Applications of Remote Sensing and Geographic Information System techniques for desertification and land degradation monitoring and assessment in the Tillabéry landscape (Niger)

Dissertation

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Dedication

This thesis is dedicated to my father and my wife for all love, help, moral support, patience, confidence and understanding in me, during the overall period of my PhD.

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Abbreviations

Abbreviation		Description
1.	RS	Remote Sensing
2.	GIS	Geography Information System
3.	GDP	Gross Domestic Product
4.	FAO	Food and Agricultural Organisation
5.	UNCOD	United Nations Conference on Desertification
6.	ECA	Economic Commission for Africa
7.	MSS	Multispectral Scanner
8.	NDVI	Normalized Difference Vegetation Index
9.	WDVI	Weighted Difference Vegetation Index
10.	SAVI	Soil-Adjusted Vegetation Index
11.	BSI	Bare Soil Index
12.	SI	Spectral Indice
13.	BI	Brightness Index
14.	RI	Redness Index
15.	RUSLE	Revised Universal Soil Loss Equation
16.	USPED	Unit Stream Power-Based Erosion Deposition
17.	SAIL	Scattering by Arbitrarity Inclined Leaves
18.	HAPEX-Sahel	Hydrologic and Atmospheric Pilot Experiment in the Sahel
19.	SRTM	Shuttle Radar Topography Mission
20.	ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
21.	CNEDD	National Environmental Council for a Sustainable Development
22.	%LAND	Percentage of Land
23.	NP	Number of Patches
24.	TA	Total Area
25.	PD	Patch Density
26.	LPI	Largest Patch Index
27.	MPA	Mean Patch Area
28.	PR	Patch Richness
29.	PRD	Patch Richness Density
30.	MSIEI	Modified Simpson’s Evenness Index
31.	SHEI	Shannon`s Evenness Index
32.	SHDI	Shannon`s Diversity Index
33.	SIDI	Simpson`s Diversity Index
34.	MSIDI	Modified Simpson`s Diversity Index
35.	LSI	Landscape Shape Index
36.	ENN_MN	Mean Euclidian Nearest-Neighbor Distance
37.	IJI	Interspersion and Juxtaposition Index
38.	COHESION	Patch Cohesion Index
39.	FRAC	Fractal Dimension Index
40.	MPFD	Mean patch fractal Dimension Index
41.	MPX	Mean Proximity Index
42.	Meff	Mesh Index
43.	LS	Landscape Structure
44.	LSC	Landscape Structure Change

45.	GPS	Global Positioning System
46.	DI	Desertified Index
47.	ADC	amount and direction of change
48.	V	Velocity
49.	GWR	Geographically Weighted Regression
50.	R	Rainfall Erosivity Factor
51.	K	Soil Erodibility Factor
52.	LS	Topographic Factor
53.	C	Cover Management Factor
54.	P	Support Practice Factor
55.	A	Average annual Soil loss
56.	NASA	National Aeronautic and Space Administration
57.	SAGA GIS	System for Automated Geoscientific Analyses
58.	ROC	Receiver Operating Characteristic
59.	NPK	Nitrogen Phosphorous and potassium
60.	SSP	Single Super Phosphate
61.	AIC	Akaike Information Criterion

Abstract

The Sahel region had a moderately good vegetation cover but presently, the landscape is experiencing serious degradation. Research carried out in the field of desertification has not contributed to reducing or reversing these impacts. The spatio-temporal dynamics and intensities of desertification over 34 years were investigated. As such, the objective of this thesis is to investigate and monitor land degradation and desertification processes by using Remote Sensing, Geoinformatics and Geographic Information System techniques, in combination with landscape metrics and soil erosion models in the Tillabéry landscape. The evaluations of land use / land cover were carried out by classifying from one Landsat Multispectral Scanner (1973-09-30), one Landsat Enhanced Thematic Mapper plus (2001-09-18) and two Landsat TM images (1989-09-29 and 2007-09-27). The results of these classifications revealed an increasing trend in desertification throughout the study period.

This study also brings into perspective the usefulness of landscape structure analysis within the context of desertification process analysis. A set of indices were selected to investigate multitemporal change in the Tillabéry landscape. These indices revealed an increase in the percentage of bare areas and also a decrease in shrub areas. The results show further that the Tillabéry landscape has a large number of patches with smaller patch sizes, indicating, that the original landscape has been converted gradually into bare area and the land degradation in the region is an acute problem.

In a bid to further understand the trend and status of desertification in the Tillabéry landscape, a desertified index was developed and dynamic soil erosion models-RUSLE and USPED were applied. In this way, the most sensitive areas and trends to the desertification processes were identified. The RUSLE and USPED models depict a rational evolution of soil loss distribution during the study period. Both soil erosion scenarios output show greater soil erosion in 2070 in the study area. The results suggest that human disturbance and topographic factors led to an increase in the affected areas. However, considerable improvements in sustainable land use systems in the study area need to be developed in order to decrease the amount, direction, velocity, fragmentation, irregularity of patches and loss of biodiversity in the future.

Kurzfassung

Die Sahelregion verfügt über eine wenig dichte bis spärliche Vegetationsbedeckung, die momentan eine schwerwiegende Desertifikation erfährt. Die Untersuchungen, in dem von Desertifikation geprägten Gebiet, haben bisher leider nicht zu einer Reduzierung oder Umkehrung dieser Entwicklung beigetragen. Die raum-zeitliche-Dynamik sowie die Intensität der Desertifikation wurden innerhalb dieser Arbeit über einen Zeitraum von 34 Jahren erforscht. Dabei wurden zur Analyse und Beobachtung des Degradations - und Desertifikationsprozesses Methoden der Fernerkundung sowie der Geoinformatik (Geographische Informationssysteme – GIS) in Kombination mit Landschaftsstrukturanalysen und einer Bodenprobennahme in der Tillabéry Region durchgeführt.

Die Evaluation von Landnutzung und Landbedeckung wurde durch die Klassifizierung von Satellitenbildern/Luftbildern von Landsat Multispectral Scannern (1973-09-30) und Landsat Enhanced Thematik Mapper (2001-09-18) sowie zweier Landsat TM Bilder (1989-09-29 und 2007-09-27) bearbeitet. Die Ergebnisse dieser Klassifizierungen verdeutlichten während des Untersuchungs-Zeitraums einen zunehmenden Trend im Desertifikationsprozess.

Diese Arbeit verdeutlicht die Nutzbarmachung von Landschaftsstrukturen im Kontext mit der Desertifikation. Für die Untersuchung von multitemporalen Veränderungen im Tillabéry Gebiet wurden Kennzahlen definiert, anhand derer eine prozentuale Zunahme der „bare area“ und ebenso eine Zunahme der „shrub area“ festgestellt werden konnten. Weiter zeigen die Ergebnisse eine große Anzahl kleiner Landschaftszüge auf, die belegen, dass die ursprüngliche Landschaft allmählich in ein vegetationsfreies Gebiet umgewandelt wurde.

Zur Verdeutlichung der Annahme wurde eine Trendentwicklung abgeleitet und das Stadium der Desertifikation in der Tillabéry Region ermittelt sowie ein Desertifikationsindex und ein dynamischer Bodenerosionsindex (Modell RUSLE USPED) entwickelt. Auf diese Weise wurden die sensibelsten Regionen und Trends des Desertifikationsprozesses identifiziert. Das RUSLE und USPED Model beschreibt eine rationale Entwicklung der Verteilung des Bodenverlustes während des Untersuchungszeitraums. Beide Bodenerosionsszenarien weisen bis 2070 weitere größere Bodene-

rosion aus. Diese Ergebnisse beweisen, dass menschliche Zerstörung und topographische Faktoren in nachhaltigen Landnutzungssystemen zur Ausweitung der Problemregionen führen. Daraus leitet sich die Notwendigkeit von Überlegungen zur Entwicklung nachhaltiger Landnutzungssysteme ab, die dem Verlust von Biodiversität in der Untersuchungsregion sowie die Desertifikation in Menge, Richtung, Geschwindigkeit, Fragmentierung und in der Unregelmäßigkeit ihrer Verteilung verringern.

1 Introduction

1.1 General Description of the Problem

Human activities in the Sahel per se, have permanently changed the ecosystem and have thus affected the land use / cover potential and invariably the biodiversity of the landscape. Changes in the landscape of the region are apparent and can also be perceived directly. They have been associated with biodiversity losses (Tucker & Townshend, 2000), negative socio-cultural impacts, loss of soil quality, dramatic and unprecedented land use / cover dynamics (Turner et al., 1994) and lately to global climate change (Pielke et al., 2002).

Several conservation and development studies point to the fact that land degradation and desertification are a result of land use in the Sahel area which is closely linked to demographic conditions. However, lack of reliable data and survey information in some Sahelian countries (Niger, Chad, Burkina Faso, and Senegal) have made the estimation of areas of intact desert and / or areas of land use change and their relation to economic indicators surprisingly difficult to establish. Consequently, the extent and rate of desertification in the Sahel are less well known than in other regions of the world. The effects of desertification and land degradation in Niger Republic are so overwhelming. They span across every aspect of human life in the area. It aggregates poverty conditions, decreases land productivity, increases the aridity of the climate, food insecurity, and further induce diseases and malnutrition. This has led to the disappearance of certain herbaceous and ligneous plants used in traditional pharmacy. To compound it, it has led to an acute reduction in groundwater and merits urgent attention and action.

Government officials are aware of a degraded environment in the Sahel. However, there is inadequate research on the environmental degradation process (its causes, consequences or severity). Notwithstanding, anyone travelling through the region can observe that desertification and land degradation are widespread and are a contemporary and boiling issue. The link between a degraded environment and poverty is direct as species diversity and soil stability are affected tremendously.

1.2 Goal of Thesis

The aim of this thesis is to investigate and monitor land degradation and desertification processes in the Sahel region by using Remote Sensing (RS) and Geography Information System (GIS) techniques. It is the first time that such an approach is used to conduct a land degradation research in the Tillabéry area. This opens up a new field, combining statistical and non-statistical methods for the investigation and analysis of any landscape by using geoscientific methods, specifically GIS and RS approaches.

1.3 Sahel Outlook

1.3.1 Sahel - Brief Overview

The Sahel (from Arabic Sahil, coast of the Sahara desert) is a semi-arid transition area between the Saharan deserts and tropical savannas. It is one of the most sensible and endangered zones in Africa. It is an area in central Africa, covering an area of approximately 3,053,200 km² (see figure 1.1) (Dai et al., 2004). It is one of the poorest and most environmentally degraded regions in the world. Eritrea, Niger, Nigeria, Chad, Sudan, Mali, Burkina Faso, Mauritania and Senegal have parts of their national territories in the Sahel. More than 80% of the Sahel population (55 million) is involved in agriculture. This sector contributes almost 35% of the Gross Domestic Product (GDP) of the majority of these countries (Ben Mohamed et al., 2001).

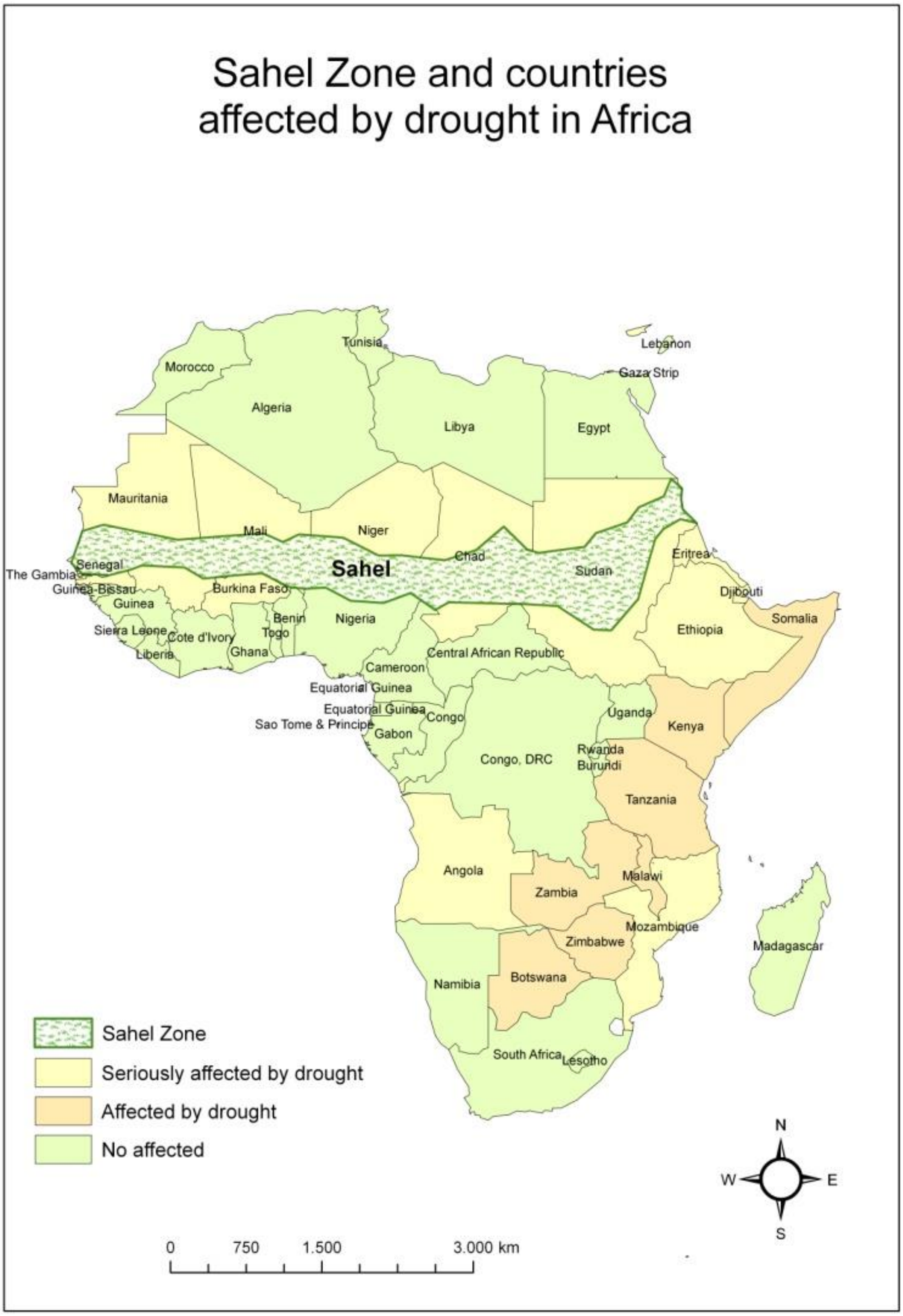


Figure 1.1: Sahel Zone and countries affected by drought in Africa.

1.3.2 Climate, Soil, Vegetation Status and Land Use of Sahel

Table 1.1: Landscape components of the Sudano-Sahelian Zone-West Africa (modified from Le Houerou, 1976).

Mean annual	Ecological domain	Physical landscape	Vegetation	Soil	Land use (irrigation excepted)	
100 mm	Saharan		None except scattered peants in depression	Lithosols, Yermosols	Large scale nomadism (-300 km)	Oasis only
250 mm	Sahelo-sahelian core	Stoney, sandy desert, dunes	Widely scattered plants open steppe	Regosols (dunes), Arenosols, Yermosols	Nomadic transhumance (-150 km) Pastoralism	Oasis and other edaphically farored sited
450 mm	Sahelo-sudanian	Patches of dunes in eroded soils with depressions temporary swamps	Wooded steppe (brousse tigre)	Gleysols, Solonchacs (solonetz), Fluvisols, Luvisols	Semi-sedentary Pastoralism with camels and cattle	No diversification, millet, short cycle groundnuts, cowpeas (niebe)
700 mm	Sudanian	Eroded slopes	Grass savanna	Fluvisols, Vertisols	Sedentary Pastoralism	Little diversification; Millet, sorghum, groundnuts
1100 mm 1500 mm	Guinean	(inverted relief)	Wooded savanna Forest savanna mosaic	Luvisols, Gleysols Nitosols, Ferrasols, Luvisols	Limit of endemic glossina	Wide diversification, long cycle millets and sorghums, groundnuts, cotton, rice in heavy soils and other crops above

Notes:

- The entire table is a modified version of Le Houerou (1976). He has labelled the entire 50-1500 mm zone “Sudano Sahelian”
- The soil classification used is that of Food and Agricultural Organisation (FAO) (World Soil Classification 1974. Legend, soil map of the world, FAO, Paris, France)
- The terms for the “ecological domains“ used here are those most commonly used by the FAO

This table shows that West Africa can be divided into five major ecological zones:

- Saharan zone (arid and desert) with an erratic rainfall of between 0 and 100 mm. Hunting, oasis agricultural production and nomadism are the main activities in this zone.
- Sahelo-sahelian core or Sahel (semi-arid zone) with an average rainfall less than 450 mm. In this zone, the agricultural farming is focused on the cultivation of millet, sorghum, maize and livestock production.
- Sahelo-sudanian, with an average rainfall less than 700 mm. Agro-pastoralism production is the principal land use system in the region.
- Sudanian (sub-humid zone) with annual rainfall between 700 and 1200 mm. Agro-forestry production based on sorghum, maize, root and fruit plants are the main activities in the sudanian landscape.
- Guinean (humid zone) with annual rainfall exceeding 1500 mm. Agricultural production based on root and tuber crops and forest production with coffee and cocoa are the predominant land use in the guinea landscape

Figure 1.2 is based on data provided by AGHYMET Regional Center and were used to show the approximate location of the 200, 400, 600 mm isohyets. This figure shows that the isohyets shifted toward the south between the two periods and led to a shift in the vegetation cover towards the south. We can use the results that show the spatial distribution of land cover / land use in 2000 and changes in the spatial distribution of precipitation in the Sahel for West Africa from 1950-1967 to 1968-2000.

The reduction in precipitation and a corresponding decrease in vegetation cover is shown in this figure. The 200 mm / year isohyets can be used to trace the changes in the boundary between deserts and non desert and also, the combination of land use / land cover and changes in Isohyets can be used to define the boundary location, from which insight can be gained about desertification.

Soil and Topography

One important limitation to land cover in the Sahel region is soil fertility. Soils are acidic and are very low in mineral fertility such as nitrogen and phosphate needed by plants. Bationo & Mokwunye (1991) reported that Sahelian soils have low organic matter content, low water retention and nutrient holding capacity. Therefore, the composition of soils in the Sahel region shows high levels of sand and low levels of clay and silt. Soils improved by leguminous species such as *Acacia albila* and *Leucaena leucocephala* are reported to cause considerable improvement on vegetation cover. The topography of the area is flat and lies between 200–400 m but there are several isolated plateaus and mountains.

Climate

The Sahel areas are characterised by climatic variations in rainy season (three months from July to September) and dry season (nine months from October to June). Annual rainfall ranges from 350 to 800 mm on a north-south transect (see table 1.1). The precipitation in this region from 1979 to 2000 was below normal. The 2005 rainy season was very moist and in 2003 the rainy season was above average rainfall (Sandra et al., 2006). Rainfall will continue to fluctuate; good (good agricultural production) and bad (bad agricultural production) rainy years will keep on occurring.

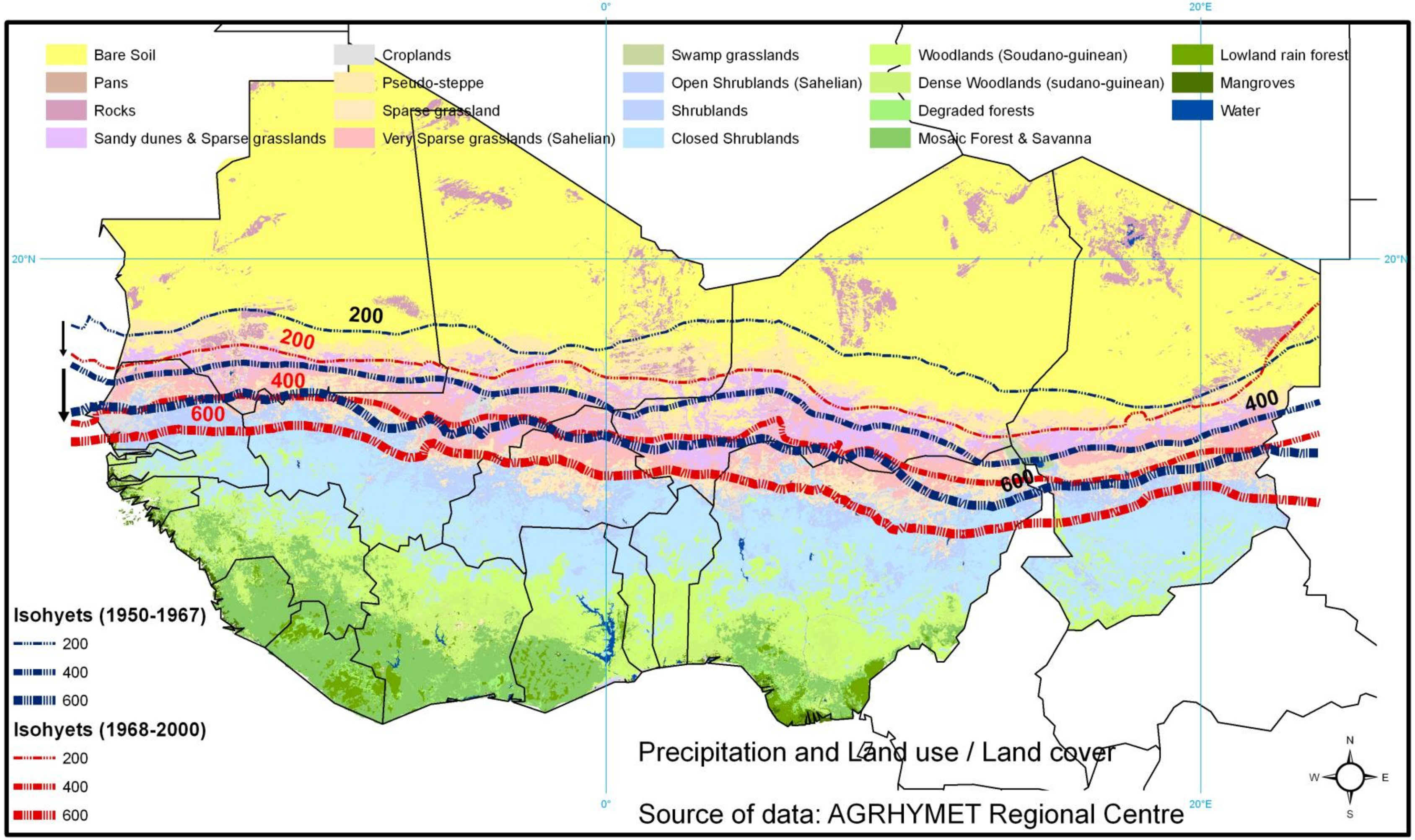


Figure 1.2: Precipitation (1950-1967 and 1968-2000) and land use / land cover (year 2000) map of the region in West Africa.

Vegetation Cover

The Sahel area is covered with grass, savannah, woodland and shrub land (see figure 1.2). The grassland is dominated by annual grass species (*Aristida stipoides*, *Schoenefeldia gracilis* and *Cenchrus biflorus*) and the woodland by acacia species (*Acacia tortilis*, *Acacia Senegal* and *Acacia laeta*) and other species such as *Commiphora Africana*, *Balanites aegyptiaca*, *Faidherbia albida* and *Bascia senegalensis*. The shrub lands are dominated by *Aristida sieberana*, *Panicum turgidum*. During the dry season the annual grasses die and the trees lose their leaves.

Famine and Drought in the Sahel

Drought is a natural phenomenon in this area and as a result of this land degradation and desertification have reduced regional rainfall. It has reduced productivity, affected vegetation cover and increased albedo, decreased water recycling and monsoon circulation, reduced vegetation cover leading to high soil erosion. A good number of literatures (Glantz & Orlovesky, 1984 and Tarhule & Woo, 1998) linked the famines of 1914, 1972, 1973 and 1984 with the largest regional rainfall deficits in the Sahel. Glantz & Orlovesky (1984) hold that the Sahel famine of 1973 was the result not only of very low rainfall, but of a lack of timely provision of famine relief after the onset of drought conditions in 1968 and the increased use of marginal land for agriculture. The authors noted that up to 200,000 people and twelve million cattle had died due to the famine (mid 1970). Socio-economic consequences of this loss were profound and affected the livelihood of large numbers of people living in this area. In the study area, many nomadic herders of goat, sheep, camel and cattle have moved to others countries south of the area of drought.

2 State-of-the-Science

2.1 The Situation of Desertification and Land Degradation in Sahel Region

Desertification was first used by Aubreville (1949) to represent the process of change of vegetation in tropical Africa. He explained, that desertification was not an extension of the existing desert and described desertification as the transformation of productive land into an ecological desert due to the ruinous act of erosion, often propelled by man-made deforestation. His description also implicated climatic variations as a factor of desertification. Earlier than this, Lavauden (1927) explained that desertification is the product of human intervention on the landscape. His solution for this process is the suppression of burning and grazing, the sedentarisation of nomadic people (Arab, Peulh and Touareg) who had created a “zone pseudo-désertique” and reforestation. Augustin (1906) argued that in the Sahel the forest gives way to shrub; the shrub to herbaceous vegetation; the herbaceous vegetation to bare soil caused by burning and overgrazing and accelerated by wind. Also, Le Houérou (2002) described the degradation of the Sahel as “man-made deserts”.

Stebbing (1935) equally described the Sahara north of Tahoua (Niger). He held that it increased at a medium speed of 1 km per year caused by human activities. Later, Lamprey (1975) using cartographic data for 1958 and air photographs of 1975 indicated that the south of the Sahara increased at a medium speed of 5.5 km per year in the west of Sudan. Much research has been carried out using satellite image with low resolution. These researches have shown that the Sahara answered fluctuations of rainfall, with the ability to stretch during periods of dryness and contract with the return of rains (Tucker & Nicholson, 1999).

During the latter decades, combating desertification did not attain its objective. One of the fundamental reasons can be attributed to inadequate universal definition of the problem. More than 130 definitions of desertification were thus inventoried in the literature (Mainguet, 1991). There was equally lack of communication amongst researchers, and also between researchers and partner institutions. The situation was further complicated by poor communication between researchers and partner institutions on the one hand and the affected population on the other hand.

The issue of desertification gained more importance in 1977, when the United Nations Conference on Desertification adopted a Plan of Action to Combat Desertification (UNCOD, 1977). In addition, in 1991 the United Nations Environment Programme described that the effects of land degradation in arid, semi-arid and dry subhumid areas has increased. In 1992, desertification was on the agenda at the United Nations Conference on Environment and Development, better known as the Rio Conference. It called for a new integrated approach to the problem and the need for action to promote sustainable development.

Land degradation is a natural process that affects land productivity. Desertification is land degradation occurring in the arid, semiarid and dry sub-humid areas of the world. Land degradation is a process which implies a reduction of potential productivity of the land (Hill et al., 1995). Conacher & Sala (1998) reported land degradation as an “alteration to all aspects of the natural environment by human action to the detriment of vegetation, soil, landform, water and ecosystems”. Hennemann (2001a, b) considered land degradation to be a collective degradation of components of the land (water, biotic and soil). FAO (2002) defined land degradation as the loss of production capacity of land in terms of loss of soil fertility, soil biodiversity and degradation of natural resources.

The United Nations Conference on Environment and Development (1992) defined desertification as “land degradation in arid, semi-arid and dry sub-humid regions resulting from various factors, including climatic variation and human activities”. However, desertification appears when land degradation becomes irreversible or when loss of total productivity reaches 50% to 60% (Katyal & Vlek, 2000). The desertification and land degradation in the Sahel is modulated by hydrological processes.

The Environmental Protection Agency of Ghana (2006) reported that “the land area prone to desertification in Ghana has almost doubled during recent times, desertification is said to be creeping at an estimated 20,000 hectares per year, with the attendant destruction of farmlands and livelihoods in the country”. Nigeria was estimated to be losing 1,355 square miles of rangeland and cropland to desertification each year. This affects each of the northern states of the country. In addition, the land area of Burkina Faso, Mali and Niger was severely or very severely degraded (more than 30% of the land) reported by Economic Commission for Africa (ECA) (2007).

The FAO (1984) reported that, the main processes of land degradation are: the degradation of the vegetative cover, soil degradation and soil erosion. In the Sahel, the soils are of low silt content (< 10%), organic matter (< 1%) and slightly acidic. In this region, most soils are sandy. Most of these sandy soils were developed in aeolian deposits.

2.2 Remote Sensing and Geographic Information Systems in the Study of Desertification and Land Degradation Processes

GIS and RS technologies have greatly increased the capability to study different parts of the environment. These technologies have provided resource managers and researchers a tool to analyse data and address specific problems at a variety of spatial scales, in less time, and in a more cost-effective manner (Sample, 1994). One major focus of using GIS techniques as a management tool is to quantify, qualify, analyse and evaluate landscape, wildlife species habitats and their distributions. For the sake of coverage, high spatial resolution and exact allocation in time, remote sensing data is a vital source of information for mapping and modelling for various applications in landscape analysis. Although recent and future sensors will offer better spatial resolution (0.5 m), satellite data with mid-resolution (15-30 m resolution, e.g. Landsat, SPOT, ASTER) still play a major role for areas under investigation on a state or continental scale. These technologies have proven to be very useful in landscape analysis by quantifying current landscape structure and monitoring the changes in landscape structure over time and also for developing computer models.

Many papers dealing with landscape ecology research have mentioned that GIS is an essential tool for the process of monitoring and assessing the impact of human activities on spatial patterns and ecosystem dynamics. It has also been projected as a tool for manipulating and displaying information in a way that can be easily understood by those involved in studying or planning landscapes and their uses. Also the technical background to GIS, with particular reference to the landscape ecologist, can be found in Johnson (1990), Maguire et al. (1991) and Gibbs & Shriver (2005).

GIS and RS serve as principal instruments to describe spatial quantitative relationships of and between landscape patterns. This approach is also known as landscape structure analysis or landscape metrics. This study will employ several methods for spatial data analysis in a landscape information systems perspective. The investigation of landscape will be accomplished by using change detection and landscape metrics methods. This thesis contributes in this perspective by analysing the concept of land degradation in the semi-arid Tillabéry area (Niger Republic) using RS and GIS techniques.

