANCHEZ et al. (1982) or the Land quality classes (cf. ESWARAN et al. 1999 or BLUM & ESWARAN 2004) were not further considered.

The ORSTOM soil map of Benin consists of 107 soil types, which were differentiated with the aid of 355 soil profiles (VOLKHOFF 1976). The map had been already digitalised within the IMPETUS project at a spatial resolution of about 1.7 km. The soils are finally evaluated based on an approach introduced by LEVEQUE (1978) defining agronomical units directly from the ORSTOM soil map of Togo.

Attempts to assign the agronomical units introduced for Togo to the soils in Benin failed. The problems were caused by a different classification and labelling scheme of the soils types, although both maps were set up by ORSTOM according to the French system of 'Classification des Sols' (CdS) (CPCS 1967). Even soils along the border line were occasionally classified differently. Although their geographical location and thus, environmental conditions are mostly comparable, several soils, which exist in Benin, do not in Togo. As a result, only 88 out of 107 soils could be transferred satisfyingly into the evaluation scheme of LEVEQUE (1978). Consequently, it was decided to set up an ordinal evaluation scheme directly based on the ORSTOM soil map and the *Notices explicatives*. Like by LEVEQUE (1978), the soils were subdivided into two groups differentiating hydromorphic (H) and non-hydromorphic soils (NH). Hydromorphic describes generally soils that develop under poor drainage conditions to which not all crops are adapted. Thus, amelioration measurements are needed for the cultivation of several crops. For the soils of both groups, the main chemical and physical characteristics were listed to simplify the general evaluation and to set up a classification scheme applying an ordinal scale. The characteristics were analysed according to their importance for the agricultural suitability as well as the possibility to compensate a constraint. Sufficient soil depth for instance, is essential for crop growth and can additionally rarely be changed. Consequently, this feature is of particularly importance within the evaluation scheme. In another step, both groups (H and NH) were subdivided into three levels of suitability (very suitable, moderately suitable, and not suitable for cultivation). Suitable hydromorphic soils are for instance not as fertile as the best soils of the NH-group. Within each group the fertility of the soils correspond to the ordinal scale already mentioned. Finally, 22 different classes of soil fertility were distinguished which approximates the number of agronomical units for Togo. There, 24 units were subdivided.

#### 5.1.2.7 Slope (SL)

CASSEL-GINTZ et al. (1997) used slope as indicator for the risk of erosion. Although slope is only one aspect influencing the risk of erosion, the interviews with farmers supported the enormous importance of topography itself. Most farmers prefer plain surrounding for their fields, especially sinks where water and nutrient availability increases agricultural suitability.



Topo Model Parameters

Topographic Kernel Size 3

Select Topographic Measures to Compute

- Slope
- Aspect
- Shaded Relief
- Profile Convexity
- Plan Convexity
- Longitudinal Convexity
- Cross Sectional Convexity
- Minimum Curvature
- Maximum Curvature
- RMS Error

Number of items selected: 1

Output Result to ● File ○ Memory

Enter Output Filename

C:\Dokumente und Einstellungen\julia\uni\promotio

**Fig. 32: Topographic modelling tool in ENVI 4.3 and slopes in Benin derived from SRTM digital elevation model**

*pographic Modeling* tool in ENVI a wide range of topographic parameters can be calculated easily from digital elevation models (cf. Fig. 32). All of the features are determined by fitting a quadratic surface to the DEM for a defined kernel size and taking the appropriate differential coefficients. The slope is thereby measured in degrees, but was converted into percent as this is more common.

Fig. 32 demonstrates the slopes in a spatial resolution of 1km. For the resampling, the *Pixel Aggregate* method was applied. Generally, the slopes are low. Steep slopes occur within the Atacora mountain range, at fringes of inselbergs, and in the south, at the borders between the sedimentary plateaus and the crystalline basement.

### 5.1.3 Conclusion

The marginality index incorporates all key biophysical constraints relevant for a capability approach on the national scale of Benin. Necessary modifications were slight and mostly with the aim to increase the tangibility for national decision makers. Nevertheless, available data, which are feasible for the national scale, are partly problematic to derive: especially climatic data are still missing even though some progress has been made for Benin within the IMPETUS project. As a consequence, data of altering spatial resolutions were necessary to implement. If no adequate alternative data were available, data of resolution lower than 1km x 1km were chosen. The use of remote sensing to derive the input data was generally possible and sometimes very useful. Remote sensing data were mainly used, when the indicator describes rather constant biophysical features, such as slope or temperature without high temporal variation. For biophysical parameters characterized by high temporal variability, such as rainfall variability or length of the growing season, although existing time series of remote sensing data are often too short and thus, not very helpful for the calculation of MI. But with rising length of the time series their implementation can be surely enhanced. MODIS data products comprise thereby a wide range of valuable information for land evaluation due to specific radiometric, temporal, and spatial resolution. If more recent biophysical conditions are considered, remote sensing is very suitable providing up-to-date information. However, the index cannot be calculated from remote sensing data alone, but it relies on additional data, such as detailed soil information.

### 5.1.4 Determination of biophysical conditions for agricultural land use of Benin in 2025

In order to investigate the effects of global change on the biophysical resources of Benin, MI was assessed for the year 2025. In doing so, two IPCC (Intergovernmental Panel on Climate Change) climate scenarios (A1B and B1) and corresponding input data were used. In this subsection, some information about the used IPCC scenarios will be given. Then, corresponding changes of indicators and data will be examined. As theses changes concern only one indicator (PVEG) and two climate parameters (temperature and precipitation), indicators and data are summarized in subsection 5.1.4.2. In doing so, probable biophysical conditions of 2025 will be illustrated.

#### 5.1.4.1 Climate scenarios from IPCC

For the determination of future biophysical conditions for agricultural land use in Benin, MI were assessed with data products based on two IPCC SRES (Special Report on Emission Scenarios) scenarios. In this subsection a brief introduction of terminology and the two used climate scenarios A1B and B1 will be given. For information that is more detailed see e.g. IPCC (2001) or IPCC (2007).

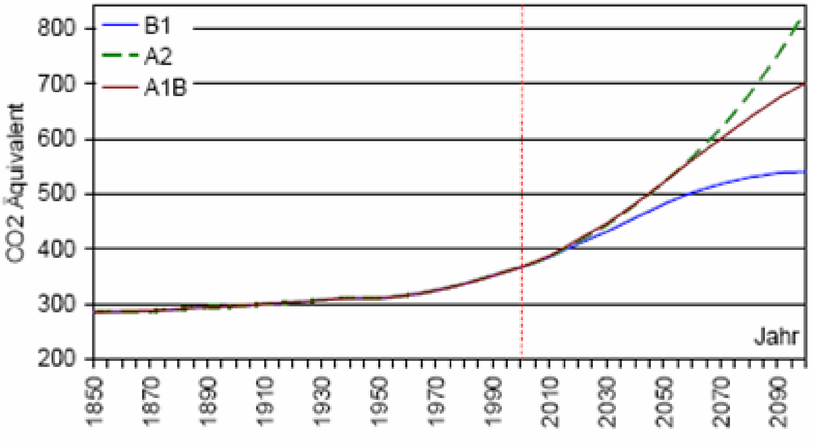


**Fig. 33: Rise of CO2 [ppmv] according to SRES scenario A1B, B1 and A2 until the year 2100 (BRÜCHER et al. 2005:198)**

Scenarios are consistent and reasonable projections of alternative futures, which are adequate to assist decision-making processes (SPETH et al. 2005, GIERTZ et al. 2006). They are not predictions and contain thus, no probability information. Instead, they permit analyses and determinations of different development paths of intricate systems. In 1996, IPCC started to develop a new set of emissions scenarios; the so-called SRES scenarios (see also IPCC 2001, IPCC 2007). Therefore, different narrative storylines were devised from IPCC to express consistently relationships between the forces driving emissions and their progression. Furthermore, the aim was to add a framework for scenario quantifications. Narrative storylines describes usually key characteristics, main driving forces and their interactions of future developments (SPETH et al. 2005). Each scenario illustrates a specific quantification of one of the storylines.

A1B denotes a future with very fast economic growth and a rapid introduction of innovative and efficient technologies. Additionally, global population is expected to peak in mid-century and decrease thereafter. The strong economic development is based on fossil and non-fossil energy resources. The IPCC SRES scenario B1 contains equal presuppositions concerning global population development as A1B. The differences lie in economic and environmental developments. Thus, scenario B1 assumes rapid alterations in the economic structures towards an information and service economy with sustainable use of the resources. Consequently, the rise of greenhouse gases is lower than within A1B. Differences between the two scenarios concerning rising greenhouse gases are, however, small until 2025 (cf Fig. 33).

The expected impact of both scenarios on the biophysical conditions for agricultural land use in Benin will be addressed in the following sections.

#### 5.1.4.2 Indicators and data to assess the biophysical conditions of 2025

In this subsection the necessary input data, used for an assessment of the MI in 2025 will be examined. For the scenario analyses one indicator (PVEG) was modified into MVEG, which will be explained in the first paragraph. Furthermore, only changes of the climate parameters were considered within the analyses. The indicators of SLOPE as well as SOIL data were not changed; although, soil conditions will probably alter under climate change and particularly under ongoing land use change. These modifications, however, were not possible to incorporate within this study, but may be interesting for future work.

For the scenario analyses, only one indicator was changed. The actual maximum vegetation (**MVEG**) instead of the potential maximum biomass, described in chapter

5.1.2.1, was used. The modification was undertaken for three reasons. First, it is difficult to model future potential NPP for the same reasons as named before. Second, the potential vegetation is certainly affected by climate change and thus, PBD by (Brown & Gaston 1996) does not reflect potential biomass of Benin in 2025. Third, agricultural land use of 2025 will be based on recent, human induced vegetation productivity and not based upon potential uses. Due to high population growth and missing alternatives to ensure food security, it is unlikely that fields or city areas will be transformed to natural vegetation forms. Consequently, for 2025 information about the real vegetative resources for agricultural production seems rational. The maximum integrated NDVI (iNDVI) of a year was used to derive the indicator MVEG.

$$\mathbf{NDVI = (NIR - RED)/(NIR + RED)} \qquad \mathbf{(3)}$$

It is a measurement of the degree of greenness through time and reflects quantitatively the capacity of the land to support photosynthesis and primary production. INDVI is suitable in this context as it is a good indicator for general land performance (see chap. 5.1.2.1). Furthermore, iNDVI has a strong relationship to NPP (e.g. Prince et al. 1998, Li et al. 2004, Symeonakis &. Drake 2004). NPP was used in the original approach to derive the corresponding indicator (cf. Chapter 5.1.2.1). The maximum iNDVI was used to incorporate the highest productivity under human impact. Therefore, the NDVI data set from GIMMS (see Chapter 5.1.2.3) was taken. For each year between 1982 and 2003 the integral over the year was assessed. Afterwards, the maximum iNDVI-value over this period was

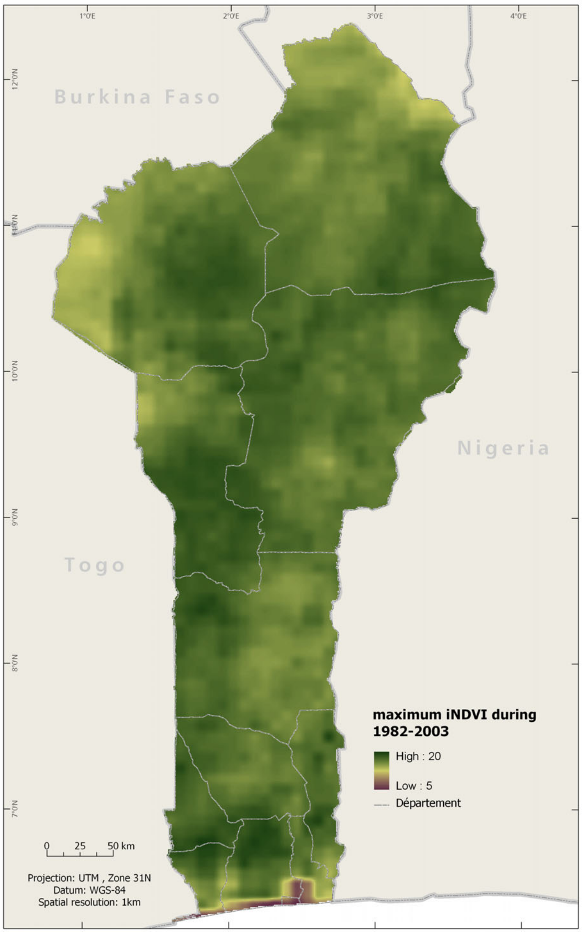


**Fig. 34: Maximum iNDVI during 1982 and 2003**

calculated. Fig. 34 illustrates that MVEG reflects well the actual patterns of land cover. Cities, like Parakou or regions of large-area cultivation, such as around Djougou or Banikoara are clearly detectable. This data was used for both scenarios.

Climate change affects directly climate conditions for agricultural land use and thus, different **climate data** were used for the scenario analyses. Therefore, temperature and rainfall scenario data products of the meteorologists of IMPETUS were used as input data. The potential irrigation capacity was not necessary to change, although changing precipitation regimes will influence the river discharges (GIERTZ 2008, personal communication). Nevertheless, perennial rivers will remain generally perennial, although they will fall dry during some years with low rainfall amounts. That is also true for minor rivers, which may become waterless during particularly dry years, but not in the rule. Thus, the applied hierarchical water network (see 5.1.2.5) will generally remain unchanged until 2025. Consequently, the following paragraphs examine only temperature and rainfall data. The pre-processing of the climate indicators remained the same as described above and will thus, not be examined further.

For all climate data, scenario products of the hydrostatic regional climate model REMO (spatial resolution: 0.5° x 0.5°) were taken (cf. 5.1.2.3). Meteorologists of the IMPETUS project performed consortial runs for the time period of 2001-2050. Here, however, only the time period until 2025 will be considered. Therefore, they took into account both information on greenhouse gas emissions (based on the IPCC-SRES scenarios) and on land use changes (FAO). The latter is important, because sensitivity analyses with the hydrostatic regional climate model REMO (cf. 5.1.2.3) indicates that land degradation plays a key role in the atmospheric processes, especially in the Congo Basin and Sahel region (SPETH et al. 2006, PAETH & THAMM 2007). Based on the IPCC scenario A1B, a greater increase of greenhouse gases and larger scale changes in land cover according to the FAO are incorporated in comparison to the B1 scenario. Meteorologists of IMPETUS in a spatial resolution of about 0.05° x 0.05° using the stochastic weather generator LARS-WG and MSG data to increase the spatial resolution (SPETH et al. 2006, PAETH, HEUER and DIEDERICH, personal communication 2007) provided the climate data.

For the scenario analyses, meteorological **temperature** instead of remote sensing data was used to derive the indicator TEMP. The use of MODIS data, as described in 5.1.2.2, was less appropriate in this case. Although general growing temperature rates were defined for the three IMPETUS-project zones of upper, middle and lower Ouémé. The direct application is however problematic as the growing rates correspond to mean temperature of the day and not of the night. Furthermore, the spatial pattern of future air temperature is reflected more directly from climate models (see 5.1.2.2). The temperature data were already resampled in a spatial resolution of about 0.04° x 0.04° based on MSG data of soil temperature, global radiation, and rainfall as well as measurements of the six weather stations (DIEDERICH, personal communication 2008). Thus, the spatial resolution is much higher than the 0.5° resolution of general REMO products.

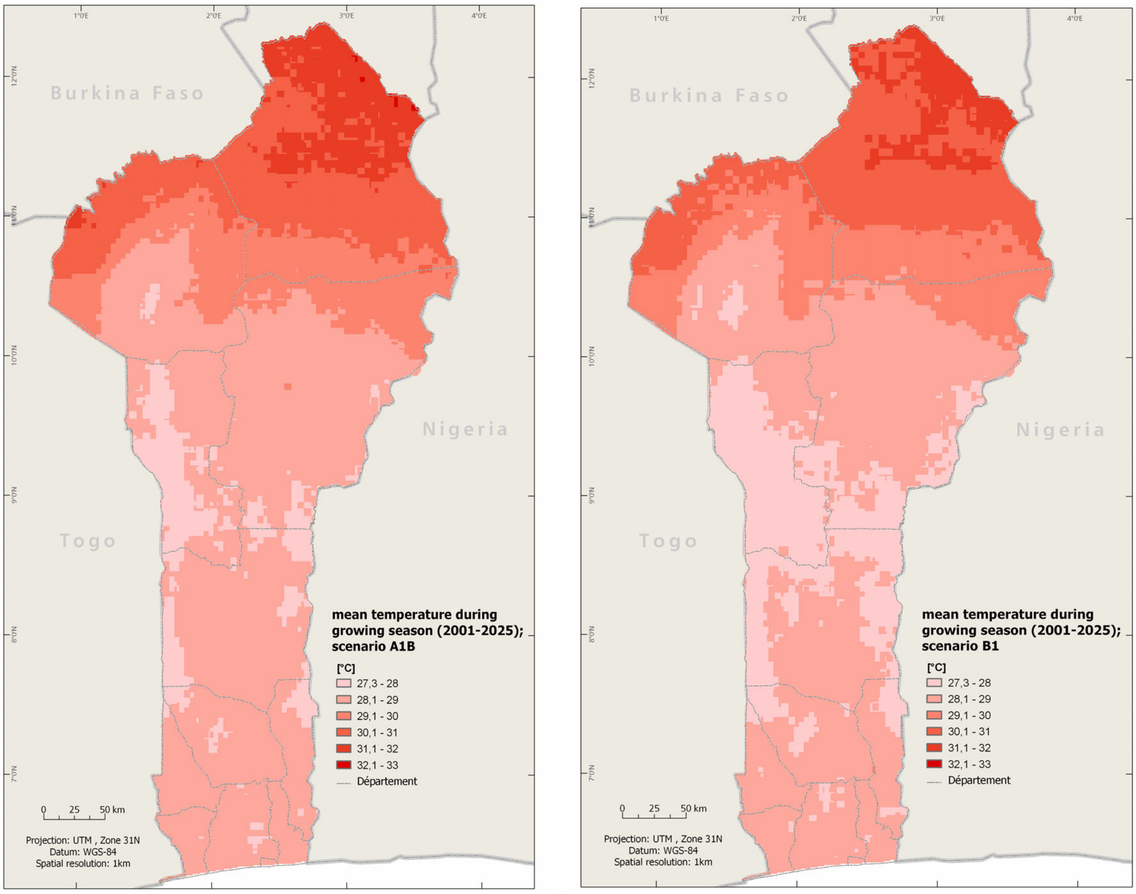


**Fig. 35: Mean temperature during growing season according to IPCC SRES scenario A1B (left) and B1 (right)**

The map projection was converted into UTM and the decadal data of all six consortial runs resampled (1km) using existing ENVI/IDL-functions. Afterwards, the indicator

TEMP was determined using the same methods already described in 5.1.2.2 and 5.1.2.3, whereby the rainfall data calculated for 2001-2025 were taken into account. Fig. 35 illustrates the expected mean temperature of the growing period according to scenario A1B and B1. Therefore, the mean TEMP over the three consortial runs for each scenario was determined as the standard deviation is very small (maximum values about 0.2°). Fig. 35 demonstrates that both scenarios show the same spatial pattern and comparable temperature degrees with only slight differences in the north and centre of Benin (see demonstrations in chapter 5.1.4.1).

The other two climate indicators, which will be probably affected by climate change, are LGP and RV. For both indicators only **precipitation** data are needed. The data modelling and pre-processing remained the same as described 5.1.2.3 and 5.1.2.4. Thus, here only the outcomes of the indicator assessments are considered. Changes corresponding to climate change will be exemplary demonstrated, but primarily discussed in chapter 6.2.

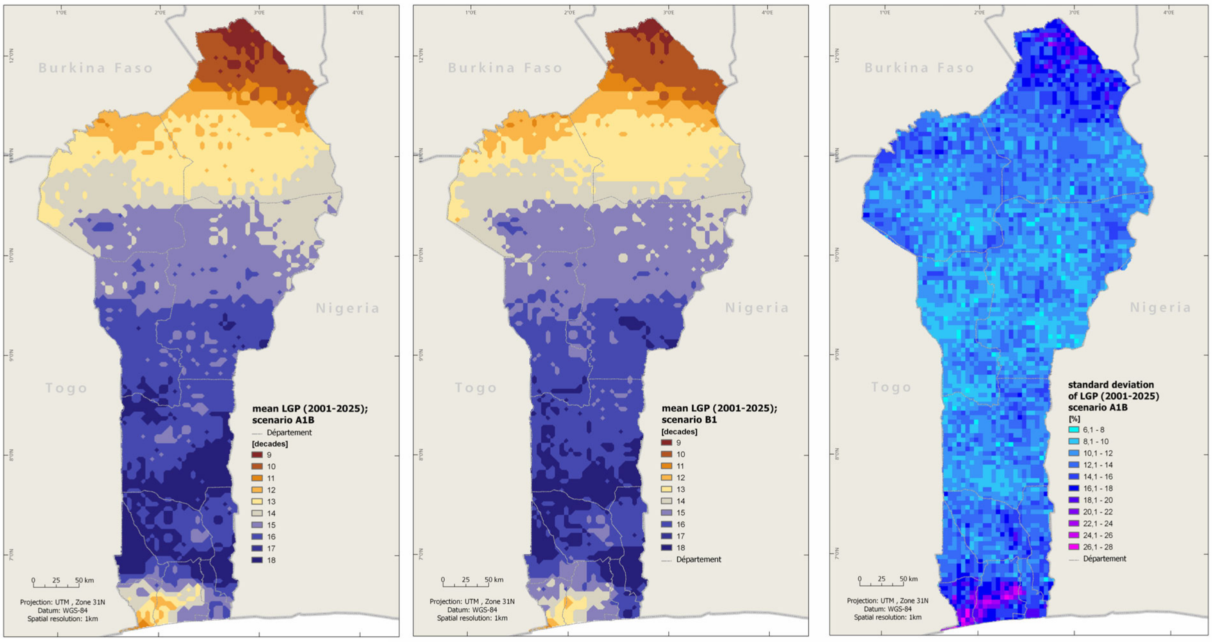


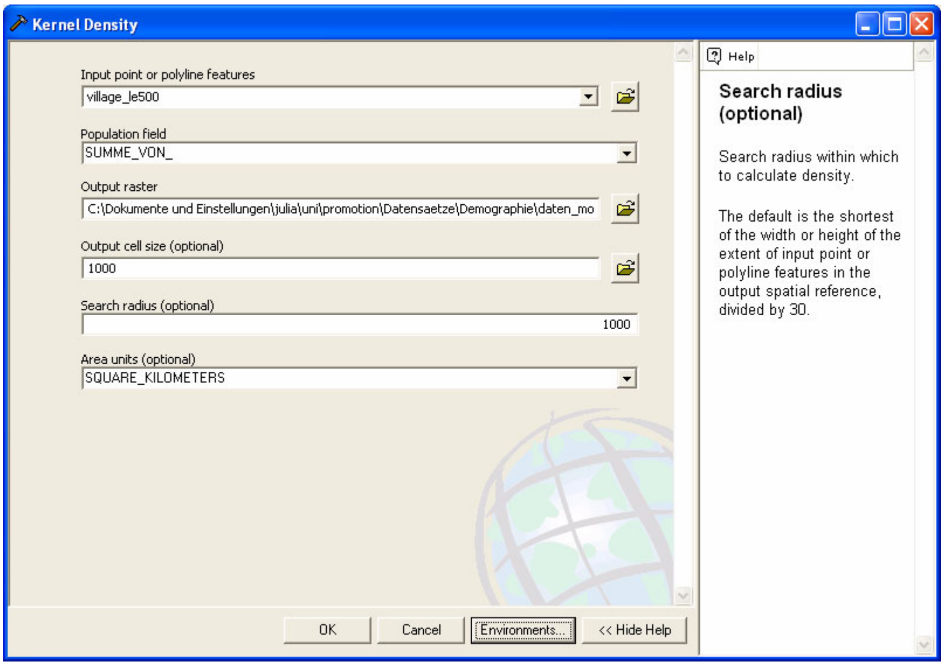
**Fig. 36: Mean length of growing period according to IPCC SRES scenario A1B (left) and B1 (middle) as well as standard deviation of A1B (right)**

Fig. 36 demonstrates that the calculated mean LGP is very similar in both scenarios. This is also true for the variability of LGP, why only the outcome of A1B is demonstrated in the same figure. The patterns of both parameters are similar to recent conditions although the values changed. Thus, the length declined slightly by about one decade for several regions. The variability of the length increases in the rule by up to 28% (maximum of recent standard deviation is 20%). The latter results in more insecurity for the farmers and may indicate an increase of rainfall variability in the future. The increase of variability affects, however, mainly the beginning and ending of LGP. The outcomes of RV for both scenarios demonstrate no significant rise in rainfall variability within the rainy season.

## *5.2 Determination of population density*

Population density is an essential figure in this study as it reflects where people live. Due to the high degree of agricultural subsistence in Benin, this is closely linked with areas, which are under cultivation. Thus, linking this information with the evaluation of biophysical conditions, favoured regions, which are not yet under cultivation, can be identified as well as regions, which are particularly prone to land degradation. The latter is one aspect of the indirect validation of the marginality index (see 4.3.2). The combination of both information sources is additionally necessary for sustainable land use planning and consequently, for national decision makers.

For the determination of the population density, the outcome of the last census of 2002 was used (INSAE 2003). In doing so, the population of villages was disaggregated using the ArcGIS tool *kernel density* (see Fig. 37).



Input point or polyline features: village_le500
Population field: SUMME_VON_
Output raster: C:\Dokumente und Einstellungen\julia\uni\promotion\Datensaetze\Demographie\daten_mo
Output cell size (optional): 1000
Search radius (optional): 1000
Area units (optional): SQUARE_KILOMETERS

Search radius (optional)

Search radius within which to calculate density.

The default is the shortest of the width or height of the extent of input point or polyline features in the output spatial reference, divided by 30.

**Fig. 37: The *Kernel Density* tool of ArcGIS**

This tool calculates a value per unit area from point or polyline features based on a kernel function to match a smoothly tapered surface to each point and polyline, respectively. A *search radius* must be defined, and therefore, empirical definitions of the radii were set up in cooperation with Moritz Heldmann and Dr. Valens Mulindabigwi. Thus, following equation was utilized to estimate the radius *r*:

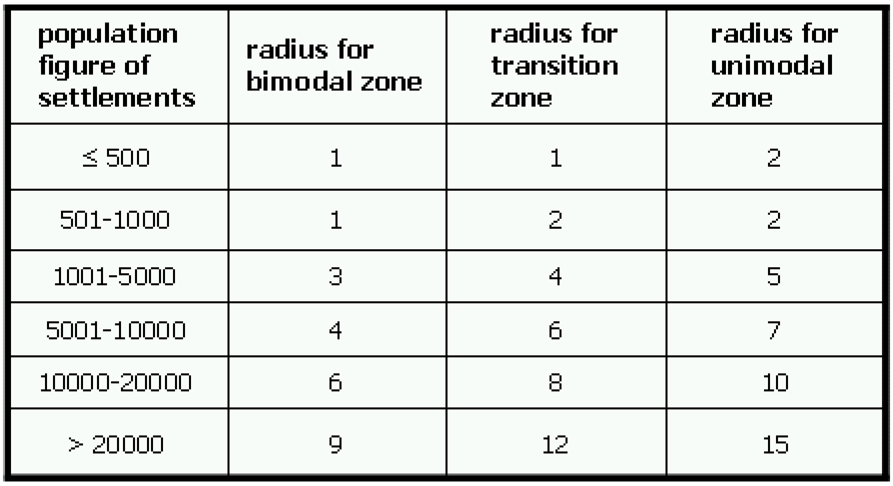
$$r = (( B * F_p)/(100*\pi))^{1/2} \qquad \textbf{(4)}$$

The villages were subdivided into six classes based on their population figures *B*. Additionally, the necessary area (including houses, fields and fallow) in ha per inhabitants of a village ($F_p$) were determined. The defined floor space required by a village is based on numbers given in the literature, such as RUTHENBERG (1980), MULINDABIGWI (2006), and FAO (2007A). In doing so, three different precipitation regimes were distinguished (see Table 5).

| climatic zone | area under cultivation [ha/inhab.] | area of fallow [ha/inhab.] | area for livestock farming | area of settlement | total area (S) |
|---|---|---|---|---|---|
| bimodal zone | 0.16 | 0.20 | 0.16 | 0.04 | 0.56 |
| transition zone | 0.27 | 0.52 | 0.27 | 0.04 | 1.10 |
| unimodal zone | 0.38 | 0.74 | 0.38 | 0.04 | 1.54 |

**Table 4: Determination of the floor space [ha/inhab.] required by a village (based on RUTHENBERG (1980), MULINDABIGWI (2006), and FAO (2007A))**

Finally, 21 different radii were assigned to the villages of Benin (cf. table below).



| population figure of settlements | radius for bimodal zone | radius for transition zone | radius for unimodal zone |
|---|---|---|---|
| ≤ 500 | 1 | 1 | 2 |
| 501-1000 | 1 | 2 | 2 |
| 1001-5000 | 3 | 4 | 5 |
| 5001-10000 | 4 | 6 | 7 |
| 10000-20000 | 6 | 8 | 10 |
| > 20000 | 9 | 12 | 15 |

**Table 5: Empirically defined search radii (rounded) for the *Kernel Density* function**

Thus, the function was run 21 times. Inshore water as well as protected areas were thereby masked out. All 21 raster data sets were reclassified and then summed using an IDL-programme. The reclassification was necessary because of the masks applied. Furthermore, a general value of 4 habitants per km² was assigned to sites, where, according to the calculation the population density was zero. This was done because in Benin nearly all sites are used at least periodically for agricultural. Consequently, a value of 2 was assigned to protected areas.

Fig. 38 illustrates the outcome of the interpolation process as well as national parks and protected forests. The map demonstrates the heterogeneous spatial distribution of human settlements with highest population density values in the economical centre Cotonou with more than 1000 inhabitants/km². Generally, the south is the area with the highest population density.

Furthermore, surroundings of Natitingou and Djougou in the west as well as Nikki and Parakou in the east are densely populated. In the north, the majority of people live in the regions of Malanville, Banikoara or Kandi. The map shows additionally, that there are still various regions, which are merely sparsely populated, beyond protected parks or forests. These areas are mainly in the centre and north.