Previous researches in this area have applied the use of multi-temporal data to monitor desert expansion and to the assessment of factors that may cause desertification. Visual interpretation of Multi-spectral Scanner (MSS) data and aerial photographs were used to identify landforms indicative of desertification and to assess desert encroachment along the Nile River (Gad & Daels, 1986). Two low-resolution satellite images (NOAA-AVHRR and SPOT acquired in November 1992 and 2000 were used to investigate desertification and changes of agricultural areas in Egypt (Shalaby et al., 2004).

Also ASTER images and IKONOS are used. The results which followed these studies are generally similar. Primarily, there were major reductions in the vegetation cover and also, significant increases in soil degradation. But the evaluations of phenomenon vary from one area to another. Karimoune (1994) reports that desertification in the south east of Niger (annual medium precipitation in the order of 350 mm) is not a linear and univocal phenomenon. Various studies (Hoffman & Jackson 2000 and Mota et al., 2003) were based on low resolution satellite images to quantify the processes of land degradation and desertification. The indicator of vegetation normalized with rainfall over periods of time is often used (Davenport & Nicholson, 1993, and Dregne & Tucker, 1988). Several studies have shown that the surface soil moisture content can be estimated by visible and thermal infra-red (walker, 1999 and Dalal & Henry, 1986).

2.2.1 Land Degradation and Desertification Indicators

Many recent reviews have demonstrated the importance of indicators for monitoring land degradation and desertification status. Possible indicators have equally been identified according to physical, biological, human and socio-economic phenomena. According to Tunstall (1994), the major functions of indicators are (1) to compare across places and situations; (2) to assess conditions and trends; (3) to assess conditions and trends in relation to goals and targets; (4) to provide early warning information and (5) to anticipate future conditions and trends.

Winograd (1997), went further to assert that, indicators should be used to: (1) determine the condition of change in the environment in relation to society and the development process; (2) diagnose the actual causes and effects of existing problems that have been detected, in order to elaborate responses and actions, and (3) predict future impacts of human activities on the environment and society to determine future or alternative strategies and policies.

FAO (1980) demonstrated the role of indicators for monitoring desertification, and proposed twenty-two indicators mostly suitable at local scale. Liu et al. (2004) investigated land degradation monitoring using indicators derived from Landsat TM based vegetation indices such as biomass, land cover and grass species. Biotic and abiotic variables such as vegetation cover, population density (human and livestock), animal masses, soil data, potential evapotranspiration and annual precipitation have shown potential desertification areas (Aharoni & Ward, 1997). Schlesinger et al. (1990) discussed in detail the potential indicators for desertification and land degradation such as soil erosion, salinisation, soil chemistry, changes in species diversity and aboveground biomass, and changes in land-use and settlement patterns.

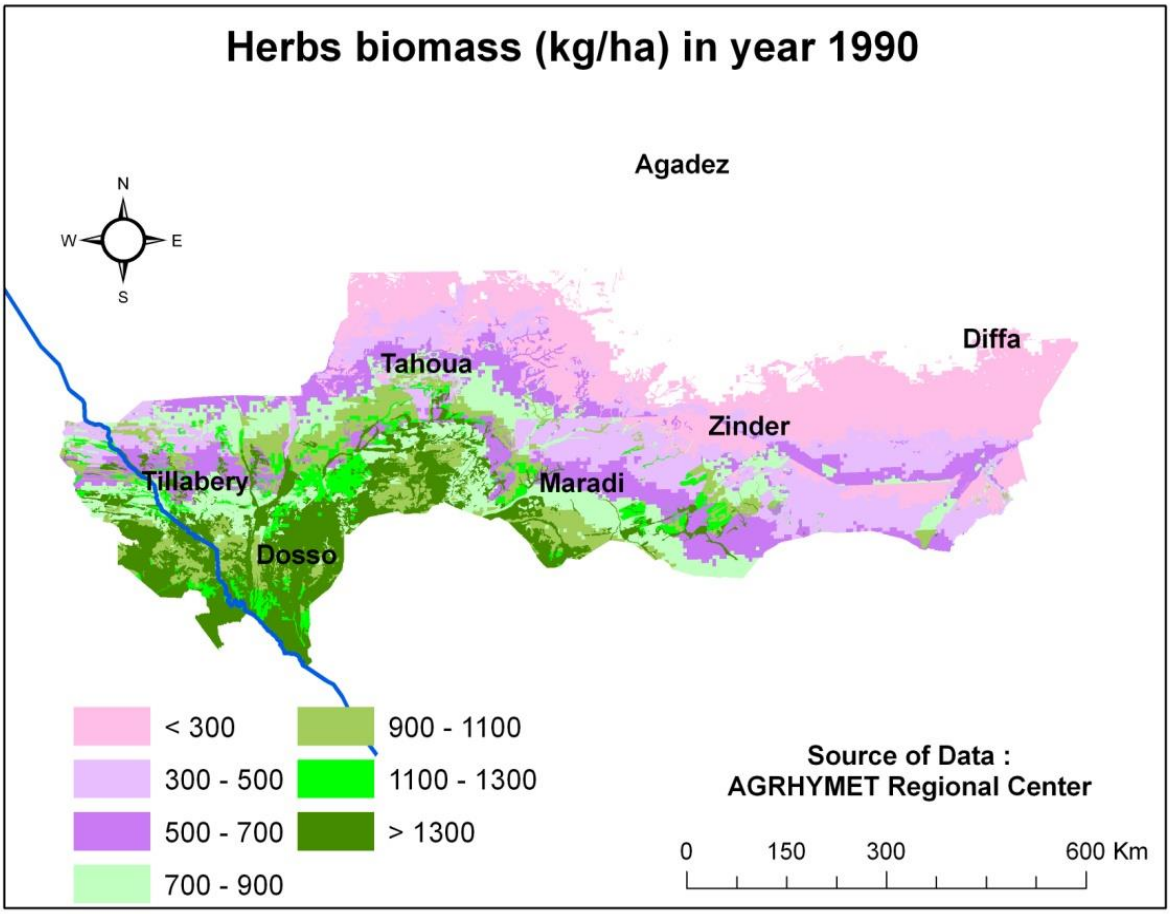
2.2.2 Vegetation and Soil Indices

The study of desertification is a complex task, including ecosystem, land-use and climate aspects. Also, land degradation and desertification in Niger Republic was studied by using normalised difference vegetation index (NDVI) and rainfall data (Symeonakis & Drake, 2004). This project identified areas within the biomass from 1981 to 1999 in Niger with apparent land degradation. It demonstrated that the degradation and desertification processes continued during the last two decades over most of the Sahelian belt of Niger (Yvon-Carmen et al., 2007). NDVI was the most commonly used index for assessing changes in a qualitative way (Williams, 2000). It provided a powerful tool to monitor the process of ecosystem at national, regional, continental and global scales.

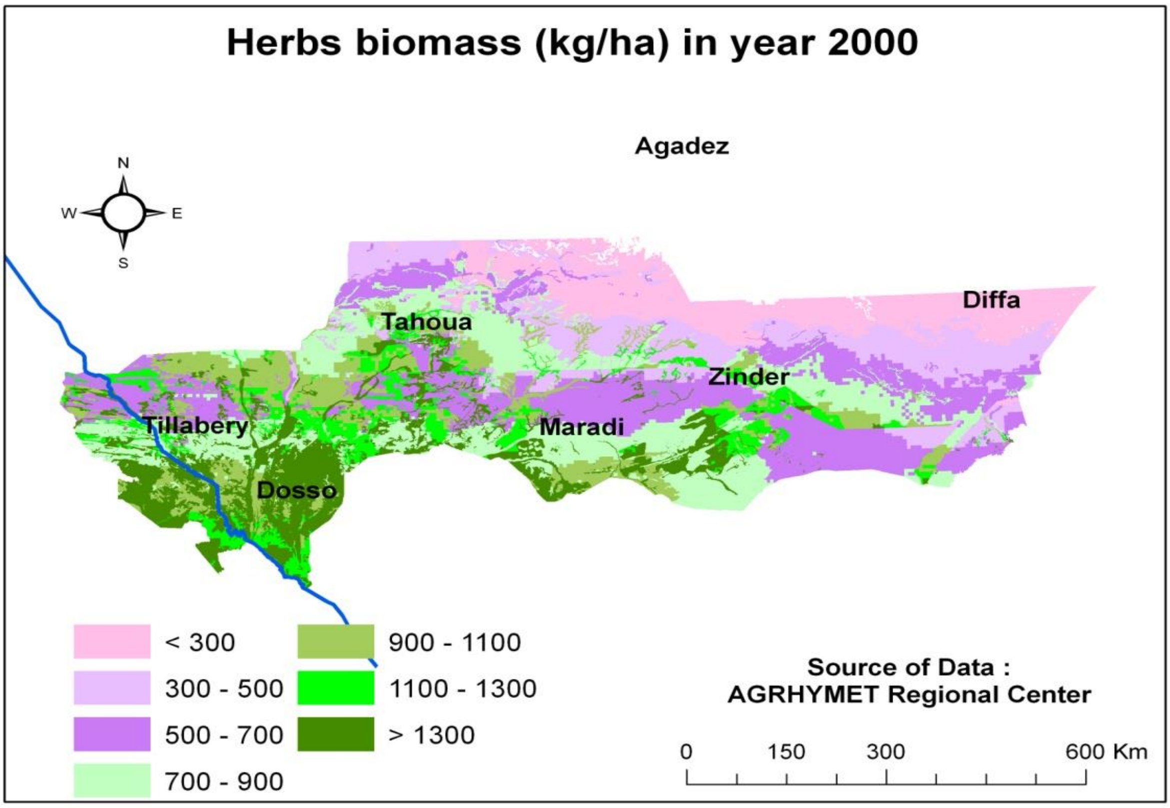
Many vegetation indices such as the weighted difference vegetation index (WDVI) and the soil-adjusted vegetation index (SAVI) have been used (Manal, 2007). The bare soil index (BSI) is commonly used to investigate land degradation and desertification processes. Much research has been carried out using soil related spectral indices (SI) such as brightness index (BI), redness index (RI). These researches have shown soil surface colour changes due to the presence of reddish soil materials and hematite content (Ray et al., 2005). Escadefal & Bacha (1996) reported that the decrease in the redness index shows the thinning of sandy soil layer, which invariably decreases the physical capacity of the soil. This is related to ongoing desertification in Tunisia.

For pastoral planning purposes the knowledge of available biomass is important. The results below show that precipitation data can be used to quantify herbs biomass of Sahel landscape. However, the model of herbs biomass needs to be validated in more areas. Mainly more test sites should be included to get a realistic distribution of the biomass value in order to understand why there was an increase in biomass from 1990 to 2010. Also the equation has to be checked and new parameters are needed. One of the aims of this study was to obtain reliable desertification and land degradation information from thematic change and landscape metrics derived from Landsat (MSS, TM, and ETM+) data.

A


Herbs biomass (kg/ha) in year 1990
Agadez
N
W
E
S
Diffa
Tahoua
Zinder
Tillabery
Maradi
Dosso
< 300
300 - 500
500 - 700
700 - 900
900 - 1100
1100 - 1300
> 1300
Source of Data :
AGRHYMET Regional Center
0
150
300
600 Km

B


Herbs biomass (kg/ha) in year 2000
Agadez
N
W
E
S
Diffa
Tahoua
Zinder
Tillabery
Maradi
Dosso
< 300
300 - 500
500 - 700
700 - 900
900 - 1100
1100 - 1300
> 1300
Source of Data :
AGRHYMET Regional Center
0
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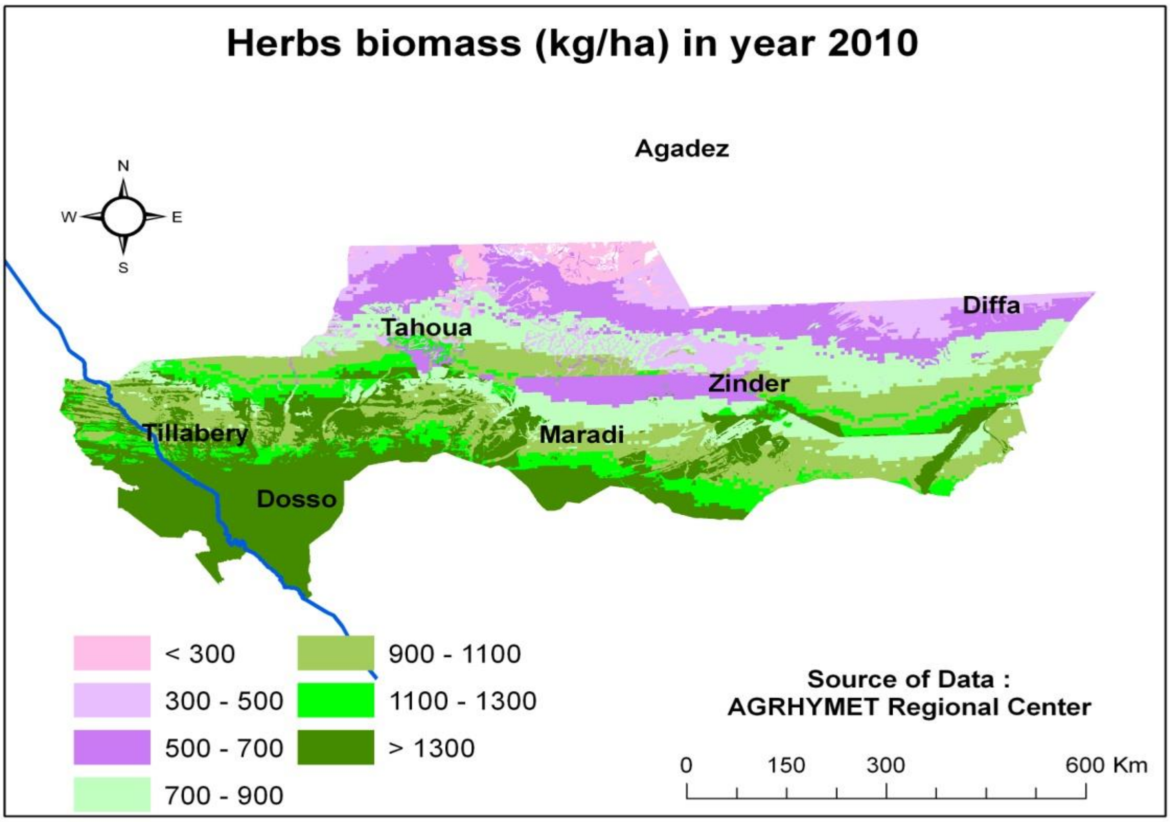
300
600 Km

C



D

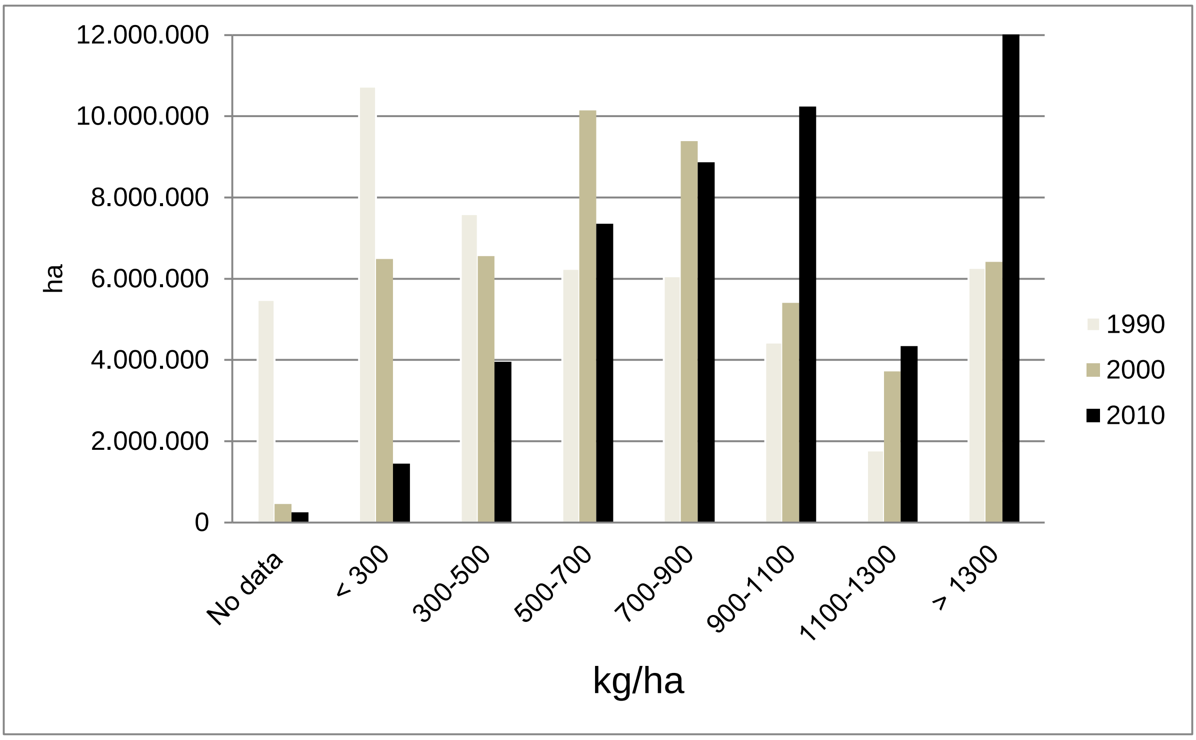


Figure 2.1: Calculated herbs biomass for Niger republic (A) Herbs biomass in year 1990 (B) Herbs biomass in year 2000 (C) Herbs biomass in year 2010 (D) Attribute information of herbs biomass from 1990 to 2010.

2.2.3 Climate Factors and its Relation to Desertification and Land Degradation

The climate of the Sahel is dominated by the movement of the monsoon and the main primary driver of climate change in this area is represented by the Indian Ocean (Brooks, 2004). The vegetation cover can be considered as the secondary driver of climate change. Brooks (2004) reported that “the evidence for positive feedback loops between vegetation clearance and aridity is sufficient to acknowledge it as an important, albeit secondary, climate driver in the Sahel”. Hoffman & Jackson (2000) also demonstrated an interdependence of climate and vegetation and a positive feedback loop between declines in rainfall and anthropogenic vegetation cover.

Troen (1994) demonstrated the impact of climatic factors on environmental processes. Imeson & Emmer (1992) reported the different approaches used to study the impact of climate factors on soil erosion. One approach is modelling the impact of future climate change on soil erosion. Another approach is using spatial and temporal analogues by studying existing conditions along climatological gradients or by looking at historical data.

Climate change has increased the susceptibility of land degradation and desertification in the Sahel. Under a range of climate scenarios, it is projected that there will be an increase of 5-8% of arid and semi arid lands in Africa (Economic Commission for Africa, 2007). Many studies have reported that rainfall increases may be expected in the Sahel, but many uncertainties for the future climate of the Sahel remain. The recent simulation in Mali demonstrates a temperature rise between 1 to 2.75^{o}C and a possible reduction in precipitation and a decline in cereal production between 15-19% causing a doubling of food prices in the year 2030 (Serigne et al., 2006). Serigne et al. further argues that rainfall will decrease in Niger by 10.20% by 2025.

2.2.4 Soil Erosion

Soil erosion is one of the major expressions of desertification in the Sahel region. It is important to understand the relation between the spatial distribution of soil erosion and desertification in order to improve food security and poverty conditions in the Sahel region. Grasping this relationship will help reveal priority areas and develop a chain of command, ordered according to needs. Table 2.1 lists some common soil erosion models and their references. In this study, the Revised Universal Soil Loss

Equation (RUSLE) and Unit Stream Power- Based Erosion Deposition (USPED) were used.

Table 2.1: Examples of soil erosion models.

Soil erosion prediction models	Reference
Universal Soil Loss Equation	Smith & Whitt, 1947
Modified Universal Soil Loss Equation	Williams, 1975
Area Nonpoint Source Watershed Environmental Resources Simulation	Beasley et al., 1980
European Soil Erosion Model	Morgan et al., 1998
Unit Stream Power-Based Erosion Deposition	Mitasava et al., 1996
Revised Universal Soil Loss Equation	Renard et al., 1997
Pan-European Soil Erosion Risk Assessment	Kirkby et al., 2004
Soil Loss Estimation Equation for Southern Africa	Stocking, 1980
Water Erosion Prediction Project	Morgan et al., 1984

2.3 Terminology and Techniques

2.3.1 Landscape Structure and Pattern

Landscape structure may be described by landscape "composition" and "configuration" respectively. Landscape composition is the variety and abundance of landscape elements within the landscape (McGarigal et al., 2002). Different mapping elements such as the amount of forest or wetland, the length of forest edge, or the densities of roads are aspects of landscape composition.

Landscape configuration is the spatial arrangement and character, orientation of landscape elements within the landscape (McGarigal et al., 2002). The juxtaposition of different landscape elements and measures of habitat fragmentation per se (independent of habitat amount) are aspects of landscape configuration (McGarigal & McComb, 1995).

A patch is a homogeneous element in a landscape and it is determined by the observer based on the objective. A patch can be delineated on the basis of land cover, such as vegetation, water, urban area and by using other criteria such as microclimate. A patch can be a city, a river, and an area of similar vegetation cover or a particular soil type.

Categories of Landscape Elements

A convenient and popular model for conceptualising and representing the elements in a categorical map pattern is known as the patch-corridor-matrix model (Forman & Godron, 1986). This model addresses three important elements which are:

- Patches: it can be described by size of area in m² or % (patch size). Patch size is an important variable that affects production, biomass and nutrient storage per unit area, and patch shape is also important in the landscape, particularly as a result of the edge effect (Forman & Godron, 1986). Forman & Godron (1986) addressed five patch types: disturbance patches, remnant patches, environmental resource patches, planted patches and habitations.
- Corridors: are linear areas differing from surroundings that connect patches, and a key characteristic of corridors is connectivity. Forman & Godron (1986) described three types of corridors (line corridors, strip corridors and stream corridors). A corridor is a very important aspect of landscape because it is a source of communication and transport between communities and affects production and provides protection.
- Matrix: it is the most abundant and connected component of landscape element category. Forman & Godron (1986) defined the following criteria for determining the matrix: It has a greater relative area than any patch type within it, it is the most connected portion of the landscape or it plays a predominant role in the dynamics of the landscape.

2.3.2 Methods to Spatially Analyse Landscapes

Many landscape investigation researchers focus on the quantification of landscape patterns at different periods and use statistical as well as non-statistical methods. Below there is a brief description of some of the above mentioned methods with a special view on desertification and land degradation.

Degree of Landscape Fragmentation

Landscape fragmentation and connectivity were needed to investigate land degradation and desertification. Schlesinger et al. (1990) reported that quantifying fragmentation is important to identify land degradation. Nagendra et al. (2003) argued that the fragmentation processes are the division of continuous land cover into smaller patches and can be linked to three parts: direct removal, reduction in patch size and increasing isolation of the remaining patches. In order to measure fragmentation and variability in the landscape patch density, size and variability metrics were calculated.

The fragmentation of a landscape due to desertification and land degradation has rigorous ecological consequences. This has contributed greatly to the loss in species diversity in the Sahel (due to the segregation of habitats and to the division of populations). It also affects the water quantity and quality. Forman et al. (2003) reported that landscape fragmentation due to human development has major impacts on wildlife, including many species of concern. Investigation methods are needed that can quantify landscape fragmentation.

Table 2.2: Examples of landscape metrics used to investigate spatial patterns of desertification.

Landscape metrics	Reference
Percentage of Landscape, Mean Nearest Neighbor Distance, Interspersion and Juxtaposition Index and Shannon`s Diversity Index	Li et al.2004
Class Area, Number of Patches and Mean Patch Size	Li et al. 2004 and Kepner et al. 2000
Patch Density, Landscape Shape Index and Fractal Dimension Index	Sun et al. 2005 and Sun et al. 2007
Largest Patch Index and Landscape Connectivity	Li et al. 2004, Sun et al. 2005 and Kepner et al. 2000

Recently, indices of landscape fragmentation have been developed that clearly integrate ecological processes into their description. Such index is the effective mesh index, which can be defined as proportional to the probability that any two points chosen in a landscape are connected (Jaeger et al., 2007). It can also be defined as the normal size of the zone that an animal placed randomly in the landscape will be capable to access without barriers (i.e., urban development or bare areas).

The effective mesh index fulfils all scientific, functional and pragmatic requirements of environmental indicators (Esswein et al., 2003). The effective mesh index is suitable for analyzing the degree of fragmentation of landscape and has already been used for case studies in Baden-Wurttemberg, Bavaria, Hessen, Thuringia, Saxony, Schleswig-Holstein and South Tyrol (Italy) reported by Jaeger et al. (2007). This index was also used in Switzerland and Canada by the European Environmental Agency (2007).

Therefore, the combination of different indexes to quantify and qualify landscape patterns during time has already been used by some authors. Sets of landscape metrics were developed and used in order to improve the comprehension of the dynamics of landscape. In the table below (table 2.3) various sets of metrics as used in the literature are shown.

Table 2.3: Combination of indices used for desertification.

Set of landscape metrics	Landscape pattern	Reference
	Landscape level	
Number of Patches + Mean Patch Area	Grain	Li et al. 2004
Interspersion and Juxtaposition Index + Contagion	Clumpiness and connectivity	
Number of Patches + Mean Patch Area+ Mean Patch Index + Interspersion and Juxtaposition	Clumpiness	
Mean Patch Area + Interspersion and Juxtaposition		
Shannon`s Diversity Index + Shannon Evenness Index	Uniformity	
	Heterogeneity and evenness	
	Class Level	
Number of Patches + Mean Patch Area + Largest Patch Index	Fragmentation	Baskent & Kadiogullari 2007
Shannon Evenness Index + Patch Density + Mean Patch Area	Urbanization	Weng 2007

Ecological Model for the Sahel Region

To study a landscape, modelling is also a dominant tool. Appropriate landscape models permit a realistic description of the phenomena under study, but are generally difficult to parameterize and sometimes very computer intensive. Bégué et al. (1996) developed a spatial model for Sub-Saharan Africa that can be used to quantify the millet crop, degraded shrub land, shrub fallow and grass fallow using the Scattering by Arbitrarily Inclined Leaves (SAIL) model. Also, the SAIL model was used by different authors in the Sahel region (Goel, 1984 and Badhwar et al., 1985).

Various authors have reported a development of ecosystem models in the Sahel region. Mougin et al. (1995) reported that the first article to present a regional ecosystem process model for the Sahel region described an herbaceous layer composed of only annual species. The modified Monteith´s production model taking into account many factors such as water and nutrient availability was presented by Prince (1991b), but the physiological and climatic elements affecting vegetation cover were not correctly analysed (Mougin et al., 1995). Mougin et al. (1995) further developed a regional Sahelian grassland model to analyse possible relationships between satellite data and physical models of reflectivity in different spectral domains.

Hydrologic and Atmospheric Pilot Experiment in the Sahel (HAPEX-Sahel) is an international program for developing ecosystem models in West Niger (Sahel region). The main objective of HAPEX-Sahel was to improve the understanding of the effects of atmospheric circulation in relation with inter-annual fluctuations of the land surface conditions in this region. HAPEX-Sahel results are published in Wallace et al. (1993),.

2.4 Research Deficits

Many studies have analysed desertification and land degradation using either statistical or non-statistical methods (Yvon-Carmen et al., 2007; Williams, 2000; Manal, 2007; Ray et al., 2005; Escadefal & Bacha, 1996). These have made significant contributions to understanding the scope, causes and mechanisms of desertification. Notwithstanding, less research has been directed towards less industrialised countries in this context. Jacobson (1997) asserted that most research carried out in the field of desertification has not contributed to reducing or reversing its impacts. This situation can be explained largely due to limited translation of scientific research into an accessible format for application by development agencies or rural communities (Seely & Wöhl, 2004). To compound it, there was also a lack of pertinent indicators for monitoring.

In the Sahel region, scientific progress in the perspective of desertification and land degradation has been stalled by a variety of factors, varying from great shortage of temporal and spatial information on the physical extent of the area, poor or no existence of data base, lack of qualified experts in many fields of research, old and irrelevant methodologies in research and inconsistent funding. This region is also prone to political instability and increasing population aggravated by low levels of education which inadvertently makes it difficult to halt or reverse the impact of desertification. As such, the theories about the “greening of the Sahel” (Herrmann & Hutchinson, 2005) have had little positive impact on the desertification research, largely due to misinterpretations of the facet and tenets of the problem, with a resulting consequence that emphasis has been redirected away from the real problems in the Sahel.

The Economic Commission for Africa (2007) reported that the land area of Burkina Faso, Mali and Niger was severely or very severely degraded (more than 30% of the land). Desertification and land degradation are real problems in the Sahel region, especially in Niger Republic. A proper investigation of the various dimensions of desertification and land degradation is a sine qua non in the Tillabéry area because of the primordial role that agriculture plays in the livelihood of the people. As such, there is an urgent need to carry out research to have a better understanding of the relationship that exists between desertification and soil erosion processes that operate within the Sahel. Research in these areas has the potential to improve on the livelihood of the inhabitants in the area. This is one of the principal goals of researchers, international and national institutions, including the local people, and policy makers. It also has the potential to contribute to their capacity for risk aversion, improved natural resources management and adaptation to changes in a multi-stressor system.

The present thesis uses a combination of various statistical and non-statistical methods in analysing landscape issues in a multidimensional perspective and adds value to existing research and data on land degradation and desertification in the Tillabéry area. Smucker et al. (2007) pointed out that "the integration of information derived from multiple methods is necessary because of the complex interactions among local and regional driving forces that underlie change". This thesis is very useful and different from previous projects where most of the tasks only provided attribute information and limited spatial information. Instead, landscape metrics is applied to provide detailed and reproducible information on landscape structure with a special view on desertification and land degradation. This advanced approach analysis will investigate the landscape composition and configuration. Finally, hybrid index systems of desertification (**desertified index**) will be developed bringing together the different relevant perspectives and knowledge to fill the research gap. Desertified index will provide new scientific results, which can be applied and used in practical development projects.

3 Objectives

The primary objective of this thesis is to investigate land degradation and desertification processes in the Sahel region by focusing on the Tillabéry landscape (Niger) with RS data and GIS techniques and combining them with other analytical methods such as landscape metrics change detection and data mining. It is the first attempt to conduct a complex land degradation and desertification research in this area. This approach may be applied in an analogous way to other parts of the Sahel region.