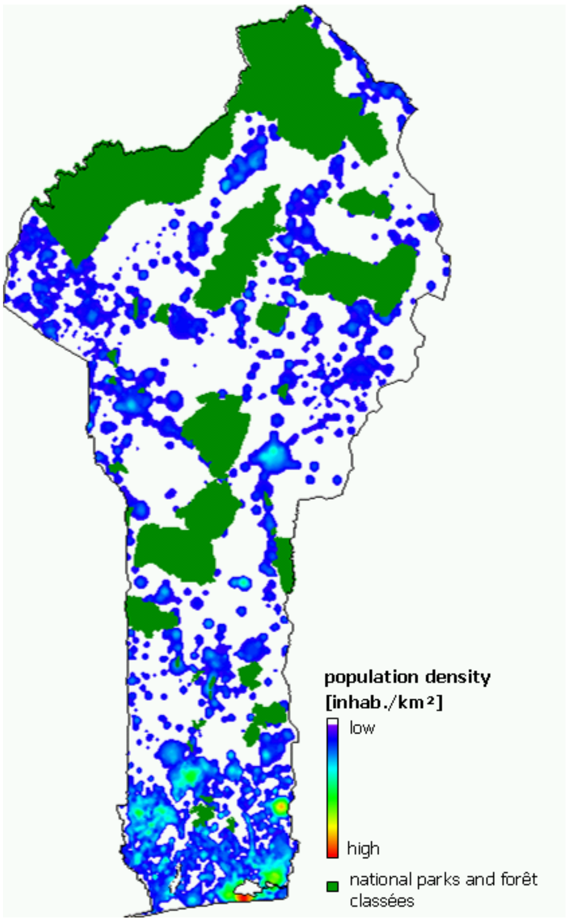


**Fig. 38: Population density of Benin; spatial resolution: 1km x 1km**

## *5.3 Determination of Land degradation*

Land degradation is a globally observable phenomenon. The occurring forms in Benin were already introduced in chapter 2.5. In this subsection, the derivation of land degradation based on satellite data will be examined. In doing so, the spatial distribution of recent trends of land degradation can be focused upon.

A recent definition of land degradation defines the term as "*a decline in the productive capacities of land that are irreversible on human time scales without significant human effort or investment"* (TURNER & GEIST 2006:164).

Remote sensing is suitable for monitoring land degradation as biophysical indicators can be derived efficiently in time and cost on different spatial and temporal scales (USTIN et al. 2005). Common monitoring approaches are based on land cover performance and thus, on vegetation indices, such as the NDVI (e.g. TUCKER 1979, BUDDE et al. 2004, PETTORELLI et al. 2005), SAVI (HUETE 1988) or EVI (HUETE et al. 2002). They are all based on characteristic high near infra-red and low visible reflectance of green vegetation. In using indices, influences of the atmosphere, soil and sun angle are reduced and the proportion of green vegetation strengthened. Recent approaches uses often rain use efficiency (RUE) as an indicator to determine land degradation (e.g. Budde et al. 2004, Li et al. 2004, Symeonakis &. Drake 2004, and Hountoundji et al. 2006). This indicator is based on a generally strong relation between vegetation dynamics and rainfall. In the case of land degradation, an ecosystem has a reduced ability to react on rainfall events, which is known as a 'loss of resilience' (cf. Dube & Pickup 2001, Eswaran et al. 2001). Consequently, scientists interpret reduced correlation coefficients as signs of land degradation.

|  | 250 sites (random) | South Benin | Central Benin | North Benin |
|---|---|---|---|---|
| r | 0.84 | 0.82 | 0.91 | 0.81 |

**Table 6: Correlation coefficients of iNDVI & yearly sums of rainfall (yrain)**

For Benin, the degree of correlation of integrated NDVI (iNDVI) and yearly rainfall sums (yrain) was analysed. Therefore, the normalised difference vegetation index (NDVI) from the NOAA Global Inventory Monitoring and Modelling Studies (GIMMS) and, in chapter 5.1.2.3 also already described, decadal rainfall sums between 1982 and 2003 were used. For Benin, correlation analyses of yrain and iNDVI show high correlation between rainfall and vegetation (Table) (see also Klein & Röhrig 2006).

Second, rain use efficiency was calculated for each site using the yearly ratio of iNDVI/yrain from 1982 to 2003 in a spatial resolution of 8km. Trends were determined by linear regression of the ratio (dependent variable) and time (independent variable). Based on the Student's t-test, the regression slope was mapped into seven classes indicating different statistically significant trends (cf. Eklundh & Olsson 2003, Hountondji et al. 2006).

The t-test is one of the most commonly used methods to test a hypothesis on the basis of a difference between sample means. In this context, the test is used to examine the hypothesis that the regression slope is zero. In a first step the Student's t-statistic was assessed based on the correlation coefficient according to Haan (1977) (cf. Önöz & Bayazit 2003). In the next step, cut-off values in a Student's t distribution with defined degrees of freedom and probability, which corresponds to the significance level, were computed using the IDL T_CVF function (see Neter et al. 2003). For Benin, classes were labelled as 'strong' trends (positive or negative) if the T-value of the slope exceeded the 0.025 p-value of either tail of the distribution. If the T-value was between the 0.025 and 0.05 p-value or between 0.05 and 0.15, the trends were 'medium' or 'weak,' respectively. All other sites were classified as 'no trend' showing no statistically significant change for this time period.

Fig. 39 illustrates that about half of the country shows no statistically significant trend for the iNDVI/yrain-ratio (RUE) since 1982. Only isolated sites in the east have significant positive trends. The majority of the remaining half, however, is characterised by negative trends. For nearly 10% of all sites in Benin, strong negative trends were determined. These areas have experienced beginning or ongoing land degradation processes from 1982 onwards. They are situated mainly in the central or northern Benin. A comparison with the information of soil degradation in 1992 given in MEHU (2003) and own records of degraded sites demonstrates that the estimated trends corresponds only partly to them. That is not surprising, as all three sources contain different information about land degradation. The own estimation considers declining processes in vegetation productivity. In contrast, MEHU (2003) contains the state of soil degradation in 1992 and the expected state in 2025. For the own documentation, degraded sites were recorded between 2005 and 2007. Thus, they are primarily small size information with a restricted explanatory power for an area of 1km².

The 80 records are based on the indicators defined by the *methodology of a visual soil-field assessment tool* in the framework of LADA (Land Degradation Assessment in Dryland) (see for more information McGarry 2006). The aim of the methodology is to provide a cheap, simple and immediate mean of land degradation assessment in developing countries, which can easily applied by farmers and their advisors.

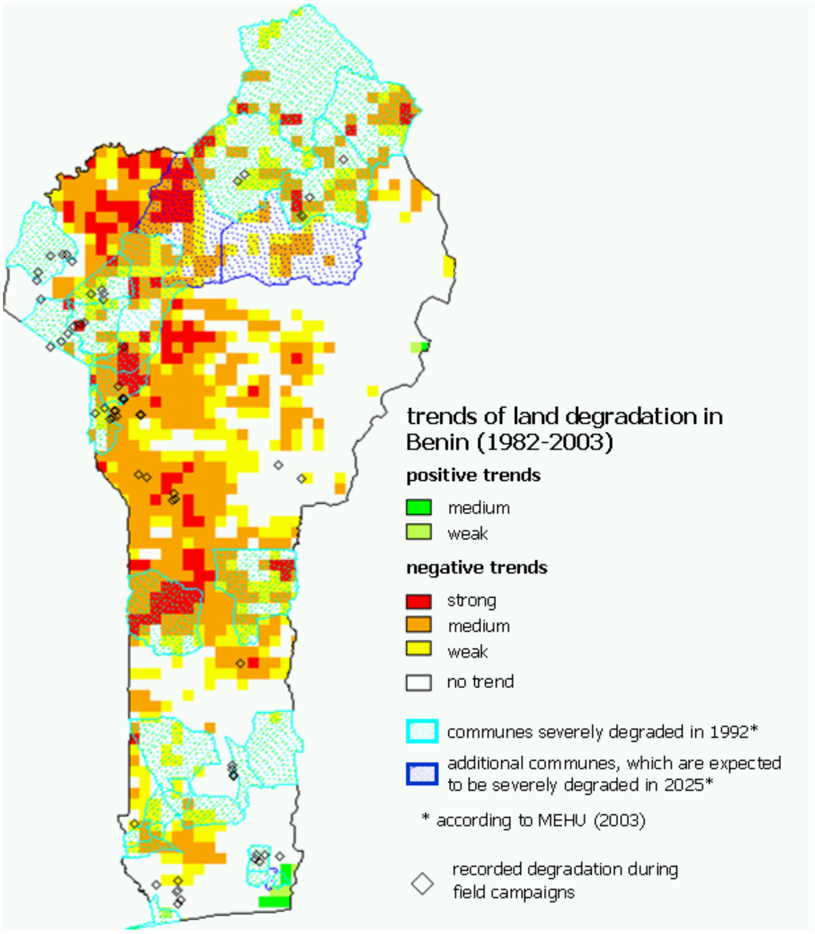


**Fig. 39: Trends of land degradation in Benin between 1982 and 2003 overlaid by communes with severely degraded soils in 1992 and expected in 2025, respectively (MEHU 2003)**

Due to the limited time of the field campaigns, the method seemed suitable to record signs of land degradation in the field. Within the documents, the author names a series of indicators visible at the surface. They are called *walk-in information*. There are both, positive and negative walk-in information and indicators. Examples for negative indicators are hard setting surface or crust, soil dispersion (white sand grains) on the soil surface or water ponding on surface or in wheel tracks.

Regions, in which land degradation occurs within all three sources, are areas in the southwest, the communes of Banté and Ouesse in the centre and the Kopargo, Malanville and Kandi in the north. They are all characterised by high population growth (cf. 2.3). This aspect will be considered in more detail in chapter 7.2.2. Large areas of negative trends are additionally in regions that were slightly degraded in 1992 or protected regions (e.g. Pendjari, Forêt de Monts Kouffé). Whereas illegal logging activities in the forests may be reasons for these negative trends (cf. ORTHMANN 2005), in the Pendjari National Park, regular fires are set to guarantee visitors good sights of wildlife. In the same regions already severely degraded by 1992 (e.g. Boukoumbé, Ouakè, Malanville or several regions in the south) negative trends are still apparent. Thus, the dynamic of the land degradation processes was analysed in more detail by subdividing the time of considerations into three overlapping periods.

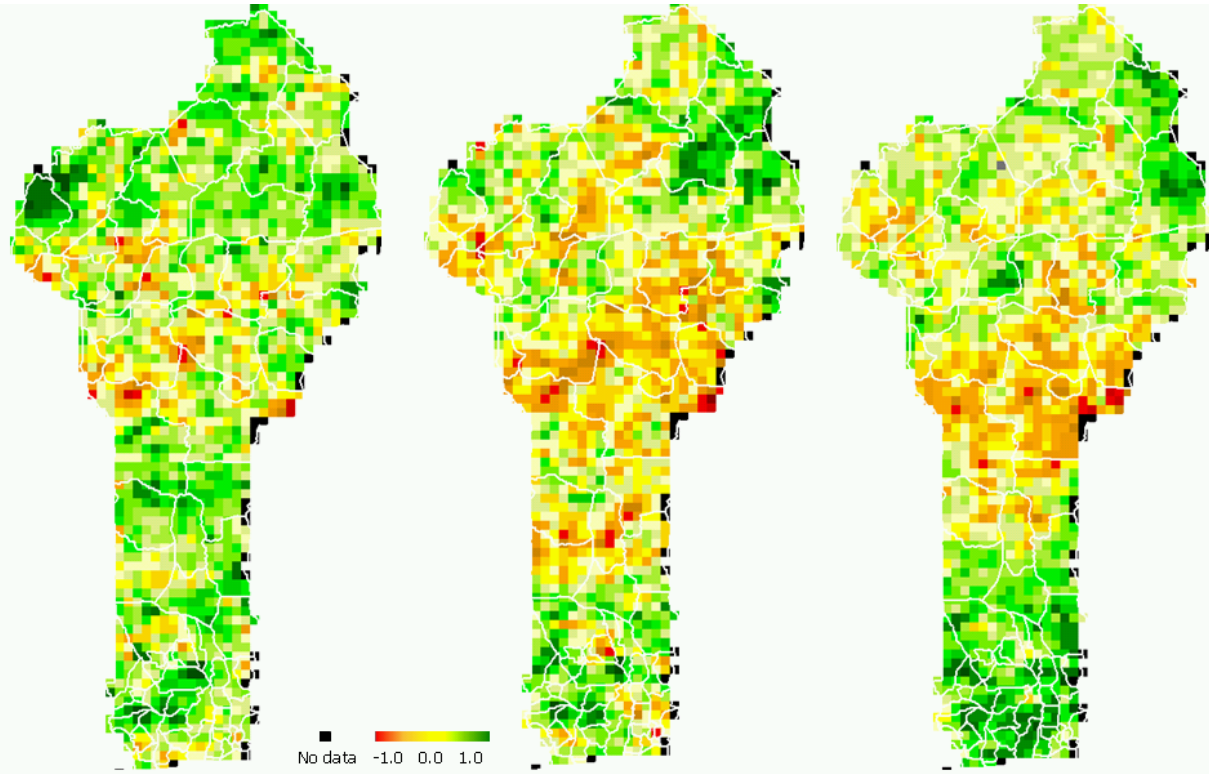


**Fig. 40: Correlation coefficients of yrain and iNDVI for three periods (from left: 1982-1993, 1986-97, and 1992-2003)**

Fig. 40 illustrates that the correlation values of iNDVI and yrain decreases mainly from 1992 onwards. In the strongly degraded south for instance, correlation coefficients were negative in the 80s but become positive in the 90s. In central and north Benin, however, rising number of sites are characterised with negative correlation values. This corresponds very well with observable flows of migration. Many people migrated from the degraded regions in the west and south into areas with rather low population density (DOEVENSPECK 2004). Here, new settlements and thus new fields arise, like along the newly built road between Woubèro and Bassila. At first, this may not be considered as land degradation and irreversible processes according to the definition above by TURNER & GEIST (2006). Nevertheless, farmlands have significantly lower productivity levels than natural vegetation forms. Furthermore, these areas often remain part of the crop-fallow rotation, which is why the discreation of the natural vegetation cover has a lasting effect. Additionally, in Benin this process has been often the start of more severe forms of land degradation. When suitable land resources become scarce, agricultural activities are intensified and expand onto marginal sites (NEUMANN et al. 2004, MULINDABIGWI 2006). Where agricultural activities are intensified without technological improvements or adaptation of farming systems, productivity declines and land degradation begins.

In conclusion, recent trends of land degradation can be derived from remote sensing data. Therefore, the RUE proved to be a suitable indicator to monitor vegetation cover due to the generally strong relation between vegetation and precipitation in Benin. However, only vegetation transformation processes within this period are detectable. Thus, known regions where severe land degradation occurred already in the 1980s cannot be identified with the method and the data. Correlation analyses have shown that the majority of RUE trends are negative. Land degradation within protected areas is caused by fire management and logging. Beyond, the method helps to detect regions, where natural vegetation cover is transformed into new settlements and fields. Such expansion of agricultural activities onto marginal sites is of particular interest and will be thus, picked up in chapter 7.2.2. These areas are hot spot areas due to restricted production potential and a principally high sensitivity to degradation processes of soils.

# 6 Evaluation of current and future agricultural land resources of Benin based on the marginality index

In this chapter, the evaluation of current and future agricultural land resources using the marginality index for Benin (MI) will be illustrated. The determination of the index can be subdivided into two main parts, definition of membership functions and application of the hierarchical logical decision tree to calculate the index. Chapter 6.1 contains the evaluation of recent biophysical constraints of Benin and the assessment of MI, the outcome of the regionalisation approach. Like in the previous chapter containing the data description, MI will be compared with the original global outcome of the marginality index in 6.1.8. Chapter 6.2 examines the outcome of scenario analyses corresponding to IPCC SRES scenario A1B and B1. Furthermore, the impact of climate change on the biophysical conditions for agricultural land use will be addressed.

## *6.1 Evaluation of recent biophysical constraints*

In this subsection the biophysical constraints will be examined. Therefore, a membership function is assigned to each indicator. In doing so, each indicator is fuzzificated based on a linguistic category (e.g. low or high) and a degree of membership is defined for each value and pixel, respectively. If the same indicator was used as in the global approach, the original membership function was applied as a first approximation. The definition of the final functions is based on regional knowledge, empirical observations and information within the literature. Hence, content and descriptions of chapter 2 will be used intermittently.

### 6.1.1 Low potential natural vegetation cover

According to CASSEL-GINTZ et al. (1997), regions that are characterised by low plant productivity are potential marginal sites. Due to the alteration of the indicator, the membership function defined by ibidem could not be used as a first approximation. Additionally, as potential vegetation is a mainly theoretical concept, discussion for its evaluation proves challenging. The evaluation of potential natural vegetation cover was based mainly on information about the potential vegetation given in the literature (e.g. Bohlinger 1998, Neumann et al. 2004) and the value range of the data set by Brown & Gaston (1996).

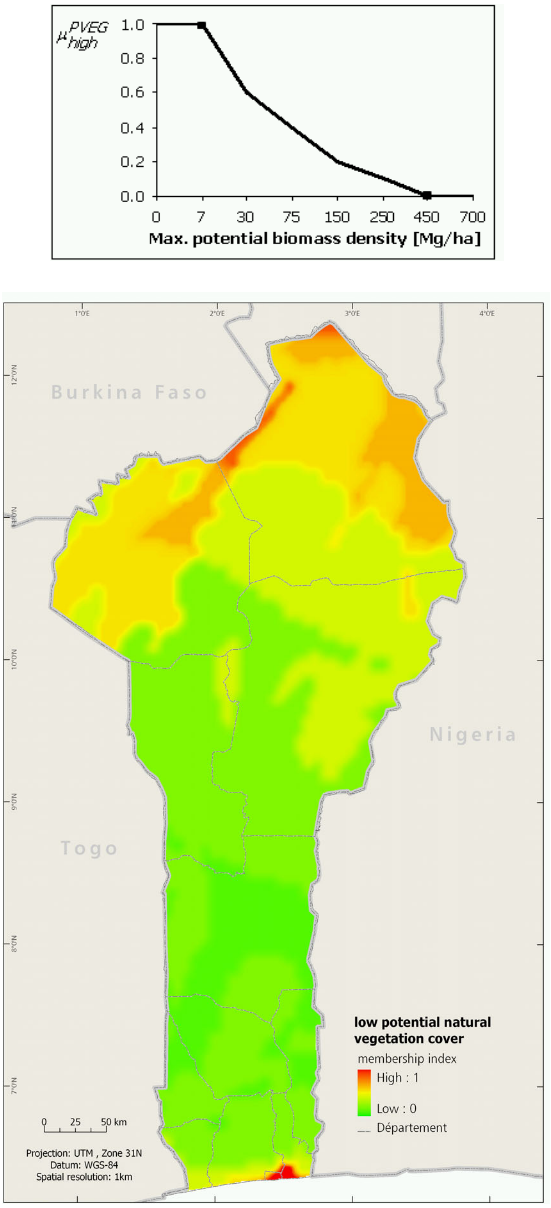


**Fig. 41: Membership function of PVEG (above) and spatial distribution of low PVEG (below)**

The data values range from a maximum potential biomass density between 500 Mg/ha in the evergreen rainforest areas to 7 Mg/ha in desserts (see chap. 5.1.2.1). Evergreen rainforests certainly do not have low potential natural vegetation cover, whereas desserts surely do. A linear membership function between these two values comes out however with too high values for Benin. This is caused by the characteristics of the data set by Brown & Gaston (1996), which contains only a limited number of values resulting originally in value differences of up to 100 Mg/ha between two pixels situated next to each other.

Consequently, with the intention to smooth the transitions, a user-defined membership function was defined instead of a linear function. The definition of the values will be described exemplary for the regions with the lowest and the highest density values. Taking into account the information about the potential vegetation of Benin (e.g. Bohlinger 1998, Neumann et al. 2004), a membership value of 0.1 was assigned to areas with the densest vegetation cover. This assignment makes allowance for the fact that moderate precipitations sums and restricted growing seasons prevent a denser potential vegetation cover, like evergreen forests, on a larger scale. Instead, semi-deciduous forests and savannas would be predominant in most of the country. Lowest density values and consequently highest membership values were assigned in the North. For these regions a membership value of 0.6, was assigned as declining rainfall amounts cause significantly lower vegetation cover. Nevertheless, the potential vegetation cover is significantly higher than in dessert or even in the Sahel regions, where a maximum value would be assigned. Membership and outcome is demonstrated by Fig. 41.

## 6.1.2 High temperature

The indicator of temperature or more precisely of night temperature during the growing period was added compared with the original approach. Thus, a new membership function was defined.

The differences between the LST-products of MODIS and conventional temperature measured at climate stations are intrinsic. Consequently, temperature requirements of specific crops like in Sys et al. (1993) or MDR & INRAB (1995) could not be used to evaluate temperature constraints. Thus, more general descriptions, like the ones of Igué (2000), Igué et al. (2000) and Weller (2002) were implemented. Igué (2000) for instance stated that the mean temperature of the growing period is for the most part above the optimum resulting in minor constraints for all crops. Thus, a linear membership function was defined which assigns generally small constraints for the main regions and moderate ones in the north. For the application of linear membership functions an IDL-routine was written (see appendix 2.1), wherein only the two thresholds no constraint (x0)

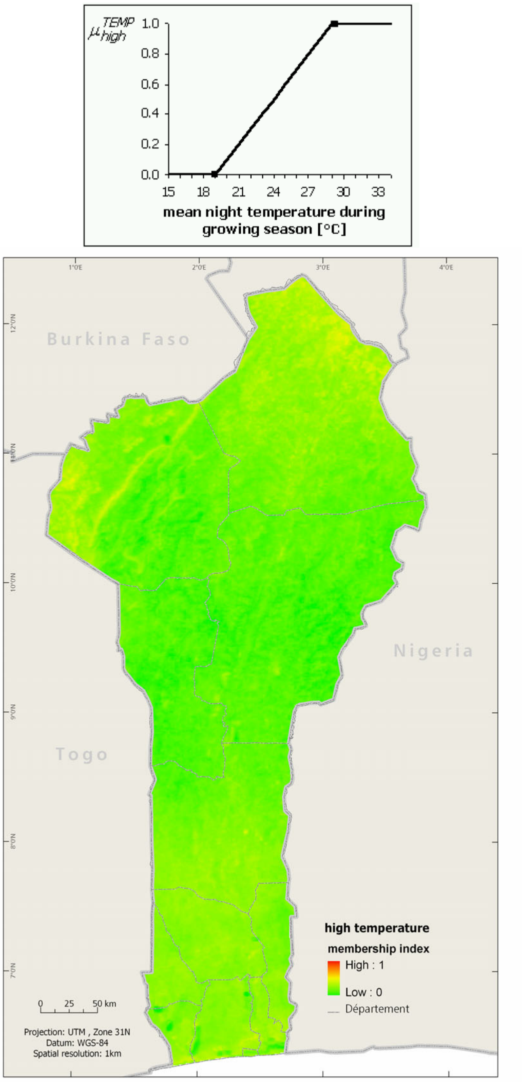


**Fig. 42: Membership function of TEMP (above) and spatial distribution of high temperature (below)**

and insufficient for agricultural land use (x1) were defined (see Fig. 42).

### 6.1.3 Limited length of growing period

For the regionalisation, instead of alpha, the length of growing period was chosen as aridity indicator. Additionally, the high temporal variability of this feature was taken into account.

For the definition of the membership function concerning the growing period length, statements given for ten of the most important crops in Benin were accounted (cf. chap. 4.1). Thus, a length of 20 decades is long enough to cultivate all crops and consequently used as the first threshold (x0). The maximum constraint (x1) is reached if even for cowpea, the crop, which requires the shortest growing period, the rainy season is too short. Between these two extremes, a linear membership function was assigned. A variability of about one decade, which corresponds approximately to a standard deviation of 5% for most of the regions, was considered as unproblematic and consequently as no constraint due to variability of LGP. In contrast, a standard deviation of 25% was regarded as maximum constraint (x1). Setting up a linear membership functions between these two values, moderate limitation values were assigned to regions in the north and south and lower values in between.

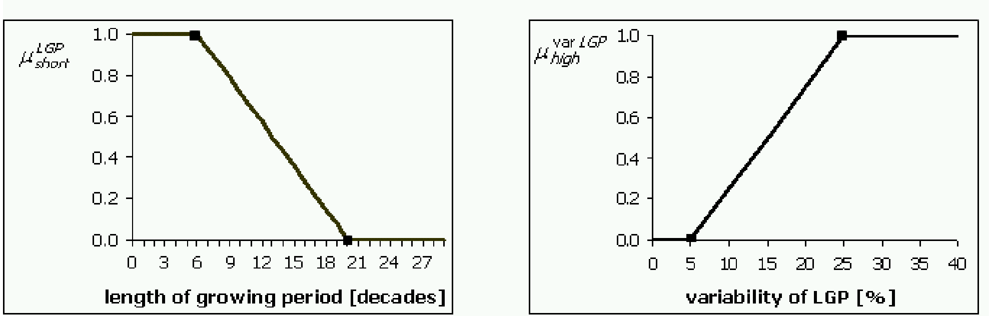


**Fig. 43: Membership functions of LGP and varLGP**

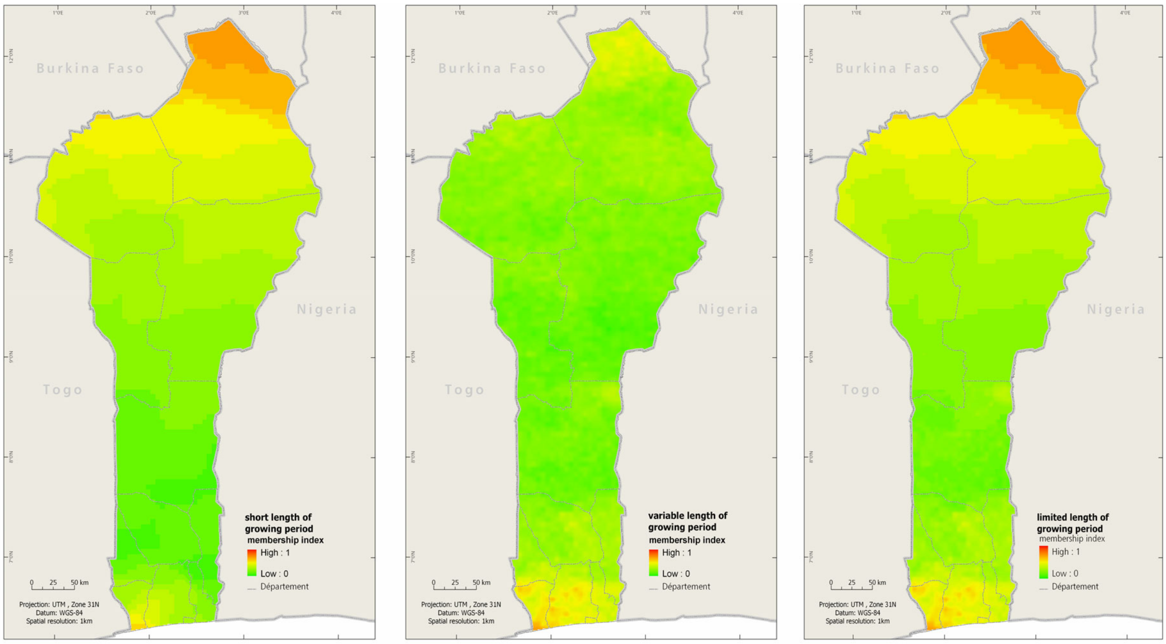


**Fig. 44: Limited length of growing period (right) and its components: LGP (left) and varLGP (middle)**

Short rainy seasons as well as high variability of the length represent a severe natural constraint for farmers. A short length cannot be improved by a low variability, for instance. Thus, a fuzzy OR-operator was chosen for the determination of the final limitation caused by LGP. Fig. 44 shows the fuzzification results of both input parameters and the outcome of limited length of growing period. Moderate to high variability of LGP increases the final constraint especially in southern regions.

### 6.1.4 High rainfall variability

In contrast to the inconsistency of the length, the limitation due to high rainfall variability is focused on precipitation anomalies within the growing season. With its incorporation yield losses caused by drought periods within the rainy seasons are considered. In contrast to the original approach, however, positive anomalies were also taken into account.

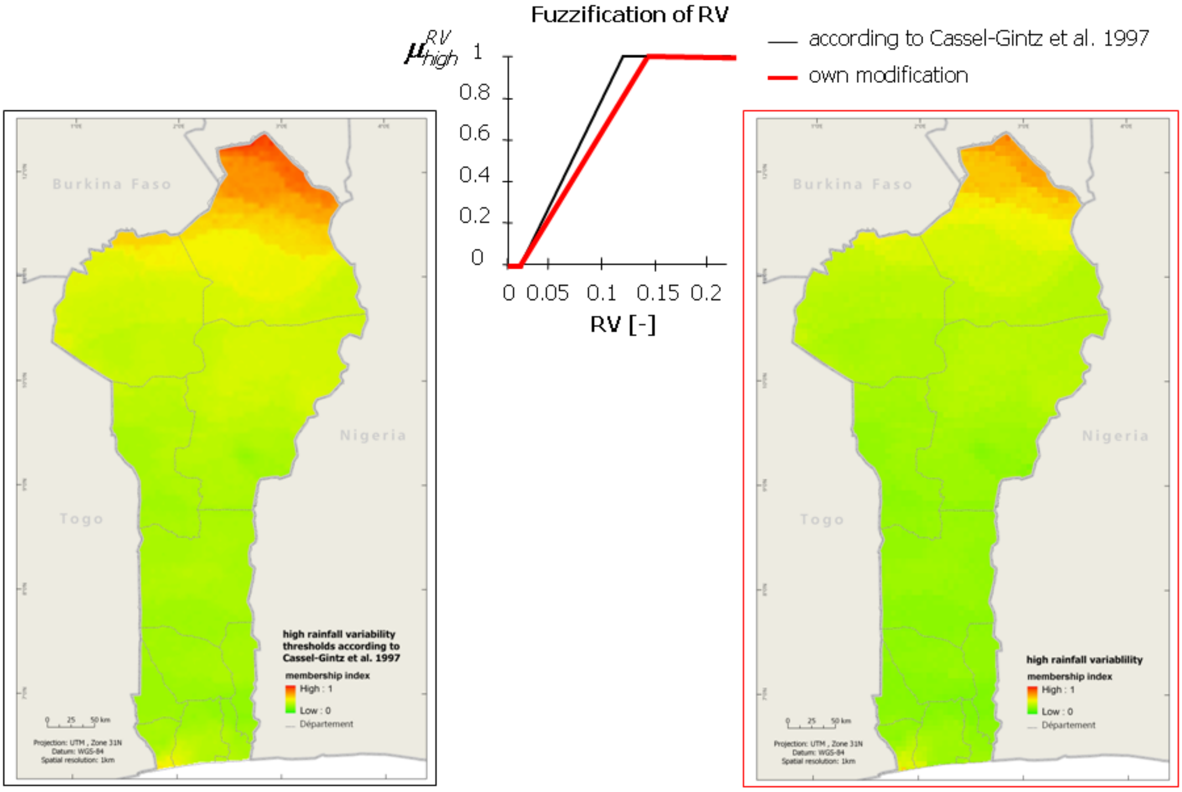


**Fig. 45: Modification of the membership function assessing high rainfall variability**

Figure Fig. 45 illustrates the outcome of the fuzzification with the thresholds of CASSEL-GINTZ et al. (1997), where maximum values of 1 are assigned to northern regions. In doing so, the insecurity in northern Benin would have the same severity than in regions known for very high precipitation variations values like the Sahel or semi-arid regions, like Kenya. Own investigations, however have shown, that the rainfall variability in semi-arid Kenya is much more crucial than in Benin (see KLEIN & RÖHRIG 2006).