The additional secondary objectives of the research address the following:

- To develop an analytical approach for landscape investigation in the Sahel region
- To identify land use / land cover changes in the region and their relationship with vegetation cover and the connectivity between these factors to climate change and land degradation, with regards to the Niger River
- To quantify, evaluate and analyse change(s) in the landscape from 1973 to 2007 in the study area and to improve understanding of key factors affecting land management
- To evaluate the landscape structure in the context of desertification, vis-á-vis the amount, direction, rate and spatial extent of desertification in the study area and also to define a methodology to evaluate the desertified index
- To develop a desertified index which includes landscape structure change (fragmentation of landscape, land cover diversity and irregularity of patches) and desertification trends (the amount, direction, rate, and spatial extent of desertification)
- To assess process dynamics and intensities in these areas concerning soil erosion in terms of diffuse or sheet erosion using two different quantitative methods (USPED /RUSLE)
- To determine and define the process dynamics and intensities in the areas indicated by the desertified index as areas with high to very high changes

4 Methodology

This work makes use of both primary and secondary data sources. Primary data constitutes climatic data, topographic data, field data and satellite data. Secondary data entails the use of scholarly articles and books related to desertification, land degradation in the study area. The secondary data were used to describe the relationship between spatial data and landscape processes and functions in the context of desertification and land degradation. Figure 4.1 shows the general work flow of the work using primary data.

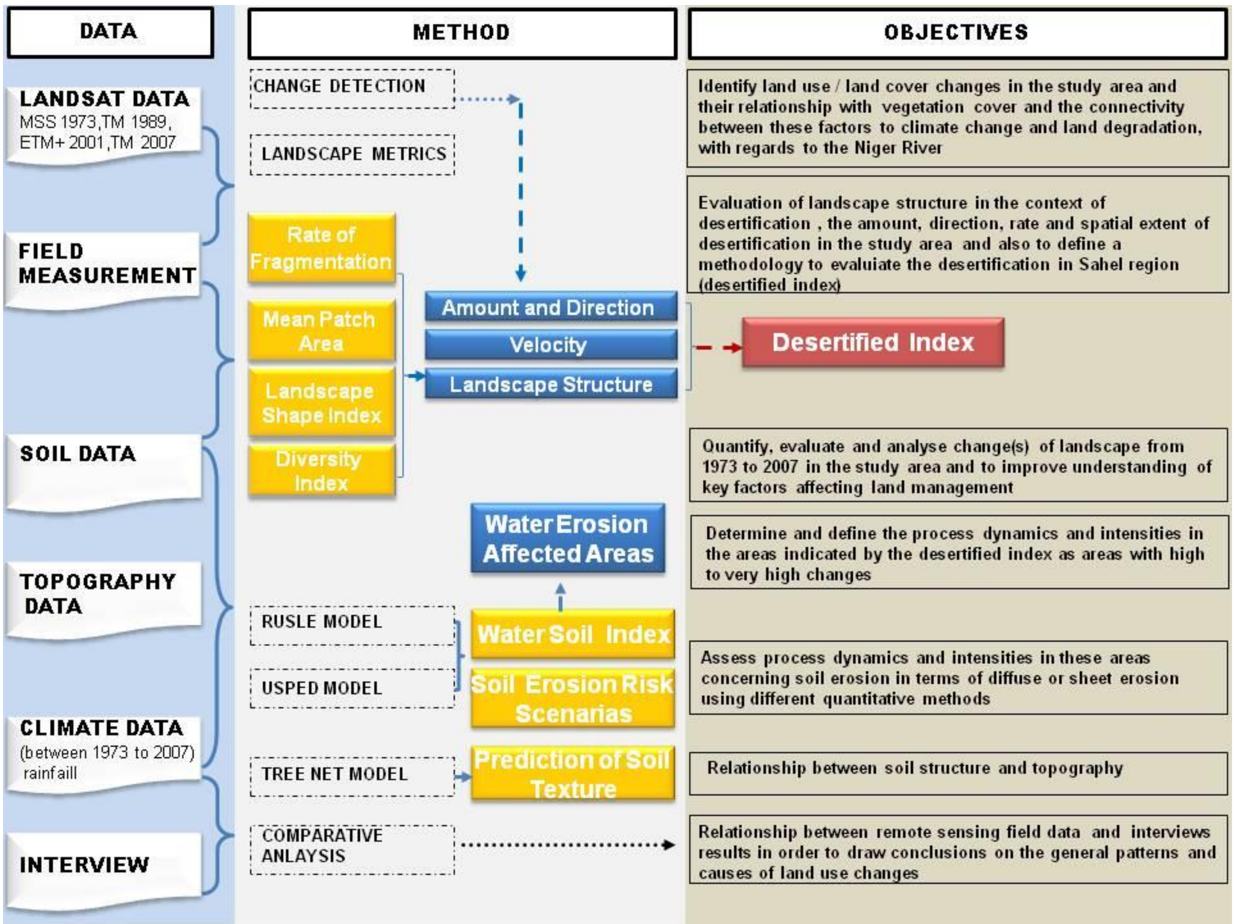


Figure 4.1: General work flow for the data, method and objective.

Several types of primary data were used in this thesis. Firstly, Landsat images in the study area (the images were acquired in similar times of the year) were used to investigate the relationship between land use / land cover. Secondly, precipitation data collected from the National Meteorological Service of Niger Republic was used. The third source is field and topographic data - Shuttle Radar Topography Mission

(SRTM) and - Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER). Descriptive and illustrative statistics from the pixels information of the satellite data were used to derive the spatial distribution data and then to create histograms and pie-charts to illustrate the amount, direction, velocity and changes in landscape structures in the study area. Therefore, the methodology applied (classical change detection analysis) in this part serves for the detection of clear changes and subtle modifications of land cover in general and vegetation covers in particular.

Besides, the usefulness of landscape metrics was evaluated in the context of desertification and land degradation in the Sahel region by using a set of landscape metrics derived from classification of the Landsat images. This approach gives additional information about the landscape structure and its change including compositional and configurational information. Another method employed in this thesis is the soil texture prediction model and the soil erosion model using two different quantitative methods the revised Universal Soil Loss Equation (RUSLE, Wischmeier and Smith, 1965) and Unit Stream Power Erosion/Deposition (USPED, Mitasova et al., 1996) for detection of erosion status in the study area.

This work seeks to clarify the contribution of climatic factors as a driver of desertification and land degradation in the Tillabéry area. The need to understand climate change in the study area is crucial for various reasons. In Niger, rainfall is a crucial factor in the ability of people (pastoralists and farmers) to produce the foodstuffs needed for consumption. Moreover, rainfall is an important climatic factor in determining areas at risk of land degradation and potential desertification. Therefore, in this thesis, analysis of past and future erosion processes and climate variability will be analysed in order to provide an insight into the causes of desertification and the information needs for more sustainable management.

4.1 Study Area

4.1.1 Niger–Brief Overview

Niger is located in the heart of the Sahel between latitudes 11°37´ and 23°33´ N and between longitudes 0° and 15° E, more than 700 km from the sea, with a surface area of 1,267,000 km² (Ben Mohamed et al., 2004). The population is estimated to be

about 13 million and has one of the highest population growth rates in Africa (3.3%) (see table 4.1), within a territory where two thirds of the land cover is quasi desert.
The New York Times (2006) reported that “Niger’s population has doubled in the last 20 years; each woman bears about seven children, giving the country one of the highest growth rates in the world”. It is characterised as a poor land due to increased environmental degradation, rendered more acute by demographic pressure. Poverty and illiteracy are known obstacles to economic development. Agricultural production constitutes the backbone of the economy with a contribution of 40% to the GDP. More than 80% of the population is engaged in agriculture and animal husbandry (Ben Mohamed et al., 2004).

Table 4.1: Population of Niger from 2003 to 2008 (data collected from Central Intelligence Agency World Fact book 2005).

Years	Population	Change in %	Date of Information
2003	11,058,590	NA	July 2003
2004	11,665,937	5.49	July 2005
2005	12,162,856	4.26	July 2005
2006	12,525,094	2.98	July 2006
2007	12,894,865	2.95	July 2007
2008	13,272,679	2.93	July 2008

The traditional cereals, millet and sorghum, represent about 85% of the total food crop production in the country and cover 80-90% of the energy requirements of the population. Livestock equally plays an important role in the economy. The objective of the government is to increase crop production to attain self-sufficiency. This is a very challenging task giving the fact that the natural resource (land) is being degraded more and more as a result of climatic conditions and land use changes, aggravated by the occurrence of pests and diseases.

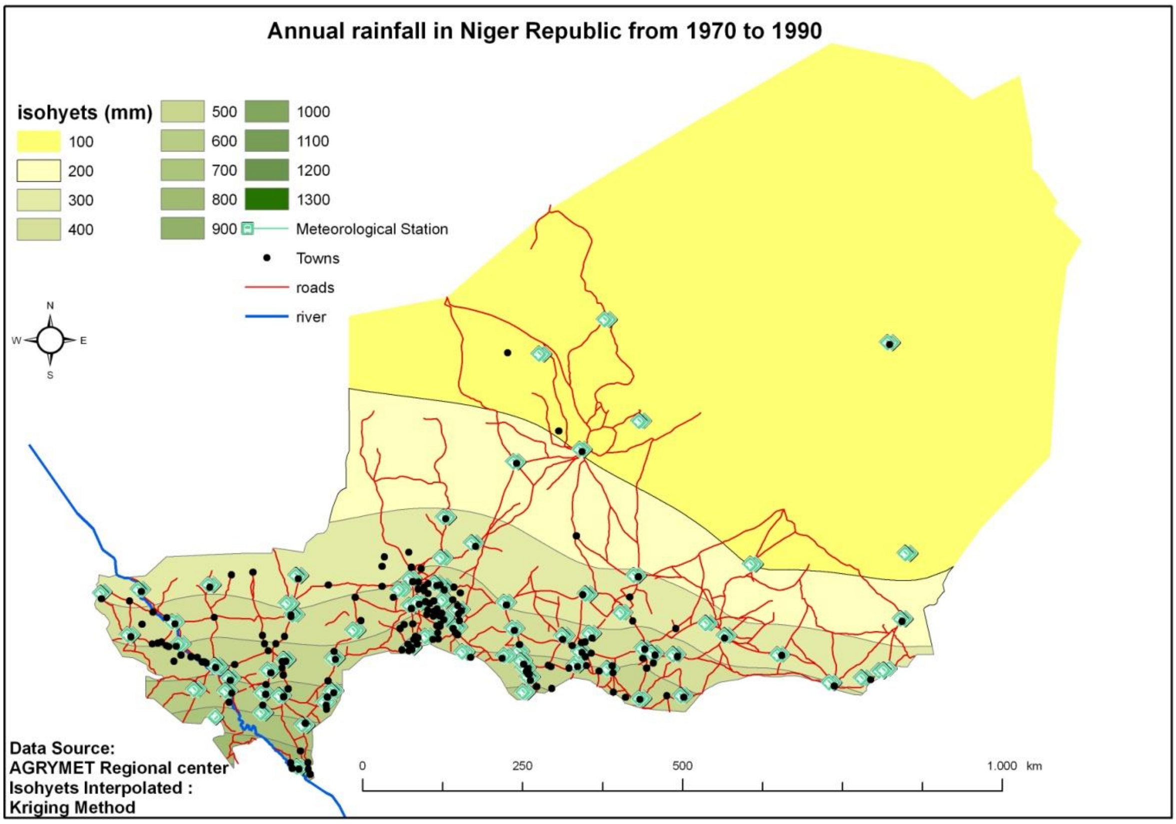


Figure 4.2: Precipitation in Niger from 1970 to 1990.

One can distinguish four rainfall zones in Niger (see Figure 4.2): (a) the Sahara zone with annual rainfall of 0-200 mm, covering 67% of the country, (b) the Sahel-Sahara zone with 200-350 mm (20%), (c) the Sahel with 350-600 mm (10%) and (d) the Sudanian zone with more than 600 mm rainfall (3%) and only about 316,750 km² (25%) is suitable for agricultural production, that is south of the 350 mm isohyets (Ministère de l´agriculture et de l élevage, 1997). The most important wild animals are: antelopes, elephants, gazelles, giraffes, lions, monkeys and hyenas. The Ténéré and Aïr Natural Reserves and W National Park are on the World Heritage list. Niger Republic has four protected areas, which represents 6.6% of the total land surface area (Ministère de l´agriculture et de l élevage, 1997).

Niger Republic landscape has evolved considerably for decades due to strong landscape changes, linked to demographic pressures and increasing poverty. Environmental degradation in Niger can be explained by a variety of factors, ranging from over-use of wood as a main source of energy to wind and water erosion, mismanagement of land and poor recycling of solid and household waste. Table 4.2 shows the production and consumption of wood in different regions of Niger Republic. Wood is increasingly getting scarce in all the regions of Niger.

Table 4.2: Wood production and consumption in Niger republic (CNEDD, 1998).

Cities	Production (t)	Consumption (t)
Agadez	1,800	91,980
Diffa	21,517	55,003
Dosso	409,770	306,600
Maradi	90,000	398,815
Tahoua	27,672	485,000
Tillabery	300,000	600,000
Zinder	60,000	200,000
Niamey	0	156,000
Total	**910,759**	**2,293,398**

The savannah and tiger bush regions are cleared in order to increase agricultural production. Cattle breeding and crop production are always competing for the fertile pieces of land available. This has spawned a series of conflicts between the various stakeholders – nomads and sedentary people. Niger Republic is further characterised by variable and irregular rainfall, a short rainy season and high temperatures and radiation (high potential evapotranspiration). The soils have a low water holding capacity and the evaporation from the soil is an important component of the water balance due to low vegetation cover.

Wind is another climatic factor influencing land degradation. Under the influence of high-speed winds, the process of wind erosion takes place. The combination of wind effect and high soil temperatures seriously affects the establishment of vegetation cover. Wind speeds exceeding 100 km/h have been observed in Niger Republic (Sivakumar et al., 1993). The topography of Niger is mainly flat; the nation's highest point is in the north-central region (Aïr Massif) called Mt. Gréboun. In the north-eastern part is a massif, with an altitude of 800 m. The southern plateau has an elevation of 300–500 m.

4.1.2 Overview of the Study Area

The research was carried out in the Tillabéry region (Niger), between 13º 30´ N and 15º 45´ N latitude, 0º 10´ E and 4º 20´ E longitudes. The region is composed of six districts namely: Fillingue, Ouallam, Tera, Kollo, Say and Tillabéry covering 91,199 km² (7.19% of the total area of Niger). The study area is located as shown in figure 4.3 within the department of Tillabéry and includes parts of the wide valley of the Niger River. The annual precipitation is between 250 mm to 400 mm. The soil in this area is very infertile and poses enormous challenges for agricultural production. This area was selected as investigation area due to the fact that desertification is the most serious environmental problem and it is located at the core of the Sahel. To compound it, the depth and width of the Niger River is continuously on a decrease, an issue associated with the moving of sand.

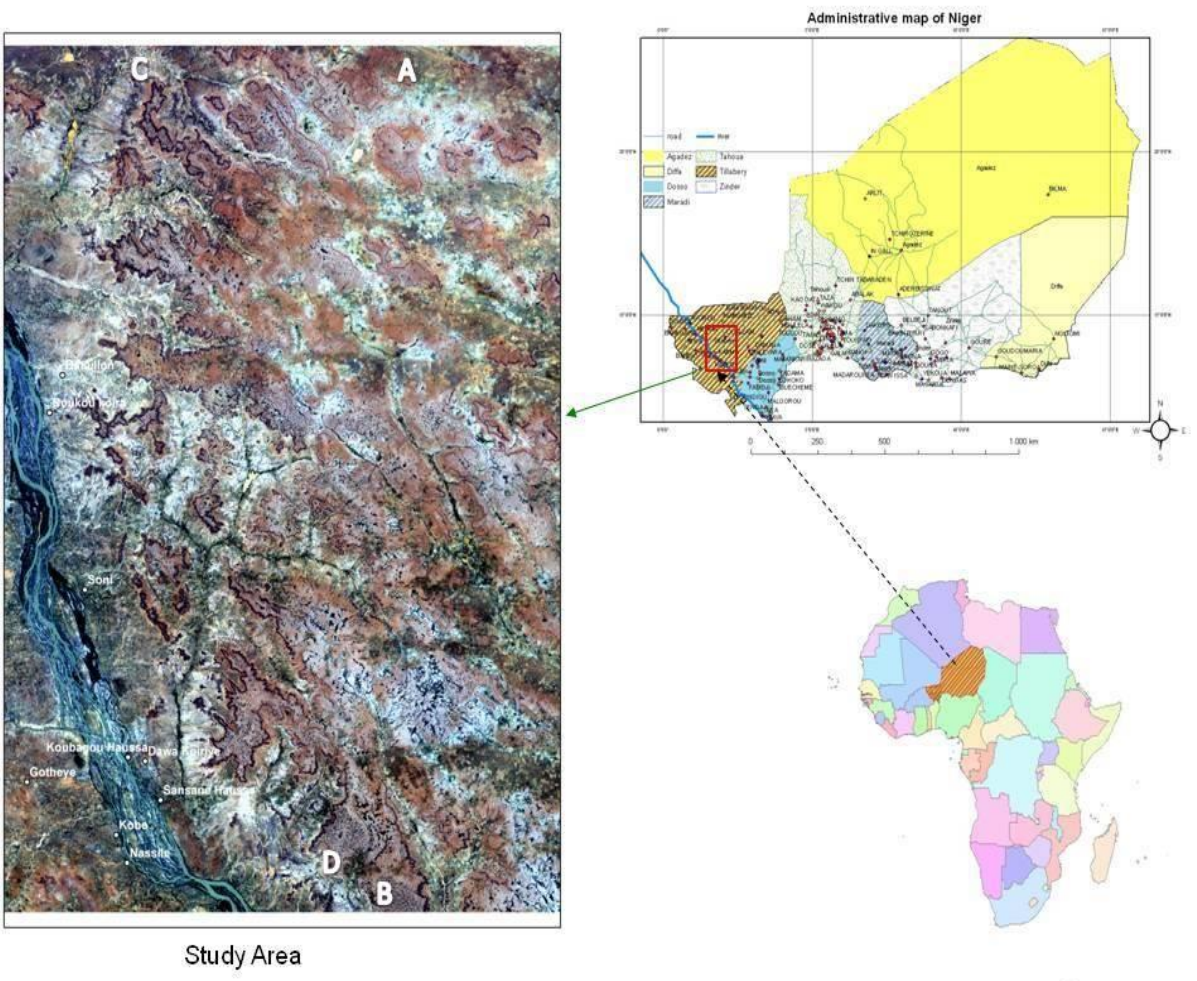


Figure 4.3: Location of study area in Niger and Africa**.**

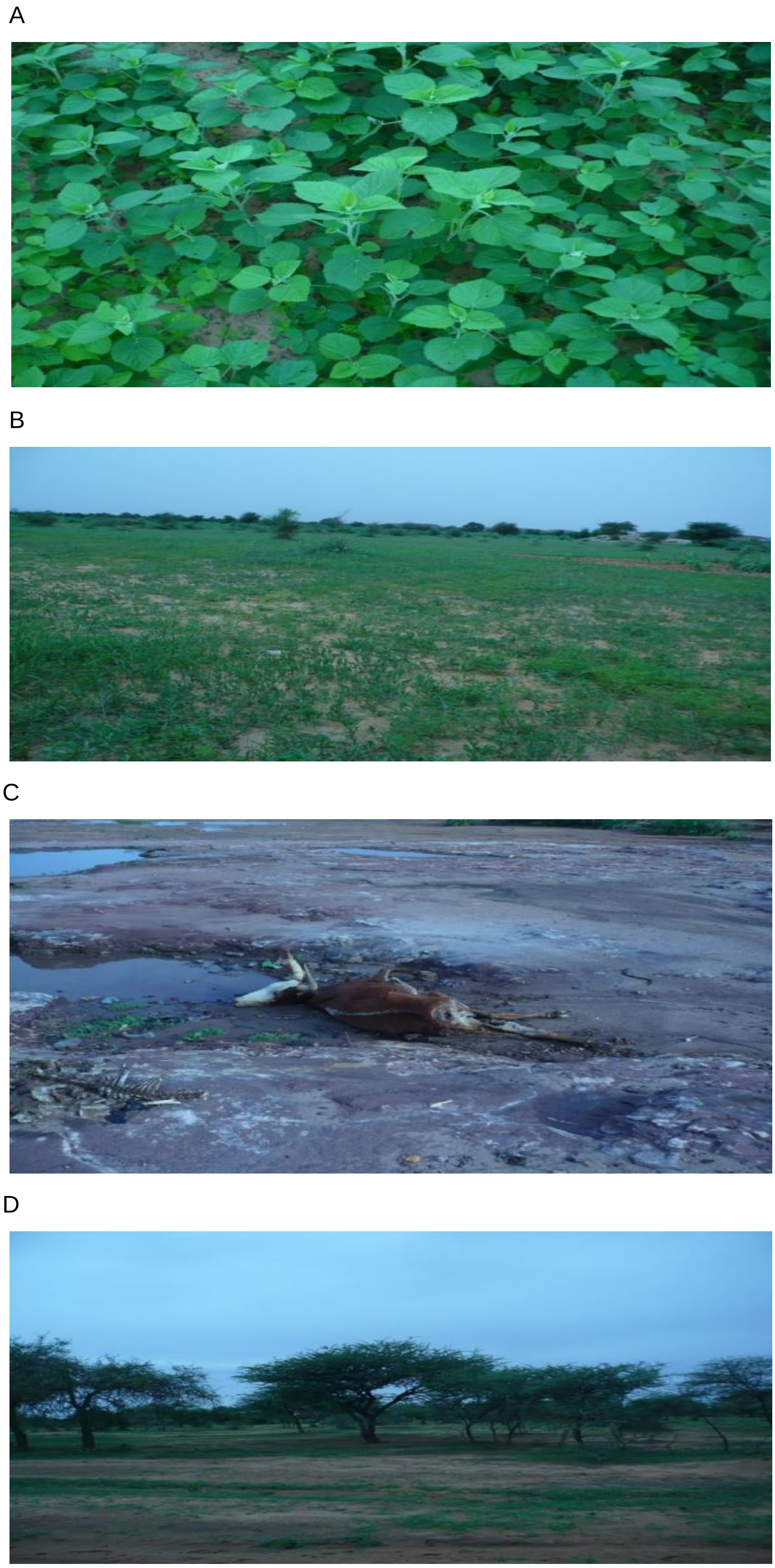


Figure 4.4: Example of land cover in the study area, (A) Grassland in the northern part and (B) Grassland in Western part (C) Bare land in the northern part and (D) Shrubs land dominated by Acacia species in the western part (photograph by the author September (2010) (list of locations in the study area (figure 4.3)).

4.2 Data Processing for Desertified Index

4.2.1 Change Detection Method

Post-classification comparison was used in interpreting the satellite images. This approach shows the amount, velocity and direction of change from one time period to the next. ERDAS IMAGINE software was used to conduct classification and accuracy assessment in the study area. A total 250 points were randomly selected for accuracy assessment. For land use / land cover 2007, field data was used as reference data and for land use / land cover 1972, 1989 and 2001, tool from ERDAS IMAGINE was developed the references data. The accuracy assessment showed that the land use and land cover maps were 83%, 91% 92% and 90% for the 1973, 1989, 2001, and 2007 images respectively. A high degree of accuracy was needed in classifying the images because the accuracy of the change map is the result of the accuracies of the entire classification. Figure 4.5 shows that a combination of change detection and landscape metrics can provide a scientific understanding to desertification and land degradation phenomenon.

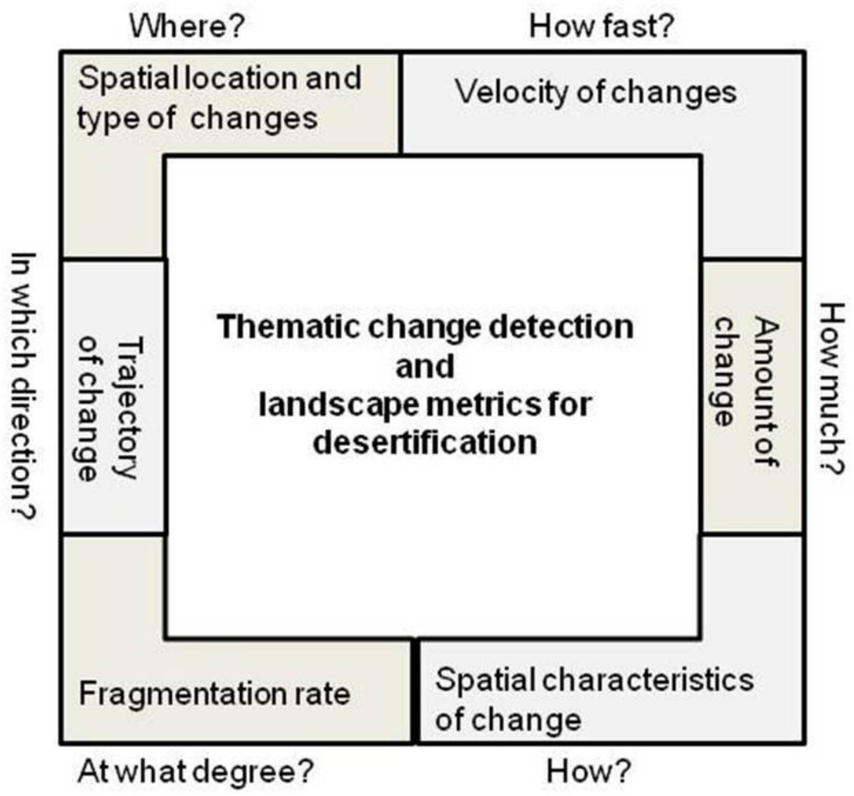


Figure 4.5: Quantitative data presented by the completing of the change detection and landscape metrics method

4.2.2 Definition of Concepts Involved in Landscape Metrics

Landscape metrics were used to investigate landscape changes over time from 1973 to 2007. In order to calculate the sophisticated landscape metrics indices, land use / land cover maps were converted into Grid and ASCII formats using ArcGIS 9.3.1 and integrated into the FRAGSTATS software (version 3.3) (McGarigal et al., 2002). Landscape metrics were divided into two main groups - composition and configuration indices. The variety of applied indices is shown in table 4.3 for compositional and in table 4.4 for configurational indices. These indices were used to describe the area of study either at the landscape level or at the class level. We can refer to McGarigal et al. (2002) for a detailed definition of these indices

- **Landscape composition**

A set of metrics that better represented the composition of the landscapes were selected with special emphasis on desertification and land degradation. The indices selected for this study were: at class level Percentage of Land (%land) and at landscape level Number of Patches (NP), Total Area (TA), Patch Density (PD), Largest Patch Index (LPI), Mean Patch Area (MPA), Patch Richness (PR), Patch Richness Density (PRD), Modified Simpson`s Evenness Index (MSIEI), Shannon`s Evenness Index (SHEI), Shannon`s Diversity Index (SHDI), Simpson`s Diversity Index (SIDI), and Modified Simpson`s Diversity Index (MSIDI).

Table 4.3: Indices selected for this work for landscape composition (McGarigal et al., 2002).

Landscape metrics	Description
$NP = n_i$ Where: n_i = number of patches in the landscape of patch type (class) i	Number of Patches (NP): Measure of the extent of fragmentation of a class. It is equal to 1 when the landscape contains only one patch of the corresponding patch type that is when the class consist of a single patch.
TA = A(1/10,000) Where: *A* = total landscape area (m²)	Total Area (TA) in ha was used to investigate the predominant land use/ land cover classes in the area of investigation and the proportion of the other classes.
PD = n_i */A(10,000)(100)* Where: n_i = number of patches in the landscape of patch type (class) i; *A* = total landscape area (m²)	The Patch Density (PD) per unit area, e.g., per ha or km² and the unit is number / 100 ha and value are larger than 0. PD equals the number of patches of the corresponding patch type divided by total landscape area (m²), multiplied by 10,000 and 100 (to convert to 100 ha)
LPI = max(a_{ij} *) j=1->n/A* Where: a_{ij} = area (m²) of patch *ij*; *A* = total landscape area (m²)	Largest Patch Index (LPI) measures the ratio of the area of the largest patch to the total area of the landscape (unit: %) and to category: Area/Density/Edge metrics. LPI equals the area (m²) of the largest patch of the corresponding patch type divided by total landscape area (m²), multiplied by 100 (to convert to %)
PR = *m* Where: *m* = number of patch types (classes) present in the landscape, including the landscape border if present.	Patch Richness (PR) measures the number of different patch types in the landscape, it is not affected by the relative abundance of each patch type or the spatial arrangement of patches.PR ≥ 1, without limit
PRD = m/A(10,000)(100) Where *m* = number of ´patch types; *A*=total landscape area(m²)	Patch Richness Density (PRD) measures the number of patch per unit area. PRD standardizes richness to a per area basis that facilitates comparison among period and landscape, also it does not correct for the interaction with scale.
$SIDI = 1 - \sum_{i=1}^{n} p_i^{\,2}$ Where *n* = number of classes, p_i = percentage of the landscape occupied by class i	Simpson`s Diversity Index (SIDI) equals 1 minus the sum, across all patch types, of the proportional abundance of each patch type. It ranges between 0 and 1; it is 0 when the landscape contains only 1 patch (no diversity) and 1 as the number of different patch types increases and the proportional distribution of area among patch types becomes more equitable.
$SHDI = -\sum_{i=1}^{n} p_i \ln p_i$ Where: *n* = number of classes, p_i = percentage of the landscape occupied by class i	Shannon`s Diversity Index (SHDI) is used for relative patch diversity in a landscape that is determined by both the number of different patch types and the proportional distribution of area among patch types. It increases with the number of patch types and as the proportional distribution of patch types increases and it is zero when there is only one patch in the landscape.
$SHEI = \dfrac{-\sum_{n=1}^{n} p_i \ln p_i}{\ln n}$ Where: *n* = number of classes, p_i = percentage of the landscape occupied by class i	Shannon's Evenness index (SHEI): It is used for patch distribution and abundance. It approaches one when the distribution of patch types becomes more even and zero when the observed patch distribution is low.

$MSIDI = -\ln \sum_{i=1}^{n} p_i^{\ 2}$ Where: n = number of classes, p_i = percentage of the landscape occupied by class i	Modified Simpson`s Diversity Index (MSIDI) equals minus the logarithm of the sum, across all patch types, of the proportional abundance of each patch type squared. MSIDI equals 0 when the landscape contains only 1 patch (no diversity). MSIDI increases as the number of different patch types increases and the proportional distribution of the area among patch types becomes more equitable.
$MSIEI = -\ln \sum_{i=1}^{n} p_i^{\ 2} / \ln m$ Where: n = number of classes, p_i = percentage of the landscape occupied by class i; m= number of patch types	Modified Simpson`s evenness Index (MSIEI) equals minus the logarithm of the sum, across all patch types, of the proportional abundance of each patch type squared, divided by the logarithm of the number of patch types. It is between 0 to 1; it is 0 when the landscape contains only 1 patch (no diversity) and equals1 when distribution of area among patch types is perfectly even (proportional abundances are the same)
$\%LAND = P_i = [\sum_{j=1}^{n} a_{ij} / A]100$ Where: a_{ij} = area(m²) of patch ij; A = total landscape area (m²)	Percent of Landscape (%LAND) equals the sum of areas(m²) of all patches of the corresponding patch type, divided by total landscape area (m²), multiplied by 100 (to convert to a percentage).This index unit is % and ranges between 100 to 0. Approaches 0 when the corresponding patch type (class) becomes increasingly rare in the landscape, equals to 100 when the entire landscape consists of a single patch type.
$MPA = A / n$ (1/10,000) Where: A = total area (m²), n = number of patch and divided by 10,000 to convert to hectares.	Mean Patch Area (MPA) belongs to the landscape metric category: Area/Density/Edge metrics. This index is indicative of a fragmentation process, particularly if associated with other index. It is measured in ha and is > 0 without an upper limit.

- **Landscape Configuration**

In this study the selection of metrics was based on monitoring and evaluation of desertification and land degradation phenomena. Landscape configuration at class and landscape level was analysed by means of the following landscape metrics: Landscape Shape Index (LSI), Mean Euclidian Nearest-Neighbor Distance (ENN_MN), Interspersion and Juxtaposition Index (IJI), Patch Cohesion Index (COHESION), Fractal Dimension Index (FRAC) and Mean Proximity Index (MPX).

Table 4.4: Indices selected for this work for landscape configuration (McGarigal et al., 2002).

Landscape metrics	**Description**
$LSI = e_i / min\ e_i$ Where: e_i = total length of edge (or perimeter) of class *i* in terms of number of cell surfaces; min e_i = minimum total length of perimeter of class *i* in terms of number of cell surfaces.	Landscape Shape Index (LSI) equals the total length of perimeter (edge) involving the corresponding class, given in number of cell surfaces, divided by the minimum length of class perimeter (edge) possible for a maximally aggregated class, also given in number of cell surfaces, which is achieved when the class is maximally clumped into a single, compact patch. LSI is larger than 1, without limit and is equal to 1 when the landscape consists of a single square or maximally compact patch of the corresponding type. It provides a measure of class and landscape aggregation or clumpiness.
$COHESION = [[1-\sum_{j=1}^{m} P_{ij} / \sum_{j=1}^{m} p_{ij}\sqrt{a_{ij}}]/[1-1/\sqrt{A}]]*100$ Where: a_{ij} = area of patch ij in terms of number of cells; P_{ij} = perimeter of patch *ij* in terms of number of cell surfaces; *A* = total number of cells in the landscape.	Patch Cohesion Index (COHESION) measures the physical connectedness of the corresponding patch type; it increases as the patch type becomes more clumped or aggregated in its distribution, consequently more physically connected. COHESION is without unit and the value range from 0 to 100. It approaches 0 as the proportion of the landscape comprised of the focal class decreases and becomes increasingly subdivided and less physically connected.
$FRAC = 2\ln(0.25 p_{ij}) / \ln a_{ij}$ Where: p_{ij} = perimeter (m) of patch ij, a_{ij}= area(m²) of patch *ij*	Fractal Dimension Index (FRAC): Measure of shape complexity at patch level, the large patches tend to be more complex than smaller. This index is used to determine patch complexity independent of its size.
$ENN\_MN = \sum_{j=i}^{n} h_{ij} / n_i$ Where: n_i =number of patches of class *i* and h_{ij} = distance (m) from patch *IJ* to nearest neighboring patch of the same type (class)	Euclidean Mean Nearest Neighbour distance (ENN_MN): this index is used to determine the patch isolation. Euclidean Nearest Neighbour distance (ENN) equals the distance in meters to the nearest neighboring patch of the same type, based on shortest edge-to-edge distance. The units are meters. ENN is larger than 0, without limit and it approaches 0 as the distance to the nearest neighbour decreases.
$PX = \sum_{g=1}^{n} a_{ijg} / h_{ijg}^2$ Where: a_{ijg} = area (m²) of patch ijg within specified neighbourhood(m) of patch ij. h_{ijg} = distance (m) between patch ijg and patch ijg; based on patch edge-to- edge distance, computed from cell center to cell center	Proximity Index (PX) is equal 0 when a patch has no neighbours of the same patch type within the specified search radius. It is increased as the area is increasingly occupied by patches of the same type, and as those patches become closer and less fragmented in distribution.
$IJI = -\sum_{k=1}^{n}\left[\left(e_{ik} / \sum_{k=i}^{n} e_{ik}\right)\ln\left(e_{ik} / \sum_{k=i}^{n} e_{ik}\right)\right] / \ln(n-1) * (100)$ Where: n = number of patches of class i e_{ij} = total length of edge between class *i* and k	Interspersion Juxtaposition Index (IJI): It is used for relative interspersion of each class. It is 100 when all patch types are equally adjacent and approaches zero when the distribution of unique patch adjacencies becomes uneven.

Moving Window

The square moving window approach was chosen to create a continuous landscape metrics index for statistical analysis and conducted on a 60 m side length. Within each window, each selected index was calculated and the value sent to the centre cell. The output was displayed on a separate grid for each metrics selected. Using the square moving window techniques, selected metrics were calculated for the center cell of the window. The results were a set of new grid formats which the grain value represent the computed metrics values.

4.2.3 Analysing and Monitoring Fragmentation and Landscape Structure in the Context of Desertification

Based on the land use / cover maps previously obtained and with the support of FRAGSTATS, an analysis of the degree of landscape fragmentation at class and landscape level was performed. The fragmentation index used in this study for each landscape element is inverse mesh index ($Meff$). The inverse mesh index was chosen because of the information provided about connectivity. This index is a well-situated method to quantify class and landscape fragmentation. Vegetation and water patches are resistant elements to desertification, therefore the fragmentation level of these patches were investigated. At landscape level, landscape metrics for capturing the spatial pattern of the fragmentation degree to desertification was taken into account in order to express the physical connectivity of the landscape by inverse mesh index.

Therefore, $Meff$ proposed by Jaeger (2000) is defined by:

$Meff = (\sum_{j=1}^{n} a_{ij}{}^2/A)(1/10{,}000)$ and

Fragmentation index = $1/(\sum_{j=1}^{n} a_{ij}{}^2/A)(1/10{,}000)$

Where:

n = number of patches; a_{ij} = *area (m²) of patch ij*; A = total area of the study area investigated which has been fragmented into n patches.

4.2.4 Synthetic Indices for Analysing and Monitoring Landscape Structure Change in the Context of Desertification

Landscape metrics for investigating and monitoring landscape structure in areas prone to desertification were selected, taking into account the landscape diversity, landscape fragmentation and the irregularity of patches on the foundation of the major results of Li et al. (2004). Desertlinks (2005) reported that landscape diversity is significant to desertification because it affects the diversity of the landscape, since small and contiguous plots of different land cover usually demonstrate a smaller risk of land deterioration and have a higher biodiversity. Therefore the following combined index for the landscape structure was selected: mesh index ($Meff$), landscape Shannon's diversity index (SHDI), mean patch area (MPA) and shape Index (LSI) at landscape level:

Landscape structure (LS) = f $(Meff\ , MPA, LSI\ , SHDI\ )$

The LS are dominated by the mesh index due to its high value. Since the above mentioned formula does not respect the changes but displays the spatial information of landscape structure in 1973, 1989, 2001 and 2007, in order to express the landscape structure change (LSC) index the change detection method was used. The Index for each spatial pattern and for each landscape metrics were reclassified, combined (12 classes), between the two different study periods under consideration (1973-1989, 1989-2001 and 2001-2007). Then the 12 classes were grouped into three categories and a score was assigned on the basis of the information derived from each landscape index .The classical categories of landscape structure are:

- High (LSC) is a combination between the low values of mesh, low values of SHDI and high irregularity of the elements of patches.
- Medium (LSC) is a combination between the medium values of mesh, medium values of SHDI and medium irregularity of the elements of patches.
- Low (LSC) is a combination between the high values of mesh, high values of SHDI and low irregularity of the elements of patches.

The index obtained from this method has the potential to reflect in a synthetic value various aspects of the spatial pattern analysed and their variation over time.

4.2.5 Field Data and Interview

The field work period was established to increase the understanding of the patterns of land use / land cover in the study area during the rainy seasons. Preliminary image classification, topography image and soil image of the study area was printed to indicate target areas to be surveyed depending on the accessibility of each site. The field work was conducted during the period 9/8/2010 to 11/10/2010. The navigation in the area was supported by a Global Positioning System (GPS) device (Garmin 60CSxGPS). The data such as vegetation characteristics (biomass measurements, percentage cover, plant density, type's distribution and species) and soil were collected during the field work. Sample location was chosen on a subjective sample bases by driving around the study area and stopping for measurements at various locations. An area of 3,600 m², considered a representative portion of the grassland, was chosen for all measurements. The soil data were collected from six different sites depending on the different soil types in the study area.

Therefore, 60 soil and 20 grassland samples were selected. Measurements were also taken from agricultural fields, bare areas, water bodies and shrub land. The selected grassland samples were taken for laboratory analysis. In laboratory, each grassland sample was dried in oven at 70°C, dry weights measured and converted into dry biomass (g/m²).

i. Survey technique

In addition, semi-structured interviewing with local residents of ten villages was conducted in order to obtain the following information:

- Detection of physical aspect of water, soil and vegetation cover in this area
- Extraction of technical aspect concerning the history of different land and land use, newly introduced plant species and the species that got extinct
- Collection of information about the general landscape such as wadi, dunes and other features of these areas

The discussions were carried out at randomly selected villages. The names of the ten villages picked within the sixty nine villages were: Sansane Haoussa, Mele Haoussa, Gotheye, Koulbagou Haoussa, Lossa, Guega Kado Babagadey Koira, Kabay, Boukou and Gouria.

ii. Sampling size and data analysis

For each village, a list of population data was obtained from the village leaders or the local administrative offices. The age group of 35 - 70 years was selected. The number of respondents ranged between 4 to 15 people in each group and 4 groups in each village were interviewed. The data collected were analysed using simple descriptive statistics such as frequency distributions.

4.2.6 Desertified Index

In the present thesis a methodology is developed to help in mapping and analysing desertification in the study area based on thematic change and landscape metrics. Three variables including amount and direction of changes, velocity and changes of landscape structure were chosen. In this step, arithmetic means of three variables were calculated for desertification index according to the formula below. A low pass (7*7 kernel) filter was applied to all the layers.

DI = f (ADC, V, LSC)

Where:

- DI is Desertified Index
- ADC is amount and direction of change
- V is velocity
- LSC is landscape structure change

Desertified index maps were prepared, and according to this model, the index values were grouped into 5 classes. These involved:

- Very high (DI) being a group between the high values of landscape structure change – conversion of shrubs to bare areas as a result of the amount and direction of change and increases in the elements of the velocity of change.
- High (DI) is a combination between the high values of landscape structure change – conversion of plateau vegetation to bare areas and increasing elements in the velocity of change.
- Moderate (DI) is a different arrangement dominated by a simple combination between medium landscape structure values, conversion of agricultural land to bare areas, and no change in the context of velocity.

- Low (DI) is a group between the low values of landscape structure change and no change in the context of amount, direction and velocity.
- Very low (DI) is an arrangement between the low values of landscape structure change – decreasing elements from velocity of change and positive changes from amount and direction of changes.

This hybrid index system of desertification brings together the different relevant perspectives and knowledge.

4.2.7 Verification and Validation Procedure

Verification and validation are used for checking the desertified index. The verification was carried out using the data from semi-interviewing with local residents of ten villages. Also, external validation of desertified index using geographically weighted regression (GWR) was undertaken between desertified index from 2001 to 2007 as dependent variable and ground truth data as explanatory variables (land cover).

4.3 Data Preparation and Processing for Soil Erosion

Soil erosion is one of the principal environmental problems and affects food production in the Sahel; it is one of the manifestations of desertification processes. Cobo et al. (2010) explained that soil erosion is one of the most ordinary and extensive forms of soil degradation and is closely related to processes of nutrient reduction and desertification in semi-arid region. It can be used as an index of land degradation. Lal (2004) reported that soil erosion phenomenon is a considerable source of soil organic carbon emission to the atmosphere, with considerable impact on global warming.

The Sahel region is considered one of the most vulnerable ecosystems in the world and the majority of the population is highly dependent on soil resources to ensure adequate crop production or to maintain their crop production and livelihoods. Also, it is characterised by erratic precipitation and water shortage due to semi-arid climatic conditions. Soil erosion affects agricultural production, contributes to the contamination and quality of water resources. Also, it decreases the soil fertility content, the fine grained soil content, the water holding capacity and the depth of the top soils. Michels et al. (1995) reported that erosion processes have a significant impact on land productivity in the West African Sahel, a semi-arid region where both wind and water take action as erosive forces.

Less attention has been paid by the scientific community to the spatial dimension of erosion in Sahel region, but a few studies have tried to address this issue of soil erosion in this area (Verstraeten et al., 2003; De Vente & Poesen 2005; Tamene, 2005 and Boardman et al., 2009). To combat desertification, it is indispensable to understand soil erosion processes in the Sahel zone. The objective of this section was to develop a simple model that uses soil texture data from the field and DEM parameters to predict soil texture map using TreeNet (Salford machine) model. It is a new approach of data mining developed by Friedman (1999).

Finally, this section assesses soil erosion research in the Sahel region, illustrated by a case study from Tillabéry landscape. The RUSLE and USPED were used to achieve one of the additional secondary objectives of this thesis. RUSLE model predicts the average annual soil loss from rill and sheet erosion and the USPED is an empirical method which determines the spatial distribution of erosion and deposition velocity process.

The RUSLE model is supported by five components: rainfall erosivity factor (R), soil erodibility factor (K), topographic factor (LS), cover management factor (C), and support practice factor (P). The average annual soil loss (A, t/ha year) is computed by multiplying these factors:

$$A = R * K * LS * C * P$$

The USPED model reported by Mitasova et al. (1996) was used in this thesis. It is a model which predicts the spatial distribution of erosion and deposition velocity. For the transport capacity limited case, the model was assumed that the sediment flow rate per unit width (q_s) is at the sediment transport capacity $T_{(r)}$, $r = (x, y)$ which is approximated by (Moore & Buch, 1986):

$$|q_{s\,(r)}| = T_{(r)} = K_t(r) * |q(r)|^m * \sin b(r)^n$$

Where: $b(r)$ is slope (express in degree), $q(r)$ is water flow rate (m^3 m^{-1} s^{-1}), $K_t(r)$ is transportability coefficient dependent on soil and cover, m and n are constants depending on the type of flow and soil properties. For overland flow the constants are usually set to $m = 1.6$ and $n = 1.3$ according to Foster et al. (1993) and where sheet erosion prevails, they are set to m=n=1 (Foster, 1994)..

In situation of steady state (intensity of precipitation uniformly distributed), water flow $q(r)$ (m^3 m^{-1} s^{-1}) can be expressed as a function of upslope contributing area $A(r)$ as following:

$$|q(r)| = A(r) * i$$

Where: i is the uniform rain intensity

Finally the $|q_{s\,(r)}|$ relation is compacted to:

$$|q_{s\,(r)}| = T_{(r)} = K_t(r) * (A(r) * i)^m * sinb(r)^n$$

The net erosion / deposition rate is computed as a divergence of the sediment flow in the direction of flow (Warren, 2005). According to Mitasova et al. (1998) the formula which describes net erosion / deposition in each grid cell(r) is:

$$ED_{(r)} = div\,[q_{s\,(r)}] = K_t\,\{[(grad(h)] * s * \sin(b) - h[k_p + k_t]\}$$

Where: $s(r)$ is the unit vector in the steepest slope direction, h is the water depth approximated from the upslope area, k_p and k_t are respectively the profile curvature and tangential curvature. Due to the lack of experimental data for USPED parameters, therefore the RUSLE parameters were combined in order to compute the transportability coefficient K_t as illustrated (Mitasova et al. 1998):

$$K_t = R * K * C * P$$

The P was taken constant (1). In order to study the effects of climate and land use / cover changes, the K, the LS as well as the P were taken constant for the past and present condition scenarios. Therefore, the modelling is exclusively depending on the C and the R.

4.3.1 Soil Sampling and Laboratory Methods

To investigate and quantify the amount and spatial distribution of the soil structure and soil erosion, a stratified random sample was established based on two-stage sampling plans with topography and land use / cover as the stratifying variables. A topographic wetness index was derived from digital elevation model (DEM-90m) with two classes. This index shows areas of potential soil moisture (with value 1) and dry areas (with value 2). The wetness index was combined with land use / cover derived from Landsat image 2001. The result displays 12 environment units within the study area. Two environment units within the water bodies were not considered because they do not show a classical category of soil attributes.

Therefore, the classical categories of soil attributes are: combinations between wadi and soil moisture or dry soil elements; combinations between shrub lands and soil moisture or dry soil elements; combination between plateau vegetation land and soil moisture or dry soil elements; combination between bare areas and soil moisture elements; combination between bare areas and dry soil elements; combination between agricultural land and soil moisture elements and combination between agricultural land and dry soil elements (see Figure 4.6). So, 25 soil samples were randomly selected within each of the 10 environmental units.

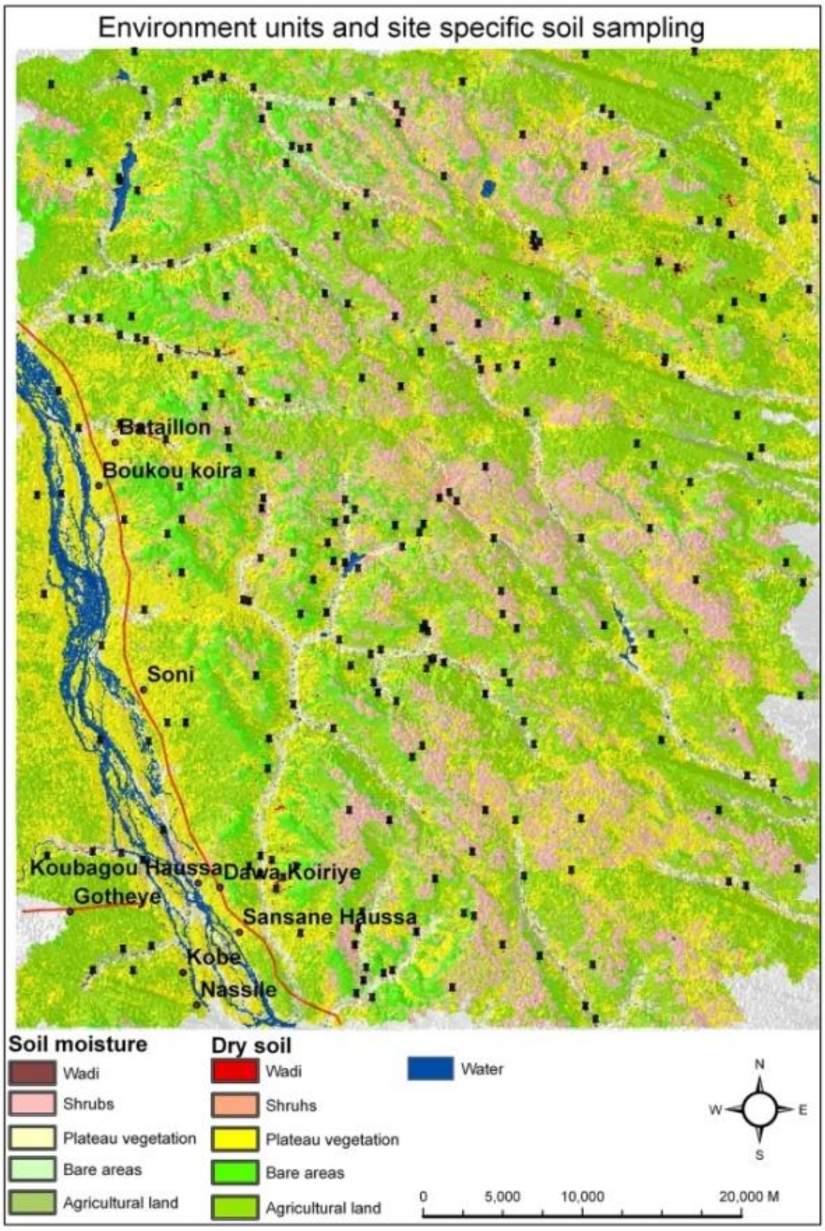


Figure 4.6: Environment units and site specific soil sampling

Also, the 250 soil samples were tested by feel soil method (Thein, 1979) in order to determine the soil texture. This method requires skill and experience and it is carried out in the following way: a small soil sample is taken, water is added to the sample, and it is worked between the fingers and thumb until the aggregates are broken down based on the guidelines proposed by Thein (1979) to determine the texture class.

Four soil samples within the 10 environmental units (40 soil samples) were submitted to laboratory analysis. The following elements were analysed in the lab: particle size percentage, USDA classes by pipette method (Gee & Bauder, 1986); organic carbon by combustion method (Read, 1921); total nitrogen by combustion method (Read, 1921), available phosphorus by Olsen method (Olsen et al., 1954); iron and aluminium extractable (Jackson et al., 1986); pH by potentiometric determination on soil-water (Bratskaya et al., 2008); exchangeable acidity by KCL method; exchangeable aluminium by KCL NaF method; cation-exchange capacity by centrifuge method (Miller & Keeney, 1982) and specific conductivity at 25°C on soil-water (Sharma, 2006).

4.3.2 Land Forms

A couple of satellite data were used to derive the land form parameters for soil erosion and soil texture regionalisation in the area of study. The Shuttle Radar Topography Mission (SRTM) DEM at 90 m resolution was obtained from the University of Maryland (Earth Science Data Interface at Global Land Cover Facility) and an Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) DEM at 30 m resolution was obtained from the National Aeronautic and Space Administration (NASA).

As such SRTM was used in this sub-section to derive Analytical hillshading (Olaya & Conrad, 2008), Slope (Zevenbergen & Thorne, 1986 and Tarboton, 1997), Aspect (Zevenbergen & Thorne, 1986), Curvature (Zevenbergen & Thorne, 1986 and Shary et al., 2002), Plan curvature (Zevenbergen & Thorne, 1986), Profile curvature (Zevenbergen & Thorne, 1986 and Shary et al., 2002), Convergence index (Köthe & Lehmeier, 1993), Catchment area (Olaya & Conrad, 2008), Wetness index (Beven & Kirby, 1993), LS-factor (Moore et al., 1991 and Feldwisch, 1995), Channel network (Olaya & Conrad, 2008), Altitude above channel network (Olaya & Conrad, 2008), Channel network base level (Olaya & Conrad, 2008) and Watershed sub-basins (Conforti et al., 2011) parameters. The filling sink technique was used in order to fill any remaining sinks.

4.3.3 Spatial Prediction of Soil Texture using TreeNet Model

A statistical model was adapted to predict the spatial distribution of soil texture from terrain parameters. For this task, the field survey x- and y-coordinate data together with the z-field representing texture information from 250 observation points was used. SAGA GIS (System for Automated Geoscientific Analyses, Conrad, 2007) was used to overlay terrain attributes (Analytical hillshading, Slope, Aspect, Curvature, Plan curvature, Profile curvature, Convergence index, Catchment area, Wetness index , LS-factor, Channel network, Altitude above channel network, Channel network base level and Watershed sub basins) derived from digital elevation models.

Spatial prediction of soil texture landscape was developed using the TreeNet model (Salford machine implementation, cf. Friedman, 1999). It is an example of a machine learning method and new method of data mining and has several advantages. Friedman (2002) demonstrated the following advantages: resistance to over-training and outliers; managing data without pre-processing; indifferent to data errors in the input variable and automatic variable subset selection; automatic managing of missing values; strength to fragmentary and partially inaccurate data. Also, input variables can be continuous or / and categorical (Ließ et al., 2011).

The dependent variable is categorical (soil texture) and the independent (Analytical hillshading, Slope, Aspect, Curvature, Plan curvature, Profile curvature, Convergence index, Catchment area, Wetness index , LS-factor, Channel network, altitude above channel network, Channel network base level and Watershed subbasin). A predictive map of soil texture was obtained under SAGA GIS through the application of a spatial interpolation method (inverse squared distance).

4.3.4 Soil Erodibility

The erodibility factor (K) is the susceptibility of the soil to erosion. It is one of the most important factors on soil erosion model. K can be determined on the basic of nomograms or calculation relation. To evaluate the K, 40 samples within the 250 samples were selected. In this work, K was expressed by two empirical equations. A calculating relation was proposed by Renard et al. (1997) in which they applied the percentage of the respective soil texture classes and geometric mean diameter to arrive at the K. This is expressed in this equation.

K = $0.0034 + 0.0405 * \exp[-0.5\left(\frac{\log \mathrm{Dg}+1.659}{0.7101}\right)^2]$

Where: *K*: is the soil erodibility (t ha h / ha MJ mm);
Dg: is the geometric mean weight diameter of the primary soil particles (mm) expressed by:

$$Dg = \exp(0.01\sum_{i=1}^{n} f_i \ln m_i)$$

Where: f_i is the primary particle size fraction in percent, n is the number of size classes in which the distribution curve has been divided and m_i is the arithmetic mean of the particle size limits of that size (Shirazi and Boersma, 1984). The results exposed that the erodibility ranges from 0.05 to 0.40 t ha h/ha MJ mm.

Torri et al. (2002) used a different approach by calculating the percentage of silt plus very fine sand, percentage of sand, percentage of organic matter and soil structure to arrive at the K.

$$K = 0.0293 * (0.65 - Dg + 0.24Dg^2) * \exp\{-0.0021 * \left(\frac{OM}{C}\right) - 0.00037 * \left[\left(\frac{OM}{C}\right)^2\right] - 4.02C + 1.72C^2\}$$

Where: *K* is the erodibility factor (Mg ha h/MJ ha mm), Dg is the geometric mean weight diameter of the primary soil particles (mm), OM is organic matter content (%) and C is soil clay content (fraction).

The results revealed that the erodibility with considering organic matter ranges from 0.015 to 0.045 t ha h/ha MJ mm. The K values were grouped into different classes. The classical categories of K class data set without considering organic matter data are (according to the classification of Vopravil et al., 2007):

- Class1 between 0.02-0.20 t ha h/ha MJ mm
- Class 2 between 0.20-0.25 t ha h/ha MJ mm
- Class 3 between 0.25-0.40 t ha h/ha MJ mm

The classical categories of k class data set with considering organic matter data are (according to the classification of Páez, 1994):

- Class 2 less than 0.015 t ha h/ha MJ mm
- Class 3 between 0.015- 0.050 t ha h/ha MJ mm

After assigning the appropriate value for each parameter, the TreeNet model was applied. The results found from the equation of the K with organic matter have lowest prediction that mean the Receiver Operating Characteristic (ROC) integral less than 0.70 for all the classes due to low amount of soil samples (40 samples) (see sub-section 4.3.7). For this reason Co-Kriging was applied.

4.3.5 Rainfall Erosivity

The annual rainfall erosivity (R) is a function of the kinetic storm energy and the maximum 30 min rainfall intensity. The R was estimated based on monthly precipitation. So, five methods have been tested. The results were compared based on iso-erodent maps for West Africa developed by Roose and De Noni (2004). The authors used precipitation to establish the relationship between the R and the average annual precipitation (P in mm / year), the applied annual rain gauge data for more than 10 years and more than 20 meteorological stations in Burkina Faso, Cameroon, Chad, Cote d`Ivoire, Senegal and Niger.

4.3.6 The C Calculation

Wischmeier and Smith (1978) defined C as “the ratio of soil loss from land cropped under specified conditions to the corresponding loss from clean-tilled, continuous fallow”. Based on a literature review on the land cover value used for soil erosion model for West Africa, land use / land cover from Landsat images of 1973, 1989, 2001 and 2007 were converted to C using “Raster Calculator” tool of the Spatial Analyst of Arc GIS 9.3.1 software package.

The agricultural land is assigned to a C of 0.4 as reported by Morgan (1995). The C varies between 0 (e.g. river), indicating that no erosion occurs, to 1, expressing the maximum of erosion (e.g., bare areas) and takes under consideration both cover and management variables. For shrub areas, a C of 0.01 was used as reported by Wischmeier & Smith (1978) and confirmed by Roose & De Noni (2004). For Plateau vegetation, a C of 0.1 was selected, which is also proposed by Roose & De Noni (2004).

4.3.7 Soil Texture and K Models Validation

A validation was carried out in order to determine the suitability of the models and to identify the aspects of the model that need improvements. The soil texture and the two K models were validated based a tenfold cross validation. The internal validation method is used to test the efficiency of TreeNet model to predict soil texture and k factors distribution using ROC curve plots, true positive rate in opposition to false positive rate (Lasko et al., 2005) and misclassification errors. The ROC calculated the values of the Area under the ROC Curve (AUC; Hanley and McNeil, 1982). Hosmer & Lemeshow (2000) reported that the predictive performance is acceptable if AUC> 0.7 and excellent if AUC> 0.8.

5 Results and Discussion

5.1 Characterization of Landscape with Spatial Data

The following results show the relation between spatial data and landscape processes and functions. The tables in this section give an overview of the spatial data that are necessary and useful to describe and/or analyse potential landscape functions. It equally throws light on the accuracy that is needed or recommended and how and from which sources they may be obtained. The identification of the causes of desertification and land degradation needs the interaction between different elements of the landscape.

5.1.1 Demographic and Poverty Data

Table 5.1: Relation between demography elements and landscape.