Nevertheless, the majority of farmers interviewed named the problem of rainfall variability and thus, insecurity. Farmers of the villages Agatoudji and Djikpame (cf. TableA 2) named rainfall variability even as the most limiting biophysical constraint. BERDING & VAN DIEPEN (1982) and WELLER (2002) named high rainfall variability as one cause for declining yields in the South. Lowest constraints are observed approximately along 10° North (BERDING & VAN DIEPEN 1982). Consequently, the function was slightly modified for Benin incorporating the information of the farmers and literature (cf. Fig. 45).

### 6.1.5 Low potential irrigation capacity

Depending on the degree of aridity, rivers and lakes can compensate this constraint. Therefore, perennial inshore waterbodies have higher potentials than waterbodies which dry out during the dry season. Additionally, the greater the amount of water available within the waterbodies, the higher is the potential.

The original membership function comes out with satisfyingly results and was hence, also used for Benin. An explanation may be that for the determination of the potential irrigation capacity the same hierarchical classification scheme for the waterbodies used in CASSEL-GINTZ et al. (1997) was applied. Consequently, the value range was similar. The membership function of slope for irrigation is similar to the one presented in 6.1.7, although for x0, 3% instead of 0% was chosen, as very small slopes does not limit irrigation in the slightest way.

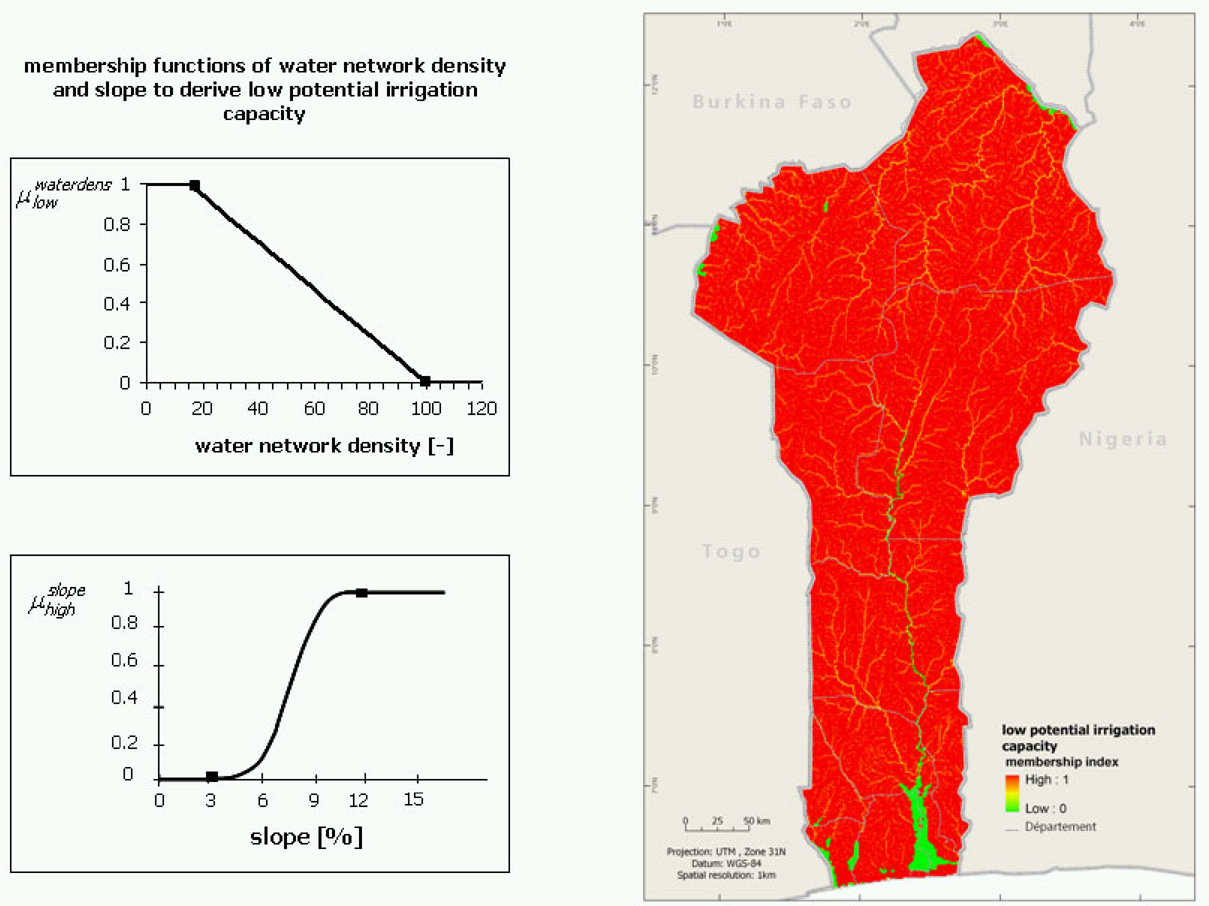


**Fig. 46: Membership functions of WATERDENS and SLOPE (left) and spatial distribution of low potential irrigation capacity (right)**

### 6.1.6 Low soil fertility

The indicator of soil fertility has been modified and thus, a new membership function was defined. For the fuzzification algorithm a user-defined membership function was assigned that matches the structure of the ordinal evaluation scheme derived from the ORSTOM soil map (cf. 5.1.2.6). The definition of this function is based on following principles: first, in accordance with the CLAUDIA HIEPE the maximum constraint due to low soil fertility in Benin was sized as 0.9. This decision is based on the regional knowledge that no site in Benin covering 1 km² is totally unsuitable for agricultural used concerning its soils. Secondly, the six groups were ordered so that the soils of the two main groups (NH and H) follow each other (see Table 7).

| **soil group**<br>NH: non-hydromorphic<br>H: hydromorphic | **classes** | **examples** | **general evaluation** | **lower thres-hold for fuzzifi-cation** | **upper thres-hold for fuzzifi-cation** |
|---|---|---|---|---|---|
| NH | 1.0-1.5 | Sols brunifiés, Sols sesquioxydes de fer et de manganèse lessivés sans concrétions sur matériau colluvial issu de quartzite et micaschiste atacoriens | very fertile | 0 | 0.3 |
| NH | 2 | Sols ferrugineux tropicaux peu lessivés, peu lessivés en argile, lessivés en sesquioxydes sur matériau kaolinique issu de granito-gneiss à biotite or de roche basique | moderate fertile | 0.5 | 0.5 |
| NH | 3.0-3.5 | Sols ferrugineux tropicaux indurés sur matériau kadinique issu, Sols ferralitiques faiblement désaturés rajeunis ou pénévolués avec érosion et remaniement sur embréchite or sur granito-gneiss, Sols peu évolués d'origine non climatique d'érosion lithiques | not suitable for agriculture | 0.6 | 0.9 |
| H | 4.0-4.3 | Vertisols, Sols ferrugineux tropicaux hydromorphe sur gneiss | fertile | 0.34 | 0.46 |
| H | 5 | Sols ferrugineux tropicaux peu lessivés hydromorphe, Sols ferrugineux tropicaux lessivés hydromorphe sur schiste | moderate fertile | 0.55 | 0.55 |
| H | 6.0-6.4 | Sols hydromorphe minéraux ou peu humifères | not suitable for agriculture | 0.9 | 0.9 |

**Table 7: Classification of the ORSTOM soil types and the evaluation of soil fertility**

Thus, a partly-linear membership function was used (cf. Fig. 47). Therefore, thresholds for all soil classes were defined.

The best soils are the very fertile soils without drainage restrictions (group 1.x). For this group membership values between 0 and 0.3 were assigned using a linear function. The second most fertile soils are the most suitable soils of the group with drainage restrictions (4.x). The moderate fertile soils of NH (2.x) are less fertile than both of the very suitable soils but more fertile than the moderate suitable soils of the H-group (5.x). The same principle is followed for the soils, which are unsuitable for agricultural land use, labelled as 3.x (NH) and 6.x (H), respectively. For each group the range of membership degrees was defined. The outcome of this user-defined membership function is presented in Fig. 47.

The map demonstrates that soil fertility is generally moderate in Benin, often low.

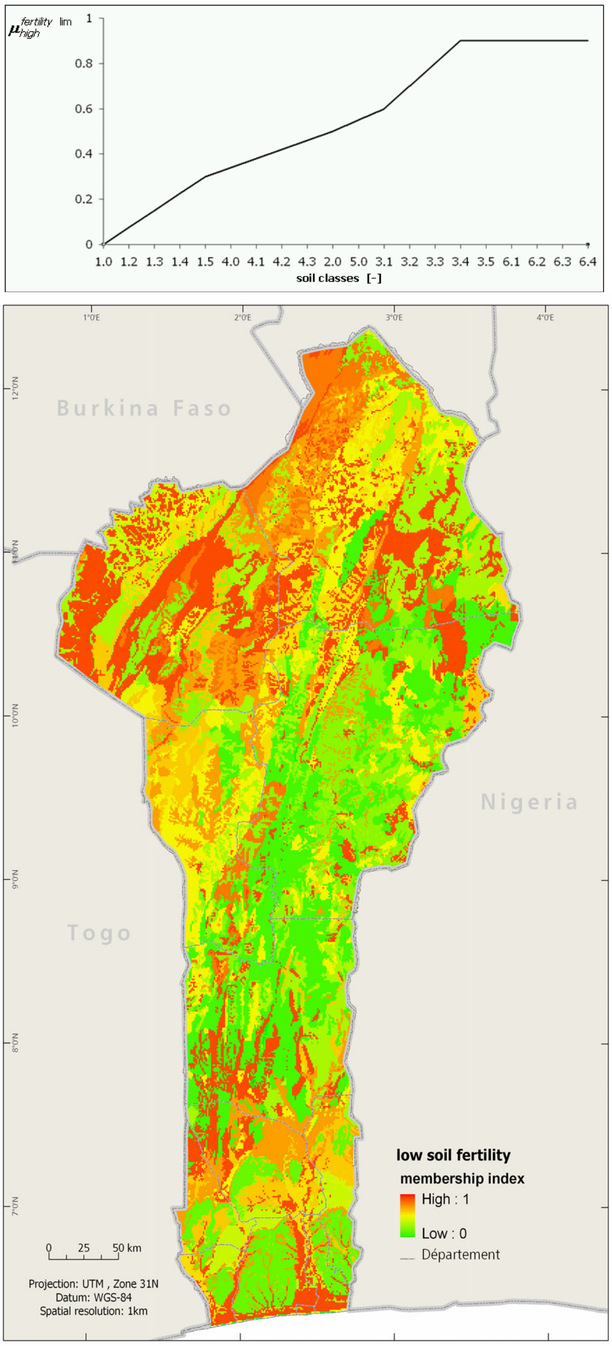


**Fig. 47: Membership function of SOIL (above) and spatial distribution of low soil fertility (below)**

## 6.1.7 High risk of erosion due to steep slopes

An assignment of the membership function of CASSEL-GINTZ et al. (1997) to the slope derived from SRTM results in general moderate to high risk of erosion in Benin (see Fig. 48). This outcome clearly overestimates the erosion risk caused by steep slopes, because in Benin the topography is rather flat. Steep slopes occur mainly within the

Atacora mountain range, at fringes of inselbergs, and in the south, at the borders between the sedimentary plateaus and the crystalline basement. Nevertheless, even slight slopes are prone to erosion due to intense and erosive rainfall (GRAEF 1999, CENATEL 2002, MEHU 2003). Beyond the thresholds themselves, a linear membership functions does not reflect the risk of erosion adequately. Furthermore, a sigmoid instead of a linear fuzzy function is more common in this context (cf. BERDING & VAN DIEPEN 1982, DOMINGO 1986, SYS ET AL. 1993). The sigmoid or "s-shaped" membership function is beyond the linear function, one of the most often used function in fuzzy set theory (KRUSE 1993, BURROUGH & MCDONNELL 1998). It is produced using a cosine function. This fuzzification was done with IDRISI, wherein the sigmoid fuzzy function is implemented as a standard tool (CLARK LABS 2002).

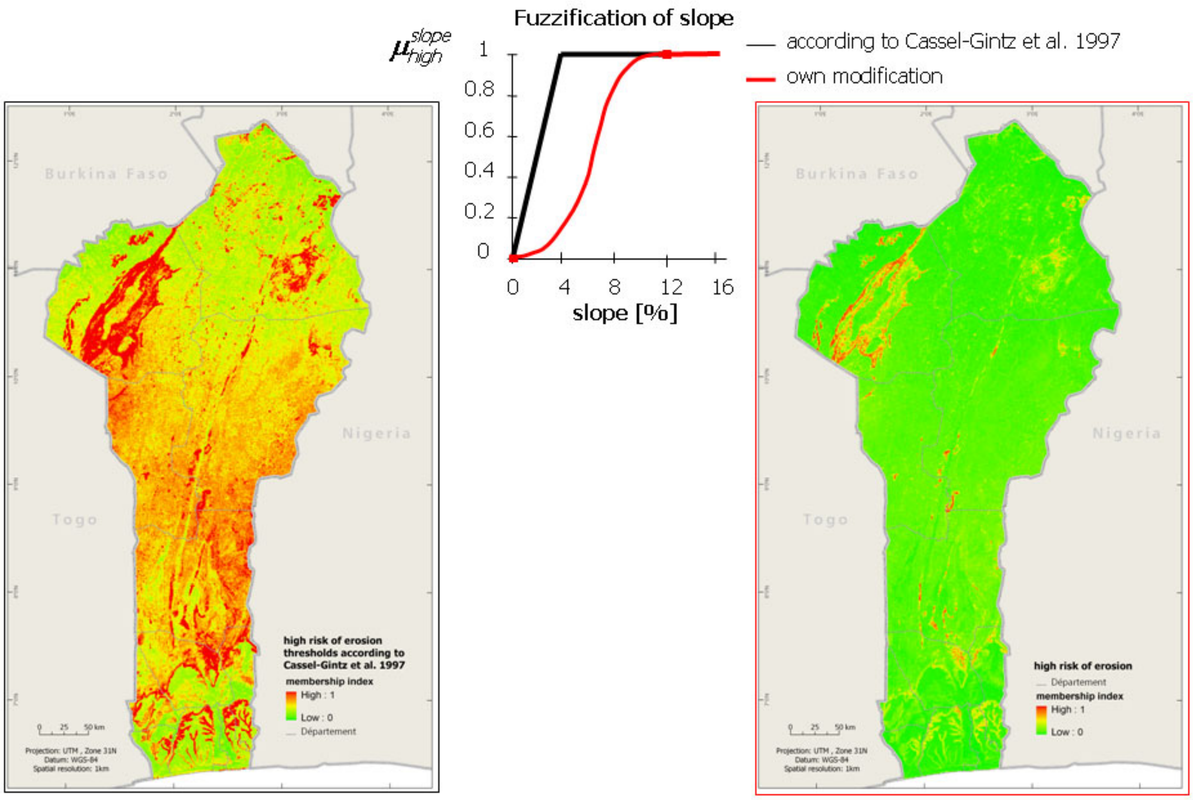


**Fig. 48: Modification of the membership function assessing high risk of erosion due to steep slopes**

Beyond the statements in the literature, the choice of the thresholds was based on the interviews with farmers. For example, the farmers of Serou, a village south of Djougou gave thereby very useful information. They stated that there are some sites within their surroundings, which are not suitable for agricultural land use due to steep slopes (see Fig. 49). In contrast, the farmers of Thochoume said they prefer plain surfaces due to better water and nutrient content of the soils, but slope causes no severe restriction of agricultural activities in this area. Consequently, near Serou some sites with maximum constraints occur, whereas only slight constraints exist nearby Thochoume.

Fig. 49 illustrates the risk due to high slopes in Benin reflecting the given information most well.

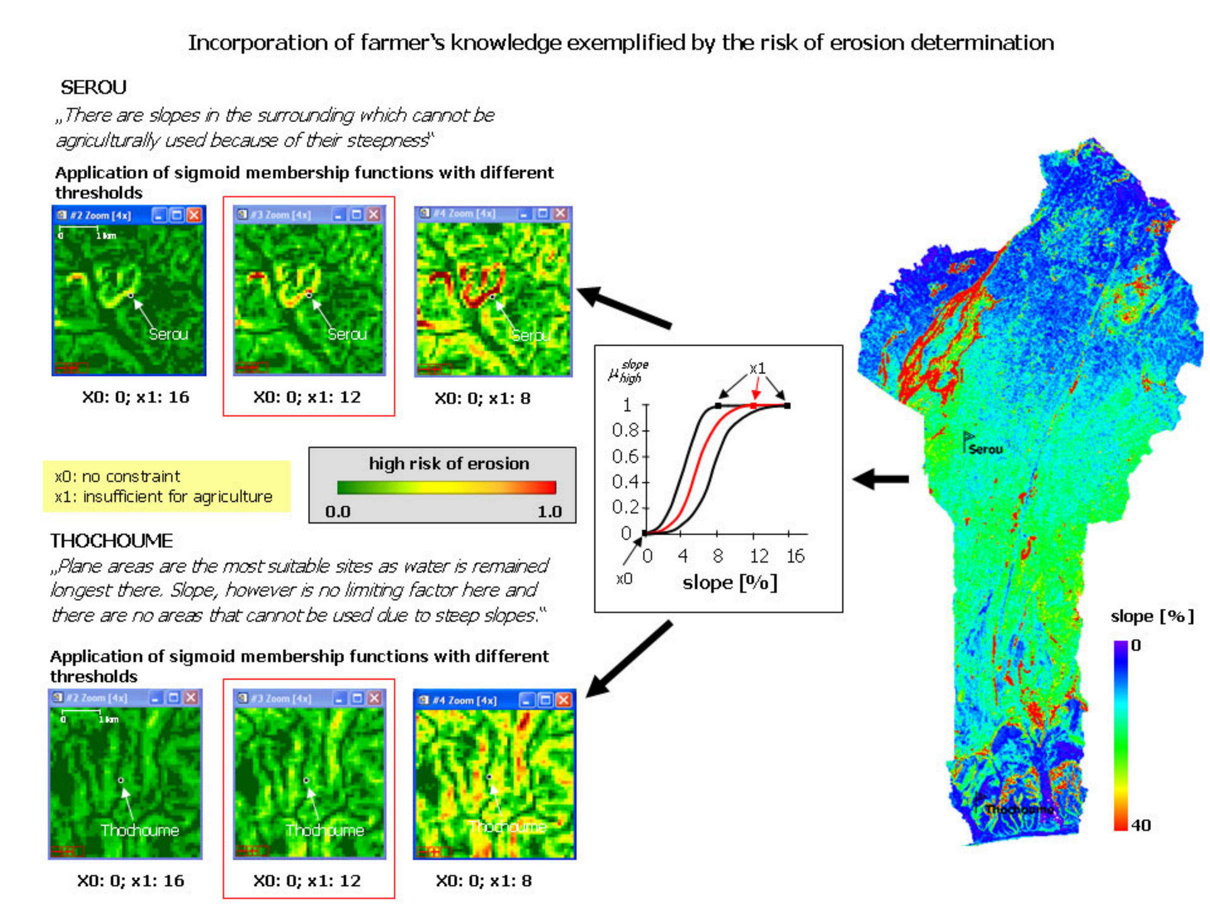


**Fig. 49: Modification of the membership function for slope based on interviews with farmers**

### 6.1.8 Determination of the marginality index for Benin (MI)

In this subsection the determination algorithm and outcome of the regionalisation, the marginality index of Benin (MI), will be examined. In doing so, the regionalisation outcome will be compared with the global result. The results and particularly the constraints will be considered in chapter 7.1 in more detail. At the end of this subsection, a brief intermediate summary of the regionalisation process will be already given.

For the assessment of the marginality index, nearly the same biophysical constraints as those in CASSEL-GINTZ et al. (1997) were incorporated as input data. Thus, the general argumentation deriving the marginality index did not change. Nevertheless, one small modification was applied. For the global assessment, the essential meaning of the fertile regions in Eastern Africa was incorporated by implementing a compensatory OR-operator. In doing so, the severity of erosion risk was diminished within eminently fertile areas. In Benin, however, the mountainous areas are not particularly suitable for agricultural land use as the soils are characterised often by physical constraints. In addition, all interviewed farmers evaluated hillsides negatively due to lower water and nutrient availability. Thus, the compensating OR-operator was replaced by a normal OR-operator.

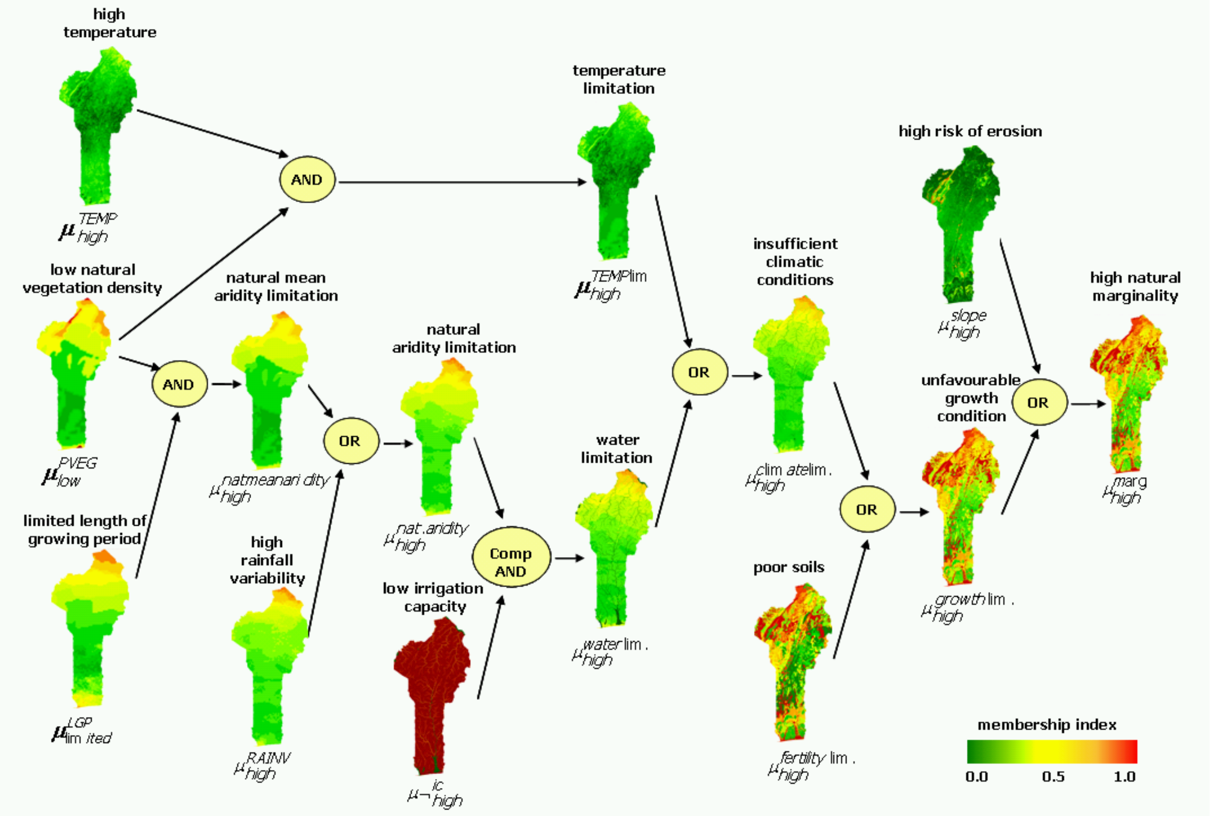


**Fig. 50: Logical decision tree for the assessment of MI**

For the calculation of the index, the fuzzificated variables of 6.1 were combined using a modified logical decision tree (see Fig. 50).

The **comparison with the global outcome** illustrates, as one would expect, a spatially much more detailed result, but additionally, a notably different spatial pattern. The former is a consequence of input parameters in a higher spatial resolution (Fig. 51). Thus, topographic features of the natural landscape, such as the mountainous regions or inshore waters are, for instance, obvious in the regionalisation result. Furthermore, the compensating effects of nearby rivers are clearly detectable in the outcome of the regionalisation, like in the flooding area of the river of Niger in the north.

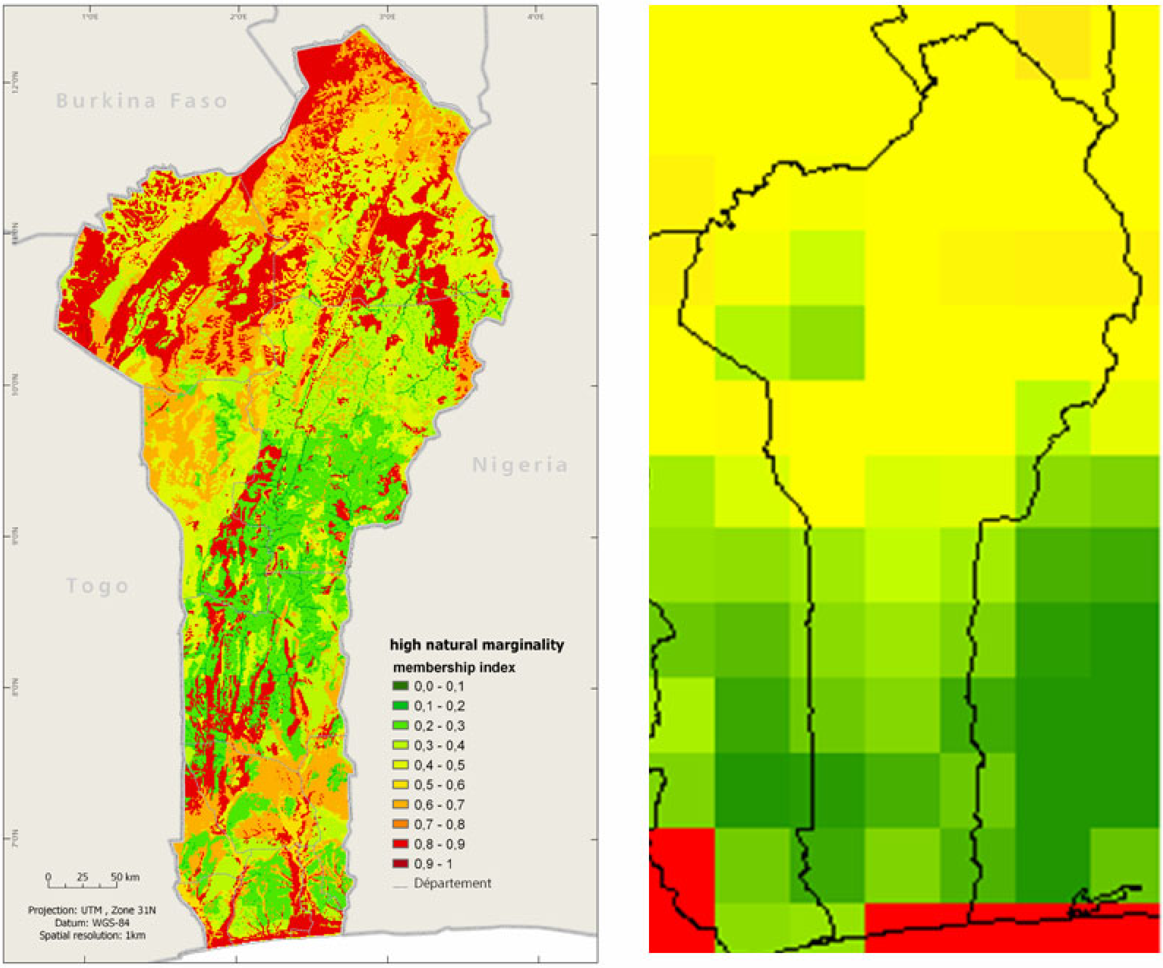


**Fig. 51: The outcome of the regionalisation (left) compared with the original determination of the marginality index by CASSEL-GINTZ et al. (1997) (right)**

The data range of both outcomes is comparable. The marginality values of the regionalisation ranges from 0 to 0.97, whereby the values range globally from 0 to 1. Thus, Benin contains sites with very good biophysical conditions for agricultural land use, but also regions, where high natural constraints make them prone to land degradation if used agriculturally.