Elements	Associated function	Value	Accuracy/ Resolution	Method	Source
Population	Primary, secondary and tertiary productivity Changing landscape from natural to artificial landscape	E.g: number of people in one area (village, town, region, district, country) or population density	E.g: 10 km*10 km 1 km*1 km or 1:50,000	Population estimation method or census of the population	Statistical service
Poverty	Primary and secondary productivity	Annual amount and source of income, annual expenses, size of family	1:50,000 1km*1km	Survey, census	Statistical service

Table 5.1 shows the relationship between demographic elements, poverty and landscape and their interaction with desertification and land degradation. On the one hand, the population plays an important role in any economic sector (primary, secondary or tertiary productivity). On the other hand, a growing population can influence

landscape by increasing the demand for agricultural land and infrastructure. Population density has a direct relationship to urban areas, recreation activities, forestry, agricultural activities and mining. Humans are agents of change in the physical and ecological characteristics of the landscape. In the Sahel, growing population has been cited by many authors as a major cause of land degradation and desertification. Clark and Munn (1986) reported that, if population increases, it has a double edged effect: a simultaneous increase in demand made upon the environment in order to support growing numbers of people, and a destruction of the resource base.

Economic poverty is an ambiguous factor and needs careful analysis and investigation in its effects and ramifications on desertification and land degradation. Economic poverty is not only the result of low income levels, but it is also lack of access to food, water, natural resources, education and medical care. Economic poverty affects how land users manage their land. In the Sahel, a significant portion of the population have less alternatives but rather to opt for immediate benefit than long-term land sustainable management system. To make matters worst, the people are economically poor and find it difficult to raise capital for the restoration of degraded lands. This accentuates the degradation process. This problem has been recognised by the World Bank as a necessary policy in the third world (Hopper, 1988). He further noted that “Poor people cannot easily postpone immediate consumption for future returns. Nor will they ignore the pressing needs of the moment if these can be met from their limited resources, even if the use of these resources jeopardizes their longer term viability”.

5.1.2 Biotope and Land Cover

Table 5.2: Relation between land cover elements and landscape.

Elements	Associated function	Value	Accuracy/ Resolution	Method	Source
Biotope types	Biodiversity	Biotope classes	100 m*100 m 1:25,000	Terrestrial mapping	Meteorology service
	Primary and secondary production	Diversities		Remote sensing (aerial photograph or satellite image)	Military ser-vice, tourist service, agricultural service
	Recreation				

Table 5.2 provides an understanding of the interactions between the biotope types and landscape change. It shows the economic value of the biotope types such as biodiversity (biological productivity), primary production (crops, wood and fisheries production). It also shows that biotopes are a source of recreation. Land degradation processes begin with the degradation of land cover. Land cover is one major factor of soil degradation. The vegetation which covers the landscape improves the soil in all its dynamics, increases microbiological activity and soil fertility. Also, the vegetation cover protects the soil from wind by decreasing wind velocity. Both, biotic and abiotic factors, as well as human activities are responsible for soil degradation in the sahel region.

Thematic change detection

5.1.3 Climate Data

Table 5.3 shows the link between climatic elements and landscape. The majority of climatic elements play an important role in the functioning of landscapes such as primary production and vegetation cover. Agriculture depends on temperature, rainfall and humidity to produce abundant crops. This table shows the negative impacts of climatic elements. Higher temperatures reduce river flows, increase erosion and decrease forest health and productivity. Wind and rainfall can cause natural disasters either as floods or typhoons. Climatic elements also have an influence on the infrastructure and topography.

Climatic elements are an important cause of desertification and land degradation in many ways such as accelerated soil erosion. The intensity and regularity of rainfall affects land degradation and desertification in the Sahel by modifying the soil properties and particles. Also, rainfall increases runoff and reduces the fertility of the soil. In the Sahel, high temperatures increase soil evaporation and reduce soil moisture.

Table 5.3: Relation between climate elements and landscape.

Elements	Associated function	Value	Accuracy/ Resolution	Method	Source
Temperature	Primary and secondary production, vegetation cover, quantity of water energy	Annual mean temperature	10 km*10 km 1 km*1 km or 1:25,000	Temperature measurement	Meteorological service (maps and tables), agricultural unit (tables or graphs)
Rainfall	Primary production, vegetation cover composition, quantity of water, hydrologic cycle, natural disaster	Mean annual precipitation	10 km*10 km or 1 km*1 km	Rainfall measurement	Meteorological service and agricultural service (maps or tables)
Wind	Primary production, vegetation composition, wind energy, natural disaster	Mean annual wind speed in m/s	10 km*10 km or 1 km*1 km	Wind speed or direction measurement using meteorological instruments anemometer weather vane measurement using remote sensing technique e.g. radiometry and Doppler LIDAR	Meteorological service and Agricultural service (tables or maps)
Humidity	Primary production, vegetation cover	Annual relative humidity, annual absolute humidity and Specific humidity in %	10 km*10 km or 1 km*1 km	Humidity measurement by hygrometer or satellite water vapour.	Meteorological unit, agricultural service and geography information service (satellites data)
Evaporation	Primary production, vegetation cover, water cycle	Average annual evaporation rate	10 km*10 km 1 km*1 km or 1:50,000	Evaporation rate measurement	Meteorological unit (annual evaporation maps or tables)
Sunshine	Primary and secondary production, vegetation cover, water cycle, solar energy, recreational value	Mean daily sunshine or main annual sunshine radiation	1 km*1 km or 1:50,000	Solar radiation measurement by a Campbell-Stokes sunshine recorder	Agricultural service and solar energy service

Thematic change detection

5.1.4 Land Use

Table 5.4: Relation between land use elements and landscape.

Elements	Associated function	Value	Accuracy/ Resolution	Method	Source
Agricultural land	Primary production, diversity, education, deforestation	Annual agricultural production collects from farming animals and growing crops	100 m*100 m 1:25,000	Terrestrial mapping, remote sensing (air photo or satellite image)	Statistics and agricultural service
Forest	Primary production, diversity, education, energy	Annual wood production	100 m*100 m 1:25,000	Terrestrial mapping, remote sensing	Forestry service
Residential land, industrial and commercial	Secondary and tertiary production, social stability security	Number of homes, architectural style, water system , energy and road	100 m*100 m 1:25,000	Terrestrial mapping, remote sensing	Statistics service and equipments services
Public and private uses	Secondary and tertiary Production, security Recreation education	Number of parks, schools etc.	100 m*100 m 1:25,000	Terrestrial mapping, remote sensing	Tourist service, police service, statistics services

Table 5.4 improves our understanding between land use and landscape. This table shows that land use play an important role in primary productivity, education, recreation and biodiversity. Land use is a primary factor of production and it is an important factor that can change the landscape. This includes not only urbanisation effects but also changes in agricultural practices, such as irrigation and deforestation. The land use causes of land degradation are inappropriate agricultural practices, fire, overgrazing, industrial activities and urbanisation. Overgrazing is considered as a prime cause of desertification. In the Sahel, traditional animal production system increases degradation of vegetation and the soil through compaction. Also, this system can increase the loss of plant species which help to improve soil structure and exposes the landscape to erosion by wind and water.

In Niger Republic overgrazing is a much greater menace than overcultivation because traditional crop production systems were perfectly at equilibrium with the environment. Notwithstanding, the applications of agrochemicals such as inorganic fertilizers, fungicides and pesticides have catastrophic effects because they destroy insects and microorganisms in the soil.

Besides, deforestation is one of the major causes of desertification in the Sahel, where trees and wood play an important role to maintain soil stability. During the dry season, wild and natural fires constitute a great threat to vegetation cover in the Sahel. These fires make it difficult for plants to regenerate naturally because few seeds survive the fires. In addition, fires equally have a negative effect on the fauna in the area. Furthermore, the urbanisation affects land degradation not only by the physical presence of buildings but increasing deforestation by demand for fuel wood.

5.1.5 Topographical, Geomorphologic and Soil Data

Table 5.5: Relation between landform elements, soil and landscape.

Elements	Associated function	Value	Accuracy/ Resolution	Method	Source
Plain	Primary production, vegetation cover	Land cover per ha	E.g: 100 m*100 m 1:25,000	Terrestrial mapping, remote sensing (air photo or satellite image)	Geology service
Plateau	Recreational value, primary production, vegetation cover	Land cover per ha	E.g: 100 m*100 m 1:25,000	Terrestrial mapping, remote sensing (air photo or satellite image)	Geology service
Mountain	Recreational value, primary production, vegetation cover	Land cover per ha	E.g: 100 m*100 m 1:25,000	Terrestrial mapping, remote sensing (air photo or satellite image)	Geology service
Minor forms (slope, dune, and valley)	Recreational value, primary production, vegetation cover	Land cover per ha	E.g: 100 m*100 m 1:25,000	Terrestrial mapping, remote sensing (air photo or satellite image)	Geology service
Soil	Habitat function, yield function, regulatory function(water balance), vegetation cover and composition, primary production	The quantity of nutrients in the soil, pH values, soil property and structure (soil texture in %)	E.g: 100 m*100 m 1:25,000	Terrestrial mapping, remote sensing (air photo or satellite image)	Agricultural service, forestry service

Table 5.5 shows the relation between landform and soil elements with the landscape. It was observed from this table that landform elements (plain, plateau, mountain and minor forms such as slope, dune, and valley) and soil play an important role in landscape functions such as primary production, vegetation cover and composition, recreation, habitat function and yield or regulatory function. Desertification and land degradation processes differ depending on the landform elements such as soil type, slope and topography. The topography has powerful influence in soil erosion. The inclination of slope affects infiltration rates and increases runoff. The slope length has a direct bearing on the rate of sediment transport.

Thematic change detection

5.1.6 Infrastructure

Table 5.6: Relation between infrastructure and landscape.

Elements	Associated function	Value	Accuracy/ Resolution	Method	Source
Industries	Secondary and tertiary production, quality of life, air pollution	Quantity and quality of production per year	E.g: 100 m*100 m 1:25,000	Terrestrial mapping, remote sensing (air photo or satellite image) measurement	Industries service or infrastructure service
Roads	Tertiary production, recreational value, travel facilities and transportation cost, air and water pollution soil contamination, kill wildlife, increasing cross breeding between population groups	Number of kilometres, long of roads or number of total vehicles	E.g: 100 m*100 m 1:25,000	Terrestrial mapping, remote sensing (air photo or satellite image), measurement	Infrastructure service; road planning service, ministry of transport
Equipment	Secondary and tertiary production, recreation value, water quantity and quality, aesthetic, public service	Number of equipments	E.g: 100 m*100 m 1:25,000	Terrestrial mapping, remote sensing (air photo or satellite image	Infrastructure service, ministry of equipment

Table 5.6 shows the relation between infrastructure and landscape. It will be observed from this table that the infrastructure increases production (secondary and tertiary), cross breeding between population groups, quality of life, public service and travel facilities and decreases transportation cost. The infrastructure affects landscape character and quality by destroying wildlife, soil and air contamination. Infrastructure also affects the tranquillity of areas (loss of tranquillity) due to increase of traffic levels. Industrial activities have negative effects on the landscape. The industrial waste goes into rivers and lakes and affects the quality of water, quantity of faunas and flora and creates pollution. The direct impact of infrastructure on landscape resources results from the continuous need for more roads and equipment from an ever growing population. This constitutes a serious reduction in agricultural land availability.

5.2 Remote Sensing Based Classification

This section presents the results obtained from the application of change detection method. At first the land use / land cover results are presented and displayed. After that, the results of two different change detection (change detection matrix and image differentiation) models were presented and explained in the context of desertification and land degradation. Therefore, change detection matrix was used to capture the direction, amount of change and image differentiation of land use / cover to measure the velocity of change.

5.2.1 Classification Results

Figure 5.1, 5.2, 5.3 and 5.4 summarizes and displays the land cover classification results using the four satellite images from 1973 till 2007. Figure 5.1 portrays the study area as green. Some 71,209 ha and 171,117 ha of the land cover are respectively shrubs and plateau vegetation. Agricultural land comes next in land cover, occupying an area of 52,269 ha.

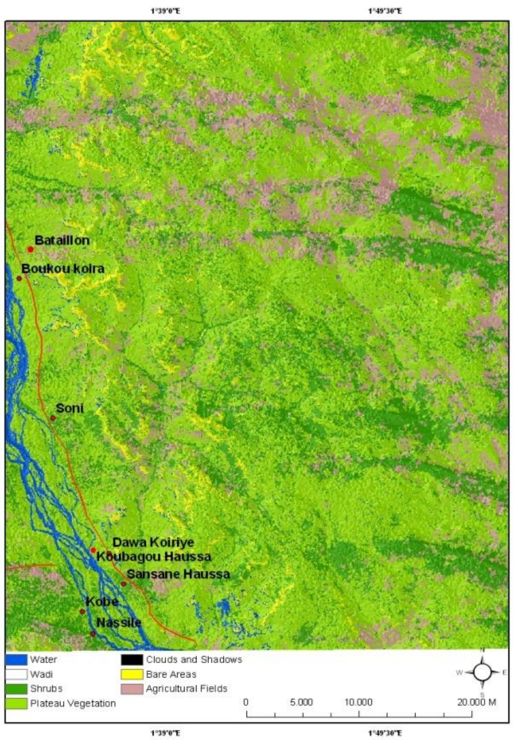


Figure 5.1: Land cover classification from Landsat MSS image acquired in 1973-09-30.

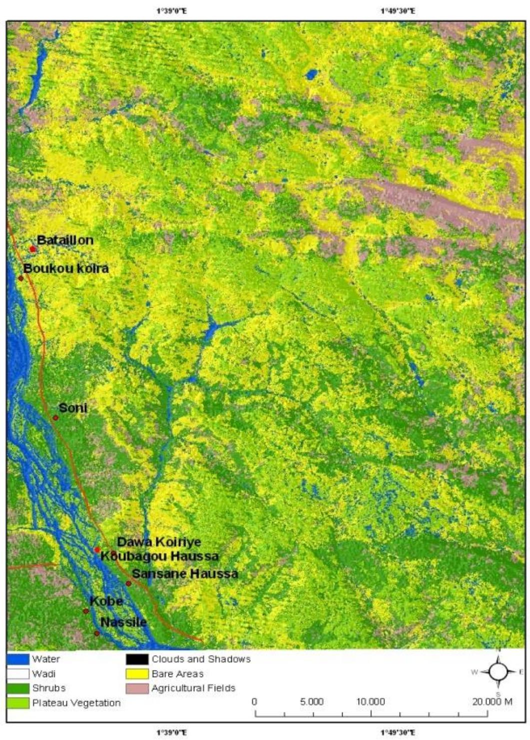


Figure 5.2: Land cover classification from Landsat TM image acquired in1989-09-17.

Thematic change detection

The Niger River and lakes are the visible water bodies in the image and they occupy 8,707 ha. The unusual presence of more lakes in the images is due to the fact that the images were taken in September at the peak of the raining season. Moreover, the resolution of the Landsat MSS does not permit it to show all the features.

The Figures 5.1, 5.2, 5.3 and 5.4 show the prevalence of land degradation and desertification during the period of study–from 1973 to 2007. In fact, it can be observed from all four images that there has been significant loss in vegetation cover. Bare areas and wadi have expanded in all directions and have taken much of the vegetation cover. Agricultural land has also increased. This can be ascribed to the absolute increase in population in the country, which necessitated a corresponding increase in food production. Water remains somehow constant, except in 1989 when water increased.

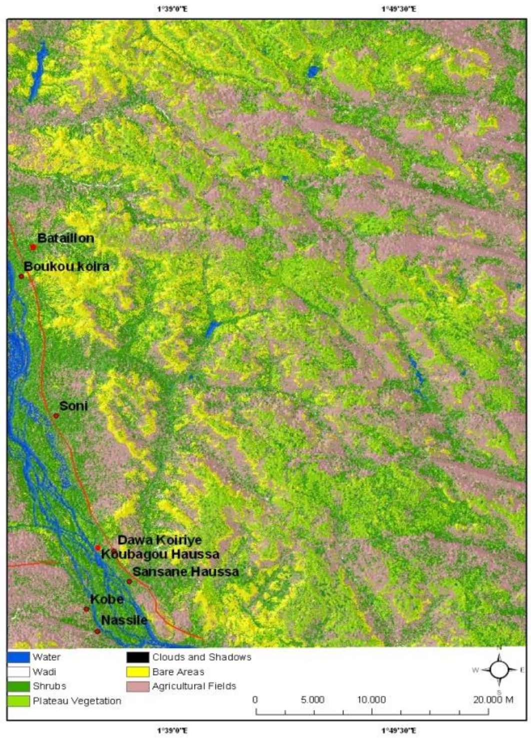


Figure 5.3: Land cover classification from Landsat ETM + image acquired in 2001-09-18.

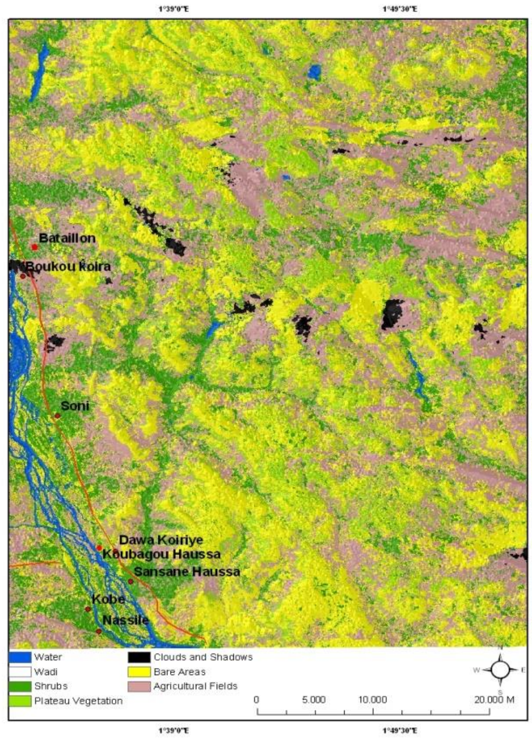


Figure 5.4: Land cover classification from Landsat TM image acquired in 2007-09-27.

Data on land use/cover distribution for the study years as derived from the Landsat images are presented in table 5.7. This table depicts the distribution of land cover from 1973 to 2007. The landscape is composed by plateau vegetation, shrubs, water, bare areas, agricultural fields and wadi.

Thematic change detection

From visual interpretation of land use imagery for 1973, 1989, 2001 and 2007 it is clear that the vegetation cover decreased, while agricultural fields and bare areas increased. In 1973 and 1989, plateau vegetation, shrubs are largely the dominant land cover type in the study area, whereas in 2001 and 2007 bare areas and agricultural fields are the dominant land cover types.

Table 5.7: Distribution and comparison of land use derived from Landsat classifications in ha.

Categories	**Comparison land use / cover**				**Direction of change**
	1973	**1989**	**2001**	**2007**	
Water	8,708	20,501	7,305	7,618	_
Bare areas	9,041	94,074	36,535	103 205	Increase
Shrubs	71, 210	91,631	88,541	49,241	Slight decrease
Agricultural fields	52,269	43,335	122,246	111,321	Increase
Plateau vegetation	171,117	62,803	56,425	37,083	Decrease
Wadi	0	0	1,292	130	_
Clouds and shadows	0	0	0	3,747	Increase
Sum	**312,345**	**312,345**	**312,345**	**312,345**	

5.2.2 Amount and Direction of Land Degradation and Desertification

Quantitative changes are visually interpreted in this section. The results of change detection method for MSS 1973, TM 1989, ETM+ 2001 and TM 2007 are revealed in figure 5.5, 5.6 and 5.7 respectively. Change detection method generates an image which maps the areas related to the amount of change in the study area. The land cover / use change can be divided into two parts: seasonal and annual change. In order to minimise the seasonal effects, all data were collected in the same season (rainy season).

Thematic change detection

Figures (5.5. 5.6 and 5.7) illustrate the amount of change from 1973-1989, 1989–2001 and 2001-2007. The northern part of the study area shows drastic changes in vegetation cover whereas the area around the Niger River highlights more stable vegetation. Increases of bare areas, wadi and agricultural fields constitute the major dominant change in the study area. The results prove the usefulness of change detection in analyzing desertification processes in the period of study (1973-2007). This result displays the direction of the changes in the study area. The areas subjected to desertification are characterised by an increase of bare areas and wadi and decrease in vegetation cover.

Table 5.8: Change detection 1973-1989 for study area (amount and type of change).

Type of change	**Areas of change (1973→1989)**		
	ha	**%**	**% of AOI (312,345 ha=100%)**
Water → Shrubs	625	0.69	0.20
Water→ Bare areas	464	0.51	0.14
Water→ Agricultural fields	321	0.35	0.10
Water→ Wadi	0	0	0
Shrubs→ Plateau vegetation	2,546	2.82	0.82
Shrubs→ Bare areas	5137	5.67	1.64
Shrubs→ Agricultural fields	16,547	18.26	5.30
Plateau vegetation→ Agricultural fields	21,312	23.52	6.82
Plateau vegetation→ Bare areas	34,620	38.20	11.08
Agricultural fields→ Bare areas	9,041	9.98	2.90
Sum	**90,616**	**100**	**29**

Table 5.8 shows that more than 29% of the area changed. The greatest change is the conversion of vegetation areas to bare areas. 11.08% of plateau vegetation changed to bare areas and another 1.64% of shrub areas changed to bare areas. Implicitly, the total increase in bare areas from previously vegetated lands is 13.72%.

Thematic change detection

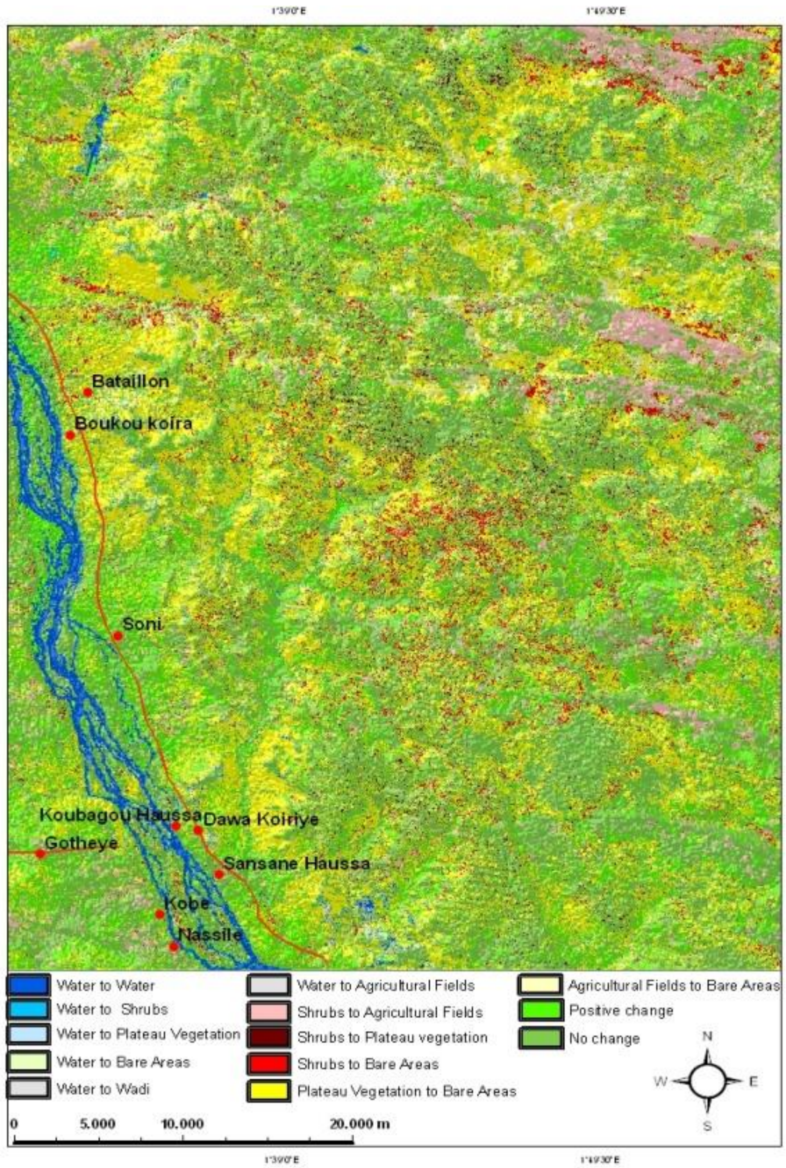


Figure 5.5: Land cover change detection map 1973 – 1989 for Tillabéry and its environs.

Besides, agricultural fields increased to 5.30% at the expense of shrubs vegetation. There was equally a noticeable conversion of 6.82% from plateau vegetation to agricultural fields. Worth commenting is a 2.90% conversion of agricultural fields to bare areas and a 0.14% conversion of water to bare areas. Ipso facto, the total gain in bare areas is 16.13% at the expense of vegetation cover and agricultural fields. From Fig 5.5, it can be observed that this conversion was greatest around the centre and close to major water bodies. This change is more remarkable in the northern part of the study area and is clearly described in Fig. 5.5. This is a lucent proof of desertification and land degradation taking place in the study area.

Thematic change detection

Table 5.9: Land cover change detection 1989-2001 for study area (amount and type of change).

Type of change	Areas of change (1989→2001)		
	ha	%	% of AOI (312,345 ha=100%)
Water → Shrubs	8,286	7.70	2.65
Water→ Bare areas	1,761	1.64	0.57
Water→ Agricultural fields	891	0.83	0.29
Water→ Wadi	81	0.08	0.03
Shrubs→ Plateau vegetation	5,216	4.85	1.67
Shrubs→ Bare Areas	31,562	29.34	10.11
Shrubs→ Agricultural fields	25,019	23.25	8.00
Plateau vegetation→ Agricultural fields	1,885	1.75	0.60
Plateau vegetation→ Bare areas	20,163	18.74	6.46
Agricultural fields→ Bare areas	12,712	11.82	4.07
Sum	**107,580**	**100**	**34.45**

The period (1989 - 2001) shows a tremendous increase in bare areas, an important factor that affects the landscape in this area. In this regard, the greatest conversion was from shrubs to bare areas (10.11%). Plateau vegetation equally decreased by 6.46% to the benefit of bare areas. The spatial distributions of the gains in bare areas from vegetation cover is more concentrated in cluster patches in the north, the centre and in the south east (see Figure 5.6).

Thematic change detection

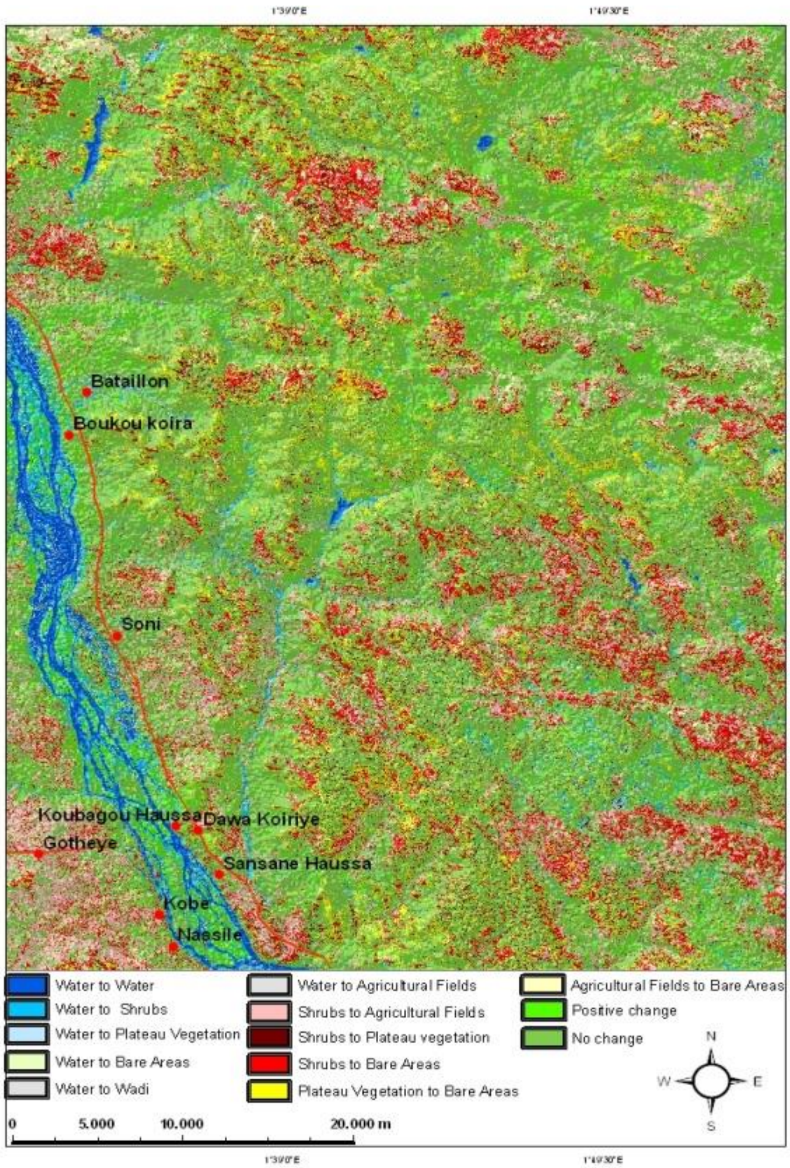


Figure 5.6: Land cover change detection map 1989–2001 for Tillabery and its environs.

Agricultural fields also increased during this period. Shrubs lost 8.00% of their surface area to agricultural fields. Plateau vegetation and water equally reduced by a corresponding 0.60% and 0.25% to agricultural fields. It is worth pointing out that a total of 20.67% of features that are considered to be deterrent to desertification were converted to bare areas and wadi during this period.

Thematic change detection

Table 5.10: Land cover change detection 2001-2007 for study area (amount and type of change).