Although the data range is comparable, the spatial pattern is definitely different. Generally, the global outcome determines lower degrees of marginality for Benin than MI. Furthermore, the pattern of particularly marginal site is evidently different. In the global result, high marginal values are only found along the coast nearby Cotonou where hydromorphic soils are found. In contrast, the regionalisation identifies about 43% sites in Benin where the MI-values are higher than 0.6. These marginal sites are assessed in the south, but also in the centre and particularly in the north. In some regions, like the centre the patterns are opposed. Thus, MI calculated high membership degrees in western and quite favourable conditions in eastern regions, whereas the global result shows generally moderate values for the eastern and good conditions for the west region. Thus, for the central-eastern region MI estimates better conditions than the global approach. This difference results from the higher rainfall amounts and thus reduced aridity constraints nearby the mountain range and better soil fertility assessed within the global approach. The global result comes out with moderate or low marginality values for the majority of the country. In the regionalisation, however, only 23% of the area of Benin has slight natural constraints (MI ≤ 0.3), while only about 2% have good natural conditions for agricultural land use (MI ≤ 0.1). High potential areas are in the centre due to fertile soils valleys. In general, the conditions calculated by MI are moderate, as demonstrated by an average value of 0.55, whereas the global average value is evidently lower.

### 6.1.9 Conclusion

For Benin a land evaluation scheme was set up, which is based on the marginality index for agricultural land use defined by CASSEL-GINTZ et al. (1997) (MI). For the evaluation of MI, several natural constraints limiting agriculture under low capital input on national scale were quantified and summed into one integrative index. MI was determined for Benin in a spatial resolution of 1km x 1km with modified input parameters and an adapted fuzzy logic based algorithm. For the latter, it was necessary to adapt the membership functions due to the higher spatial resolution or the modified input data. Thus, for the majority of indicators the thresholds defining 'no constraints' (x0) and 'insufficient for agricultural land use' (x1) were redefined. Furthermore, for several indicators instead of a linear relationship either a sigmoid (SLOPE) or a user-defined membership function was assigned (PVEG and SOIL).

The comparison of MI with the global outcome illustrates not merely a spatially more detailed result but also different spatial patterns. Generally, the degree of marginality is lower in the global assessment than in the regionalisation outcome. Only in the centre of the country, MI estimates better conditions. Concerning marginal sites, the regionalisation identifies marginal sites all over the country, particularly in the north, whereas the global data product calculated only for the south maximum values.

## *6.2 Impact of climate change on the biophysical conditions for agricultural land use of Benin until 2025*

In this subsection, the impact of climate change on the biophysical constraints in Benin and the outcome of MI are described. Therefore, first the two membership functions for MVEG and TEMP, which had to be redefined, will be examined. Afterwards, future climate constraints and MI according to the IPCC SRES scenarios A1B and B1 will be demonstrated and discussed.

### 6.2.1 Redefinition of membership functions

Before the scenario analyses of MI could be carried out, the membership functions of MVEG and TEMP needed to be redefined as the indicator itself or the input data changed.

For the fuzzification of **MVEG,** a modified form of PVEG, a linear membership function was chosen (see Fig. 52). The new membership function was defined based on following consideration. Forest should be assigned about the same membership degree than within the evaluation of the recent conditions (cf. 6.1.1) as they approximate protected natural and thus, potential natural vegetation types.

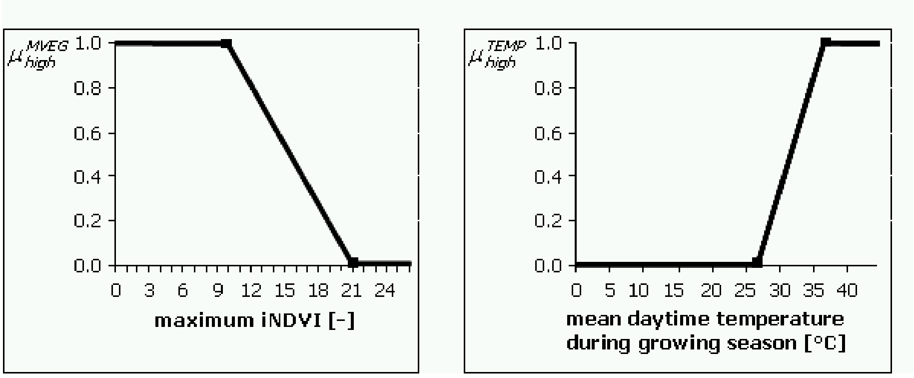


**Fig. 52: Membership functions of MVEG (left) and TEMP (right)**

However, because of recent degradation trends (cf. chap. 5.3), which also affected forests, slightly higher membership degrees were assigned.

Nevertheless, the outcome illustrates that constraints within recent forest zones are still slight. Additionally, maximum constraints are assigned in the south like in the evaluation of PVEG. The constraints in the north are evaluated as highly constraining, but still not reaching maximum values. Fig. 53 demonstrates the membership function of MVEG.

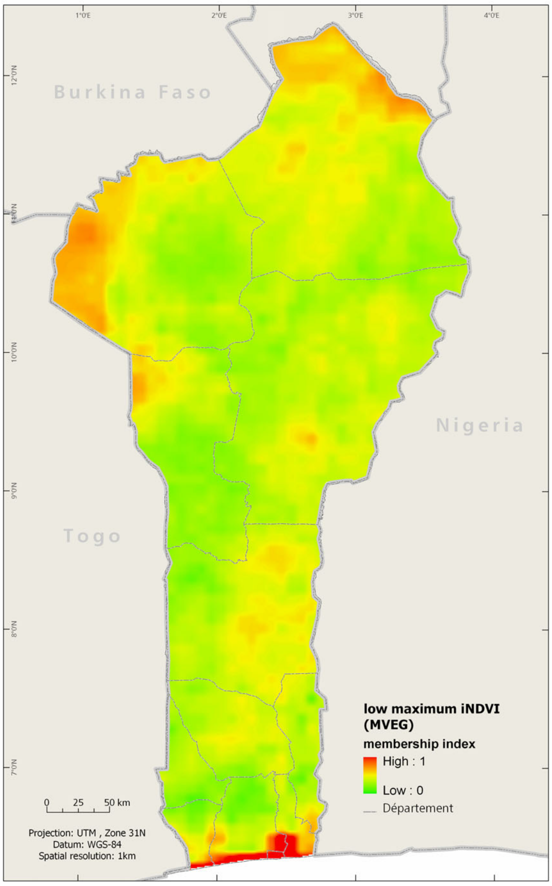


**Fig. 53: Low maximum iNDVI (MVEG)**

Additionally, the membership function of **TEMP** was redefined, as the scenario analyses utilized meteorological instead of satellite data. The advantage of using simulated meteorological data is that now temperature requirements of specific crops like given in Sys et al. (1993) or MDR & INRAB (1995) could be used evaluating temperature constraints (cf. 4.1). In doing so, 26°C and 33°C were used as thresholds x0 and x1, respectively.

### 6.2.2 Determination of future biophysical constraints in Benin

This subsection illustrates first future climatic constraints for agricultural land use and finally the impact of climate change on MI. Chapter 5.1.4.2 has demonstrated that the differences between scenario A1B and B1 until 2025 are very small. Thus, in this subsection mainly the outcomes of scenario A1B will be considered and differences to recent limitations are addressed.

Fig. 54 demonstrates that **temperature constraints** according to scenario A1B will be nearly everywhere more severe in Benin. Highest increases will occur in the north, where high constraints were calculated. Nevertheless, temperature will remain for most of the country a slight or moderate constraint for the cultivation of the majority of crops.

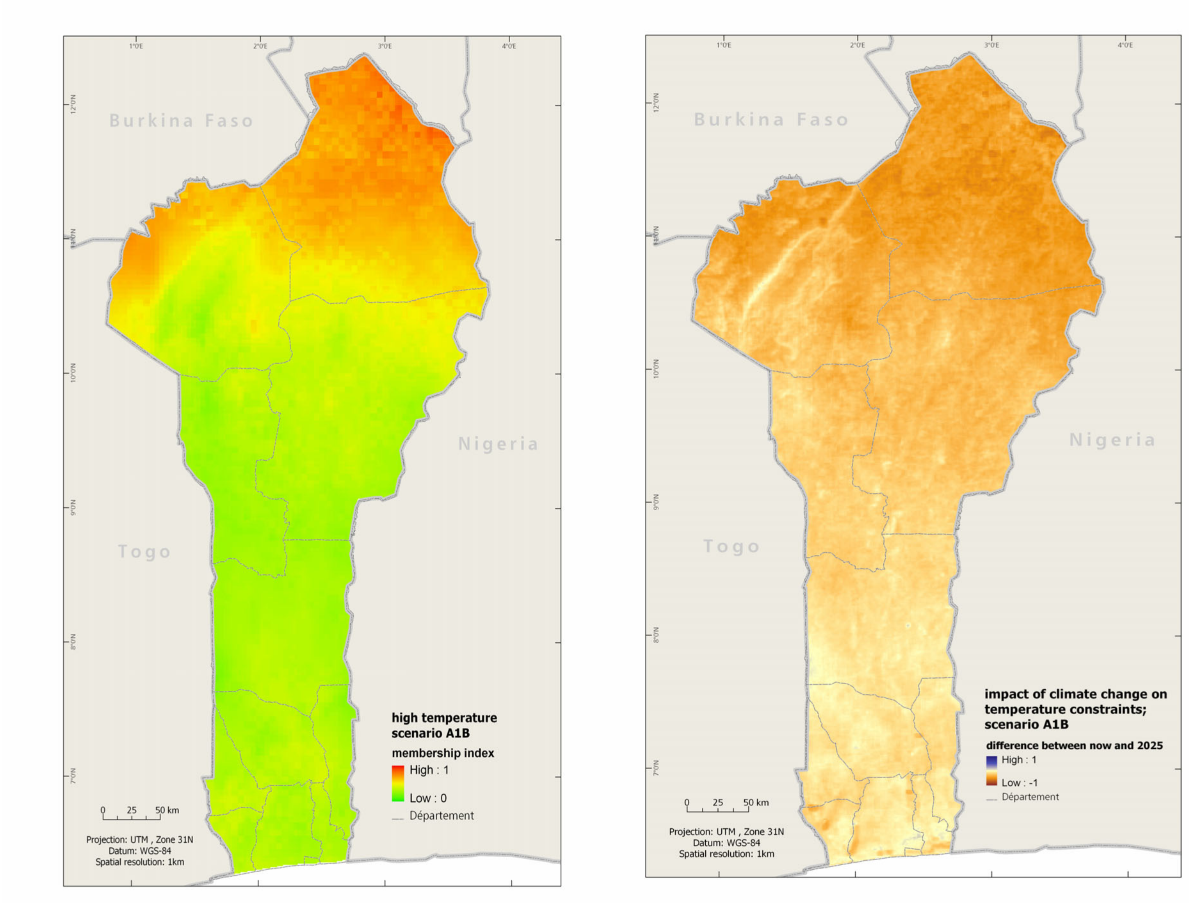


**Fig. 54: High temperature constraints according to scenario A1B (left) and changes compared to recent constraints (right)**

The constraint **limited length of growing period** will also rise in the future (see Fig. 55). For this indicator the changes are strongest in south and central Benin with a maximum change of about 0.5. These changes are due to rising variability as well as shorter mean growing season lengths. Thus, the rainy season will be generally shorter and the beginning and ending more variable. Only in single areas in the north and in the south will this constraint weaken, albeit only slightly (about 0.1).

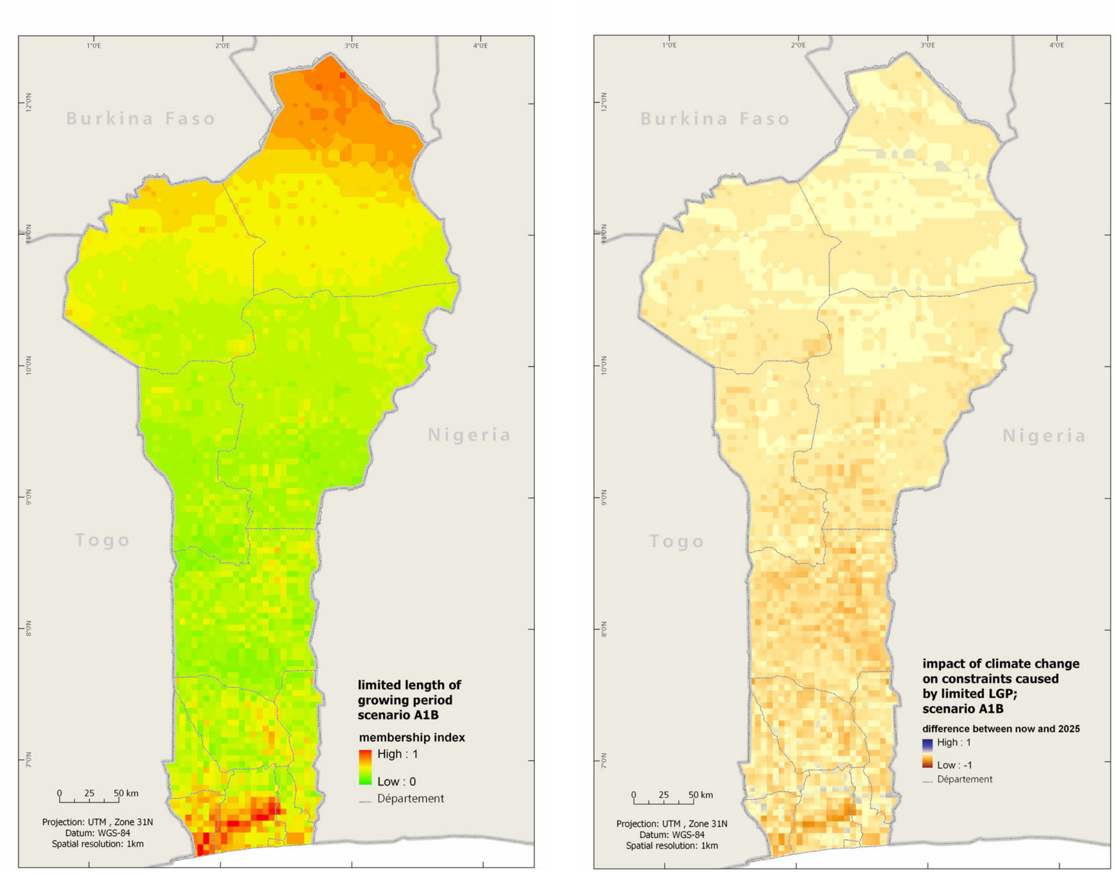


**Fig. 55: Constraints caused by limited length of growing season according to scenario A1B (left) and changes compared to recent constraints (right)**

Taken together, Fig. 56 demonstrates spatial patterns of projected future **climate constraints** according to both scenarios for Benin. This comparison calculates aggravation of climate constraints mainly in the north and south with difference values between 0.3 and 0.5. In 2025, rivers will be still able to compensate aridity in many parts of Benin. Then, however, temperature constraints are higher so that the places remain rather marginal agricultural sites. This change is particularly severe in the north where water is already a limiting factor for agricultural land use. Furthermore, the worsening climate conditions in the south are alarming due to the high population density there.

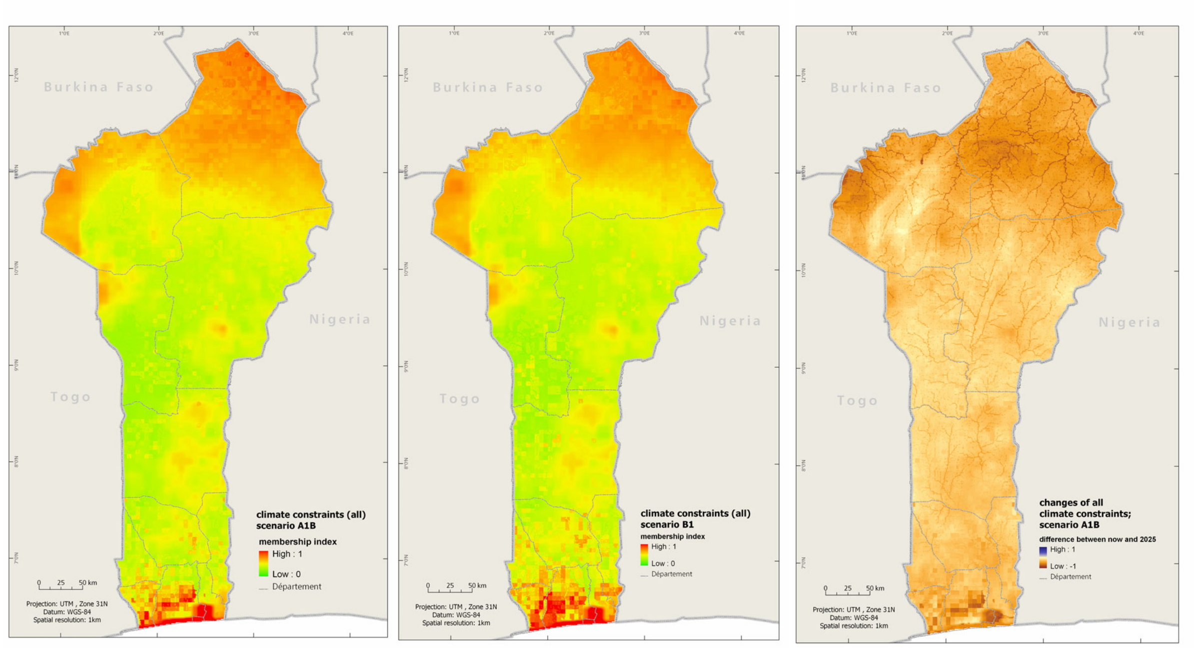


**Fig. 56: Climate constraints according to scenario A1B (left), B1 (middle) and changes compared with current climate constraints (right)**

Finally, the impact of climate change on the outcome of the **marginality index of 2025** is demonstrated in Fig. 57. Under climate change and corresponding worsening of the climate conditions for agricultural land use, the general biophysical conditions will be aggravated. Best conditions will be limited to the centre and isolated areas in the south with slight constraints and membership degrees of about 0.25. This value is clearly above the minimum of recent conditions (0.0). Until 2025, the mean marginality value will be 0.63 and thus, the general biophysical conditions will be rather marginal instead of moderate. This distinct worsening of the conditions is mainly due the rather slight or moderate recent climate constraints. Thus, the outcome is sensitive according to climate change, particular in regions where soil and topographic conditions are suitable. Additionally, northern Benin reacts sensitively to changing climate. There, moderate suitable sites will become also marginal; the membership degrees are at least 0.7.

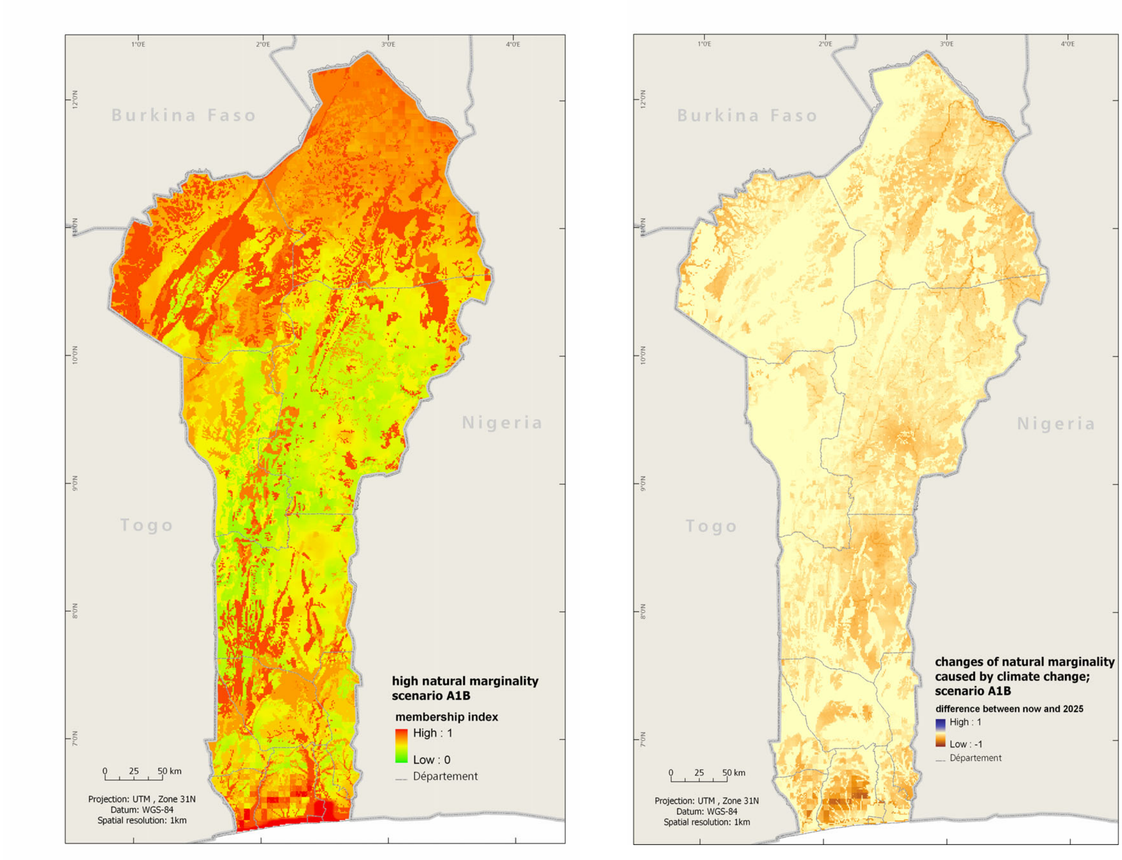


**Fig. 57: The marginality index according to scenario A1B (left) and differences compared to current natural marginality conditions (MI) (right)**

### 6.2.3 Conclusion

Climate change will affect the biophysical conditions in Benin notably. Until 2025, both climate and general biophysical conditions for Benin will worsen according to the IPCC scenarios A1B and B1. Differences between the two scenarios are very small, which verify the general trends of the analyses. Climate change scenarios affect all parts of Benin with strongest aggravations in the south and north, where the degree of marginality will ascend at about 0.5. Additionally, several areas in the western centre are affected by high changes. Concerning the climate limitations, particularly temperature will become a severer constraint, but also the length of growing season will slightly decrease and its variability increase. For the rainfall variability (RV), however no real change was calculated in either of the scenarios. Thus, the variability until 2025 concerns mainly the beginning and ending of the rainy season.

# 7 Is the marginality index suitable to evaluate biophysical potentials and constraints in Benin?

To answer this question, several aspects were investigated that will be examined in this chapter. First, marginal sites and key biophysical constraints calculated with MI will be considered and compared with information given in literature in 7.1. At the end of this subsection a brief outlook will be given demonstrating how the key constraints will be affected by climate change until 2025. In 7.2, the results of the direct and indirect validation approach will be examined. The direct validation is based on recorded ground truth data, whereas the indirect validation is based on auxiliary data.

## *7.1 Marginal sites in Benin*

In this subsection, the biophysical constraints causing agricultural marginality in Benin will be analysed. First, the significance of the different natural restrictions will be investigated using correlation analyses. Second, site specific key reasons for the degree of marginality will be examined.

Correlation coefficients between MI (dependent variable) and climate, pedologic and topographic constraints (independent variable) were calculated to **investigate the significance of the chosen biophysical constraints**. Therefore, the *M_CORRELATE* function in IDL was applied. The function uses relationships based upon partial correlation to calculate the multiple correlation coefficients of linear models with at least two independent variables (for more details, see e.g. NETER ET AL. 2001).

The outcome indicates that the marginality index correlates highly with soil constraints in Benin (correlation coefficient: 0.96). The correlation coefficients between MI and climate is moderate (about 0.32) and low between MI and slope (about 0.14), respectively. The significance of soil fertility in Benin is based on two key elements: First, soil fertility is essential for any agricultural land use and thus, poor soils cannot be compensated by any other biophysical feature. Second, soil fertility is moderate or even low in many parts of Benin. For central Benin, IGUÉ et al. (2004:48) wrote exemplarily, that "*most soils in the study area are moderately to marginally suitable for the six* [cowpea, cassava, cotton, groundnut, maize, and sorghum; note of the author] *crops*". Due to low chemical fertility, the use of nutrients or regular periods of fallows are advisable and necessary for cultivation of the soils. Fertilizer use becomes essential when farmland is permanently exploited (BERDING & VAN DIEPEN 1982, BOHLINGER 1998, JUNGE 2004). Furthermore, unapt physical soil characteristics constrain agricultural suitability in many regions (GRAEF 1999, IGUÉ 2000).

Concerning climatic constraints, the highest correlation coefficients were calculated between general climate limitation and rainfall variability (0.83) and LGP (0.79). A lower correlation coefficient came out for temperature constraints (0.41). Again, both constraints, RV and LGP, are those which are seen as crucial factors for agricultural land use in Benin (cf. BERDING & VAN DIEPEN 1982, MDR & INRAB 1995, CENATEL 2002, ADOMOU 2005). Temperature constraints are often evaluated as minor constraints (e.g. BERDING & VAN DIEPEN 1982, WELLER 2002, IGUÉ et al. 2004).

To **examine the reasons for site-specific marginality values**, in general, two different aspects were investigated. On the one hand, the highest constraint was assessed for each site (see appendix 2.2). On the other hand, all constraints of a membership degree of at least 0.6 were calculated. Both aspects are important when planning amelioration or compensating measures.

Information about the maximum constraint is essential as natural restrictions will not improve, unless the highest constraint is not compensated (cf. VON LIEBIG 1855). Fig. 58 demonstrates the spatial

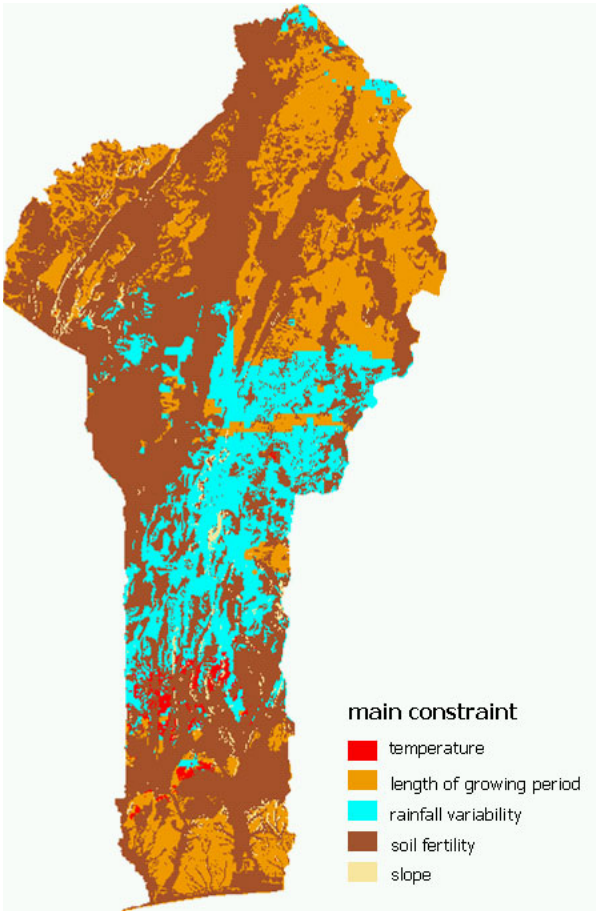


**Fig. 58: Spatial distribution of the main bio-physical constraints in Benin**

distribution of the main natural limitations. The map confirms the relevance of soil fertility, rainfall variability and aridity. Poor soils restrict primarily the suitability of agricultural land use on the majority sites of Benin (about 57%) (see explanation above). On 24% of all sites, aridity constraints are the most severe and on 17% rainfall variability, respectively. Furthermore, temperature constraints limit agricultural activities in some areas in the south. There, however, the temperature restrictions are merely slightly higher than rainfall variability. Slope marginality occurs only within the Atacora region, on inselbergs and at the borders between the sedimentary plateaus and the crystalline basement in south.

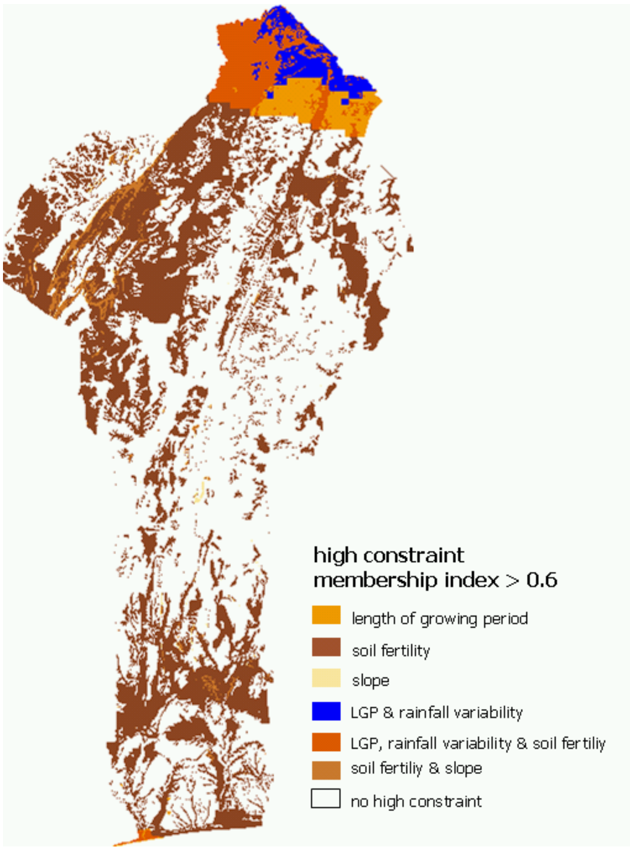


**Fig. 59: Spatial distribution of high natural constraints in Benin**

For several applications, however, the consideration of all high constraints is more important than the absolute constraint. Thus, all high constraints (MI > 0.6) on each site are calculated (see appendix 2.2). Fig. 59 demonstrates that in the north two or three natural constraints restrict agricultural activities severely. In addition, high slopes and low soil fertility together limit agriculture within the Atacora in the north or nearby Dassa in the south. The majority of marginal sites and 35% of all sites in Benin however, are characterised by low soil fertility alone. This means that soil amelioration measurements could significantly improve the natural agricultural potential. Low chemical soil fertility is thereby more easy to compensate than low physical fertility.

Under **climate change**, climatic constraints will become more severe and consequently play a greater role. As the outcomes of scenario A1B and B1 do not differ fundamentally, only the future key constraints according to A1B will be illustrated in this case. In particular, temperature will determine the degree of marginality within more regions whereas the significance of rainfall variability constraints decreases (see Fig. 60). On 28.9% of all areas in Benin, temperature will be the highest biophysical constraint in 2025 according to scenario A1B. Recently, temperature has determined the degree of marginality only on about 6% of the area. Furthermore, more regions in the north and south will be affected by more than one high constraint.

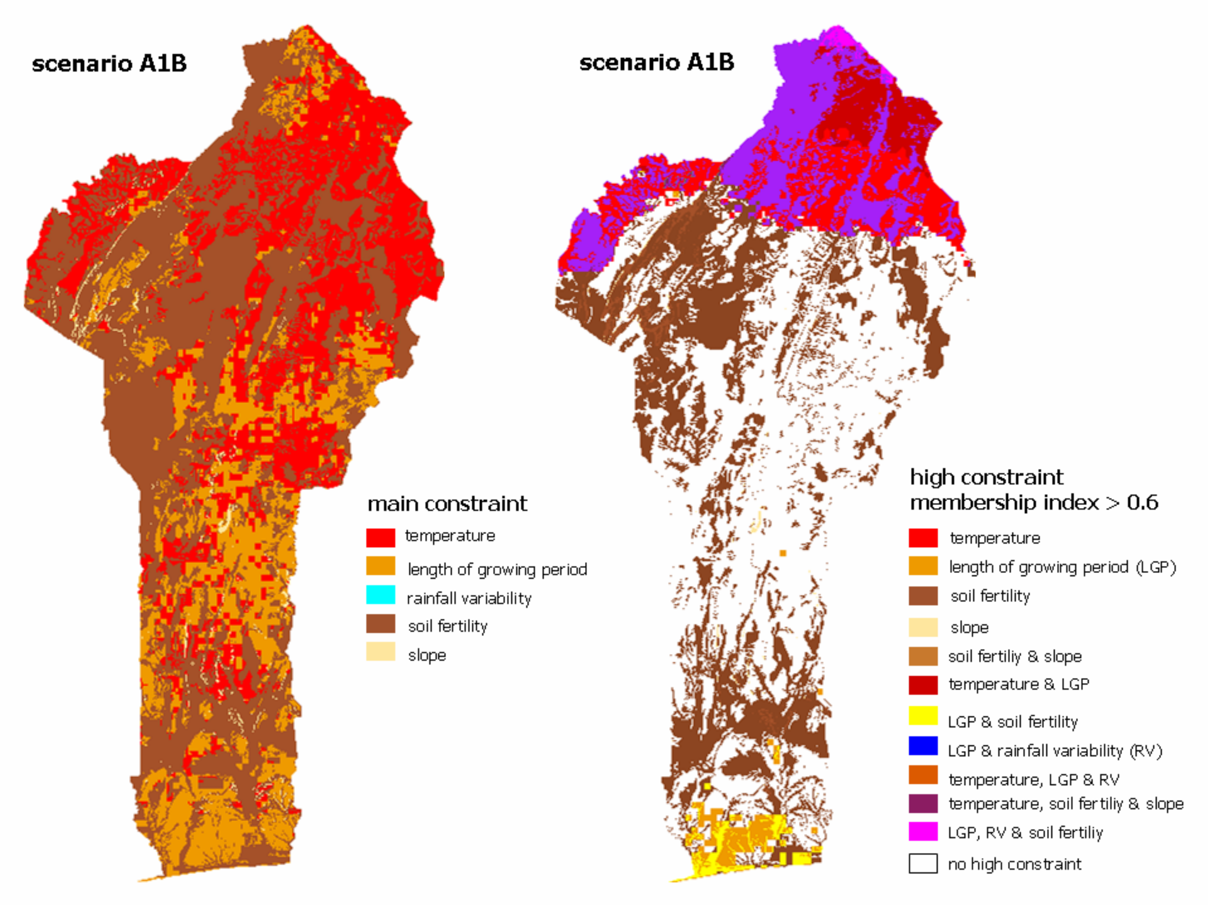


**Fig. 60: Spatial distribution of main (left) and high (right) biophysical constraint in 2025 according to scenario A1B**

## 7.2 Validation

### 7.2.1 Direct validation based on ground truth data

The direct validation is based on about 100 marginal sites recorded during the fieldwork. From the recorded reference data, 67% have a MI-value of at least 0.6 and 72% of at least 0.4, respectively. Thus, most of the ground truth data show a high degree of membership. Sites with lower MI-values may be caused by small extents of the marginality. Particular pedological features are characterised by a vast spatial heterogeneity (cf. Igué 2000, JUNGE 2004).

The mean value of marginal sites recorded in the field is about 0.66 and thus, considerably higher than the mean value of Benin, which is about 0.55. To test the significance of this differentiation, the Wilcoxon rank-sum test and thus, the *RS_Test* function in IDL was applied. As the computed probability (0.0000144) is lower than the 0.05 significance level, the hypothesis that the two samples have the same mean of distribution must be rejected. In other words, the test proved that the mean value of MI of the reference data is significantly higher than the average value of Benin at the 0.05 significance level. Hence, the direct comparison with reference data indicates that MI reflects marginal sites very well on a national scale.

### 7.2.2 Indirect validation based on auxiliary data

The indirect validation approach is based on the assumption that farmers choose agricultural land selectively, at least in the long term. Thus, the hypothesis will be analysed that farmers usually cultivate suitable land. Furthermore, it is assumed that marginal sites under cultivation are particularly prone to land degradation. Hence, investigations were carried out to examine the relationship between population density, MI and land degradation. Therefore, reference data, but mainly auxiliary data are taken.

During the author’s fieldwork ground truth data were collected containing information about the land cover. 675 of these sites showed signs of current or recent agricultural activities. The average MI-value of these sites is 0.52 and hence, slightly lower than the MI-mean of Benin (see 7.2.1). The Wilcoxon rank-sum test provides evidence that although small, the difference is significant at the 0.05 level. However, only 28% of the pixels are suitable cultivation areas according to their biophysical conditions (MI ≤ 0.3). This means that the majority of recorded cultivated sites are characterised by at least moderate, and in some cases, high natural constraints. About 40% of the sites have a MI-value of at least 0.6. According to the syndrome kernel these areas are particularly endangered by land degradation. During the author's fieldwork it was, however, not possible to adequately analyse whether these sites are already degraded and, if so, how severe the degradation is. Thus, analyses about settlement and agricultural activities, biophysical conditions and land degradation were carried out on a national scale.

For the settlement and agricultural activities the disaggregated population density of the census was used as an indicator (cf. chap. 5.2). In Benin, about 23% of the area can be considered as favoured according to the biophysical conditions for agricultural land use (MI ≤ 0.3). About 286,525 people or approximately 30% of the population in Benin live in these favoured regions. The mean MI-value of areas, where at least 10 inhabitants/km² live, is 0.53. This value equals circa the mean MI-value of the reference data.

To test the hypothesis that farmers generally cultivate suitable land and avoid marginal regions, seven classes of population density were set up (see Fig. 61). According to the hypothesis the mean MI-values are expected to decline with rising population density. For each population density class the mean MI value was calculated. Fig. 61 illustrates that the analysis confirmed the hypothesis. The correlation coefficient R² indicates a strong relationship (R²=0.86) for the linear trend line.

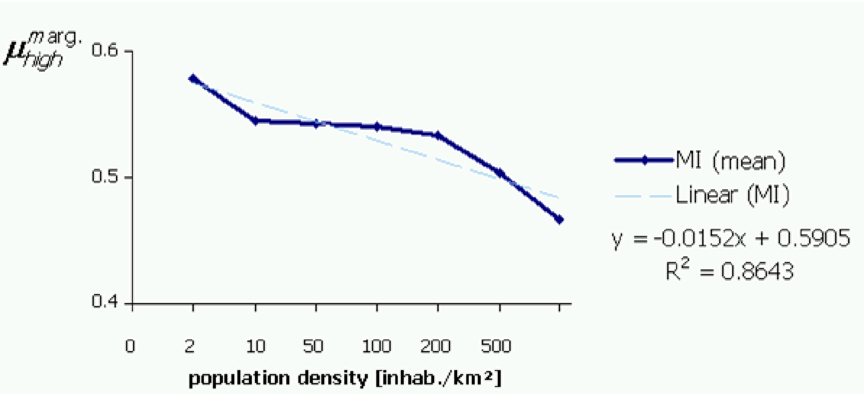


**Fig. 61: Mean MI-values for different population density classes**

With the Wilcoxon rank-sum test it was additionally tested, whether the mean values of each class differ significantly from the mean MI-value of Benin. This was true for all classes. Furthermore, the *KW_TEST* function of IDL confirmed that the means differ significantly from each other. The computed probability (0.000000; degrees of freedom=6) is lower than the 0.05 significance level and therefore the hypothesis that the sample populations have the same mean of distribution was rejected. This outcome substantiates the hypothesis that farmers generally cultivate suitable land rather than marginal land.

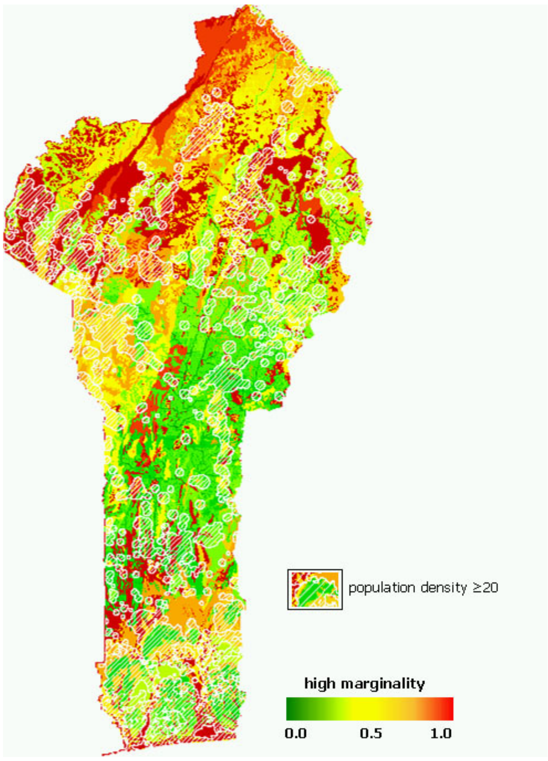


**Fig. 62: Spatial pattern of settlements overlaid to MI outcome**

Nevertheless, an overlay of MI and population density indicates that the farmers' decision, where to settle, does not depend exclusively on biophysical conditions (see Fig. 62). Instead, colonial history and socio-economic aspects, like infrastructure, determine spatial patterns of settlement on the national scale (see e.g. Doevenspeck 2005, Thamm et al. 2005b, Orekan 2007). Thus, there are several marginal regions that are agriculturally used as well as favoured sites, where the population density is very low. The first regions are according to the syndrome theory (cf. 3.3.5) vulnerable areas as they are particularly prone to land degradation. Favoured sites are of interest for recent land-use planning schemes, because they are areas where agricultural activities could still be expanded or intensified.

In the following, **marginal sites under cultivation** will be considered in more detail. They are according to the syndrome approach vulnerable sites prone to land degradation. In other words, if those areas are affected by degradation, this provides evidence that indirectly the correctness of the regionalisation outcome (see also Cassel-Gintz et al. 1997). In doing so, marginal sites under cultivation will first be compared with degraded regions given in the literature. Then, such areas will be compared with the trends of land degradation derived from satellite data.

The spatial information about occurrence of **land degradation in literature** is often restricted to administrative levels (e.g. communes), surroundings of cities or specific landscape unites (e.g. river valleys). Consequently, a spatial comparison entails some weaknesses. Nevertheless, an overlay of communes, which are considered to be strongly degraded by MEHU (2003) and confirmed by other authors (e.g. Igué

2000, WELLER 2002, JUNGE 2004, MULINDABIGWI 2006) demonstrates that most of the marginal areas, on which at least 10 inhabitants/km² live, are located in these regions (cf. Fig. 63). These references rank the regions of Boukoumbé, Ouakè, Matéri, Banikoara, Djidja or Grand-Popo, for instance, among severely degraded communes. Hence, this aspect also evidences the correctness of the marginality index as well as the syndrome kernel.

However, Fig. 64 illustrates that recent **land degradation trends** do not emerge primarily on marginal sites. Instead, only about 40% of areas with moderate or strong negative trends have high MI-values (MI ≥ 0.6). This means that agricultural activities are expanded not merely onto marginal sites, but also onto favourable areas. This situation confirms the above made appraisal, that there are at the moment still favourable agricultural land resources available, which are cultivated extensively.

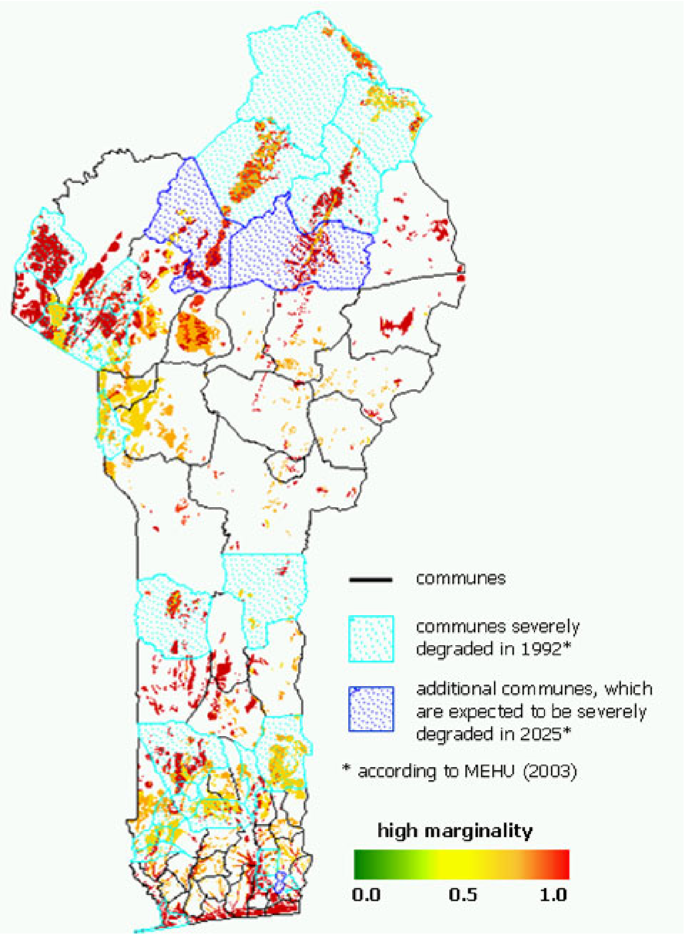
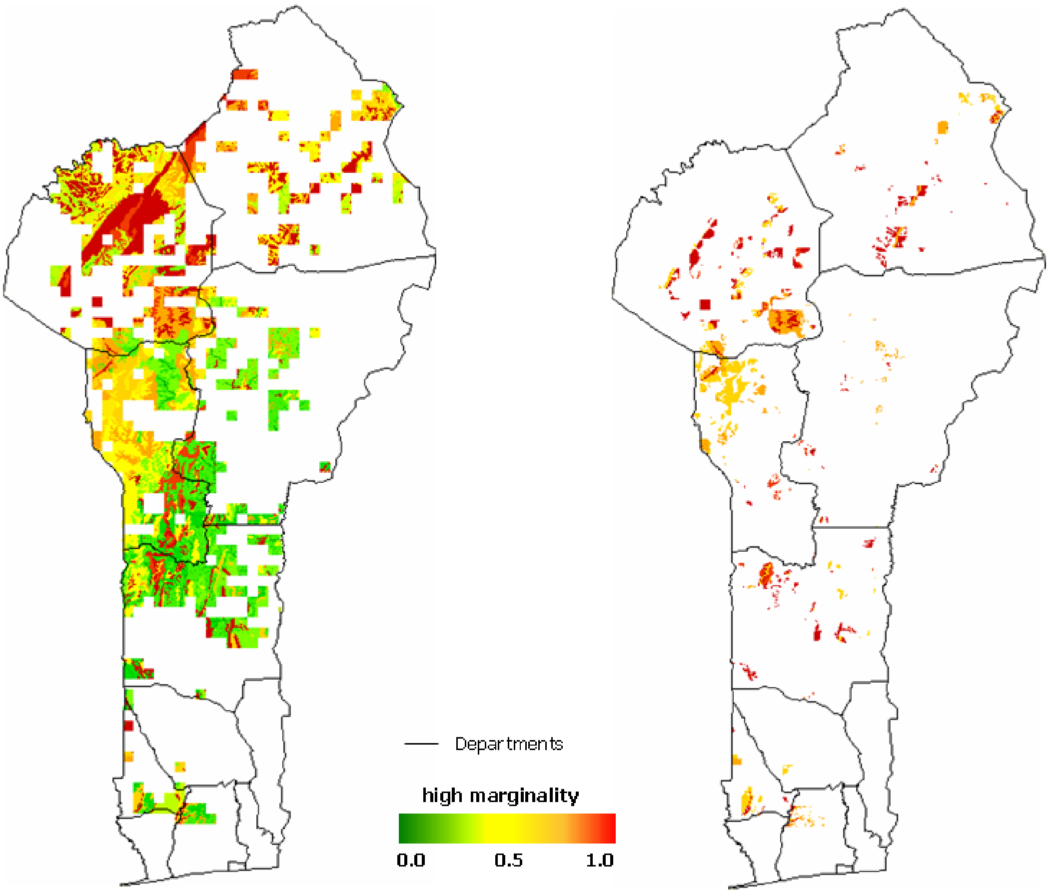


**Fig. 63: marginal areas under cultivation overlaid by communes affected severely by degradation**

The additional incorporation of population density indicates, however that there are some regions where land resources are already becoming sparse and farmers are forced to extend agricultural activities onto marginal areas. The map on the right demonstrates that about one quarter of all sites showing at least moderate negative trends are marginal areas under cultivation.



a) regions showing at least moderate land degradation trends

b) marginal sites under cultivation showing at least moderate land degradation trends

**Fig. 64: MI (a) as well as marginal areas under cultivation (b) overlaid by regions with at least moderate negative land degradation trends between 1982 and 2003**

Cultivated marginal sites in the northwest or south do not demonstrate, however, a significant trend. As many of these areas were already affected by severe soil degradation in 1992 (see Fig. 63), it is not surprising that no trends are observable. No trend here, although implies, that no signs of recovery of the vegetations cover is detectable, at least in this spatial resolution, and consequently those sites are still severely degraded. My own observation verifies this, at least for some places (see Fig. 65). Thus, no significant trend according to the assessment of this study can automatically be proved as an error in the MI outcome.

Furthermore, it was investigated, how far recent trends of land degradation are caused by overuse of agricultural land. Therefore, the **relationships between bio-physical constraints and population pressure**, on the one hand, **and land degradation** on the other hand, were investigated using two correlation analyses. The first analysis considers only the 33 locations of the interviews and the second considers all areas with at least moderate negative trends.

**Fig. 65: Degraded landscape near Manta in the northwest (Photo: J. Röhrig, 2005)**

For the first analysis, MI, population density and growth, crop intensity, and trends of land degradation were taken into account. Population density together with population growth is often used to determine human population pressure (Sisk et al. 1994, Amos 2003). As an indicator for crop intensity, the Ruthenberg factor R was chosen (cf Ruthenberg 1980). R is the ratio of cropping length to the total rotation length, and then multiplied by 100. It has to be, however, kept in minds that the cropping and rotation length is a complex feature depending on e.g. crops and soil fertility. As a result, the spatial and temporal variability of the factor R is enormous (cf. Mulindabigwi 2006).The IDL-tool *M_CORRELATE* calculated an overall correlation coefficient of 0.68 for those sites. The highest correlations are between the trend of land degradation and population growth ($R^2=0.61$). Between land degradation and the other features only a slight correlation exists (0.17 with crop intensity factor R and 0.13 with population density).

On national scale, no information about the intensity of agricultural activities exists in an adequate resolution, thus the second correlation analysis takes into account only MI, population density and growth. The latter data set is the one presented in chapter 2.3. Therefore, only (at least moderate) negative trends of land degradation were taken into account. For the correlation analysis, the IDL-tool *M_CORRELATE* was again applied on the area of Benin, excluding forests and national parks. They were excluded as agricultural activities are generally forbidden and thus, land degradation is primarily not caused by agricultural land use there (see also 5.3). The assessed correlation coefficient is rather low (0.34), whereas the highest correlation exists between degradation and population growth (0.31). One reason that the correlation is less than before may be explained by the population growth data set. The data are processed on the level of communes without disaggregation. The highest correlation is not surprising as both are dynamic features. Furthermore, as already discussed in chapter 5.3, the spatial location of the negative trends often corresponds with land use changes, whereby natural vegetation cover is converted into new settlements and fields. The relationship between the other two parameters and land degradation is negligible (0.2 with MI and 0.01 with population density).

Taken together, the degree of the land degradation trend is not explainable with the processed data of biophysical constraints and population pressure. Two main aspects may cause weak correlation. First, there are still favoured agricultural areas available in Benin and thus, the general pressure on land is slight to moderate. Second, the trends in land degradation show mainly degradation of vegetation between 1982 and 2003. In other words, predominantly agricultural expansion processes have been detected. This excludes the identification of areas already severely degraded in the 1990s.

## 7.3 Conclusion

In summary, the marginality index demonstrates emboldening results on the national scale in a spatial resolution of 1km x 1km. The results of MI proved that the chosen indicators on a global scale to describe and define marginal sites are, in an initial examination, also useful indicators on a national scale. Crucial natural constraints for recent agricultural land use in Benin are soil fertility, rainfall variability and aridity. Until 2025, climatic constraints will be more severe and consequently play a greater role. In particular, temperature will determine the degree of constraint in more regions. Furthermore, more regions in the north and south will be affected by more than one severe biophysical constraint.

Both the direct and the indirect validation approach indicate the accuracy of the regionalisation outcome. Ground truth data validated that the result reflects marginal sites in Benin very well. Furthermore, it was possible to confirm the hypothesis that farmers generally cultivate suitable land. Nevertheless, an overlay of MI and population density indicates that the farmers' decision, where to settle, does not depend solely on biophysical conditions. Consequently, several marginal regions are under cultivation and favoured sites are hardly cultivated. The first regions are, according to the syndrome theory, vulnerable areas that are particularly endangered by land degradation. The incorporation of land degradation information named in literature indicates that marginal sites under cultivation are ranked among particularly degraded landscapes in Benin. This outcome verifies indirectly the accuracy of the syndrome assumption and the outcome of the regionalisation.

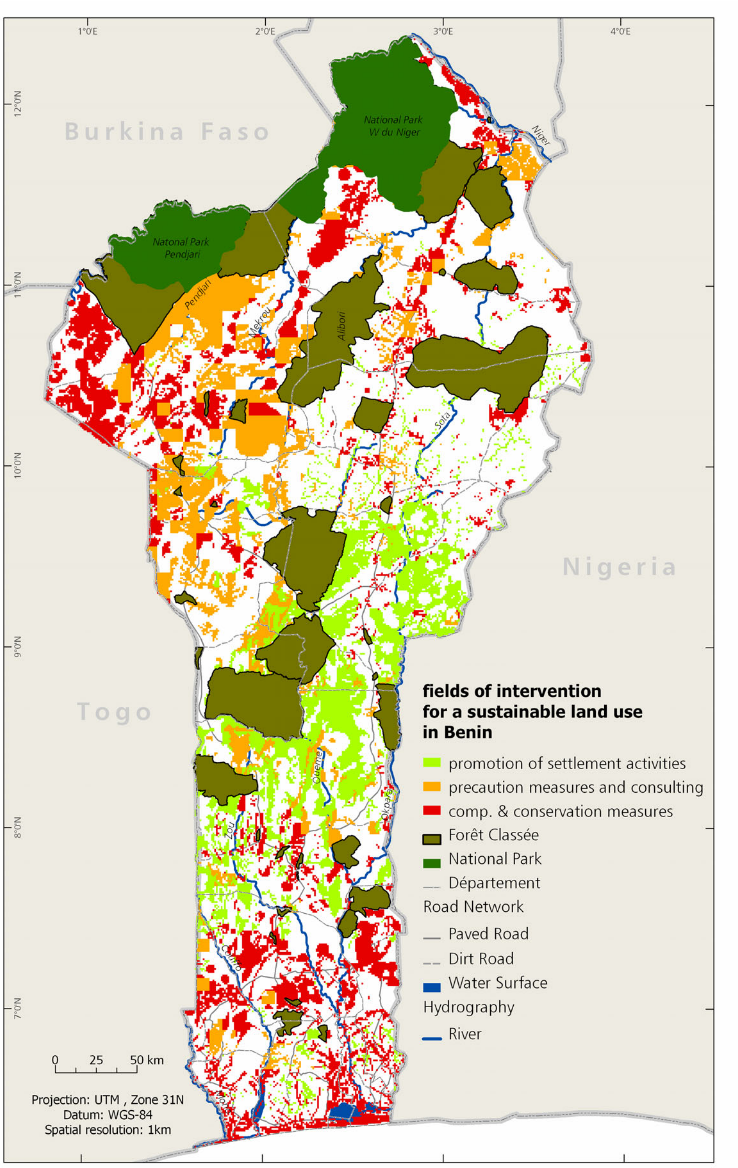


**Fig. 66: Fields of intervention for a sustainable use of agricultural land resources in Benin based on MI, population density and trends of land degradation**

Finally, based on the information obtained about biophysical constraint, population density and trends of land degradation, the following three fields of investigation can be drafted to ensure sustainable land use and conservation of natural resources in Benin. Nevertheless, scenario analyses indicate that the biophysical conditions of Benin will change and generally worsen. Thus, the scenario outcomes should be considered while developing national land-use plans. Fig. 66 demonstrates the spatial focus areas of each field of investigation. The first areas are marginal regions under cultivation (MI ≥ 0.6 and population density ≥ 10). These are particularly vulnerable regions with a current high risk of land degradation. Some of them are already affected by land degradation. Thus, it is necessary to initiate compensation as well as conservation measures. The calculated key biophysical constraints are thereby helpful to implement site-specific compensation measures (see Fig. 58). A good example can be found in the surrounding of Ouakè, where conservation programmes have already been installed. The focus there is mainly on conservation and amelioration measures to increase soil fertility (e.g. agro forestry, cultivation of legumes). Furthermore, the creation of alternative ways to earn a living by diversifying income would help to protect the natural resources and prevent migration.

Second areas are marginal regions characterised by trends of land degradation. Here, agricultural activities are expanded onto marginal sites: a sign of beginning scarcity of land resources. Hence, particularly precautionary measures and the availability of agricultural consulting agencies are needed to prevent irreversible land degradation. Agricultural consulting could assist the farmers in choosing adapted farming systems and suitable crops based on biophysical conditions. In other words, measures to restrict land degradation and cope with the constraints are needed for a sustainable land use in these areas. Furthermore, regulatory measures should be installed to avoid conflicts between ethnic groups about scarce resources. In this context, QAG (2004) provide a good summary of existing theoretical concepts of social-ecological research.

Finally, the third areas are favourable lands with minimum human impact. These regions, mainly in the centre of Benin, provide the greatest land reserves to fulfil food security requirements in the future. Consequently, agricultural activities should be encouraged in these areas. To avoid social and ethnic conflicts, such promotion programmes of settlement should be, however, carefully planned and involve all groups. Recent incidents have shown that high population growth and beginning scarcity of land and water resources can cause severe and violent conflicts (e.g. AKAPI 2002, DOEVENSPECK 2004, SINGER 2005). Furthermore, forests and protected areas should be further protected to conserve biodiversity and ecological sustainability.

# 8 Discussion

Investigations on the inventory of natural resources and an improved resource management are a main topic for agro-geographical studies in developing countries (MANSHARD 1997). Information about land resources supports rational land-use planning a sustainable use of natural and human resources (LANDON 1994, ROSSITER 1996, ESWARAN et al. 1999, DORRONSORO 2002). In this context, the marginality index for agricultural land use was used to evaluate current and future agricultural land resources of Benin. In using this index, the feasibility of a global approach on a national scale was examined. Furthermore, demographic data and trends of land degradation were derived to achieve spatial information about real risk and current trends of land degradation caused by agricultural overuse. This information is used to derive fields of investigations for national decision makers aiming at a sustainable use of land resources. In the following, key findings of this work will be discussed and summarised.

**1. A new land evaluation scheme for agricultural land use in Benin was successfully set up based on biophysical resources**

An essential aim of this thesis was to **evaluate the agricultural land resources** for agricultural land use in Benin based on biophysical constraints. Due to low capital input, natural constraints still determine the agrarian potential in Benin. Therefore, a capability evaluation approach was chosen focusing on the general suitability for agricultural land use and the sustainability of agrarian activities. Furthermore, there are already good approaches to determine suitability levels for crops, like the AEZ (FAO 1996, 2002) approach or the parametric evaluation scheme by FAO/Ghent (SYS et al. $1991_{A,B}$ or SYS et al. 1993). Thus, it was more challenging to apply a capability approach to Benin. Recent problems of land scarcity and soil degradation were further reasons to set up a land evaluation scheme aiming to provide information for sustainable use of land resources.

The implementation of socioeconomic data, like the level of capital input, would be desirable, but such data have not been recently available in an adequate spatial resolution on the national scale. The author's fieldwork additionally indicates an enormous spatial heterogeneity of socioeconomic features, so that an interpolation of the recorded information during interviews was not possible.

The marginality index of agricultural land use, introduced by CASSEL-GINTZ et al. (1997), was used for the evaluation of the biophysical resources. This index was determined for Benin in a spatial resolution of 1km x 1km using fuzzy logic (MI). Therefore, IDL-routines were written for the determination algorithm. The values of MI ranges from 0 to 0.97, which indicates that Benin contains sites with very good biophysical conditions for agricultural land use (MI-values about 0), but also contains regions, where high natural constraints make them prone to land degradation while they are under cultivation (MI-values about 1). These areas may be more valuable for pasturage or forestry. In general, the approach determines generally moderate conditions for agricultural land use, as demonstrated by an average value of 0.55. About 43% of Benin is characterised by MI-values higher than 0.6. These highly marginal sites are located all over the country, with greatest expansions in the north. Areas with the highest natural potential are located in the south and centre of the country.

Additionally, investigations on the **spatial distribution of main constraints** causing a specific degree of marginality were carried out by writing an IDL-routine. The outcomes demonstrated that primarily low soil fertility restrict the suitability of agricultural land use on the majority of sites in Benin (about 57%). In addition, low soil fertility, limited length of the growing period and high rainfall variability are the crucial biophysical constraints on the national scale. In the north and in the Atacora region generally three or two natural constraints restrict agricultural activities severely (degree of membership > 0.6). High marginality values are caused by limited LGP, high temperature and low soil fertility in the north and soil fertility and slope in the mountain range of the Atacora. The majority of marginal sites, however, is characterised by low soil fertility alone. This means that soil amelioration measures could significantly improve the natural agricultural potential. Low chemical soil fertility is thereby easier to compensate than low physical fertility. Thus, research carried out in IMPETUS provides evidence of the positive effects of, for instance, manure on soil fertility (JUNGE 2004) or on biomass (MULINDABIGWI 2006).