Type of change	Areas of change (2001→2007)		
	ha	%	% of AOI (312,345 ha=100%)
Water → Shrubs	234	0.21	0.08
Water→ Bare Areas	183	0.17	0.06
Water→ Agricultural fields	6	0.00	0.00
Water→ Wadi	0	0.00	0.00
Shrubs→ Plateau vegetation	6,562	5.99	2.10
Shrubs→ Bare areas	21,871	19.96	7.00
Shrubs→ Agricultural fields	27,341	25.95	8.75
Agricultural fields→ Bare areas	16,519	14.08	5.29
Plateau vegetation→ Bare areas	23,094	21.09	7.40
Plateau vegetation→ Agricultural fields	13,750	12.55	4.40
Sum	**109,566**	**100**	**35.08**

The greatest changes were recorded by the agricultural fields. It made a total increase of 13.15%, being gains from plateau vegetation and shrubs. This is a pointer to an ever growing population. This is found more in the northern part of the area of study (see figure 5.7). From Tables 5.8 to 5.10, one can observe that agricultural fields, bare areas were gradually on an increase during the different intervals of study. Bare areas increased by 7.40% and 7.00% being gains from plateau vegetation and shrubs respectively.

The spatial distribution of these gains seems a bit randomly distributed but with an inclination of increased intensity towards the south of the study area. It is worth mentioning that during this same period, there were no changes in terms of conversion from either water to bare areas or water to agricultural fields, neither was there a change from water to wadi. This is an important subject for investigation. On a general note, the overall increase in bare areas is an indication of a continuous trend in land degradation.

Thematic change detection

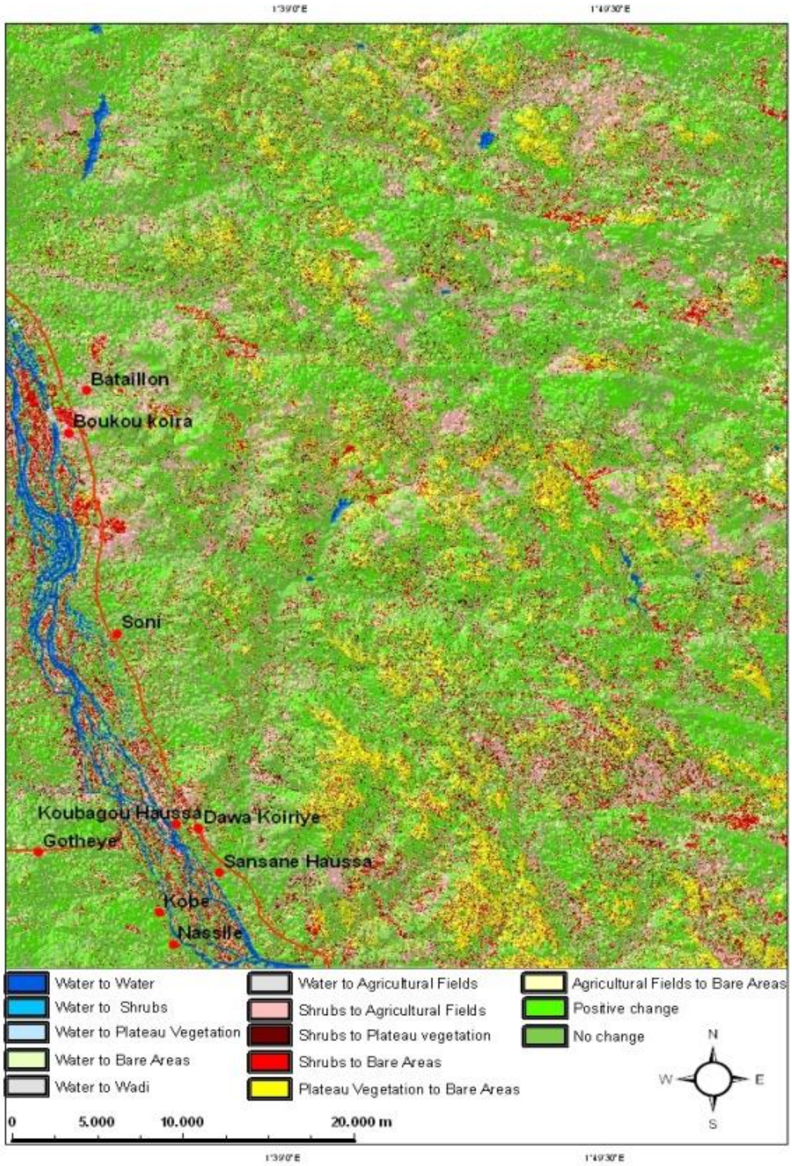


Figure 5.7: Land cover change detection map 2001–2007 for Tillabery and its environs.

5.2.3 Desertification Velocity Index

The desertification velocity index indicates the trend of desertification over a period of time. In this thesis, two classes are characterized that show a trend in the direction of further deterioration, and two classes with a trend in the direction of decreasing desertification due to human influence or natural stabilisation; water and no changes are considered separately.

Thematic change detection

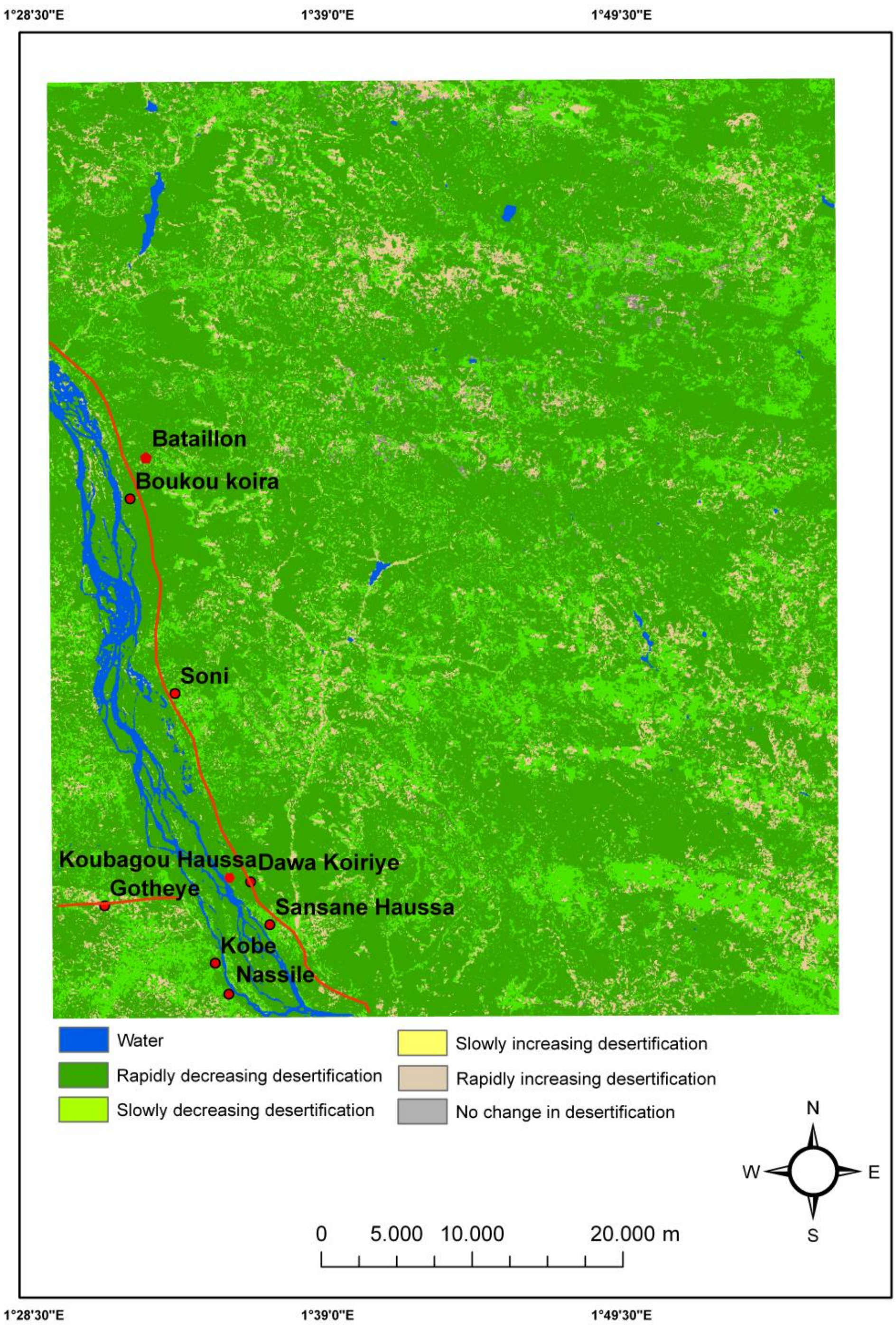


Figure 5.8: Velocity of desertification from1973 to 1989.

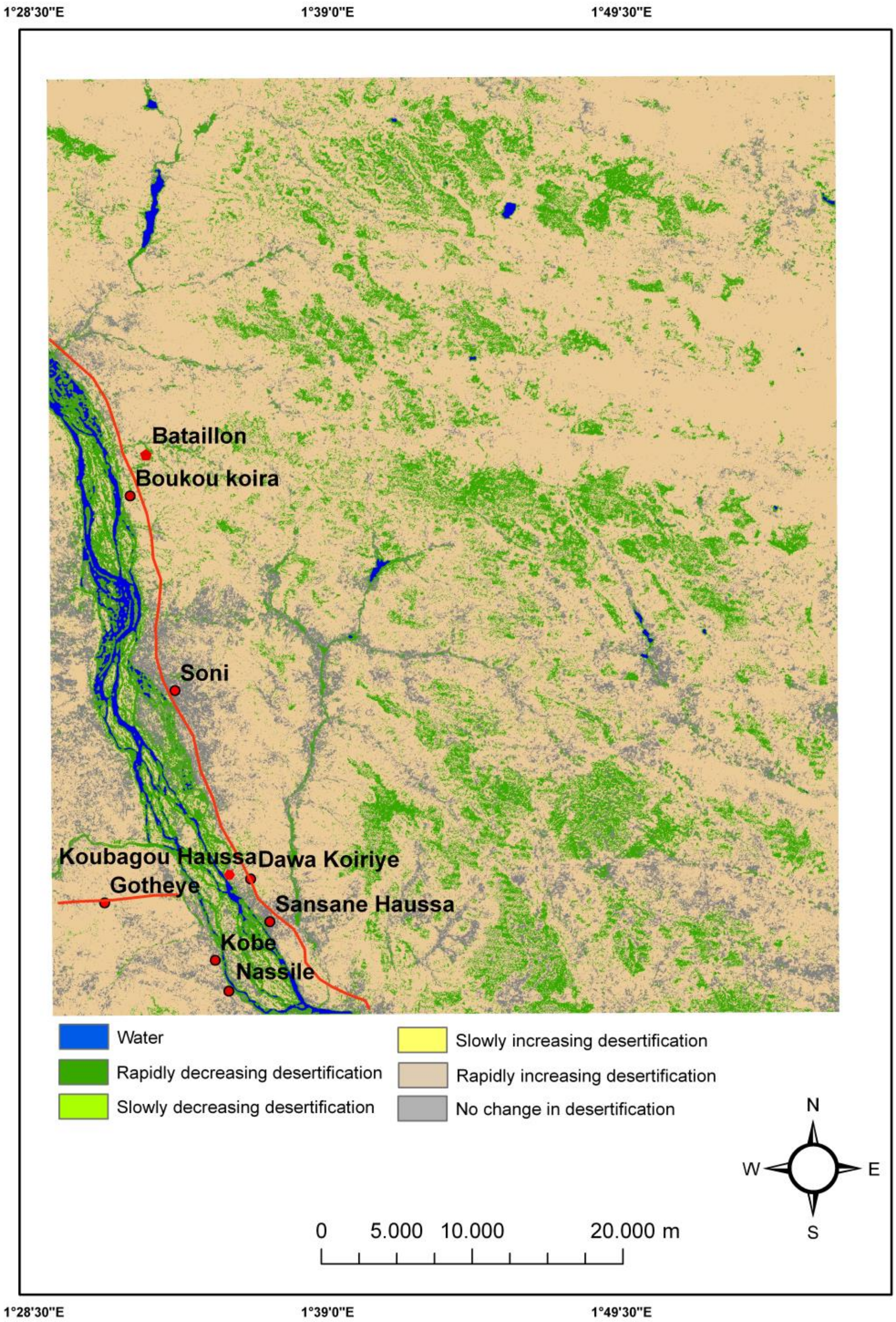


Figure 5.9: Velocity of desertification from 1989 to 2001.

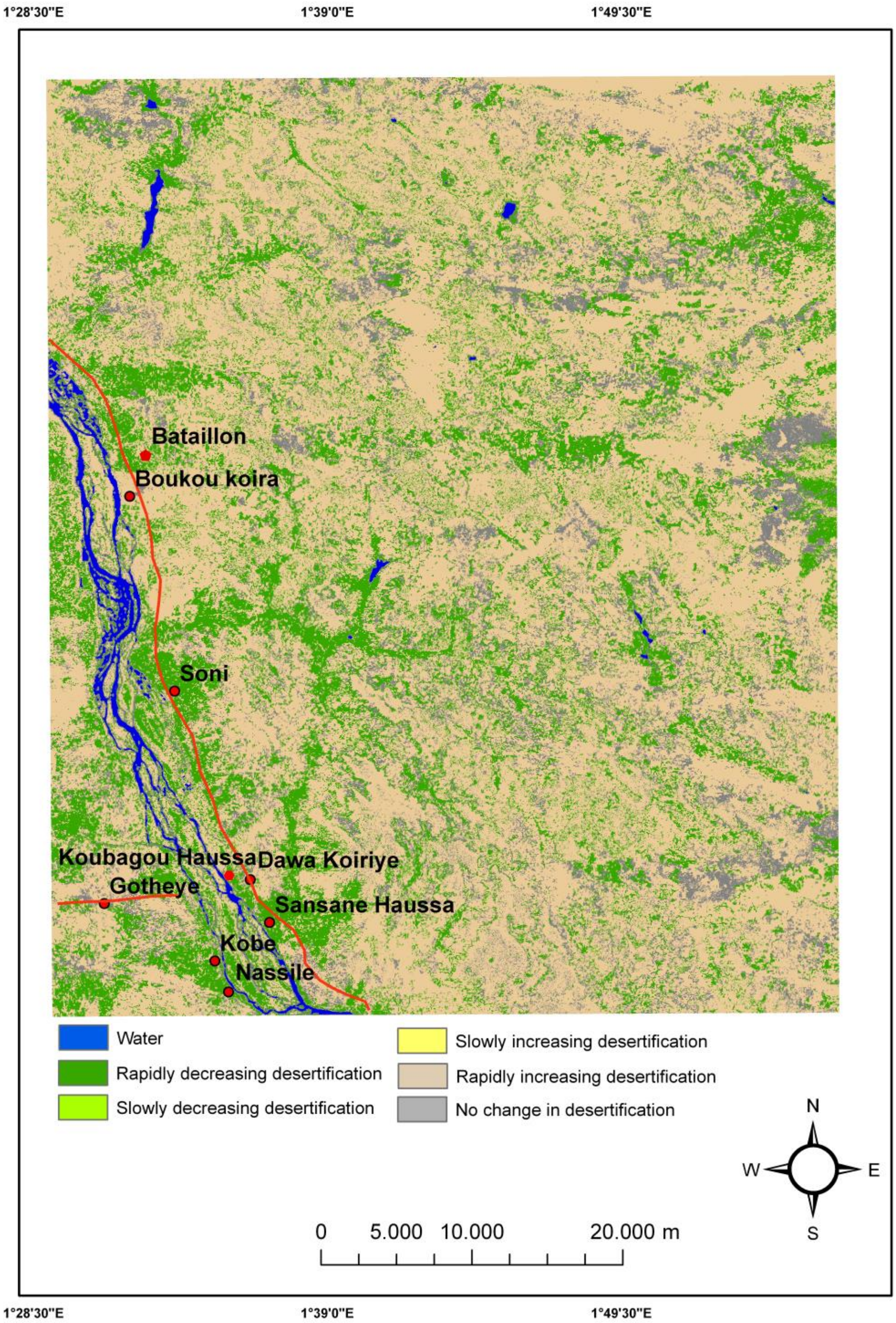


Figure 5.10: Velocity of desertification from 2001 to 2007.

Thematic change detection

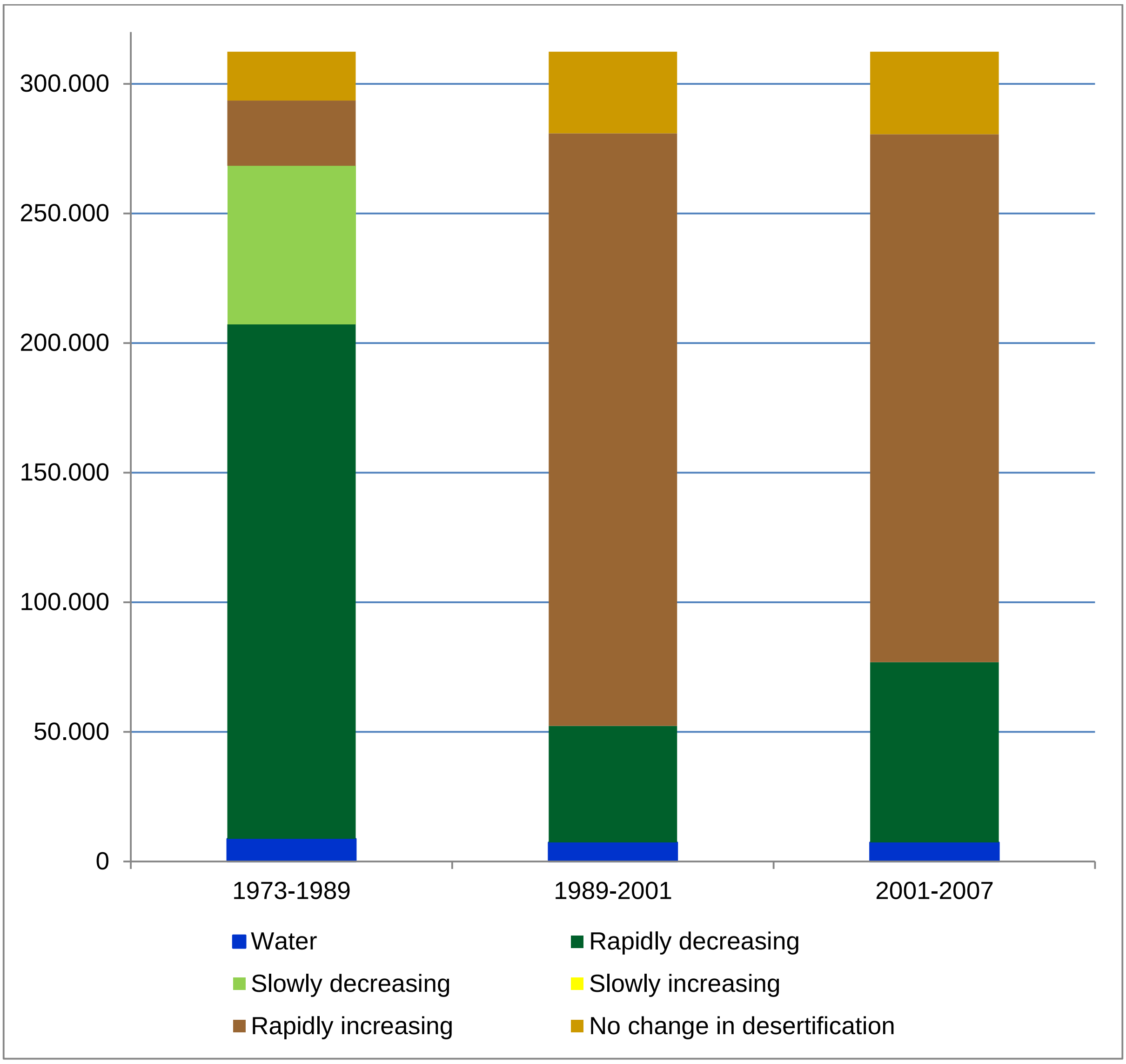


Figure 5.11: Velocity of change (in ha).

Analysis of the Landsat images shows an increase of land prone to desertification by 25,245 ha and 228,616 ha respectively in between the periods 1973 - 1989 and 1989 – 2001(figure 5.8, 5.9 and 5.11). A slight decrease is shown by 228,616 ha and 203,733 ha respectively in the periods 1989 - 2001 and 2001 - 2007 (figures 5.9, 5.10 and 5.11). The spatial distribution of rapidly increasing of desertification state in the northern part of the study area and the velocity of land desertification is obviously randomly distributed during of the study period.

5.3 Landscape Metrics for Monitoring and Evaluating Desertification and Land Degradation Phenomena

In this study the selection of metrics was based on monitoring and evaluating desertification and land degradation phenomena. A set of indices that represents the composition and configuration of landscapes was selected with a special view on desertification and land degradation. The set of indices given follows an order to detect the local drivers of land degradation and to improve management decisions in the study area. Due to difficulties in drawing the landscape metrics for the proposed area and to the problem caused of cloud cover with Landsat 2007 image, as a consequence of the required experience, not all of the study area was covered. In this section the capability of individual metrics to reliably quantify landscape structure will be investigated in the context of land degradation and desertification.

5.3.1 Landscape Composition Metrics

5.3.1.1 Area Metrics

The %LAND measures the proportional abundance of each class in the landscape. It is an important index for the investigation of the landscape composition.

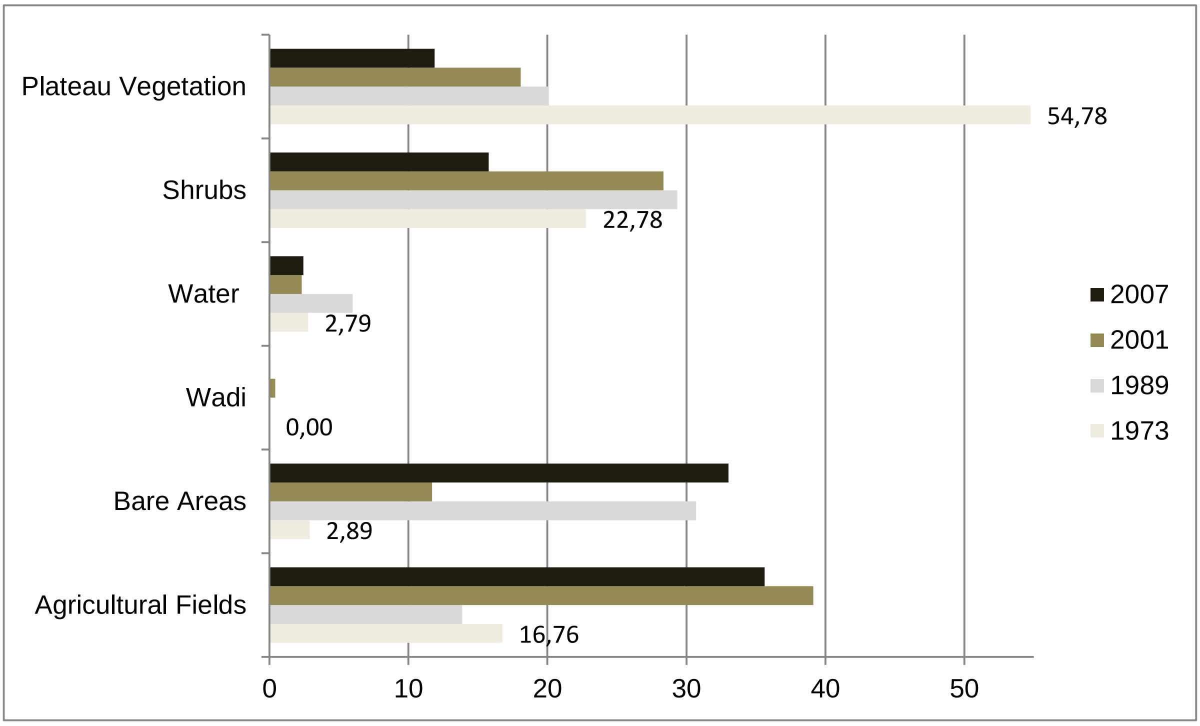


Figure 5.12: %LAND at class level from 1973 - 2007.

Landscape metrics

The %LAND indices show a decrease of plateau vegetation (54.78% in 1973, 20.11% in 1989, 18.07% in 2001 and 11.87% in 2007) and water (5.98% in 1989, and 2.34% in 2001). Also these indices show an increase of bare soil. The shrubs increased (22.78% in 1973 and 29.34% in 1989) as a result of greater planting activities. The shrubs decrease from 1989 to 2007 is attributed to human activities. %LAND is a very useful indicator for desertification investigations because it shows the degree of land degradation in the study area.

5.3.1.2 Patch Density, Patch Size and Variability Metrics

PD is the number of patches divided by the total landscape area. The unit of PD is number per 100 ha and it will be calculated at landscape level. PN measures the total number of patches of a specified land use/cover class. If PN is high it shows that the patch class is highly fragmented. Less connectivity, greater isolation and higher percentage of edge area in patches are provided by a fragmented landscape. PN can indicate the fragmentation level of a landscape. Knowledge how fragmented a landscape is helps in better planning of the landscape in question. PD, PN and LPI are calculated at landscape level.

Table 5.11: Indices of landscape structure from land cover classification maps.

Years / Indices	Image acquired in Sep. 1973	Image acquired in Sep. 1989	Image acquired in Sep. 2001	Image acquired in Sep. 2007
TA (ha)	312,545	312,345	312,345	312,345
PN (#)	33,678	148,298	189,013	54,721
PD (#/100ha)	11	47	61	18
LPI (%)	36	8	20	10

The investigation of the study area indicated that the PN increased (see table 5.11) as a consequence of fragmentation caused by greater development of bare areas. In general, the PN increased all over the study period. Consequently, the region became more fragmented. Development of bare areas is the main cause of landscape fragmentation, leading to desertification in the study area. PD increased between 1973 and 2001 and is evident for the growing desertification caused by growing population and overgrazing. The Tillabéry landscape has a large number of patches with smaller patch size, indicating, that the original landscape has been gradually converted into bare areas and the land degradation in the region has become serious.

5.3.1.3 Diversity Metrics

Diversity metrics are usually derived from information theory and involve the use of indices such as PR, SHDI and SIDI (Margalef, 1958). PR measures the number of classes within the landscape boundary. A greater diversity / heterogeneity is present if PR increases. SHDI measures the proportional abundance of patches and the equitable distribution of patch type areas; it increases with PR and equitability of the area. It is zero when there is only one patch in the landscape and increases with the number of patch types and as the proportional distribution of patch types increases. SIDI ranges between 0 and 1. A low value means that the landscape is dominated by a single land cover type and a high value means that the number of land cover types is high and they have equal proportion.

SHEI measures the distribution and abundance of patches. If it is zero it means the observed patch distribution is low and approaches one when the distribution of patch types becomes more even. MSIEI measures the distribution of area of patch types within a landscape over evenly distributed area of patch types. Low value (0) indicates uneven distribution of patch type areas and high value (1) indicates even distribution of area for the given number of patch types. For diversity (see table 5.12) PRD increased slightly throughout the observed period. PR increased from 1973 to 2007 caused by increasing of landscape elements (more classes), which means the decreasing of biodiversity as well as nutrient storage (soil degradation) and storm water retention in the study areas. The decline in nutrients shows trends in the decrease of soil fertility and affects the food security in the study area and also as a major contributing factor to conflict between farmers and pastoralists.

SIDI and SHDI increased from 1973 to 1989, but declined slightly from 1989 to 2007. This reflects a reduction in evenness, the landscape becoming dominated by large patches of a few land use types (shrubs and bare areas). During all the study period the SIDI indices are high (close to 1) that means the study area is not dominated by a single land cover type. MSIDI increased slightly from 1973 to 1989 and declined slightly from 1989 to 2007. All the three evenness indices (MSIDI, SIEI and MSIEI) increased from 1973 to 1989 and decreased slightly from 1989 to 2001. The increase of diversity and evenness during 1989 - 2001 is mainly attributed to the existence and increase of the river corridor and increase of landscape elements (classes).

Table 5.12: The quantitative indices of landscape diversity from land cover classification maps.

year / Index	Image acquired in Sep. 1973	Image acquired in Sep. 1989	Image acquired in Sep. 2001	Image acquired in Sep. 2007
PR (#)	5.0000	5.0000	6.0000	7.0000
PRD (#/100ha)	0.0016	0.0016	0.0019	0.0022
SHDI	1.1700	1.4900	1.4000	1.4200
SIDI	0.6200	0.7600	0.7200	0.7200
MSIDI	0.9600	1.4100	1.2700	1.2900
SHEI	0.7300	0.9200	0.7800	0.7300
MSIEI	0.6000	0.8800	0.7100	0.6600

Further interpretation of the land cover diversity processes can be done by evaluating and comparing maps of PRD and SHDI at landscape level using moving window approach (60 m radius). These maps (Figures 5.13 and 5.14) show the spatial distribution of diversity in the study area for the years 1973, 1989, 2001 and 2007. The diversity index is a combination of richness and evenness.

From the viewpoint of time series analysis, from 1973 to 2001 diversity and evenness became higher (see Figure 5.13 and 5.14); it indicates that the landscape heterogeneity and evenness increased and this can be attributed to an increasing in the number of classes (richness). Patch richness density increased from 1973 to 2001 attesting the increasing landscape heterogeneity. The more equal the share of the landscape elements, the higher the diversity and evenness.

Landscape metrics

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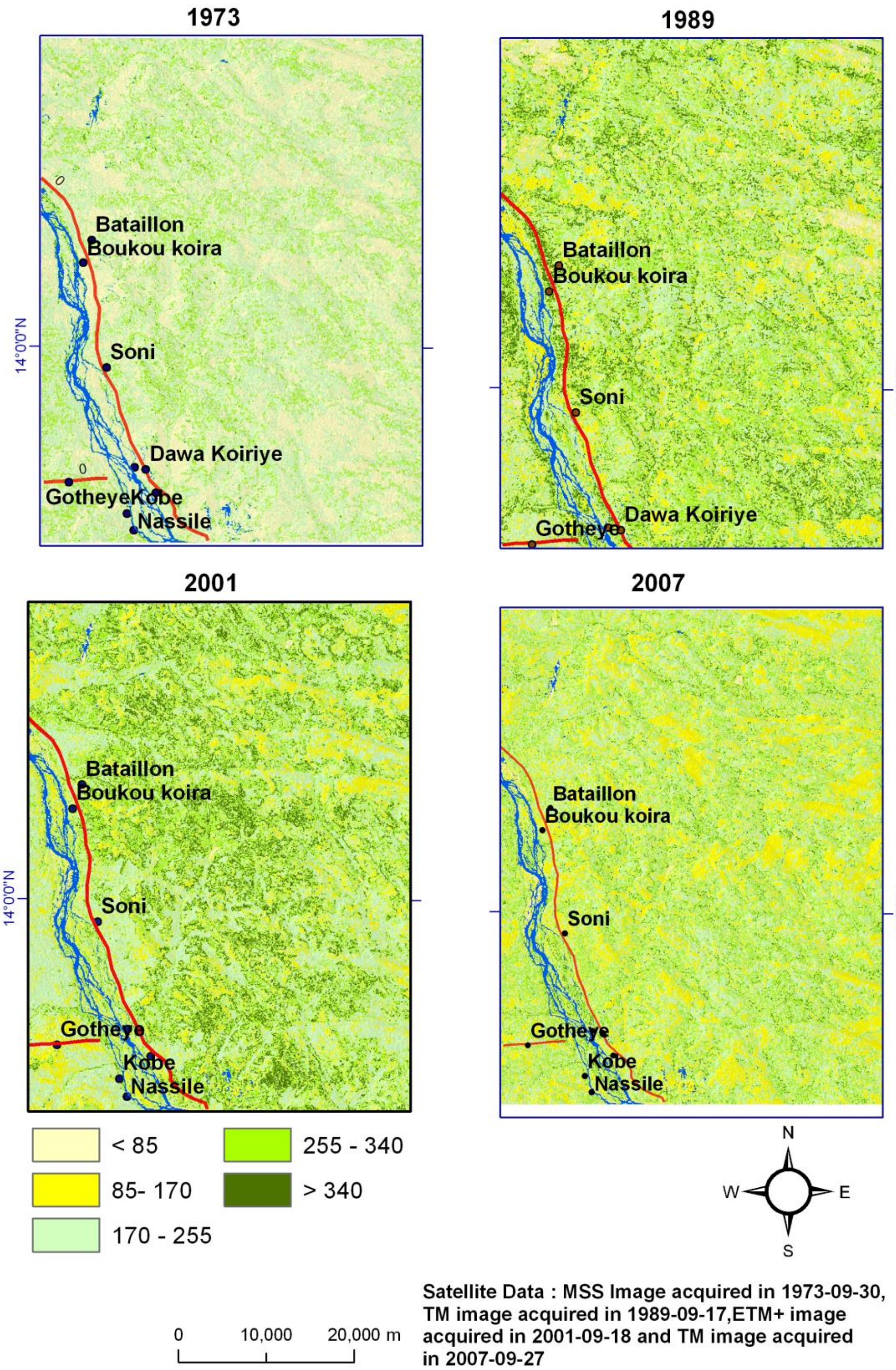

Figure 5.13: Patch richness density.

Landscape metrics

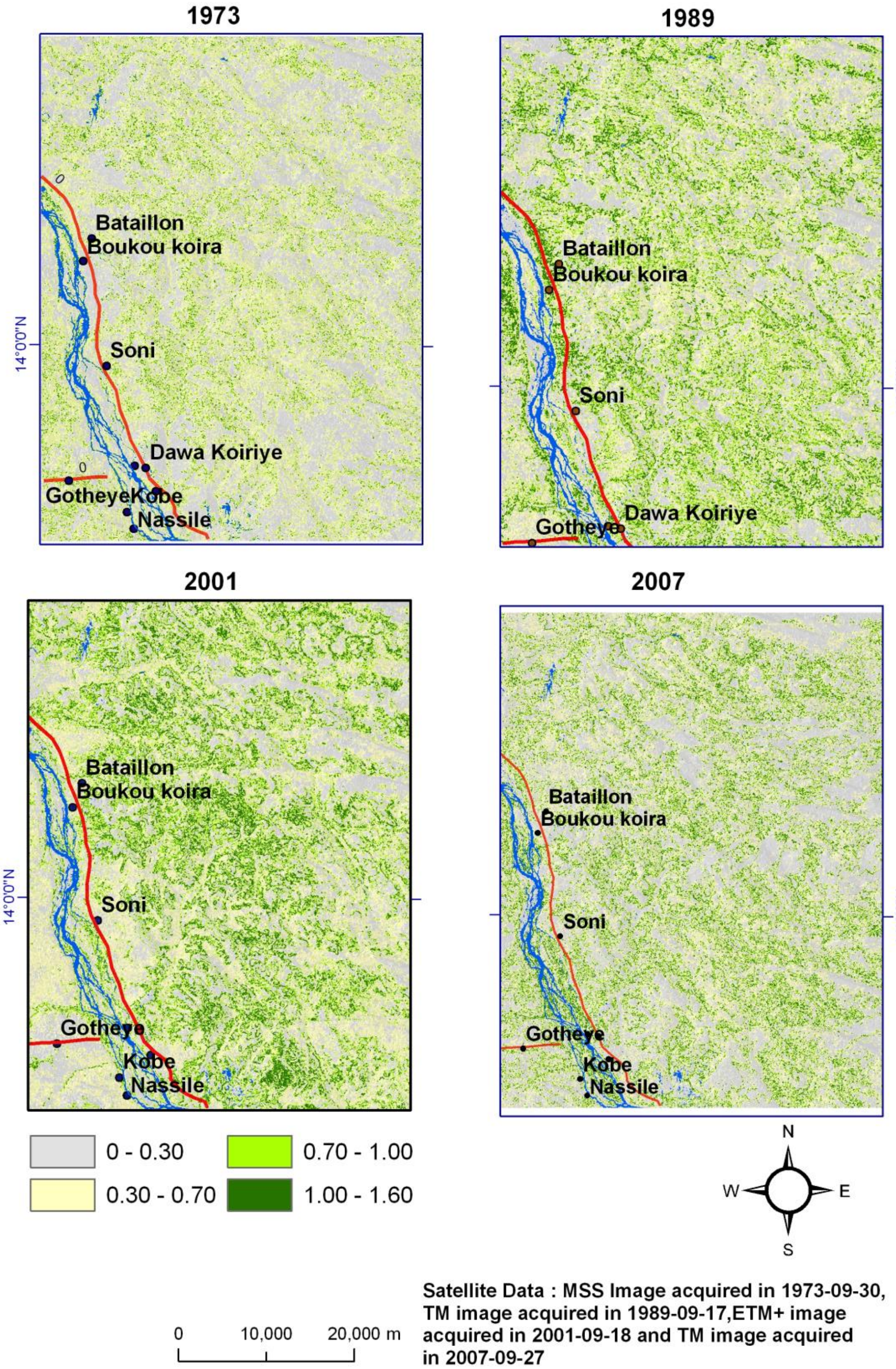

Figure 5.14: Shannon diversity Index.

Landscape metrics

During the study period, vegetation cover is characterised by high diversity index values. Bare areas exhibit the low diversity index values. From 2001 to 2007, the large areas that have been severely degraded and with low vegetation cover are characterised by low diversity index values. Low diversity index values are associated with degraded land. Diversity index is a sensitive indicator of landscape degradation.

5.3.2 Landscape Configuration Metrics

5.3.2.1 Shape Complexity: Shape Metrics and Fractal Dimension

LSI is the average patch perimeter / area ratio. It measures the shape of different patches. It shows change at the aggregation level, at class level. Mean patch fractal dimension (MPFD) it is more complex than those metrics previously mentioned. It measures the shape complexity at patch level. It is close to one when the shapes having simple perimeters and close to two when shapes are more complex (McGarigal & Marks, 1994). The calculation is weighted by individual patch area and larger patches tend to be more complex than smaller patches. This has the impact of measuring patch complexity independent of its size.

LSI is an index for landscape complexity. The evolution of LSI at the class level reveals that the majority of elements LSI elements increased from 1973 to 2001. That means all patches became increasingly disaggregated in the process of desertification. On the contrary, LSI of all patches decreased continuously from 2001 to 2007, indicating that those patches become more aggregated. A high value was observed in 2001 with Plateau vegetation indicating elongated shapes and small value in 1973 with agricultural field indicating compact shapes. Therefore, all the values of mean patch fractal dimension at class level are relatively high (close to one) values, which imply the shape of the landscape in this area is of rather simple forms (see Table 5.13).

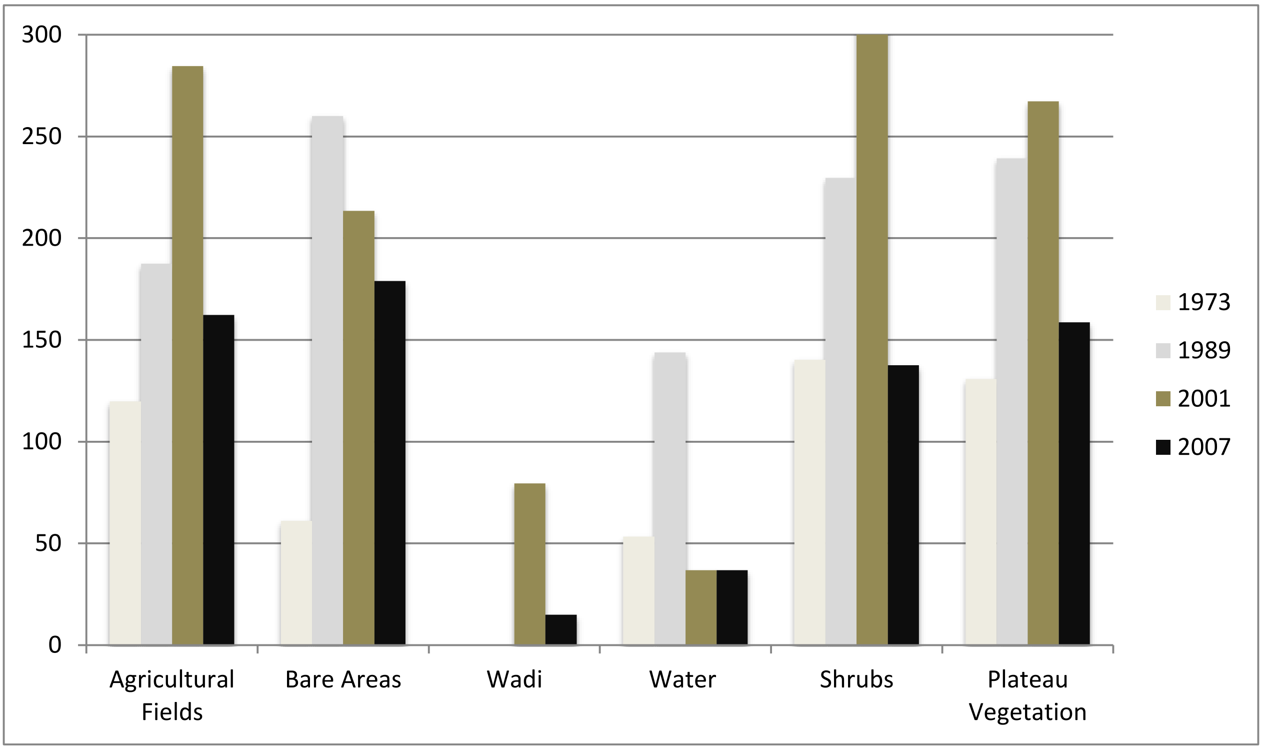

Figure 5.15: Evolution of Landscape Shape Index (LSI) at the class level (1973 - 2007).

Table 5.13: The value of Mean Patch Fractal Dimension (MPFD) at class level.

Class \ Year	Image acquired in Sep. 1973	Image acquired in Sep. 1989	Image acquired in Sep. 2001	Image acquired in Sep. 2007
Agricultural fields	1.04	1.04	1.04	1.04
Bare areas	1.03	1.04	1.03	1.04
Wadi	N/A	N/A	1.03	1.01
Water	1.03	1.03	1.03	1.02
Shrubs	1.04	1.04	1.04	1.04
Plateau vegetation	1.04	1.04	1.04	1.04

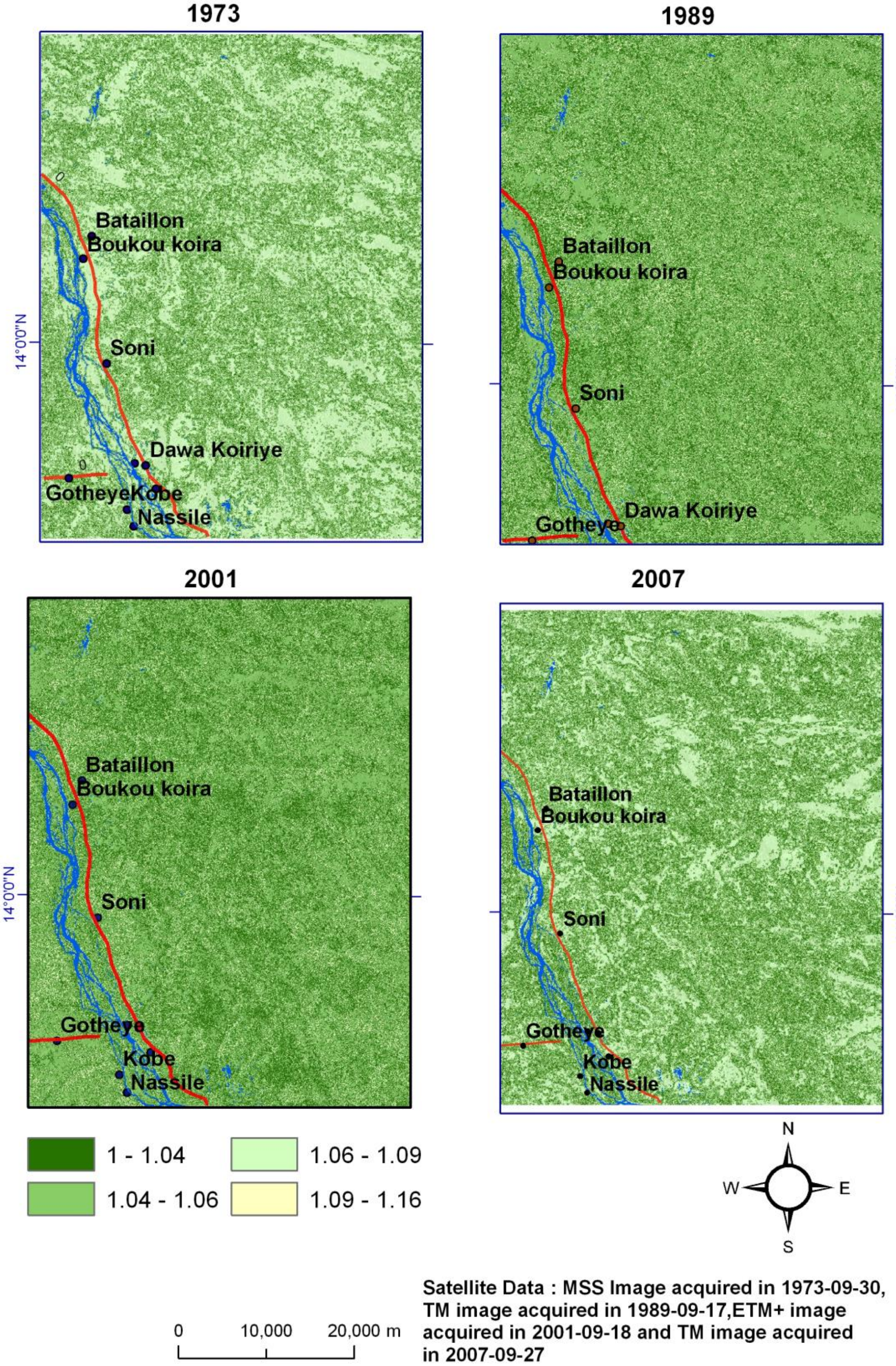

Figure 5.16 : Spatial distribution of Mean Patch Fractal Dimension Index.

Landscape metrics

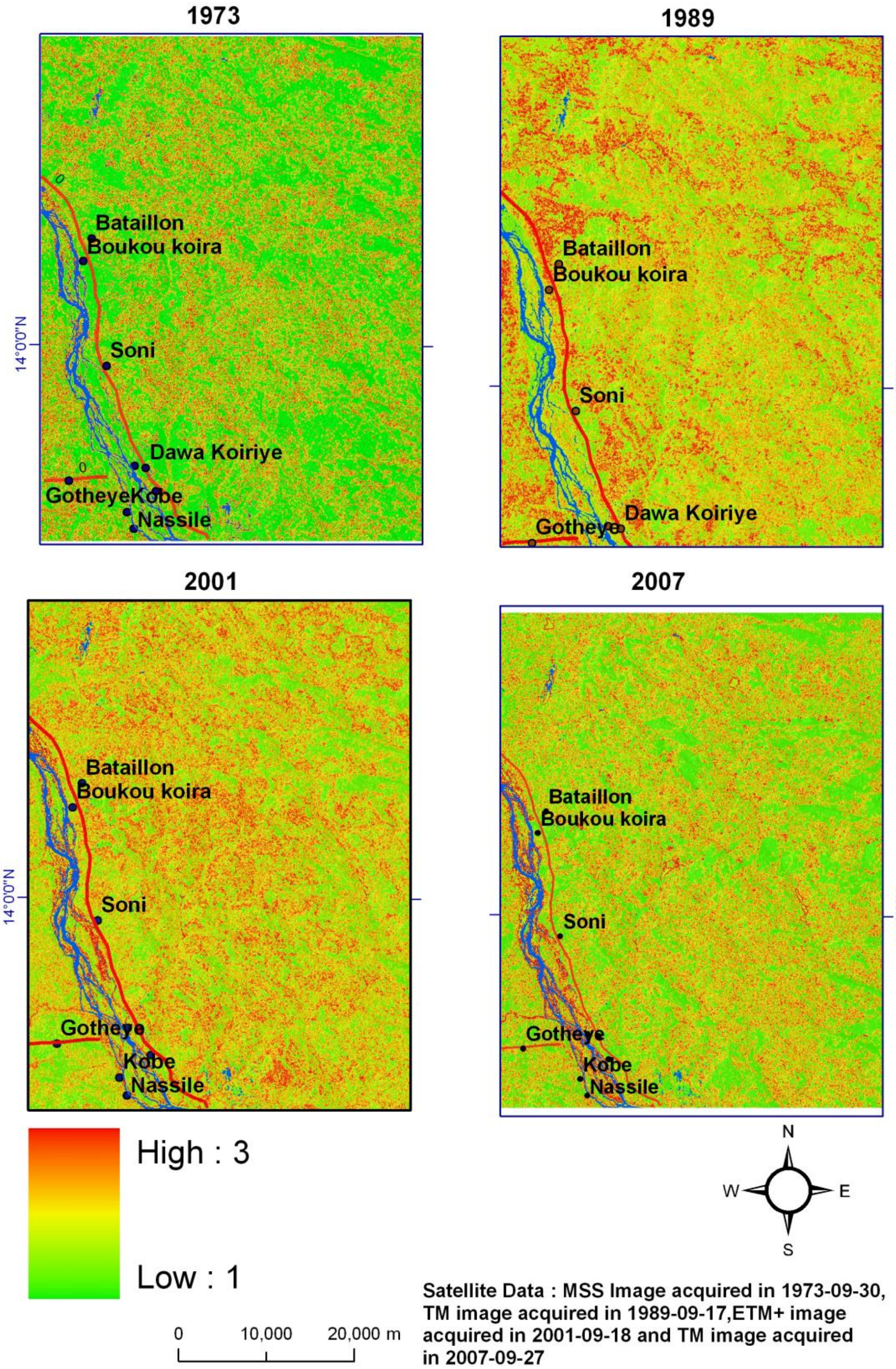

Figure 5.17: Spatial distribution of Landscape Shape Index (LSI) for study area.

Landscape metrics

Figure (5.16) shows the spatial distribution of the MPFD during the whole study period. High values are represented with a yellow colour while small values are identified with green. The yellow patches represent that the fractal dimension index are more complex in terms of the shape. Patches with green represent the lowest complexity and it indicates that the shape complexity for these patches decreased. Spatial distribution of LSI for study area is presented in figure 5.17. The figure indicates that the higher the LSI, the more fragmented the landscape is.

5.3.2.2 The Degree of Aggregation (Interspersion and Juxtaposition Index (IJI))

The goal of this part is to investigate the degree of clumping. The degree of clumping deals with two spatial aspects (dispersion and interspersion); for this reason IJI is selected for this investigation. It is expressed in percentage. IJI value approaches 0 when patch types are clumped (the distribution of unique patch adjacencies becomes uneven) and 100 when all patch types are equally adjacent to all other patch types. The index is independent of the number, size or dispersion of landscape elements.

The figures 5.18 and 5.19 show that the IJI for the majority of landscape elements decreased from 2001 to 2007, that means the land use types become poorly interspersed. But the IJI for all elements increases from 1973 to 2001 indicating a more uniform spatial distribution of these elements (uniform configuration of the landscape) and reflecting that they are dependent on water sources. High values of IJI are observed in 2001 with plateau vegetation implying the vegetation is adjacent to almost all other elements. In 1989, a low value is observed with agricultural areas element. This result agrees with the findings by Lal (2001).

Landscape metrics

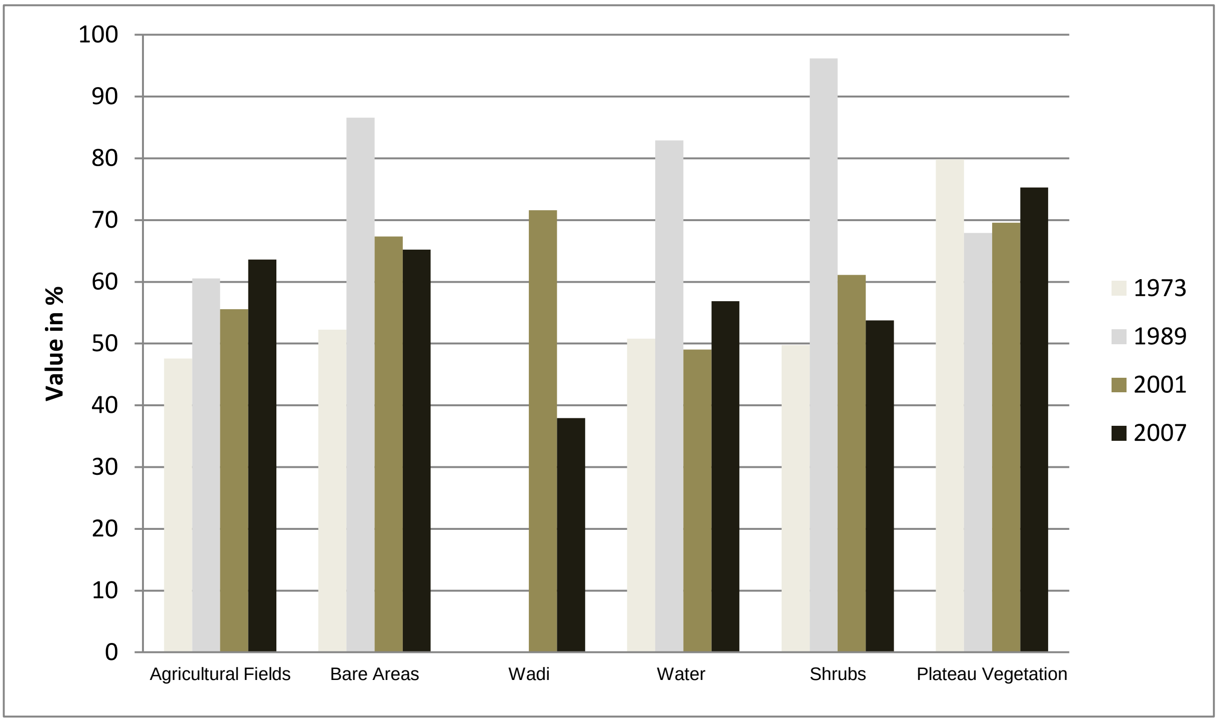

Figure 5.18: Evolution of Interspersion and Juxtaposition Index (IJI) at the class level (1973-2007).

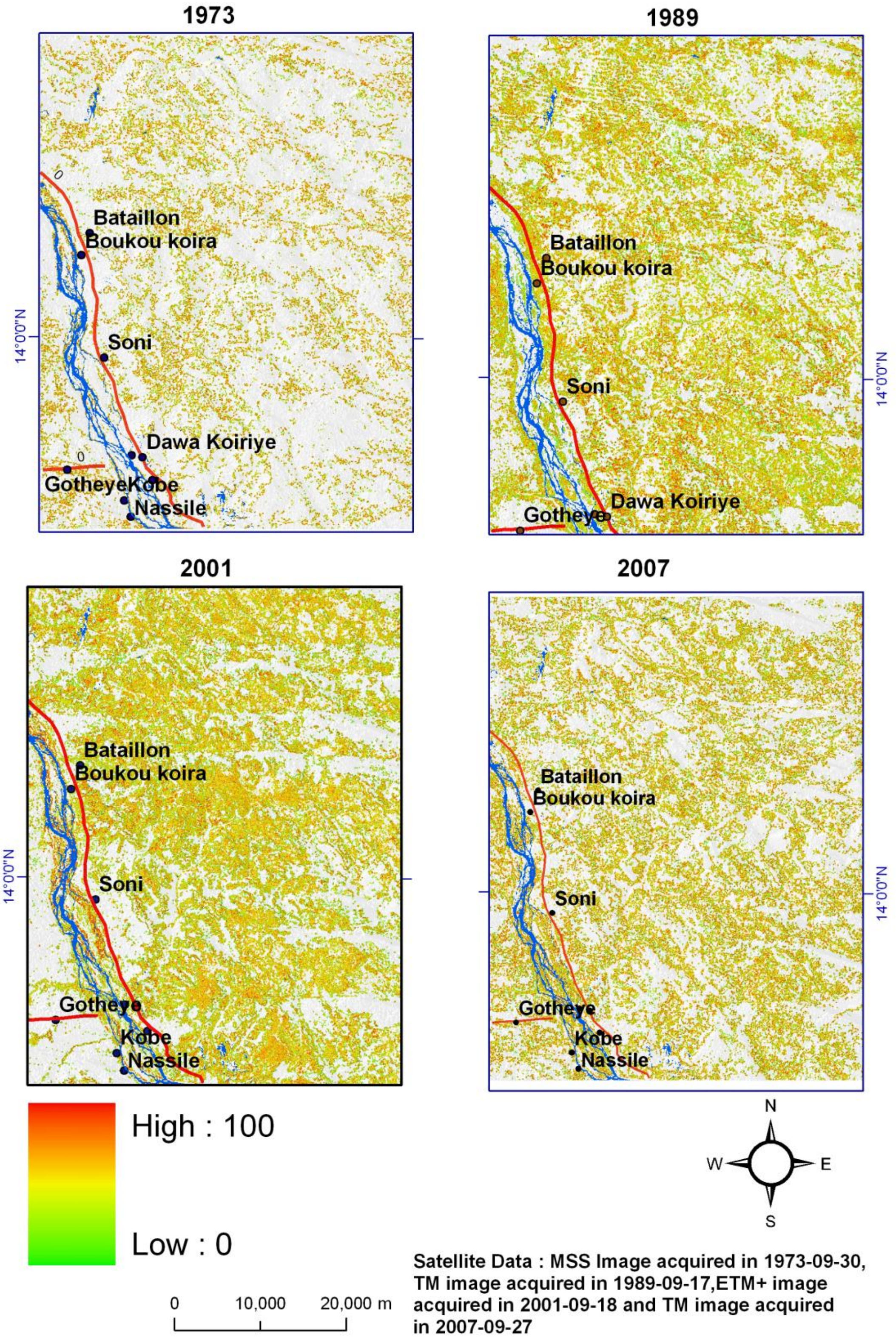

Figure 5.19: Spatial distribution of Interspersion and Juxtaposition Index (IJI) at the landscape level (1973-2007).

5.3.2.3 Isolation / Proximity: Mean Proximity Index, Cohesion and Mean Nearest Neighbour Distance

Proximity index is most suitable to analyse high contrast landscape where the land cover elements are distinct from the surrounding matrix and it is insensitive to the type of boundaries that exist within the landscape. This index distinguishes sparse distribution of small patches from clusters of large patches (McGarigal et al., 2002). A mean proximity index value is derived for each landscape class.

The MPX increases when the patch is larger and decreases as patches became smaller and sparse (Figure 5.20). Analysis on the class level shows the largest proximity index in the plateau vegetation zone is in 1973, suggesting strong continuity and concentrated distribution. The lowest values are observed within the wadi class during all the study period, indicating a very insular distribution of these patches. The mean proximity index of the plateau vegetation decreased during whole the study period. The mean proximity index of agricultural fields from 1973 to 2007 and for water from 1973 to 2001 became greater indicating that the spatial distribution of those elements during this period became more continuous.

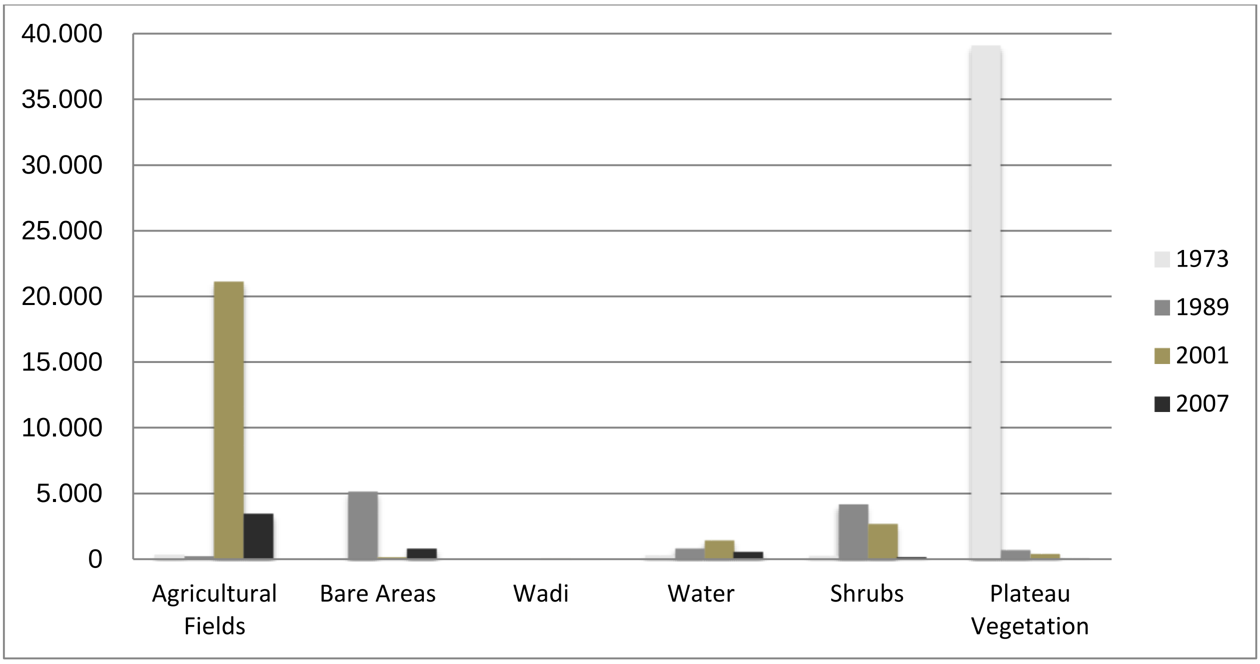

Figure 5.20: Evolution of Mean Proximity Index (MPX) at the class level (1973-2007).