## 2. The marginality index is transferable to the national scale

The marginality index was successfully determined for Benin in a spatial resolution of 1km x 1km. The results of the approach proved that the chosen six **constraints** on a global scale describing and defining marginal sites are, in an initial examination, also useful indicators on a national scale. Compared to the global approach, the indicator *NPP* was substituted by *PVEG* as well as *alpha high* and *low* was replaced by *LGP* and *TEMP*, respectively. The latter changes are a helpful and necessary modification of the global approach, because temperature constraints are thus, directly incorporated. Furthermore, the length of the growing period is a more suitable aridity indicator on the national scale. Necessary modifications of the indicators on the national scale were slight and primarily aimed at increasing the tangibility for national decision makers. National stakeholders in Benin appreciated particularly the limited number of incorporated indicators. Nevertheless, some interlocutors had problems with the capability concept and particularly with the marginality index and fuzzy logic. Agronomists sometimes found it difficult to discuss constraints for agriculture in general and not for specific crops.

Concerning input data and membership functions, stronger modifications were necessary to settle the claim of national conditions and decision makers.

Comparable **input data sets**, like the ones used in the global approach, were either, missing in an adequate spatial resolution, or the input data, itself was inappropriate on a national scale. Especially climate data are still missing on a national scale in an adequate spatial resolution or temporal coverage, even though some progress has been made for Benin due to the IMPETUS project. This fact emphasizes again the advantage of a capability approach: while crop requirements are very different concerning climate features, they are similar concerning pedologic or topographic conditions (GRAEF 1999). As a consequence for this thesis, it was necessary to be implement climate data in a spatial resolution lower than 1km. The overlay of input data in different spatial resolutions may increase spatial uncertainties and errors of the features.

In addition, three input data were completely replaced by other approaches to determine the indicator: NPP, alpha and the soil fertility. Therefore, approaches were chosen, which incorporate freely available data sets. These modifications led to better comprehension and acceptance on the parts of national decision makers.

The application of the original **membership functions** resulted generally in a inappropriate evaluation of the indicators. Hence, with the aid of the literature review and interviews carried out with farmers, the membership functions were adapted. Fuzzy logic was thereby an adequate method to incorporate site-specific qualitative knowledge of the farmers. Furthermore, for several indicators instead of a linear either a sigmoid (SLOPE) or a user-defined membership function was assigned (PVEG and SOIL).

The **comparison of MI with the global outcome** illustrates not merely a spatially more detailed result but also different spatial patterns. Generally, the degree of marginality is lower in the global assessment than in the regionalisation outcome. Only in the centre of the country, does MI come out with better conditions. Concerning marginal sites, the regionalisation identifies many more areas with high natural constraints than the global outcome. Furthermore, MI calculated marginal sites everywhere in Benin, particularly in the north, whereas the global data product calculated maximum values only for the south. Therewith, MI provides much more detailed information for national decision makers than the global outcome containing larger extension of marginal, and thus vulnerable, sites.

The **validation** of the approach was challenging due to the novelty of regionalisation approach and the selection of a capability approach. In the context of this thesis, direct and indirect validation methods were applied by applying GIS analyses and statistical tests. The direct validation is based on ground truth data, whereas the indirect validation scheme is based on mainly auxiliary data. The auxiliary data consist of population density and land degradation data, which are determined within the framework of this research. Population density was disaggregated from census data using GIS functionalities and trends of land degradation were derived from GIMMS NDVI time series analyses.

Both the direct and the indirect validation approach indicate the accuracy of the regionalisation outcome. The Wilcoxon rank-sum test proved that the mean MI-value of marginal sites recorded in Benin is significantly higher than the average value of Benin at the 0.05 significance level. Hence, the **direct** comparison with reference data indicates that MI reflects marginal sites very well on a national scale.

For an **indirect** validation, the hypotheses that farmers generally cultivate suitable land was tested and confirmed. Nevertheless, an overlay of MI and population density demonstrates that the farmers’ decision, where to settle, does not depend exclusively on biophysical conditions on the national scale. Additionally, the occurrence of land degradation on marginal sites under cultivation was investigated. Indeed, these regions are ranked among particularly degraded landscapes. This outcome supports both the accuracy of the assumptions of CASSEL-GINTZ et al. (1997) on the national scale and the outcome of the regionalisation approach. Taken together, the marginality index is transferable to a national scale providing an encouraging method to evaluate biophysical constraints and to identify marginal sites.

### 3. Remote sensing provides interesting input data for a national evaluation scheme based on biophysical resources

The use of remote sensing to derive the input data was generally possible for most of the necessary indicators. Three out of seven constraints are derived single-handedly from satellite data (TEMP, IC, and SLOPE) and two constraints are pre-processed with the aid of satellite data (LGP and RV). Remote sensing data are especially helpful to derive rather constant biophysical features. For biophysical parameters characterized by high temporal variability, such as rainfall variability or length of growing season, existing time series of remote sensing data are often too short to reflect this feature adequately. But with rising length of the time series their implementation can surely be enhanced. MODIS data products comprise thereby a wide range of valuable information for land evaluation due to specific radiometric, temporal and spatial resolution. Nevertheless, it is not likely, now or in the future, that the index will be calculated using remote sensing data alone, as satellite data provide essential data in a good spatial resolution on the national scale.

## 4. IPCC scenarios calculate negative consequences of climate change for the biophysical conditions for agricultural land use of Benin until 2025

Climate change will affect the biophysical conditions in Benin notably. Until 2025, both climate and general biophysical conditions for Benin will worsen according to the IPCC scenarios A1B and B1. Differences between the two scenarios and consortial runs of REMO are very small, which confirm the general trends of the analyses. Climate change will affect all parts of Benin with strongest aggravations in the south and north, where the degree of marginality will ascend by about 0.5. Additionally, several areas in the eastern centre are affected by considerable changes. Concerning the climate limitations particularly temperature will become a severe constraint, but also the length of growing season will also slightly decrease and its variability rise. For the rainfall variability (RV), however, no real change was calculated in either of the scenarios. Thus, the variability until 2025 will affect mainly the beginning and ending of the rainy season.

## 5. Fields of investigations necessary for sustainable land use were derived from spatial patterns of risk and occurrence of human induced land degradation

Based on spatial information about biophysical constraints, population density and trends of land degradation, three fields of investigation needed to conserve the natural resources were derived. On marginal sites under cultivation, necessary fields of investigations include compensation and conservation measures to maintain natural resources for food production and to prevent further degradation and migration. The surrounding of Ouakè is a good example demonstrating that in some parts of Benin, conservation programmes have already been installed. The focus there is mainly on amelioration measures to increase soil fertility. Different measures are needed within regions where high population pressure forces the farmers to expand agricultural activities. In these regions, precautionary measures and establishment of agrarian consulting services are helpful to promote sustainable land use. Finally, the third field of investigations are the promotion of settlement activities within favourable regions, where human impact is still low. The greatest land reserves are located in these regions, mainly in the centre of Benin, which have the capacity to fulfil future food security needs. To avoid social and ethnic conflicts, such promotion programmes should, however, be carefully planned with the involvement of all groups. Uncontrolled agrarian expansions have already caused severe and violent conflicts (e.g. AKAPI 2002, DOEVENSPECK 2004, and SINGER 2006). In addition, forests and protected areas should be further protected to conserve biodiversity and ecological sustainability.

## *8.1 Outlook*

The marginality index is an innovative method to evaluate biophysical resources for agricultural land use. Together with information about population density and trends of land degradation essential indications for a sustainable land use scheme in Benin can be derived. As it was not possible to include all interesting aspects in this study, some fields of possible further research will be illustrated.

One aim of the IMPETUS project is to recommend concrete ways of translating scientific results into action through scientifically-based strategies (SPETH et al. 2005). Thus, MI was implemented within the computer-based Spatial Decision Support System (SDSS), named *AGROLAND* to support national decision makers in setting up a national land-use plan. The recent version of AGROLAND enables the user to visualise and analyse agricultural land resources based on the MI. Advanced model based raster analyses as well as the possibility of user interactions during runtime are also implemented (see LAUDIEN et al. 2007). Within the final version, scenario analyses will be incorporated as well as information about settlement patterns. The preliminary development results in terms of the Beta version of AGROLAND have already been presented to some national decision makers and advisers from diverse fields and institutions, such as governmental organisations, university and Peace Corps workers, which have shown a high interest in the system.

The current land evaluation scheme consists mainly of the evaluation of the biophysical resources. An interesting target would be to implement socio-economic features taking into account adaptation and compensating measures. In addition, indicators to describe the pressure on agricultural resources more precisely would be an interesting task. To determine the pressure on land resources, intensity of agricultural land use or availability of alternative sources of income are essential features. To set up such information in an adequate spatial resolution is, however, challenging as spatial and temporal heterogeneity of length and characteristics of growing cycle, for instance, is enormous. Thus, it might be advisable to carry out case studies. Such case studies could be linked with the monitoring of land degradation to investigate the relationship between the degree of natural constraint, population pressure and development of land degradation.

In addition, socioeconomic, land use classification schemes would be an interesting way to derive information about spatial patterns of field. Nevertheless, such maps contain some weaknesses. Many sensors cannot distinguish fallows from savannah due to similar reflectance and as a result, many classifications derived from one image come out with poor results. Within the IMPETUS project, some progress has been made for the Ouémé catchment (THAMM et al. 2005B). Its outcome will be incorporated within ongoing research.

Furthermore, scenario analyses could be expanded by incorporating different levels of capital input and recent trends of degradation. First, possibilities to compensate biophysical constraints and investigate adaptation measures might be considerable. One interesting field of research, which is planned within the framework of IMPETUS, is to analyse consequences of increasing use of fertilizer. The consideration of recent extends of soil degradation and trends would also improve the approach as it would the better reflect the future biophysical conditions. Additionally, measures to conserve and protect natural resources could also be implemented.

# 9 References

ACHARD, F., EVA, H. & P. MAYAUX (2001): Tropical forest mapping from coarse spatial resolution satellite data: production and accuracy assessment issues. In: *International Journal of Remote Sensing* 22 (14): 2741-2762.

ADJANOHOUN, E.J. (1989): Contribution aux études ethnobotaniques et floristiques en République Populaire du Bénin. Médecine traditionnelle et pharmacopée. Agence de Coopération Culturelle et Technique 111.

ADOMOU, A. C. (2005): Vegetation patterns and environmental gradients in Benin: Implications for biogeography and conservation. PhD thesis. Wageningen University and Research Centre. Wageningen.

AGRHYMET (1996): Méthodologie de suivi des zones a risque. *AGRHYMET FLASH* 2 (0/96). Niamey.

AJTAY, G. L., KETNER, P. & P. DUVIGNEAUD (1979): Terrestrial primary production and phytomas. In: BOLIN, B., DEGENS, E.T., KEMPE, S. & P. KETNER (EDS.): The global carbon cycle. *Scope* 13 (5). John Wiley & Sons. Chichester: 129-182.

AKAPI, J. A. (2002): Ackerbauern und mobile Tierhalter in Zentral- und Nordbenin. Landnutzungskonflikte und Landesentwicklung. In: BRAUN, G., FREITAG, U., KLUCZKA, G., LENZ, K., SCHARFE, W. & F. SCHOLZ (EDS.): *Abhandlungen – Anthropogeographie* 63. Institut für Geographische Wissenschaften. Freie Universität Berlin. Berlin.

ALLEN, R. G., PEREIRA, L. S., RAES, D. & M. SMITH (1998): Crop evapotranspiration: guidelines for computing crop water requirements. FAO Irrigation and drainage paper. FAO. Rome.

ALIDOU, S., LANG, J., BONVALOT, J., ROMAN, E. & A. SEILACHER (1991): Marine influence in the so-called continental sediments of the Paleozoic–Mesosoic Kandi Basin (Northernn Benin, West Africa). In: *Journal of African Earth Sciences* 12 (1–2): 55–65.

AMOS, C. S. (2003): Modelling agricultural expansion and human population pressure on semi-arid landscapes. MSc. Thesis. Enschede.

ANHUF, D. & P. FRANKENBERG (1991): Die naturnahen Vegetationszonen Westafrikas. In: *Die Erde* 122. Berlin: 243-265.

ANDREAE, B. (1977): Agrargeographie: Strukturzonen und Betriebsformen in der Weltlandwirtschaft. Walter de Gruyter. Berlin.

ARNOLD, A. (1997): Allgemeine Agrargeographie. Perthes GeographieKolleg. Klett Verlag Stuttgart. Stuttgart.

AUBREVILLE, A. (1949): Climats, forêts et désertification de l'Afrique tropicale. Société d'Editions Géographiques, Maritimes et Coloniales. Paris.

BATJES, N. H. (2002): ISRIC-WISE global data set of derived soil properties on a 0.5 by 0.5 degree grid (Version 2.0). *Report* 2002/03. International Soil Reference and Information Centre (ISRIC). Wageningen. Internet: http://www.isric.org (01.12.2002.).

BERDING, F. & C. A. VAN DIEPEN (1982): Notice explicative des cartes d'aptitude culturale de la République Populaire du Bénin. *Projet Agro Pedologie* 251. Cotonou.

BERNHARD, H. (1973): Die Agrargeographie als wissenschaftliche Disziplin. In: RUPPERT, K. (ED.): Wege der Forschung CLXXI: Agrargeographie. Wissenschaftliche Buchgesellschaft Darmstadt: 1-17.

BILLINGS, W. D, GOLLEY, F., LANGE, O.L, OLSON, J. S. & H. REMMERT (EDS.) (1989): The Grazing Land Ecosystems of African Sahel. *Ecological Studies* 75. New York.

BLUM, W. E. H. & H. ESWARAN (2004): Soils for sustaining global food production. In: *Journal of food science* 69 (2): 37-42.

BOHLINGER, B. (1998): Die Spontane Vegetation in traditionellen Anbausystemen Benins: Ihre Bedeutung und Möglichkeiten des Managements. *PLITS* 16 (1). University of Hohenheim. Stuttgart.

BOSCHETTI, L., FLASSE, S., TRIGG, S., BIVIO, P. A. & M. MAGGI (2001): A methodology for the validation of low resolution remotely sensed data products. In: *Proceedings of 4th ASITA conference* 1. Rimini 9-12 October 2001. Rimini: 293-298.

BROWN, S. & G. GASTON (1996): Tropical Africa: Land Use, Biomass, and Carbon Estimates for 1980. NDP-055. Carbon Dioxide Information Center. Oak Ridge National Laboratory. Oak Rigde, Tennessee. Internet: http://cdiac.esd.ornl.gov/epubs/ndp/ndp055/ndp055.html (revised for the web: 2001).

BROWN, S., G. GASTON & R. C. DANIELS (1996): Tropical Africa: Land Use, Biomass, and Carbon Estimates for 1980: With a Method for Extending the Data to 1990 and Beyond. Environmental Sciences Division 4566. Carbon Dioxide Information Center. Oak Ridge National Laboratory. Oak Rigde, Tennessee.

BROWN, S. (1997): Estimating biomass and biomass change of tropical forests. A primer. *FAO Forestry Paper* 134. FAO. Rome.

BRÜCHER, T., FINK, A., SPETH, P. (2005): Klimasimulationen im Rahmen des interdisziplinären Forschungsprojektes IMPETUS. In: FREIMUTH, A. (2005): Kooperative Informationsverarbeitung an der Universität zu Köln: Bericht für das Jahr 2005 des RRZK. University of Cologne. Cologne: 196–204.

BUDDE, M. E., TAPPAN, G., ROWLAND, J., LEWIS, J. & L. L. TIESZEN (2004): Assessing land cover performance in Senegal, West Africa using 1-km integrated NDVI and local variance analysis. In: *Journal of Arid Environments* 59 (3): 481-498.

BURROUGH, P. A. & R. A. MCDONNELL (1998): Principles of geographical information systems. University Press. Oxford.

CASSEL-GINTZ, M. A., LÜDEKE, M. K. B., PETSCHEL-HELD, G., REUSSWIG, F., PÖCHL, M., LAMMEL, G. & H. J. SCHELLNHUBER (1997): Fuzzy logic based global assessment of marginality of agricultural land use. In: *Climate Research. Interactions of Climate with Organism, Ecosystems, and Human Societies*. 8 (2): 135-150.

CASSEL-GINTZ, M. A. (2001): GIS-gestützte Analyse globaler Muster anthropogener Waldschädigung: Eine sektorale Anwendung des Syndromkonzepts. PhD thesis. Berlin.

CENATEL (2002): Rapport final: Base de données georeferencées sur l'utilisation agricole des terres au Bénin. *Contrat N°* 23428. Cotonou.

CGIAR TAC (1999): Report of the study on CGIAR research priorities for marginal lands, the framework for prioritizing land types in agricultural research, the rural poverty and land degradation: a reality check for the CGIAR. Consultative Group on International Agricultural Research CGIAR, Technical Advisory Committee, Washington D.C. Internet: http://www.fao.org/Wairdocs/TAC/X5784E/x5784e00.htm (01.10.1999).

CHURKINA, G., SCHIMEL, D., BRASWELL, B. & X. XIAO (2005): Spatial analysis of growing season length control over net ecosystem exchange. In: *Global Change Biology* 11: 1777-1787.

CIHLAR, J. (2000): Land cover mapping of large areas from satellites: status and research priorities. In: *International Journal of Remote Sensing* 21 (6 & 7): 1093-1114.

CLARK, D. A., BROWN, S. KICKLIGHTER, D. W. CHAMBERS, J. Q., THOMLINSON, J. R., NI, J. & E. A. HOLLAND (2001): Net primary production in tropical forests: An evaluation and synthesis of existing field data. In: *Ecological Applications* 11 (2): 371-384.

CLARK LABS (2002): Idrisi 32. Clark University. Worchester.

COLOMBI, A., MICHELE, C. D., PEPE, M. & A. RAMPINI (2007): Estimation of daily mean air temperature from MODIS LST in Alpine areas. In: *EARSeL eProceedings* 6 (1): 38-46.

CORBETT, J. D. (1996): The changing face of agroecosystem characterization: Models and Spatial Data, the Basis for Robust Agroecosystem Characterization. Third International Workshop on Integrating GIS and Environmental Modelling at Santa Fe, New Mexico, USA, 21-25 Jan 1996. Internet: http://www.ncgia.ucsb.edu/conf/SANTA_FE_CD-ROM/sf_papers/corbett_john/corbett.html (25.01.1996).

CPCS (1967): Classification des sols. Grignon.

CRAMER, W. AND THE PARTICIPANTS OF THE "POTSDAM '95" NPP MODEL INTERCOMPARISON WORKSHOP (1999): Net primary productivity model intercomparison activity (NPP). In: HIBBARD, K. & D. SAHAGIAN (EDS.): *IGBP/GAIM report series* 5. Potsdam.

CSA (ed.) (1956): Specialist meeting on phytogeography, Yangambi. *Scientific Council for Africa South of the Sahara* 53: 1-33.

DAVIS, B. (2003): Choosing a method of poverty mapping. FAO. Rome.

DED SCHULPROGRAMM BERLIN, EPIZ E.V., MODELLVORHABEN TRANSFER-21 & SENATSVERWALTUNG FÜR BILDUNG, WISSENSCHAFT UND FORSCHUNG BERLIN (2007): Handreichung Geografie: Rahmenlehrplan Sekundarstufe I und Kerncurriculum Gymnasiale Oberstufe. Unterrichtsmaterialien, Lehrerfortbildungen, Referentinnen und Referenten zur Bildung für Nachhaltige Entwicklung und zum Globalen Lernen. Berlin.

DOEVENSPECK, M. (2004): Migration im ländlichen Benin: Sozialgeographische Untersuchungen an einer afrikanischen Frontier. PhD thesis. University of Bayreuth. Bayreuth.

DOMINGO, E. (1996): Pression agricole et risque d'érosion dans le bassin versant du Lomon, affluent du Mono (département du Mono-Benin). In : DE NONI, G., LAMACHERE, J.-M. & E. ROOSE (EDS.): Etats de surface du sol et risques de ruissellement et d'érosion. Bulletin - Réseau Erosion. In: *Journées du Réseau Erosion* 12. Paris: 181-194.

DORRONSORO, C. (2002): Soil evaluation. The role of soil science in land evaluation. Sustainable use and management of soils in arid and semiarid regions. In: FAZ, A., ORITZ, R. & A. R. MERMUT (EDS.): SUMASS 2002. *Cartagena* 1. Quaderna Editoral. Murcia: 106-128.

DUBE, O. P. & G. PICKUP (2001): Effects of rainfall variability and communal and semi-commercial grazing on land cover in southern African rangelands. In: *Climate Research* 17:195-208.

DUESTERHAUS, R. (1990): Sustainability's Promise. In: *Journal of Soil and Water Conservation* 45(1) [NAL Call # 56.8 J822].

EKLUNDH, L. & L. OLSSON (2003): Vegetation index trends for the African Sahel 1982-1999. In. *Geophysical Research Letters paper* 30: 131-134.

ESRI (1992): ArcWorld 1992. Environmental Systems Research Institute Inc. Redlands, CA. CD-ROM #098.

ESRI (2002): ArcPad 6.0. Environmental Systems Research Institute Inc. Redlands, CA.

ESRI (2007): ArcGIS 9.2. Environmental Systems Research Institute Inc. Redlands, CA.

ESSER, G. (1993): Eingriffe der Landwirtschaft in den Kohlenstoffkreislauf: Studie A für die Enquête-Kommission des Deutschen Bundestages „Schutz der Erdatmosphäre". Wissenschaftlicher Fachverlag. Gießen.

ESSER, G., HOFFSTADT, J., MACK, F. & U. WITTENBERG (1994): High resolution biosphere model: Documentation Model Version 3.00.00. *Mitteilungen aus dem Institut für Pflanzenökologie der Justus-Liebig-Universität Gießen* 2. Gießen.

ESWARAN, H., BEINROTH, F. & P. F. REICH (1999): Global land resources and population-supporting capacity. In: *American Journal of Alternative Agriculture* 14 (3): 129-136.

ESWARAN, H., R. LAL & P. F. REICH (2001): Land degradation: an overview. In: BRIDGES, E. M., HANNAM, I. D. OLDEMAN, L. R. PENING DE VRIES, F. W. T., SCHERR, S. J. & S. SOMPATPANIT (EDS.): Responses to Land Degradation. Proceedings of the 2nd International Conference on Land Degradation and Desertification, Khon Kaen, Thailand. Oxford Press. New Delhi: 25-29.

FAO (ED.) (1974): Soil map of the world 1. Paris.

FAO (ED.) (1976): A framework for land evaluation*. FAO Soils Bulletin* 32. FAO. Rom.

FAO, UNFPA & IIASA (1982): Potential Population Supporting Capacities of Lands in the Developing World. Technical Report of Project INT/75/P13 *Land Resources for Populations of the Future*. Rome.

FAO (ED.) (1995): Global and national soils and terrain digital databases (SOTER): Procedures Manual. *World Soil Resources Reports* 74 (1). Rome.

FAO (ED.) (1996$_{A}$): Agro-ecological zoning: Guidelines. *FAO Soils Bulletin* 73. FAO. Rom.

FAO (ED.) (1996$_{B}$): Rome Declaration of World Food Security. *Report of the World Food Summit* (including Technical Background Documents, Vols. 1 and 2). Rome.

FAO (ED.) (2002): Global agro-ecological assessment for agriculture in the 21st century: Methodology and results. Rome.

FAO (2007A): AQUASTAT country profile Benin. FAO. Rome. Internet: http://www.fao.org/nr/water/aquastat/data/query/index.html. (12.08.2007).

FAO (2007B): Ecocrop. FAO. Internet: http://ecocrop.fao.org/ (26.07.2007).

FARR, T. G. & M. KOBRICK (2000): Shuttle Radar Topography Mission produces a wealth of data. In: *American Geophysical Union Eos* 81: 583-585.

FAURE, P. & B. VOLKOFF (1998): Some factors affecting regional differentiation of the soils in the Republic of Benin (West Africa). In: *Catena* 32: 281-306.

FEDDEMA, J. J. & S. FREIRE (2001): Soil degradation, global warming and climate impacts. In: *Climate Research* 17: 209-216.

FENSHOLD, R., NIELSEN, T. T. & S. STISEN (2007): Evaluation of AVHRR PAL and GIMMS 10-day composite NDVI time series product using SPOT-4 vegetation data for the African continent. In: *International Journal of Remote Sensing* 27 (13): 2719-2733.

FERENCZ, C., BOGNÁR, P., LICHTENBERGER, J., HAMAR, D, TARCSAI, G., TIM´R, G., MOLNÁR, G., FERECNCZ, O. E. & I. FERENCZ-ÁRKOS (2004): Crop yield estimation by satellite remote sensing. In: *International Journal of Remote Sensing* 25 (20): 4113-4149.

FINK, A. H. (2006): Das Westafrikanische Monsunsystem. In: *Promet* 32 (3/4): 114-122.

FINK, A. H., VINCENT, D. G. & V. ERMERT (2006): Rainfall types in the West African sudanian zone during the summer monsoon 2002. In: *Monthly Weather Review* 134:2143-2163.

FISCHER, G. W. & J. ANTOINE (1994): Agro-ecological land resources assessment for agricultural development planning: A case study of Kenya. Making land use choices for district planning. FAO. Rome.

FISCHER, G., DE PAUW, E., VAN VELTHUIZEN, H., NACHTERGAELE, F. & J. ANTOINE (1995): A provisional world climatic resource inventory based on the length-of-growing-period concept. Paper presented at the NASREC Conference, 5-12 November 1995. Wageningen.

FOODY, G. M. (2002): Status of land-cover classification accuracy assessment. In: *Remote Sensing of Environment* 80: 185-201.

GAISER, T. & F. GRAEF (2001): Optimisation of a parametric land evaluation method for cowpea and pearl millet production in semiarid regions. In: *Agronomie* 21: 705-712.

GEBHARDT, H., GLASER, R., RADTKE U. & P. REUBER (EDS.) (2006): Geographie: Physische Geographie und Humangeographie. Spektrum Akademischer Verlag. Heidelberg, Berlin, and Oxford.

GIERTZ, S. (2004): Analyse der hydrologischen Prozesse in den sub-humiden Tropen Westafrikas unter besonderer Berücksichtigung der Landnutzung am Beispiel des Aguima-Einzugsgebietes in Benin. PhD Thesis. University of Bonn. Bonn.

GRAEF, F. (1999): Evaluation of agricultural potentials in semi-arid sw-Niger: A Soil and Terrain (NiSOTER) Study. *Hohenheimer Bodenkundliche Hefte* 54. University of Hohenheim. Stuttgart.

GREENLEE, D. D. (1987): Raster and vector processing for scanned linework. In: *Photogrammetric Engineering and Remote Sensing* 53 (10): 1383–1387.

HAAN, C. T. (1977): Statistical Methods in Hydrology. Iowa State University Press. Ames, Iowa.

HARENBERG, D. (2004): Syndrome globalen Wandels als überfachliches Unterrichtsprinzip. Internet: http://www.transfer-21.de/daten/texte/SyndromtextHarenberg.pdf (last visit: 2.11.2007).

HELLBERG-RODE, G. (ED.) (2004): HyperSoil - Entwicklung einer hypermedialen Lern- und Arbeitsumgebung zum Themenfeld "Boden" im (Sach-)Unterricht. Institut für Didaktik der Biologie Westfälische Wilhelms-Universität Münster. Münster. Internet: http://hypersoil.uni-muenster.de/0/02/02/04.htm (last visit: 2.11.2007).

HENRICKSEN, B. L. & J. W. DURKIN (1986): Growing period and drought early warning in Africa using satellite data. In: *International Journal of Remote Sensing* 7 (11): 1583 - 1608.

HIBBARD, K. & D. SAHAGIAN (EDS.) (1999): Net primary productivity model intercomparison activity (NPP). *IGBP/GAIM report series* 5. Potsdam.

HOUNTONDJI, Y.-C., SOKPON, N. & P. OZER (2006): Analysis of the vegetation trends using low resolution remote sensing data in Burkina Faso (1982-1999) for monitoring of desertification. In: *International Journal of Remote Sensing* 27 (5-6): 871-884.

HUETE, A. R (1988): A soil-adjusted vegetation index (SAVE). In: *Remote Sensing of Environment* 25: 295-309.

HUETE A., DIDAN, K., MIURA, T. & E. RODRIGUEZ (2002): Overview of the radiometric and biophysical performance of the MODIS vegetation indices. In: *Remote Sensing of Environment* 83: 195-213.

HUETE, (2003): Monitoring vegetation phenology using MODIS. In: *Remote Sensing of Environment* (84): 471-475.

IGUÉ, A. M. (2000): The use of a soil and terrain database for land evaluation procedures: Case study of Central Benin. *Hohenheimer Bodenkundliche Hefte* 58. University of Hohenheim. Stuttgart.

IGUÉ, A. M., GAISER, T. & K. STAHR (2004): A soil and terrain digital database for improved land use planning in Central Benin. In: *European Journal of Agronomy* 21: 41-52.

IGUÉ A. M. (2005): Soil information system for the Ouémé basin. Cotonou. Internet: http://www.rivertwin.de/assets/publications/D15_SLISYS_Oueme basin2.pdf (last visit: 30.07.2007).

IIASA (ED.) (2001): In-depth analyses: The AEZ methodology. Internet http://www.iiasa.ac.at/Research/LUC/ChinaFood/indepth/id_11.htm (29.10.2001).

ILBERY, B. W. (1985): Agricultural geography: A social and economic analysis. Oxford University Press. New York.

INSAE (2003): Troisième Recensement Général de la Population et de l'Habitat de Février 2002. La population des communes de Tchaourou, N'dali, Parakou, Bassila, Djougou. Cotonou.

IPCC (2001): Climate Change 2001: The Scientific Basis. In: HOUGHTON, J. T., DING, Y. GRIGGS, D. J., NOGUER, M., VAN DER LINDEN, P. J., DAI, X., MASKELL, K. & C. A. JOHNSON (EDS.): A contribution of working group I to the third assessment report of the intergovernmental Panel on Climate. Cambridge University Press. Cambridge, United Kingdom, and New York.

IPCC (2007): Climate Change 2007: Impacts, adaptation and vulnerability. In: PARRY, M. CANZIANI, L., OSVALDO, F., PALUTIKOF, J. P., VAN DER LINDEN, P. J., & C. E. HANSON (EDS.): Contribution of working group II to the fourth assessment report of the IPCC. Cambridge University Press. Cambridge, United Kingdom, and New York.

IVERSON, L. R., BROWN, S., PRASAD, A., MITASOVA, H., GILLESPIE, A. J. R. & A. E. LUGO (1994): Use of GIS for estimating potential and actual forest biomass for continental south and southeast Asia. In: DALE, V. H. (ED.): Effects of land-use change on atmospheric CO2 concentrations. South and Southeast Asia as a Case Study. *Ecological Studies* 101. Springer Verlag. Berlin, Heidelberg, and New York: 67-117.

JENSON S. K. & J. O. DOMINGUE (1988): Extracting topographic structure from digital elevation data for geographic information system analysis. In: *Photogrammetric Engineering and Remote Sensing* 54 (11): 1593-1600.

JIANG, L. & S. ISLAM (1999): A methodology for estimation of surface evapotranspiration over large areas using remote sensing observations. In: *Geophysical research letters* 26 (17): 2773-2776.

JUDEX, M. (2003): Analyse und Erklärung der Landbedeckungs- und Landnutzungsänderungen im Upper Ouémé Catchment (Benin, Westafrika) durch die Verknüpfung von LANDSAT-Daten mit sozioökonomischen Daten. Diploma Thesis. University of Bonn.

JUNGE, B. (2004): Die Böden des oberen Ouémé-Einzuggebietes in Benin/Westafrika: Pedologie, Klassifizierung, Nutzung und Degradierung. PhD thesis. Bonn.

JUSTICE, C. O. HOLBEN, B. N. & M. D. GWYNNE (1986): Monitoring East African vegetation using AVHRR data. In: *International Journal of Remote Sensing* 7 (11): 1453 - 1474.

KLEIN, D. & RÖHRIG, J. (2006): How does vegetation respond to rainfall variability in a semi-humid West African in comparison to a semi-arid East African environment? In: Braun, M. (ed.): *Proceedings of Second Workshop of the EARSeL SIG on Remote Sensing of Land Use & Land Cover*: Application & Development. Bonn, 28-30 September 2006: 149-156.

KLINGEBIEL, A. A. & P. H., MONTGOMERY (1961): Land capability classification. *USDA Agricultural Handbook* 210. US Government Printing Office. Washington, DC.

KRUSE, R., GEBHARDT, J. & F. KLAWONN (1993): Fuzzy-Systeme. Teubner. Stuttgart.

LAMBIN, E. F. (1997): Modeling and monitoring land-cover change processes in tropical regions. In: *Progress in Physical Geography* 21: 375–393.

LANDON, J. R. (ED.) (1984): Booker tropical soil manual: A handbook for soil survey and agricultural land evaluation in the tropics and subtropics. Booker Agriculture International Limited. London.

LANDSBERG, J. J., PRINCE, S. D., JARVIS, P. G., MCMURTRIE, R. E. LUXMOORE, R. & B. E. MEDLYN (1997): Energy conversion and use in forest: An analysis of forest production in terms of radiation utilisation efficiency ($\varepsilon$). In: GHOLZ, H. L., NAKANE, K. & H. SHIMODA (EDS.): The use of remote sensing in the modelling of forest productivity. *Forest Sciences* 50. Kluwer Academic Publishers. Dordrecht: 273-298.

LAUDIEN, R., RÖHRIG, J., BARETH, G. & G. MENZ (2007): Spatial Decision Support System zur Modellierung der agrarischen Marginalität in Benin (Westafrika). In: STROBL, J., BLASCHKE, T. & G. GRIESEBNER (EDS.): Angewandte Geoinformatik 2007. Wichmann. Heidelberg: 430-439.

LE COCQ, A. (1986): Carte pédologique et carte des capacités agronomiques des sols à 1:100 000 région de Bassar (Togo): Les sols et leurs capacités agronomiques. In: ORSTOM (ED.): *Collection notice explicative* 102. ORSTOM. Paris.

LEEMANS, R. & G. J. VAN DEN BORN (1994): Determining the potential distribution of vegetation crops and agriculture productivity. In: *Water, Air & Soil pollution. An international journal of environmental pollution* 76: 133-161.

LEONHARD, H. J. (ED.) (1989): Environment and the poor: Development strategies for a common agenda. Oxford.

LEVEQUE, A. (1978): Ressources en sols du Togo: Carte à 1/200 000 des unités agronomiques déduites de la carte pédologique. Socle granito-gneissique limité à l'ouest et au nord par les Monts Togo. In: ORSTOM (ED.): *Notice Explicative* 73. ORSTOM. Paris.

LI, J., LEWIS, J., ROWLAND, J., TAPPAN, G. & L. L. TIESZEN (2004): Evaluation of land performance in Senegal using multi-temporal NDVI and rainfall series. In: *Journal of Arid Environments* 59 (3): 463-480.

LIEBIG J., VON (1855): Die Grundsätze der Agricultur-Chemie mit Rücksicht auf die in England angestellten Untersuchungen. Vieweg Verlag. Braunschweig.

LIETH, H. & R. H. WHITTAKER (EDS.) (1975): Primary productivity of the biosphere. *Ecological Studies* 14. Springer Verlag. Berlin, Heidelberg, and New York.

LINDERHOLM, H. W. (2006): Growing season changes in the last century. In: *Agricultural and Forest Meteorology* 137 (1-2): 1-14.

LIPPER, L., PINGALI, P. & M. ZUREK (2006): Less-favoured areas: Looking beyond agriculture towards ecosystem services. *ESA Working Paper* 06-08. FAO. Rome. Internet: ftp://ftp.fao.org/docrep/fao/009/ag431e/ag431e00.pdf (01.09.2006)

LLOYD, D. (1990): A phenological classification of terrestrial vegetation cover using shortwave vegetation index imagery. In: *International Journal of Remote Sensing* 11 (12): 2269-2279.

LÜDEKE, M. K. B., MOLDENHAUER, O. & G. PETSCHEL-HELD (1999): Rural poverty driven soil degradation under climate change: The sensitivity of the disposition towards the Sahel Syndrome with respect to climate. In: *Environmental Modelling and Assessment*. 4: 315-326.

LÜDEKE, M. K. B., PETSCHEL-HELD, G. & H.-J. SCHELLNHUBER (2004): Syndromes of Global Change: The first panoramic view. In: *GAIA*. 13 (1): 42-49.

MAMA, V. J., OREKAN, O. A. V., HOUNDAGBA, C. J., AZONTONDE, A., TONI, E., AKPASSOUNOU, P., ADAMBIOKOU-AKAKPO, J. & A. HOUNMENOU (1998): La gestion de l'information sur les sols et les eaux pour la sécurité alimentaire au Bénin. Rapport du Bénin. Atelier sous-régional sur la gestion de l'information des sols et des eaux pour la sécurité alimentaire. FAO & CENATEL. Cotonou, du 07 au 12 décembre 1998.

MANSHARD, W. (1983): Die Bedeutung des Ressourcen-Managements für die Entwicklungszusammenarbeit. In: *Geographische Zeitschrift* 71: 41-50.

MANSHARD, W. (1997): Complex phenomenon, complex solutions. In: *Land Use Policy* 14 (4): 338-339.

MATTHEWS, E. (1983): Global vegetation and land use: new high resolution data bases for climate studies. In: *Journal of Climate Application and Meteorology* 22: 474-487.

MAZZUCATO, V. & D. NIEMEIJER (2001): Overestimating land degradation, underestimating farmers in the Sahel. *Issue Paper Drylands Programme* 101. International Institute for Environment and Development. London.

MCGARRY, D. (2006): A methodology of visual-soil field assessment tool to support, enhance, and contribute to the LADA program. FAO. Rome.

MEHU (ED.) (2003): Aptitudes des sols et leur répartition au Bénin: Etat des lieux et perspectives d'aménagement à l'horizon 2025. Cotonou.

MEHU (ED.) (2004): Troisième rapport national sur la mise en œuvre de la convention des nations-unies sur la lutte contre la désertification. Cotonou.

MERCHANT, J.W., YANG, L. & W. YANG (1994). Validation of continental-scale land cover databases developed from AVHRR data. In: Proceedings of Pecora 12 Land Information from Space-based Systems. 24–26 August 1993. ASPRS. Bethesda: 63–72.

MEURER, M. (1997): Geoökologie und Umweltforschung: Fiktion oder Vision? Beiträge zum 1. Kongreß für Geoökologie am 9. November 1996 an der Universität Karlsruhe. In: BURGER, D., M. MEURER & J. VOGT (EDS.): *Karlsruher Schriften zur Geographie und Geoökologie* 7. Karlsruhe: 13-24.

MDR & GTZ (2000): Initiative sur la fertilité des sols (IFS, FAO/Banque Mondiale): Etude des filières des intrants agricole au Benin. Tome 2. Rapport Principal. Cotonou.

MDR & INRAB (EDS.) (1995): Sur les ressources naturelles: Les sols et leurs potentialités agricoles les essences forestières. Fiche technique. Cotonou.

MOLDENHAUER, O. & M. K. B. LÜDEKE (2002): Climate sensitivity of global terrestrial Net Primary Production (NPP) calculated using the reduced form model NNN. In: *Climate Research* 21: 43-57.

MORGAN, W.B. & R. J. C. MUNTON (1971): Agricultural geography. St. Martin's Press. New York.

MOSTOVOY, G. V., KING, R., REDDY, K. R. & V. G. KAKANI (2005): Using MODIS LST data for high-resolution estimates of daily air temperature over Mississippi. In: *IEEE*: 76-80.

MOSTOVOY, G. V., KING, R., REDDY, K. R. & V. G. KAKANI (2006): Statistical estimation of daily maximum and minimum air temperatures from MODIS LST data over the state of Mississippi. In: *GIScience & Remote Sensing* 43 (1): 78-110.

MOULIN, S., KERGOAT, L., VIOVY, N. & G. DEDIEU (1997): Global-scale assessment of vegetation phenology using NOAA/AVHRR satellite measurements. In: *Journal of Climate* 10: 1154-1170.

MUCHONEY, D., STRAHLER, A., HODGES, J. & J. LOCASTRO (1999): The IGBP DISCover confidence sites and the system for terrestrial ecosystem parameterization: Tools for Validating Global Land-Cover Data. In: *Photogrammetric Engineering and Remote Sensing* 65 (9): 1061-1067.

MULINDABIGWI, V. (2006): Influence des systèmes agraires sur l'utilisation des terroirs, la séquestration du carbone et la sécurité alimentaire dans le bassin versant de l'Ouémé supérieur au Bénin. PhD thesis. University of Bonn. Bonn.

MUNZINGER-ARCHIV (ED.) (2002): Munzinger Länderhefte: Politik, Wirtschaft, Soziales Benin. Munzinger-Archiv. Ravensburg.

NACHTERGAELE, F. O. (2003): From the Soil Map of the World to the digital Global Soil and Terrain Database: 1960-2002. Internet: www.itc.nl/~rossiter/Docs/WRB/SoilMapWorld .pdf (last visit: 09.12.2007).

NEMANI, R., KEELING, C., HASHIMOTO, H., JOLLY, W., PIPER, S., TUCKER, C., MYNENI, R. & S. RUNNING (2003): Climate-Driven Increases in Global Terrestrial Net Primary Production from 1982 to 1999. In: *Science* 300: 1560-1563.

NETER, J., WASSERMAN, W. & G. A. WHITMORE (1992)$^3$: Study guide to accompany applied statistics. Allyn & Bacon. Boston.

NEUMANN, K., HAHN-HADJALI, K. & U. SALZMANN (2004): Die Savanne der Sudanzone in Westafrika: Natürlich oder menschengemacht. In: ALBERT, K.-D., LÖHR, D. & K. NEUMANN (EDS.): Mensch und Natur in Westafrika: Kapitel. 2.1. Ergebnisse aus dem Sonderforschungsbereich 268 „Kulturentwicklung und Sprachgeschichte im Naturraum Westafrikanische Savanne. DFG. Wiley-VCH Verlag GmbH & Co. KGaA. Weinheim: 39-68.

NILLER, H.-P. (2004): Wissenschaftstheoretische und methodologische Grundprobleme der Geographie, WS04/05. Kap. 2. Department of Geography, University of Regensburg. Internet: http://www.uni-regensurg.de/Fakultaeten/phil_Fak_III/Geographie/phygeo/downloads/nille06wt04_05.pdf (last visit: 03.02.2006).

NISHIDA, K., NEMANI, R. R., RUNNING, W. & J. M. GLASSY (2003): An operational remote sensing algorithm of land surface evaporation. In: *Journal of geophysical research* 108 (D9): 4270-4283.

NÜSSER, M. (2003): Humanökologische Aspekte der Ressourcennutzung und Umweltdegradation in Lesotho. In: POPP, H. (ED.): Das Konzept der Kulturerdteile in der Diskussion: das Beispiel Afrikas. *Bayreuther Kontaktstudium Geographie* 2. Bayreuth: 231-244.

NÜSSER, M., SCHENK, W. & G. BUB (2005): Agrar- und Forstgeographie. In: SCHENK, W. & K. SCHLIEPHAKE (EDS.): Allgemeine Anthropogeographie. Chapter 8. Perthes Geographiekolleg. Klett-Perthes Verlag. Gotha and Stuttgart: 353-384.

ORTHMANN, B. (2005): Vegetation ecology of a woodland-savanna mosaic in central Benin (West Africa): Ecosystem analysis with a focus on the impact of selective logging. PhD thesis. University of Rostock. Rostock.

ÖNÖZ, B. & M. BAYAZIT (2003): The power of statistical tests for trend detection. In: *Turkish Journal of Engineering & Environmental Sciences* 27: 247-251.

PAETH, H. (2004): Key factors in African climate change evaluated by a regional climate model. In: *Erdkunde* 58: 290-315.

PAETH, H. & A. HENSE (2004): SST versus climate change signals in West African rainfall: 20th -century variations and future projections. In: *Climatic Change* 65: 179-208.

PAETH, H. & HENSE, A. (2005): Mean versus extreme climate in the Mediterranean region and its sensitivity to future global warming conditions. In: *Meteorologische Zeitschrift* 14: 329-347.

PAETH, H. & H.-P. THAMM (2007): Regional modelling of future African climate north of 15°S including greenhouse warming and land degradation. In: *Climatic Change* 83: 401-427.

PEDEN, G. D. (1987): Livestock and wildlife population distribution in relation to aridity and human population in Kenya. In: *Journal of Range management* 40 (1): 67-71.

PENDER, J. & HAZELL, P. (2000): Promoting sustainable development in Less-Favoured Areas: Overview. 2020 Focus 4 letter1. IFPRI. Washington, DC.

PENMAN, H. C. (1948): Natural evapotranspiration from open water, bare soil and grass. In: *Proceedings of the Royal Society London* A 193: 120-145.

PETSCHEL-HELD, G., BLOCK, A., CASSEL-GINTZ, M., KROPP, J., LÜDEKE, M. K. B., MOLDENHAUER, O., REUSSWIG, F. & H. J SCHELLNHUBER (1999): Syndromes of Global Change: a qualitative modelling approach to assist global environmental management. In: *Environmental Modelling and Assessment*. 4: 295-314.

PETSCHEL-HELD, G., LÜDEKE, M. K. B. & F. REUSSWIG (2001): Mustermodellierung anthropogener Landnutzung: Von globalen zu lokalen Skalen und zurück. In: LINNEWEBER, V. (ED.): Zukünftige Bedrohung durch (anthropogene) Naturkatastrophen. *Schriftreihe des Deutschen Komitees für Katastrophenvorsorge* 22. Bonn: 72-87.

PETTORELLI N., VIK J. O., MYSTERUD A., GAILLARD J. M., TUCKER, C. J. & N. C. STENSETH (2005): Using the satellite-derived Normalized Difference Vegetation Index (NDVI) to assess ecological effects of environmental change. In: *TRENDS in Ecology and Evolution* 20 (9): 503-510.

PILARDEAUX, B. (1997): Syndrome des Globalen Wandels: Ein neuer Ansatz zur Erdsystemanalyse. In: *Geographische Rundschau* 50 (5): 314-315.

PINZON J., BROWN M. E. & C. J. TUCKER (2004): Satellite time series correction of orbital drift artifacts using empirical mode decomposition. In: HUANG, N. (ED.): Hilbert-Huang Transform: Introduction and Applications. Chapter 10 (II). Applications. World Scientific Publishing: 167–186.

POSS, R. & S. WOROU (1985): Carte pédologique et planification régionale: L'Exemple de Bassar. Problèmes de choix et d'interprétation des données pédologiques. Communication présentée à la 7è réunion du sous-Comité Ouest et Centre Africain de corrélation des sols pour l'évaluation et la mise en valeur des terres (Ouagadougou, 10-17 novembre 1985). ORSTOM. Lomé. FAO. Rome.

PRENTICE, I. C., CRAMER, W. C., HARRISON, S. P., LEEMANS, R. MONSERUD, R. A. & A. M. SOLOMON (1992): A global biome model based on plant physiology and dominance, soil properties and climate. In: *Journal of Biogeography* 19: 117-134.

PRIESTLEY, C. H. B. & R. J. TAYLOR (1972): On the assessment of surface heat flux and evaporation using large-scale parameters. In*: Monthly weather review* 100 (2): 81-92.

PRINCE, S. D., GOETZ, S. L., CZAJKOWSKI, K., DUBAYAH, R. & GOWARD, S. N. (1998): Inference of surface and air temperature, atmospheric precipitable water and vapour pressure deficit using AVHRR satellite observations: validation of algorithms. In: *Journal of Hydrology* 212+213: 231-250.

QUERSCHNITTSGRUPPE STEUERUNG UND TRANSFORMATION IM FÖRDERSCHWERPUNKT SOZIAL-ÖKOLOGISCHE FORSCHUNG DES BUNDESMINISTERIUMS FÜR BILDUNG UND FORSCHUNG (BMBF) (QAG) (ED.) (2004): Steuerung und Transformation: Überblick über theoretische Konzepte in den Projekten der sozial-ökologischen Forschung. Diskussionspapier 01. Berlin.

REED, B. C., BROWN, J. F., VANDERZEE, D., LOVELAND, T. R., MERCHANT, J. W & D. O. OHLEN (1994): Measuring phenological variability from satellite imagery. In: *Journal of Vegetation Science* (5): 703-714.

REIFF, K. (1998): Geo- und weideökologische Untersuchungen in der subhumiden Savannenzone NW-Benins. In: M. MEURER (ED.): Das Weidewirtschaftliche Nutzungspotential der Savannen Nordwest-Benins aus floristischervegetationskundlicher Sicht 1. Karlsruhe: 51–86.

REENBERG, A. & B. PAARUP-LAURSEN (1997): Determinants for land use strategies in a sahelian agroecosystem: anthropological and ecological geographical aspects of natural resource management. In: *Agricultural Systems* 53: 209-229.

RICHTERS, J. (2004): Automated yearly land cover discrimination using a tree classifier and phenologic metrics approach. In: GOOSENS, R. (ED.): Remote Sensing in Transition. Rotterdam: 191-194.

RICHTERS, J. (2005): Entwicklung eines fernerkundungsgestützten Modells zur Erfassung von pflanzlicher Biomasse in NW-Namibia. PhD thesis. Bonn.

RÖHRIG, J. (2002): Ermittlung des Marginalitätsindexes für die landwirtschaftliche Produktion im westlichen Afrika mit Fuzzy-Logik. Diploma Thesis. University of Bonn.

RÖHRIG, J. & G. MENZ (2005): The determination of natural agricultural potential in Western Africa using the fuzzy logic based marginality index. *In: EARSeL eProceedings* 4 (1): 9-17.

RÖHRIG, J., THAMM, H.-P., MENZ, G., POREMBSKI, S. & B. ORTHMANN (2005): A phenological classification approach for the upper Ouémé in Benin, West Africa using SPOT VEGETATION. In: VEROUSTRAETE, F., BARTHOLOMÉ, E. & W. W. VERSTRAETEN (EDS.): Proceedings of the Second International SPOT VEGETATION Users Conference. 1998-2004: 6 years of operational activities. Ispra: 301-306.

ROSSITER, D. G. (1996): A theoretical framework for land evaluation. In: *Geoderma* 72: 165-202.

ROTHER, K. (1988): Agrargeographie. In: *Geographische Rundschau*. Stand und Aufgaben der Geographie 40 (2): 36-41.

RSI, Research System Inc (2000): ENVI's Programmer's guide. RSI.

RUNNING, S. W., THORNTON, P. E., NEMANI, R. & J. M. GLASSY (2000): Global terrestrial gross and net primary productivity from the Earth Observing System. In: SALA, O. E., JACKSON, R. B., MOONEY, H. A. & R. W. HOWARTH (EDS.): Methods in Ecosystem Science. Springer-Verlag. New York: 44-57.

RUPPERT, K. (1984): Agrargeographie im Wandel. In: *Geographica Helvetica* 4: 168-172.

RUTHENBERG, H. (1980)$^3$: Farming systems in the tropics. Clarendon Press. Oxford.

SAKAMOTO, T., YOKOZAWA, M., TORITANI, H., SHIBAYAMA, M., ISHITSUKA, N. & H. OHNO (2005): A crop phenology detection method using time-series MODIS data. In: *Remote Sensing of Environment* 96: 366-374.

SALAZAR, L., KOGAN F. & L. ROYTMAN (2007): Using vegetation health indices and partial least squares method for estimation of corn yield. In: *International Journal of Remote Sensing* 26 (16): 175 - 189.

SANCHEZ, P. A., COUTO, W. & S. W. BUOL (1982): The fertility capability soil classification system: Interpretation, application and modification. In: *Geoderma* 27: 283-309.

SCHELLNHUBER, H. J., BLOCK, A., CASSEL-GINTZ, M., KROPP, J., LAMMEL, G., LASS, W. LIENENKAMP, R., LOOSE, C., LÜDEKE, M. K. B. MOLDENHAUER, O., PETSCHEL-HELD, G., PLÖCHL, M. & F. REUSSWIG (1997): Syndromes of global change. In: *GAIA*. 6 (1): 19-34.

SCHÄTZL, L. (2003): Wirtschaftsgeographie 1. Theorie. UTB. Paderborn.

SCHMIDT, M. (2003): Development of a fuzzy expert system for detailed land cover mapping in the Dra catchment (Morocco) using high resolution satellite images. PhD thesis. University of Bonn. Bonn.

SCHNELL, R., HILL. P. B. & E. ESSER (1995)$^5$: Methoden der empirischen Sozialforschung. R. Oldenbourg Verlag München. München.

SCHWARTZ, M. D. & B. C. REED (1999): Surface phenology and satellite sensor-derived onset of greenness: an initial comparison. In: *International Journal of Remote Sensing* 20 (17): 3451-3457.

SCHWERTZ, J. N. (1836): Beschreibung der Landwirtschaft in Westfalen und Rheinpreußen. 2 parts. Hoffmannsche Verlags-Buchhandlung. Stuttgart.

SEAQUIST, J. W., OLSSON, L. & J. ARDÖ (2003): A remote sensing-based primary production model for grassland biomes. In: *Ecological Modelling* 169: 131-155.

SHEN, J. (2004): Population growth, ecological degradation and construction in the Western region of China. In: *Journal of Contemporary China* 13 (41): 637-661.

SHI, W. Z., EHLERS, M. & M. MOLENAAR (2005): Uncertainties in integrated remote sensing and GIS. In: *International Journal of Remote Sensing* 26 (14): 2911-2915.

SHREVE, R. L. (1966): Statistical Law of Stream Number. In: *Journal of Geology* 74: 17-37.

SINGER, U. (2006): Entwicklungsprojekte im ländlichen Benin im Kontext von Migration und Ressourcenverknappung. PhD thesis. University of Bayreuth. Bayreuth.

SISK, T. D., LAUNER, A. E., SWITKY, K. R. & P. R. EHRLICH (1994): Identifying extinction threats: global analyses of the distribution of biodiversity and the expansion of the human enterprise. *BioScience* 44: 592–604.

SKYES, M. T., PRENTICE, C., SMITH, B., CRAMER, W. & S. VENEVSKY (2001): An introduction to the European terrestrial ecosystem modelling activity. In: *Global Ecology & Biography* 10: 581-593.

SONG, J. & W. GAO (1999): An improved method to derive surface albedo form narrowband AVHRR satellite data: Narrowband to broadband conversion. In: *Journal of Applied Meteorology* 38: 239-249.

SONG, X., SAITO, G., KODAMA, M. & H. SAWADA (2004): Early detection system of drought in East Asia using NDVI from NOAA/AVHRR data. In: *International Journal of Remote Sensing* 25 (16): 3105-3111.

SPETH, P., DIEKKRÜGER, B., CHRISTOPH, M. & A JAEGER (2005): IMPETUS-West Africa- An integrated approach to the efficient management of scarce water resources in West Africa – Case studies for selected river catchments in different climate zones. In: GSF (ED.): GLOWA: German Programme on Global Change in the Hydrological Cycle. *Status Report* 2005: 86-94.

SPETH, P., DIEKKRÜGER, B. & M. CHRISTOPH (EDS.) (2006): IMPETUS-West Africa- An integrated approach to the efficient management of scarce water resources in West Africa – Case studies for selected river catchments in different climate zones. *Second final report* (period 1.5.2003-31.7.2006). Cologne.

STOCKING, M. A. & N. MURNAGHAN (2001): Handbook for the field assessment of land degradation. Earthscan Publications. London.

STORIE, R.E. (1933): An index for rating the agricultural value of soils. *Agricultural Experiment Station Bulletin* 556. University of California Agricultural Experiment Station. Berkley, CA.

STORIE, R. E. (1978): Storie Index Soil Rating (Revised). *Special publication* 3203. Division of agricultural science. University of California. Berkeley, CA.

STRAHLER, A. N. (1957): Quantitative analysis of watershed geomorphology. In: *Transactions of the American Geophysical Union* 8 (6): 913-920.

STUDENSKY, G. (1973): Die Grundideen und Methoden der landwirtschaftlichen Geographie. In: RUPPERT, K. (ED.): Wege der Forschung CLXXI. Agrargeographie. Wissenschaftliche Buchgesellschaft Darmstadt. Darmstadt: 18-41.

STURM, H.-J. (1993): Produktions- und weideökologische Untersuchungen in der subhumiden Savannenzone Nordbenins. *Karlsruher Schriften zur Geographie und Geoökologie* 2. Karlsruhe.

SYMEONAKIS, E. & N. DRAKE (2004): Monitoring desertification and land degradation over sub-Saharan Africa. In: *International Journal of Remote Sensing* 25 (3): 573-592.

SYS, C. (1978): Evaluation of land limitations in the humid tropics. In: *Pédologie* 28: 307-335.

SYS, C., VAN RANST, E. & J. DEBAVEYE (1991A): Land evaluation. Part 1: Principles in land evaluation and crop production calculations. *Agricultural publications* 7. General Administration for Development Cooperation. Brussels.

SYS, C., VAN RANST, E. & J. DEBAVEYE (1991B): Land evaluation. Part 2: Methods in land evaluation. *Agricultural publications* 7. General Administration for Development Cooperation. Brussels.

SYS, C., VAN RANST, E. & J. DEBAVEYE (1993): Land evaluation. Part 3: Crop requirements. *Agricultural publications* 7. General Administration for Development Cooperation. Brussels.

TARBOTON, D. G., R. L. BRAS & I. RODRIGUEZ–ITURBE (1991): On the extraction of channel networks from digital elevation data. In: *Hydrological Processes* 5: 81–100.

THAMM, H.-P.; RECHA, P.; CHRISTOPH, M. & SCHÜTZ, O. (2005A): Interactive IMPETUS digital atlas. Remote Sensing Reaseach Group. Bonn.

THAMM, H.-P.; JUDEX, M. & G. MENZ (2005B): Modelling of land-use and land-cover change (LUCC) in Western Africa using remote sensing. In: *Zeitschrift für Photogrammetrie und Fernerkundung* 3: 191-199.

THÜNEN, J. H. VON (1826): Der isolierte Staat in Beziehung zu Landwirtschaft und Nationalökonomie. Perthes. Hamburg.

TUCKER, C. J. (1979): Red and photographic infrared linear combinations for monitoring vegetation. In: *Remote Sensing of Environments* 8: 127-150.

TUCKER, C. J., PINZON, J. E. & M. E. BROWN (2004): Global Inventory Modeling and Mapping Studies. NA94apr15b.n11-VIg, 2.0. Global Land Cover Facility. University of Maryland. College Park, Maryland.

TUCKER, C. J., PINZON, J. E., BROWN, M. E., SLAYBACK, D., PAK, E. W., MAHONEY, R., VERMOTE, E. & N. EL SALEOUS (2005): An extended AVHRR 8-km NDVI data set compatible with MODIS and SPOT Vegetation NDVI Data. In: *International Journal of Remote Sensing* 26 (20): 4485–4498.

TURNER, M. & H. GEIST (2006): Desertification. In: GEIST, H. (ED.): Our earth's changing land I. Greenwood Press. London: 164–170.

TÜXEN, R. (1956): Die heutige potentielle natürliche Vegetation als Gegenstand der Vegetationskartierung. In: *Angewandte Pflanzensoziologie* 13: 5-42.

UNDP (ED.) (2003): Human development report 2003: Millennium development goals. A compact among nations to end human poverty. UNDP. Oxford.

UNEP, ISSS, ISRIC & FAO (1995): Global and national Soils and Terrain Digital Databases (SOTER) procedures manual. *World Soil Resources Report* 74. FAO. Rome.

U.S. NATIONAL GEOPHYSICAL DATA CENTER (1988): ETOPO5 Global elevation at 5 minutes resolution. USNGDC. Boulder, CO.

USGS (ED.) (2006): Accuracy assessment of 1992 national land cover data: methods and results. Internet: http://landcover.usgs.gov/accuracy/index.asp (06.03.2006).

USGS, NASA & DAAC (2007): MODIS: Terra Land Surface Temperature/Emissivity Daily L3 Global 1km SIN Grid. Internet: http://edcdaac.usgs.gov/modis/mod11a1v4.aspi (last visit: 14.05.2007).

USTIN, S. L., JACQUEMOUD, S., PALACIOS-ORUETA, A., LI, L. & M. L. WHITING (2005): Remote sensing based assessment of biophysical indicators for land degradation and desertification. In: Röder, A. & J. Hill: Proceedings of the 1st international conference on remote sensing and geoinformation processing in the assessment and monitoring of land degradation and desertification. 7.-9. September 2005. Trier: 2-21.

YOUNG, A. (1998): Land resources: Now and for the future. Cambridge University Press. Cambridge.

VANACKER, V., LINDERMAN, M., LUPO, F., FLASSE, S. & E. LAMBIN (2005): Impact of short-term rainfall fluctuation on interannual land cover change in sub-Saharan Africa. In: *Global Ecology and Biogeography* 14: 123-135.

VAN DIEPEN, C. A., VAN KEULEN, H. WOLF, J. & J. A. A. BERKHOUT (1991): Land evaluation: From intuition to quantification. In: *Advances in Soil Science* 15: 139-204.

VOLKHOFF, B. (1976): Carte pedologique de reconnaissance de la Republique Populaire du Benin. ORSTOM. Paris.

VOLLMERT, P., FINK, A. H. & H. BESLER (2003): „Ghana Dry Zone" und „Dahomey Gap": Ursachen für eine Niederschlagsanomalie im tropischen Westafrika. In: *Erde* 134 (4): 375-393.

VOß, K. (2005): Beitrag zur skalenabhängigen Erfassung teilschlagspezifischer Pflanzenschäden mit Methoden der Fernerkundung und Geoinformation. PhD thesis. University of Bonn. Bonn.

WALPOLE, R. E. & R. H. MEYERS (1985)³: Probability and statistics for engineers and scientists. MacMillan Publishing Co. New York.

WAN, Z. (2002): Land Surface Temperature measurements form EOS MODIS data. Semiannual Report for January – June. Santa Barbara.

WAN, Z. (2006): MODIS Land Surface Temperature products users' guide. Internet: http://www.icess.ucsb.edu/modis/LstUsrGuide/usrguide.html (01.03.2006).

WARNANT, P., FRANCOIS, L., NEMRY, B., HUBERT B. MOLITOR N., COLINET, G. & J. C. GERARD (1995): A new distribution of vegetation types and its inclusion in a global biosphere model. In: GUYOT, G. (ED.) Proceedings of the International Colloquium Photosynthesis and Remote Sensing, 28-30 August 1995. Montpellier. EARSel-INRA: 385-392.

WELLER, U. (1999): Agro-ecological potential of maize in Southern Benin. In: HERRMANN, K., VENNEMANN K., STRAHR, K. & M. VON OPPEN (EDS.): Agricultural Atlas of natural and agronomic resources of Benin and Niger. University of Hohenheim. SFB308. Internet: https://www.uni-hohenheim.de/~atlas308/c_benin/projects/c2_2_2/html/english/ bframe _en_c2_2_2. htm (last visit: 20.03.2007)

WELLER, U. (2002): Land evaluation and land use planning for Southern Benin (West Africa) BENSOTER. *Hohenheimer Bodenkundliche Hefte* 67. Institut für Bodenkunde und Standortlehre. University of Hohenheim. Stuttgart.

WEISCHET, W. (1977): Die ökologische Benachteiligung der Tropen. B.G. Teubner. Stuttgart.

WEZEL, A., BOHLINGER, B. & R. BÖCKER (1999): Vegetation zones in Niger and Benin: present and past zonation. In: HERRMANN, K., VENNEMANN K., STRAHR, K. & M. VON OPPEN (EDS.): Agricultural Atlas of natural and agronomic resources of Benin and Niger. University of Hohenheim. SFB308. Internet: http://www.uni-hohenheim.de/~atlas308/a_overview/a3_1/ html/english/nframe.htm) (last visit: 20.12.2007).

WEZEL, A. & R. BÖCKER (2000): Vegetation of Benin. In: GRAEF, F., LAWRENCE, I. M. & M. VON OPPEN (EDS.): Adapted Farming in West Africa: Issues, potentials and perspectives. Verlag Ulrich E. Grauer. Stuttgart: 219–226.

WHITE, F. (1983): The vegetation of Africa. UNESCO. Paris.

WHITE, M. A., THOMTON, P. E. & S. W. RUNNING (1997): A continental phenology model for monitoring vegetation responses to interannual climatic variability. In: *Global Biogeochemical cycles* 11 (2): 217-234.

WHITE, M. A. & R. R. NEMANI (2006): Real-time monitoring and short-term forecasting of land surface phenology. In: *Remote Sensing of Environment* 104: 43-49.

WULDER, M. A., FRANKLIN, S. E., WHITE, J. C., LINKE, J. & S. MAGNUSSEN (2006): An accuracy assessment framework for large-area land cover classification products derived from medium-resolution satellite data. In: *International Journal of Remote Sensing* 27 (4): 663-683.

ZOBLER, L. (1986): A world soil file for global climate modelling. *NASA Technical Memorandum* 87802. Goddard Institute for Space Studies. New York.

ZHANG, X., FRIEDL, M. A., SCHAAF, C. B., STRAHLER, A. H., HODGES, J. C. F. & F. GAO (2003): Monitoring vegetation phenology using MODIS. In: *Remote Sensing of Environment* 84: 471–475.

ZHANG, X., FRIEDL, M. A., SCHAAF, C. B. & A. H. STRAHLER (2005): Monitoring the response of vegetation phenology to precipitation in Africa by coupling MODIS and TRMM instruments. In: *Journal of geophysical research* 110. D12103, doi:10.1029/2004JD005263.

ZIMMERMANN, H.-J. (1991)²: Fuzzy Set Theory: And its applications. Kluwer Academic Publishers. Boston, Dordrecht and London.

## Personal communications

DIEDERICH, M. (2008): Temperature data according to IPCC scenarios A1B and B1.

DR. CASSEL-GINTZ, M. (2007): Marginality index of agricultural land use.

DR. GIERTZ, S. (2007): Temporal availability of water in the rivers of Benin.

DR. GIERTZ, S. (2008): Impact of climate change on water network in Benin.

DR. IGUÉ, A. M. (2005): Suitability of ORSTOM soil map for own research.

DR. PAETH, H., HEUER, O. & M. DIEDERICH (2007): Precipitation data according to scenarios

Prof. Dr. SKOVRONEK, A. (2006): Soil evaluation in Benin: Methods and data.

# 10 Appendix

## Appendix 1: Interviews in Benin

| Name | Position | Institution | Date | Contents of the meetings |
|---|---|---|---|---|
| C. P.I AKPASSONOU | Specalist in cartography and GIS | CENATEL | 27/11/06 | • Regionalisation approach<br>• Main biophysical constraints in Benin<br>• Outcome of the regionalisation |
| Prof. M. A. BAGLO | Director | Agence Beninoise d'Environment (ABE) | 10/10/05 | • Regionalisation approach<br>• Main biophysical constraints in Benin<br>• Outcome of the regionalisation<br>• Land degradation in Benin |
| Dr. A. M. IGUÉ | Head of department: Inventaire et Evaluation des Ressources en Sols | INRAB | 02/05/05<br>07/10/05<br>28/11/07 | • Regionalisation approach<br>• Main biophysical constraints in Benin<br>• Evaluation of soil fertility<br>• Outcome of the regionalisation<br>• Land degradation in Benin |
| Dr. E. JOYI | Assistant professor | UAC, department of Geography | 28/11/06 | • Regionalisation approach<br>• Main biophysical constraints in Benin<br>• Evaluation of soil fertility<br>• Outcome of the regionalisation<br>• Land degradation in Benin |
| D. Z. LOCONON | Acting manager | AGEDREN | 29/11/06 | • Land degradation in Diagbalo and Banté |
| Dr. P. MUTLU | Co-ordinator of ProCGRN | GTZ | 04/05/05 | • Regionalisation approach<br>• Main biophysical constraints in Benin |
| Dr. F. TCHIBOZO | Assistant professor | UAC, department of Geography | 28/11/06 | • Regionalisation approach<br>• Main biophysical constraints in Benin<br>• Evaluation of soil fertility<br>• Outcome of the regionalisation<br>• Land degradation in Benin |
| Frau ZANOU | Co-ordinator of CCD | MEHU | 07/10/05 | • Regionalisation approach<br>• Main biophysical constraints in Benin<br>• Land degradation in Benin |
| Gabi ZINK | Co-ordinator of the program Agro Ecologique Bénin Nord | DED | 29/04/05<br>14/09/05<br>22/11/06<br>30/11/07 | • Regionalisation approach<br>• Main biophysical constraints in Benin<br>• Outcome of the regionalisation |

**TableA 1: List of experts questioned during fieldworks in Benin**

| Location | Date | Number of farmers | Latitude (UTM, 31 N) | Longitude (UTM, 31N) |
|---|---|---|---|---|
| Serou | 12/04/05 | 2 | 357695.92 | 1068597.32 |
| Toukoutouna | 14/04/05 | 1 | 321159.15 | 1157102.21 |
| Avogbanna | 26/04/05 | 4 | 392638.87 | 798850.17 |
| Monkpa | 27/04/05 | 3 | 392992.56 | 876935.01 |
| Barei | 14/09/05 | 1 | 341665.24 | 1068595.52 |
| Parakou I | 18/09/05 | 2 | 458534.64 | 1040849.91 |
| Parakou II | 19/09/05 | 1 | 460728.81 | 1031211.05 |
| Gouarou | 19/09/05 | 5 | 448425.81 | 1020315.89 |
| Yamsala | 21/09/05 | 1 | 325543.05 | 1067318.74 |
| Kopargo | 23/09/05 | 3 | 341596.82 | 1088959.87 |
| Kpabegou | 23/09/05 | 1 | 345407.22 | 1083989.19 |
| Assotè | 24/09/05 | 1 | 339166.24 | 1066490.04 |
| Kakpala | 24/09/05 | 2 | 326414.54 | 1075973.40 |
| Kimkim | 24/09/05 | 2 | 321776.69 | 1060202.27 |
| Foyo | 25/09/05 | 5 | 382935.13 | 1073622.55 |
| Kolonkonde | 28/09/05 | 3 | 355381.03 | 1076665.76 |
| Gaouga | 28/09/05 | 1 | 384606.83 | 1078031.52 |
| Donga | 28/09/05 | 1 | 384653.01 | 1075814.48 |
| Boko Tanhou | 28/09/05 | 3 | 477041.59 | 1214891.11 |
| Sidikparo | 29/09/05 | 4 | 350283.88 | 1075874.55 |
| Kparsi | 29/09/05 | 1 | 374745.94 | 1075859.00 |
| Banikoara | 29/09/05 | 1 | 437964.79 | 1247816.18 |
| Sirikou | 29/09/05 | 2 | 429535.74 | 1240638.34 |
| Mone | 30/09/05 | 2 | 374078.39 | 1077907.38 |
| Agatoudji | 01/10/05 | 7 | 457689.53 | 889013.30 |
| Dogue | 03/10/05 | 6 | 383029.68 | 1006501.56 |
| Sé | 18/11/06 | 3 | 368646.62 | 720324.24 |
| Thochoume | 18/11/06 | 5 | 368877.00 | 722673.83 |
| Agnarrvo | 18/11/06 | 5 | 354442.05 | 745827.67 |
| Djikpamé | 18/11/06 | 2 | 352606.09 | 766586.29 |
| Manigri | 23/11/06 | 6 | 359366.10 | 991670.62 |
| Saramanga | 24/11/06 | 7 | 365316.10 | 1019267.04 |

**TableA 2: List of farmers questioned during fieldworks in Benin**

# Appendix 2: IDL-programs

## 2.1 Linear fuzzification of an indicator

```
; This program fuzzificates data, whereby the two
; thresholds of the linear functions must be
; predefined manually:
; x0: no limitation
; x1: inadequate for agricultural land use
; linear equation: y=1/(x1-x0)*x - x0/(x1-x0)

; last modification: 3.5.06

; written by Julia Röhrig

; -------------------------------------------------------
; Selection of the input data
; -------------------------------------------------------
datei=envi_pickfile(title='Please select the image
you want to fuzzificate', filter='*.img')

datadir = STRMID(datei, 0,(STRPOS(datei, '\', $
/REVERSE_SEARCH))+1)

;------------------------------------------------
; Read primary image information
;------------------------------------------------
envi_open_file, datei,r_fid=fid, /no_realize
envi_file_query, fid, ns=ns, nl=nl, nb=nb
map_info = envi_get_map_info(fid=fid)
envi_file_mng, id=fid
dims = [-1, 0, ns-1, 0, nl-1]
pos=intarr(nb)

;--------------------------------------------------------
; Definition of variables
;--------------------------------------------------------
; Definition of the array, which contain the input
; data
   input=make_array(ns,nl)
; Array, which contains the outcome
   output=fltarr(ns,nl)
; Definition of threshold x0
   x0=26.
; Definition of threshold x1
   x1=33.
; Dummy containing the slope of equation
   dummy=x1-x0

;--------------------------------------------------------
; Retrieve image data
;--------------------------------------------------
; Retrieve image data
 input(*,*)=ENVI_GET_DATA(fid=fid,dims=dims,$
pos=0)

;--------------------------------------------------------
; Main process level: Fuzzification
;--------------------------------------------------------
; Application of the membership function
 for s=0, ns-1 do begin
   for l=0, nl-1 do begin
         output(s,l)=1/dummy*input(s,l)-x0/dummy
    endfor
  endfor
;--------------------------------------------------------
; Reclassification of values higher and lower than
;thresholds, respectively
;------------------------------------------------------
    if x0 lt x1 then begin
       null=where(input le x0, zeroc)
    if zeroc le 0 then begin
       print,'keine Werte unter x0'
   ENDIF ELSE BEGIN
      output(null)=0
   ENDELSE

    eins=where(input ge x1, one)
    if one le 0 then begin
        print,'keine Werte groesser x1'
   ENDIF ELSE BEGIN
   output(eins)=1
   ENDELSE

    null=where(input ge x0, dummy3)
    if dummy3 ne 0 then     output(null)=0.0
    eins=where(input le x1, dummy2)
    if dummy2 ne 0 then output(eins)=1.0

;-----------------------------------------------
; Illustration of the membership function
;---------------------------------------------
    x=findgen(100)/10.0
    y=1/(x1-x0)*x - x0/(x1-x0)
    zero=where(x ge x0, test)
    if test le 0 then begin
          print,'keine Werte groesser x0'
   ENDIF ELSE BEGIN
      y(zero)=0
    endelse
       one=where(x le x1, dummy3)
    if dummy3 ne 0 then y(one)=1.0
    endelse
     iplot, y, max_value=1, min_value=0

;----------------------------------------------------------
;  Write outcome
;---------------------------------------------------------
;Definition of pathway
av_outpfad=datadir+'fuzzy_temp _26-33.dat'

 openw,1,av_outpfad
 writeu,1,output
ENVI_SETUP_HEAD, fname=av_outpfad, $
ns=ns, nl=nl, nb=nb, map_info=map_info,$
interleave=0, data_type=4, $
offset=0,      /write, /open
close,1

end
```

## 2.2 Determination of MI and calculation of key and high constraints

```
; This program determines MI based on already
; fuzzificated input
; For more details about fuzzy-operators see
; Cassel-Gintz et al. 1997
; Operator Compensating-OR is still included but in
; the actual version not applied
; Furthermore site-specific key and high constraints
; are calculated

; last modification: 6.12.07
; written by: Julia Röhrig

;***************************************
; Subroutines containing fuzzy-operators
;---------------------------------------------------
; FUZZY_AND.pro
; -------------------------------------------------
PRO FUZZY_AND, Var1, Var2,Erg,mask,outname
ns=N_ELEMENTS(Var1(*,0))
nl=N_ELEMENTS(Var1(0,*))
Erg=FLTARR(ns,nl)
hlp=FLTARR(2)
for y=0,nl-1 DO BEGIN
 for x=0,ns-1 DO BEGIN
    hlp(0)=Var1(x,y)
    hlp(1)=Var2(x,y)
    Erg(x,y)=MIN(hlp)
 endfor
endfor
erg(mask)=-1.0

; write result
  openw,1,outname
    writeu,1,Erg(*,*)
  close,1
end
; ---------------------------------------------------
; FUZZY_OR.pro
; -------------------------------------------------
PRO FUZZY_OR, Var1, Var2,Erg,mask,outname
ns=N_ELEMENTS(Var1(*,0))
nl=N_ELEMENTS(Var1(0,*))
Erg=FLTARR(ns,nl)
hlp=FLTARR(2)
for y=0,nl-1 DO BEGIN
 for x=0,ns-1 DO BEGIN
    hlp(0)=Var1(x,y)
    hlp(1)=VAR2(x,y)
    Erg(x,y)=MAX(hlp)
 endfor
endfor
erg(mask)=-1.0

; write result
openw,1,outname
    writeu,1,Erg(*,*)
close,1
end
;---------------------------------------------------
; FUZZY_comp_AND.pro
;---------------------------------------------------
PRO
FUZZY_comp_AND,Var1,Var2,Erg,mask,outname
Erg=fltarr(n_elements(Var1(*,0)),$
n_elements(Var1(0,*)))
Erg(*,*)=var1(*,*)+var2(*,*)-1
index = WHERE(Erg(*,*) lt 0, count)
  IF count NE 0 THEN Erg(index) = 0
erg(mask)=-1.0

; write result
openw,1,outname
   writeu,1,Erg(*,*)
close,1
end
;-----------------------------------------------------------
; FUZZY_comp_OR.pro
;----------------------------------------------------
PRO FUZZY_comp_OR,Var1,Var2,Erg,mask,outname
; definition of parameters according to CASSEL-GINTZ
;et al. 1997
a=0.85
b=0.4
c=1

; Definition of outcome array
Erg=fltarr(n_elements(Var1(*,0)), $
n_elements(Var1 (0,*)))
; Application of operator
Erg(*,*) = (1-(1-Var1(*,*))^a * (1-var2(*,*))^b) $
^c * ((Var1(*,*)^a) * (Var2(*,*)^b))^(1-c)
index = WHERE(Erg(*,*) lt 0, count)
IF count NE 0 THEN Erg(index) = 0
erg(mask)=-1.0

; write result
  openw,1,outname
    writeu,1,Erg(*,*)
  close,1
end

;***************************************

;-----------------------------------------------
; Read primary image information
;-----------------------------------------------
; read and open first image
 pfad_npp=envi_pickfile(title='Please select fuzzy
NPP', filter='*fuzzy*.dat')

print, pfad_npp

pfad = STRMID(pfad_npp, 0,(STRPOS(pfad_npp, $
'\', /REVERSE_SEARCH))+1)
print, 'Pfad: ', pfad

envi_open_file, pfad_npp,r_fid=fid, /no_realize
envi_file_query, fid, ns=ns, nl=nl, nb=nb
map_info = envi_get_map_info(fid=fid)
envi_file_mng, id=fid
dims = [-1, 0, ns-1, 0, nl-1]
pos=intarr(nb)
```

```
;--------------------------------------------------------
; Definition of variables
;--------------------------------------------------------
; array for PVEG
   NPP_high=fltarr(ns,nl)
; array for TEMP
   alpha_low=fltarr(ns,nl)
; array for temp/light
   temp_high=fltarr(ns,nl)
; array for LGP
   alpha_high=fltarr(ns,nl)
; array for mean aridity
   arid_high=fltarr(ns,nl)
; array for RV
   PV_high=fltarr(ns,nl)
; hohe natürliche Trockenheit
   natarid_high=fltarr(ns,nl)
; array for IC
   irrig_high=fltarr(ns,nl)
; array for water limitation
   water_high=fltarr(ns,nl)
; array for climate constraints
   climate_high=fltarr(ns,nl)
; array for SOIL
   fert_high=fltarr(ns,nl)
; array for unsuitable growing conditions
   growth_high=fltarr(ns,nl)
; array for SLOPE
   slope_high=fltarr(ns,nl)
; array for MI
   marg_high=fltarr(ns,nl)
; Array that contains all input data and MI
   all=fltarr(ns,nl,8)
; Array to mask boundaries of Benin
   maske=bytarr(ns,nl)

; Definition of band names
bnames_all=['PVEG','TEMP','LENGTH_RAINY','PV','N
EG_IRRIGATION','POOR_SOILS','SLOPE','GESAMT_
MARG']
bnames_limit_all=['VEGDENS','TEMP','LENGTH_RAI
NY','PV','komp_ARID','POOR_SOILS','SLOPE']

; Main and high constraints
;    2: temperature
;    3: LENGTH_RAINY
;    4: PV
;    6: poor soils
;    7: slope

; Array, containing main constraints
  high_limits=fltarr(ns,nl)
; Array, containing high constraints
   limit=fltarr(ns,nl)

;--------------------------------------------------------
; Main process level: MI-Calculation
;--------------------------------------------------------
;MI-calculation based on adapted logical decision
; tree introduced by CASSEL-GINTZ et al. 1997

; Prefix added
   zusatz='92x_2001-2025_'
;--------------------------------------------------------
; read low PVEG
;-------------------------------------------------
; read image data
NPP_high(*,*)=ENVI_GET_DATA(fid=fid, $
dims=dims, pos=0)
all(*,*,0)=NPP_high(*,*)
;--------------------------------------------------
; Calculation of temperature/light constraints
;--------------------------------------------------
; open mask
pfad_maske=envi_pickfile(title=select mask')
envi_open_file, pfad_maske, r_fid=fid, /no_realize
envi_file_query, fid, ns=ns, nl=nl, nb=nb
maske(*,*)=ENVI_GET_DATA(fid=fid,dims=dims,$
pos=0)
envi_file_mng, id=fid

; mask all pixels outside Benin
   no_data=where(maske eq 0)

; open TEMP
pfad_alpha_low=envi_pickfile(title='Please select
fuzzy temp high', filter='*fuzzy*.dat')
envi_open_file, pfad_alpha_low, r_fid=fid, $
/no_realize
envi_file_query, fid, ns=ns, nl=nl, nb=nb
alpha_low(*,*)=ENVI_GET_DATA(fid=fid,
dims=dims, pos=0)
envi_file_mng, id=fid

all(*,*,1)=alpha_low(*,*)

; definition of pathway for result
outpfad_temp=pfad+zusatz+'Temp_high.img'

; applying AND-operator
FUZZY_AND, NPP_high, alpha_low, temp_high,
no_data, outpfad_temp

; write ENVI-header
ENVI_SETUP_HEAD, fname=outpfad_temp, $
ns=ns, nl=nl, nb=nb, map_info=map_info,$
interleave=0, data_type=4, $
offset=0,  /write, /open
;--------------------------------------------------------
; Calculation of mean adritidy constraints
;-----------------------------------------------------------
; read data
pfad_alpha_high=envi_pickfile(title='Please select
fuzzy length rainy season', filter='*fuzzy*.img')
envi_open_file, pfad_alpha_high, r_fid=fid, $
/no_realize
envi_file_query, fid, ns=ns, nl=nl, nb=nb
alpha_high(*,*)=ENVI_GET_DATA(fid=fid,$
dims=dims, pos=0)
envi_file_mng, id=fid
```

```
all(*,*,2)=alpha_high(*,*)

; Definition of pathway
outpfad_arid=pfad+zusatz+'mean_Aridity_high.img'

; Calculation applying AND-operator
FUZZY_AND,   NPP_high,   alpha_high,   arid_high,$
no_data, outpfad_arid

; write Envi-Header
ENVI_SETUP_HEAD, fname=outpfad_arid, $
ns=ns, nl=nl, nb=nb, map_info=map_info,$
interleave=0, data_type=4, $
offset=0,   /write, /open
;-----------------------------------------------------
; Calculation of adritidy constraints
;-------------------------------------------------------
; open RV
pfad_PV=envi_pickfile(title='Please select fuzzy RV')
envi_open_file, pfad_PV, r_fid=fid, /no_realize
envi_file_query, fid, ns=ns, nl=nl, nb=nb
PV_high(*,*)=ENVI_GET_DATA(fid=fid, $
dims=dims, pos=0)

envi_file_mng, id=fid

all(*,*,3)=PV_high(*,*)

; Definition of pathway
outpfad_natarid=pfad+zusatz+'nat_Arid_high.img'

; write Envi-header
ENVI_SETUP_HEAD, fname=outpfad_natarid, $
ns=ns, nl=nl, nb=nb, map_info=map_info,$
interleave=0, data_type=4, $
offset=0,  /write, /open
;--------------------------------------------------------
; Calculation of water scarcity constraints
;-------------------------------------------------------------
; open IC
pfad_irrig=envi_pickfile(title='Please   select   fuzzy
Irrigation Capacity',  filter='*fuzzy*.img')
envi_open_file, pfad_irrig, r_fid=fid, /no_realize
envi_file_query, fid, ns=ns, nl=nl, nb=nb
irrig_high(*,*)=ENVI_GET_DATA(fid=fid,
dims=dims, pos=0)

envi_file_mng, id=fid

all(*,*,4)=irrig_high(*,*)

; Definition of pathway
outpfad_waterlim=pfad+zusatz+'water_lim.img'

; calculation applying comp AND-operator
FUZZY_comp_AND,   irrig_high,   natarid_high,   water_high, no_data, outpfad_waterlim

; write Envi-Header
   ENVI_SETUP_HEAD, fname=outpfad_waterlim, $
   ns=ns, nl=nl, nb=nb, map_info=map_info,$
   interleave=0, data_type=4, $
   offset=0,   /write, /open
;-----------------------------------------------------
; Calculation of climate constraints
;-------------------------------------------------------
; Definition of pathway
outpfad_climatelim=pfad+zusatz+'climate_lim.dat'

; applying OR-operator
FUZZY_OR, water_high, temp_high, climate_high, $
no_data,outpfad_climatelim

; write envi-header
ENVI_SETUP_HEAD,fname=outpfad_climatelim, $
ns=ns, nl=nl, nb=nb, map_info=map_info,$
interleave=0, data_type=4, $
offset=0,   /write, /open
;-----------------------------------------------------
; Calculation of growing constraints
;-------------------------------------------------------
; open SOIL
pfad_fert=envi_pickfile(title='Please  select  Soil',  $
filter='*fuzzy*.img')
envi_open_file, pfad_fert, r_fid=fid, /no_realize
envi_file_query, fid, ns=ns, nl=nl, nb=nb
fert_high(*,*)=ENVI_GET_DATA(fid=fid,
dims=dims, pos=0)
envi_file_mng, id=fid

all(*,*,5)=fert_high(*,*)

; Definition of pathway
outpfad_growthlim=pfad+zusatz+'growth_lim.img'

; applying OR-operator
FUZZY_OR,  climate_high,  fert_high,  growth_high,$
no_data,outpfad_growthlim

; write Envi-header
 ENVI_SETUP_HEAD, fname=outpfad_growthlim, $
ns=ns, nl=nl, nb=nb, map_info=map_info,$
interleave=0, data_type=4, $
 offset=0,   /write, /open
;----------------------------------------------
; Calculation of MI
;-----------------------------------------------------------
; open SLOPE
pfad_slope=envi_pickfile(title='select SLOPE')
envi_open_file, pfad_slope, r_fid=fid, /no_realize
envi_file_query, fid, ns=ns, nl=nl, nb=nb
slope_high(*,*)=ENVI_GET_DATA(fid=fid, $
dims=dims, pos=0)
envi_file_mng, id=fid

all(*,*,6)=slope_high(*,*)

; Definition of pathway
outpfad_marg=pfad+zusatz+'MI.img'

; calculation applying OR-operator
FUZZY_OR,  growth_high,  slope_high,marg_high,  $
no_data,outpfad_marg

; write envi-header
ENVI_SETUP_HEAD, fname=outpfad_marg, $
ns=ns, nl=nl, nb=nb, map_info=map_info,$
interleave=0, data_type=4, $
```

```
offset=0,    /write, /open

all(*,*,7)=marg_high(*,*)

; application of mask
    mask=where(all lt 0, count_mask)
    if count_mask gt 0 then all(mask)=99.
    marg_high(*,*)=all(*,*,7)

; pathway for data with all inputdata
outpfad_all=pfad+zusatz+'MI_fuzzydata.img'

; write data
openw,7, outpfad_all
writeu,7,all
close,7

ENVI_SETUP_HEAD, fname=outpfad_all, $
ns=ns, nl=nl, nb=8, map_info=map_info,$
interleave=0, data_type=4, $
bnames=bnames_all, offset=0,   /write, /open

;------------------------------------------------------
; Determination of main and all high constraints
;--------------------------------------------------------
; excluds PVEG and IC
all_dummy=all
all_dummy(*,*,0)=0.0
all_dummy(*,*,4)=0.0
dummy=fltarr(7)

for s=0, ns-1 do begin
  for l=0, nl-1 do begin
     for b=0, 6 do begin
        dummy(b)=all_dummy(s,l,b)
    endfor

   mainlimit=max(dummy)
   mainpara=where(dummy eq mainlimit,countmain)
   limit(s,l)=min(mainpara)+1
   highconstr=where(dummy ge 0.6,counthigh)
   dummy_lauf=high_limits(s,l)
   dummy_lauf=0.0
   if counthigh gt 0 then begin
        x=1.
        for c=0, counthigh-1 do begin
               value=highconstr(c)+1
               new=float(value/x)
               dummy_lauf=dummy_lauf+new
               x=x*10.
       endfor
      high_limits(s,l)=dummy_lauf
     endif else begin
      high_limits(s,l)=0.0
     endelse

   endfor
endfor

; Defintion of pathway
outpfad_limit=pfad+zusatz+'max_limit.img'

; write data
openw,8, outpfad_limit
writeu,8,limit
close,8

ENVI_SETUP_HEAD, fname=outpfad_limit, $
ns=ns, nl=nl, nb=1, map_info=map_info,$
interleave=0, data_type=4, $
bnames=bnames_all, offset=0,  /write, /open

; write data containing main constraints
outpfad_limitall=pfad+zusatz+'highconstr_each.img'

openw,9, outpfad_limitall
writeu,9,high_limits
close,9

ENVI_SETUP_HEAD, fname=outpfad_limitall, $
ns=ns, nl=nl, nb=1, map_info=map_info,$
interleave=0, data_type=4, $
bnames=bnames_limit_all, offset=0,  /write, /open


end
```