Landscape metrics

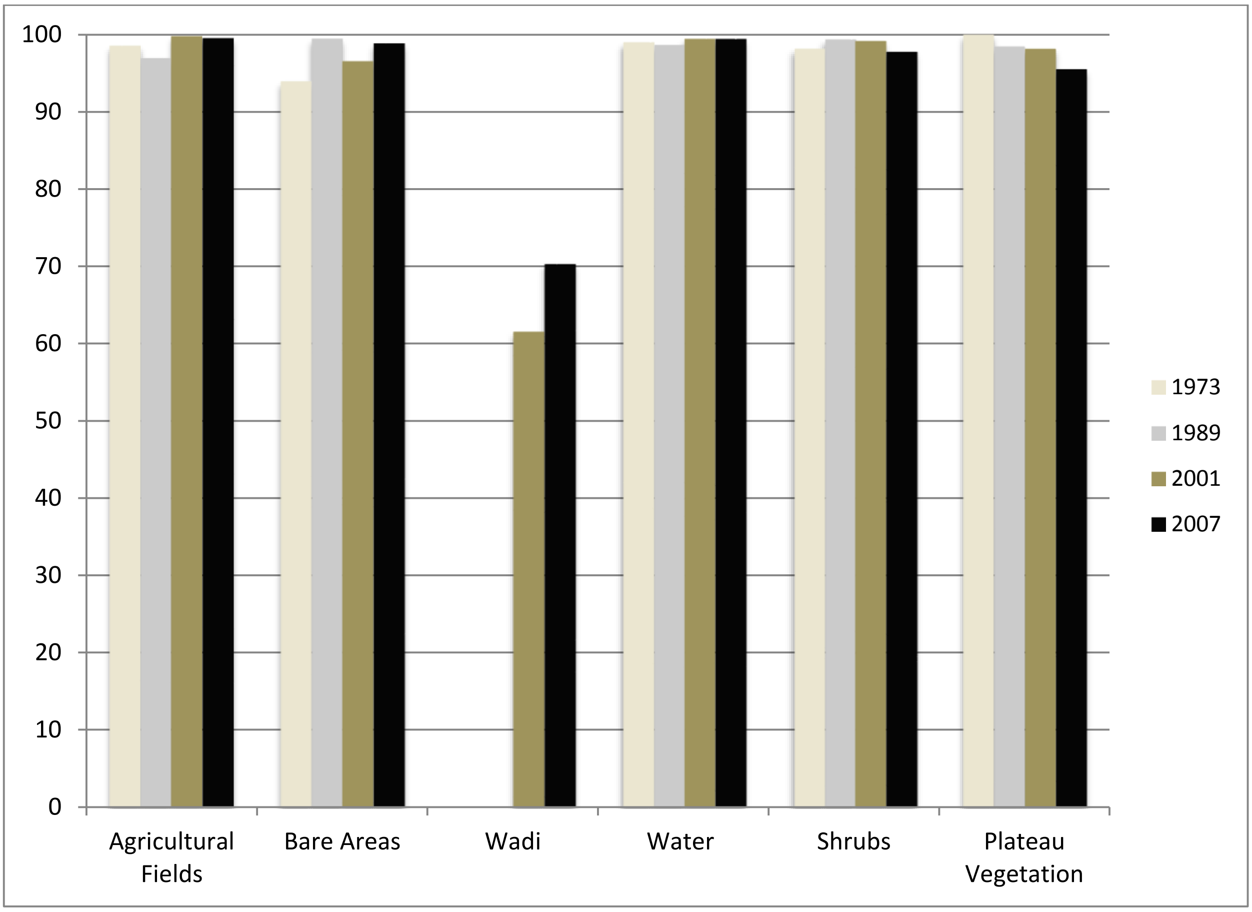

Figure 5.21: Evolution of Cohesion Index at the class level (1973-2007).

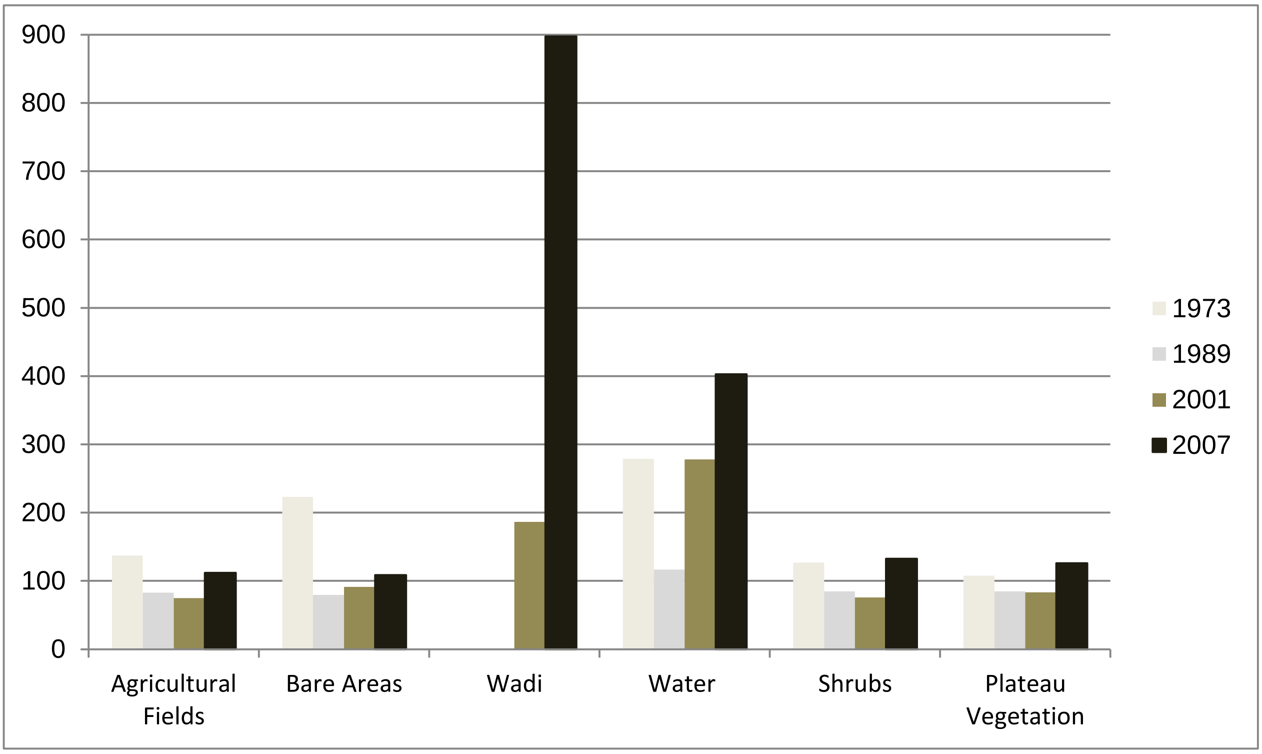

Figure 5.22: Evolution of Mean Euclidian Nearest Neighbour Distance at the class level (1973-2007).

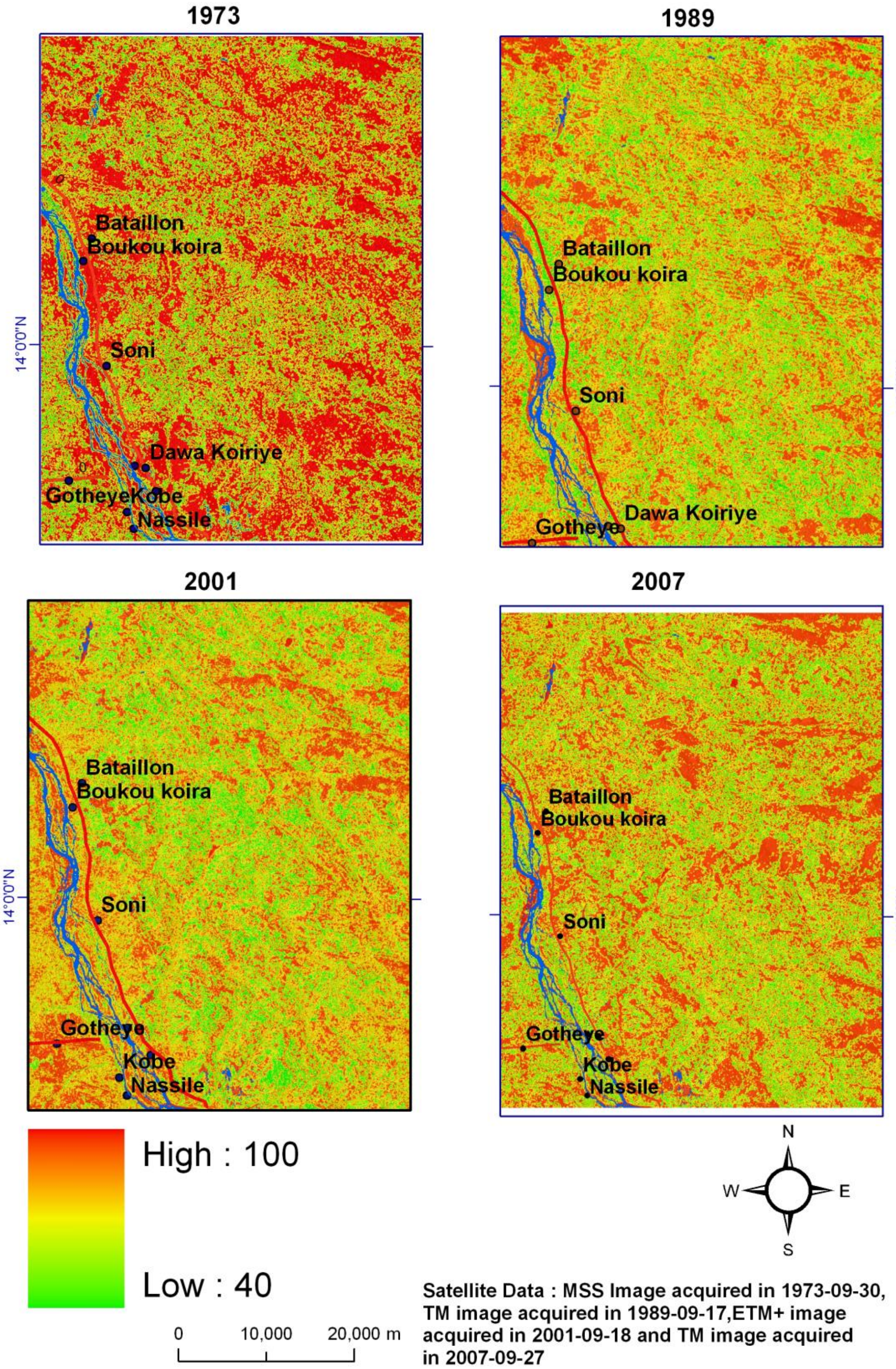

Figure 5.23: Spatial distribution of Cohesion Index during study period.

Landscape metrics

The cohesion index is very high during all the study period and for all the classes. The spatial distributions of these results are shown in Fig 5.23. High values are denoted with a red colour while small values are identified with light green. There was a significant sensibility of cohesion index among the land cover elements. A higher degree of cohesion was found with shrubs meanwhile the lowest degrees of cohesion were observed with bare areas. Furthermore, the cohesion index showed a reduction over the period 1973-2001. This is greatly related to the unchanged main component of the landscape and showed a decrease in physical connectedness of the land cover, but it faced some increases in the 200-2007 study period as shown by the cohesion index. The increased cohesion for the wadi class during all the study period offers evidence of a growing Niger River degradation.

5.4 Synthetic Indices for the Monitoring of the Fragmentation Rate

At class level, we investigated the change of vegetation cover and water fragmentation spatial patterns by using the mesh index. The vegetation (shrubs and plateau vegetation) and water patches are resistant elements to desertification, therefore the fragmentation of this class diminishes the resistance of the landscape towards desertification. The mesh index is a capacity for the degree of freedom to move. It gives an easy-to-use and helpful method to quantifying landscape fragmentation. The developments and application of this index were executed by many researchers (Jaeger, 2000; Forman et al., and Jaeger et al., 2007).

Jaeger et al. (2007) reported that this index is a potential indicator to test the differences in fragmentation caused by physical barriers and anthropogenic barriers between ecosystems. The mesh index further allowed for an equitable comparison of the rate of fragmentation among regions and among different land covers (Jaeger et al., 2007). In 2004, the German Conference of the Ministers of the Environment adopted this index as a “core indicator“ for calculation effective mesh size in all German federal states (Jaeger et al., 2007).

At landscape level the change of landscape fragmentation, was performed by means of particular sets of metrics selected in order to highlight the understanding. It is commonly accepted that no single index can quantify all aspect of landscape fragmentation (McGarigal et al., 2002). The change of landscape diversity was investigated at landscape level by means of particular sets of indices proposed in the methodology in order to reinforce our interpretation.

5.4.1 Internal Water and Vegetation Landscape Fragmentation Analyses

The following sub-paragraphs demonstrate the results of the landscape fragmentation analysis performed at class level for the four Landsat images. Particularly, the rate of fragmentation analysis is based on an algorithm called **one- step inverse mesh index** approach. The algorithm is suitable for fragmentation model.

Landscape metrics

5.4.1.1 Fragmentation Rate of Niger Rivers Areas

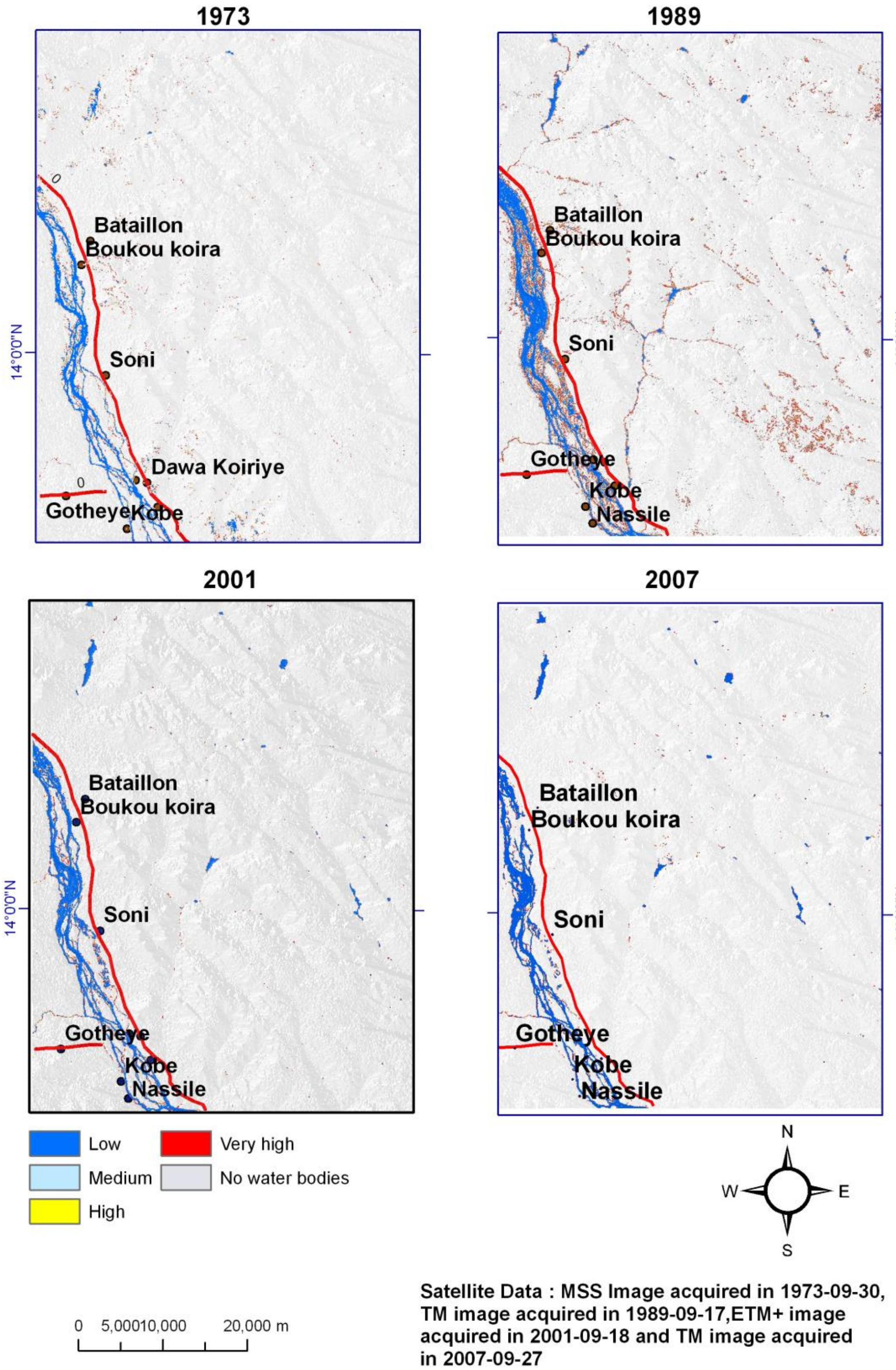

Figure 5.24: Water fragmentation rate (1973, 1989, 2001 and 2007).

Landscape metrics

The figure 5.24 illustrates the spatial variation of fragmentation of water surface in the study area and in the different years under investigation. The figure includes rate of fragmentation of water bodies classes, subdivided into four groups: low, medium, high and very high. Dark blue, blue, yellow and red indicated low, medium, high and very high respectively. Gray areas indicate areas not affected by water fragmentation or unfragmented.

This index does not reflect only the fragmentation rate of water areas, but also the connectivity level (very high connectivity of water areas) and how the fragmentation took place over time. As seen in the figures, the maps indicate low fragmentation and high connectivity of water surfaces during all the study periods due to lack of dams and low irrigation systems. Also, the results showed that the Niger River (water area) decreased from 1989 to 2007.

5.4.1.2 Fragmentation of Shrub Areas

Estimation of fragmentation is a good indicator of the status of diversity. The spatial distribution of shrubs fragmentation could provide us more information in deciding about what to conserve and where to conserve. Figure 5.25 show the spatial rates at which shrubs areas were fragmentated and these are represented according to the different years under investigation.

The biggest rates are represented with a red colour, small rates are identified with yellow while gray areas indicate land not covered by water or unfragmented. It was observed that in 1973 the spatial distribution of the fragmentation of shrubs occupied a small area, even though the spatial distribution of this index increases continuously over time. The very high rates are observed from 1989 to 2007 in the centre and northern part of the study area.

Landscape metrics

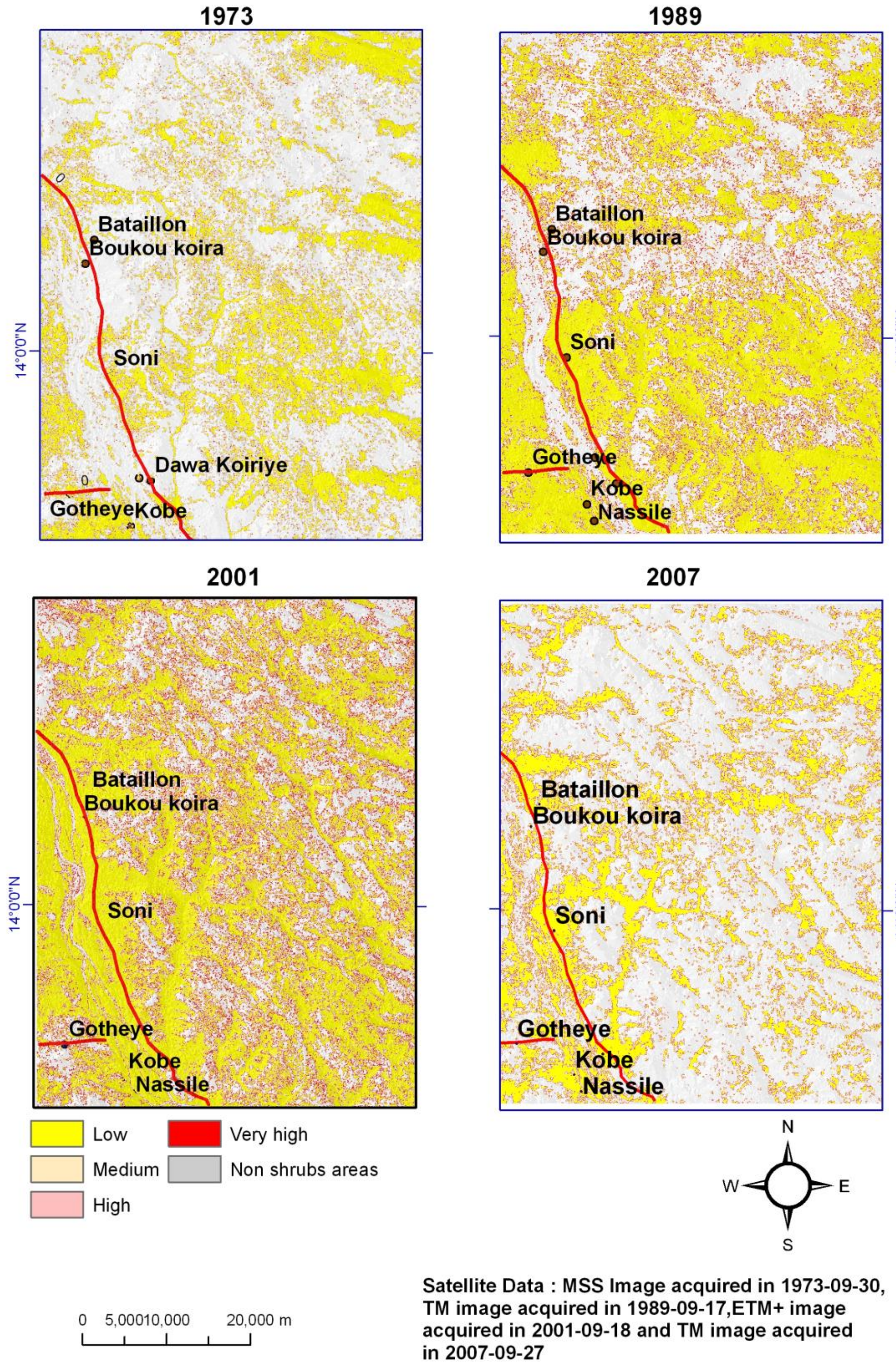

Figure 5.25: Shrubs fragmentation rate (1973, 1989, 2001 and 2007).

5.4.1.3 Fragmentation Rate of Plateau Vegetation

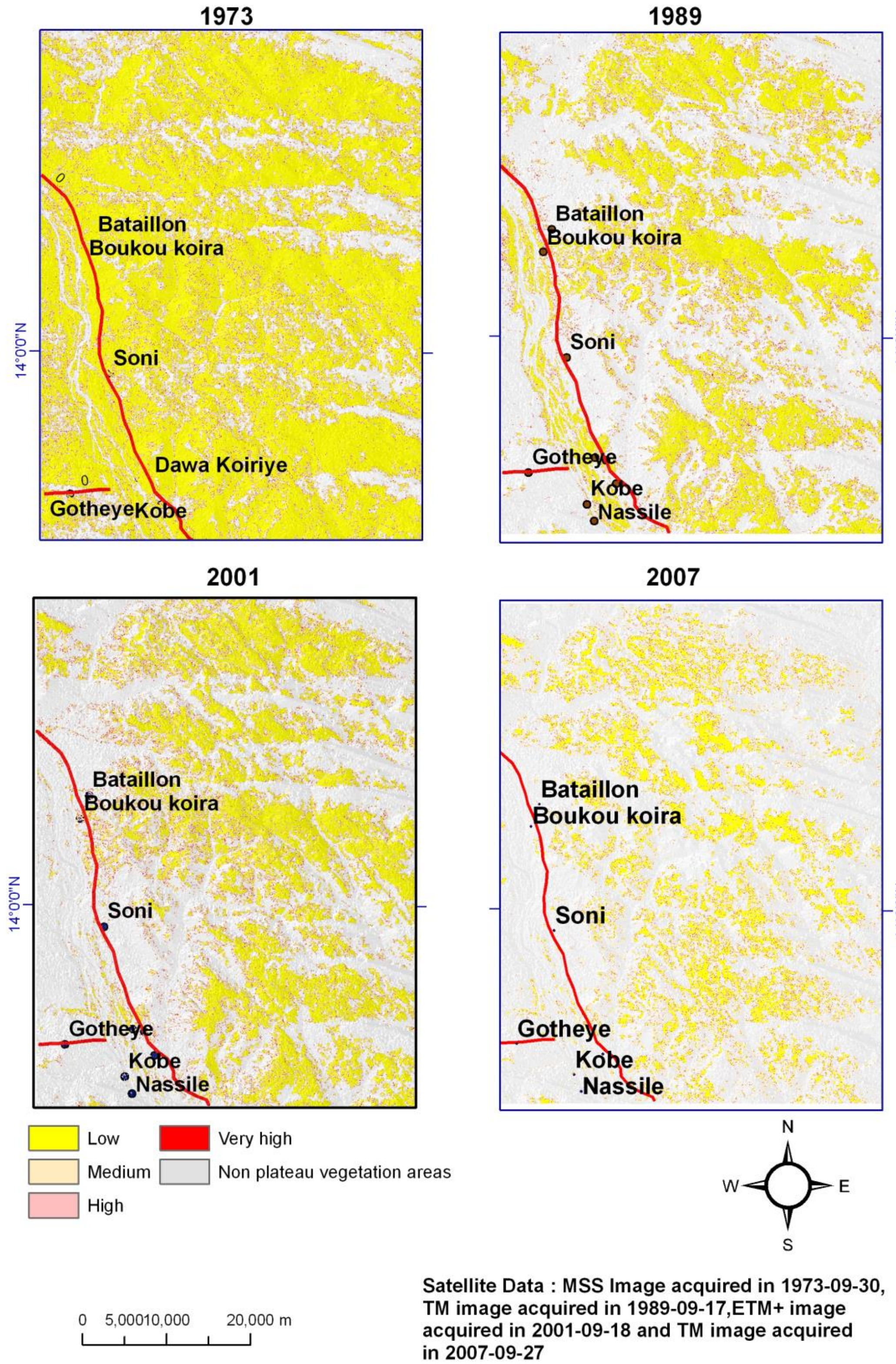

Figure 5.26: Plateau vegetation fragmentation rate (1973, 1989, 2001 and 2007).

Landscape metrics

Plateau vegetation fragmentation is expected to influence the abundance of different plant species to a different extent. The figure 5.26 depicts the degree of plateau vegetation fragmentation. Small degrees are represented with yellow and the biggest degree by red. Gray areas indicate land not covered by plateau vegetation. During all the study period, the dominant level of plateau vegetation fragmentation is low level. But from 1989 to 2007 the high and very high levels are presented in the centre and the northern part of study area. It may result from land use features such as road, agricultural field and built-up. Today, this plateau vegetation is in danger of extinction by changes in agricultural practices or development of bare areas.

5.4.2 Monitoring Landscape Fragmentation at Landscape Level (as Environmental Indicator)

Landscape fragmentation is considered as a main menace to biodiversity and desertification in the study area. It decreases the area suitable to the species (animal and vegetation) and generates isolated subpopulations. Also, the landscape fragmentation manipulates interactions among species (Braschler et al., 2003). The following sub-paragraphs demonstrate the results of the rate of landscape fragmentation and the reduction of landscape connectivity.

The results of the fragmentation analysis at landscape level are shown in figures 5.27, 5.28, 5.29, and 5.30. High values are identified with a red colour and low values are represented with a yellow colour. The yellow colour further indicates that the patches have low destruction degree and high connectivity. A visual interpretation of the degree of fragmentation based on the images for 1973, 1989, 2001 and 2007, it is clear that the high value increased from 1973 (0.9) to 2001 (2.15) and decreased from 2001 (2.15) to 2007 (1.20). The spatial distribution of the high value of fragmentation seems a bit randomly distributed and corresponds to the land cover without vegetation cover (bare areas). It can be noted that this areas have been severely fragmented. Therefore, a low fragmentation value corresponds to the land cover class such as river, shrubs and plateau vegetation.

Landscape metrics

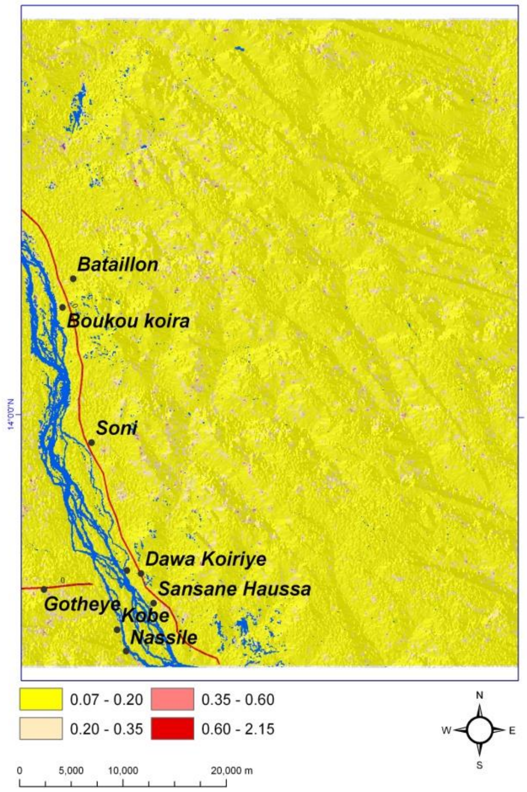

Figure 5.27: Degree of fragmentation rate from Landsat MSS image acquired in 1973-09-30.

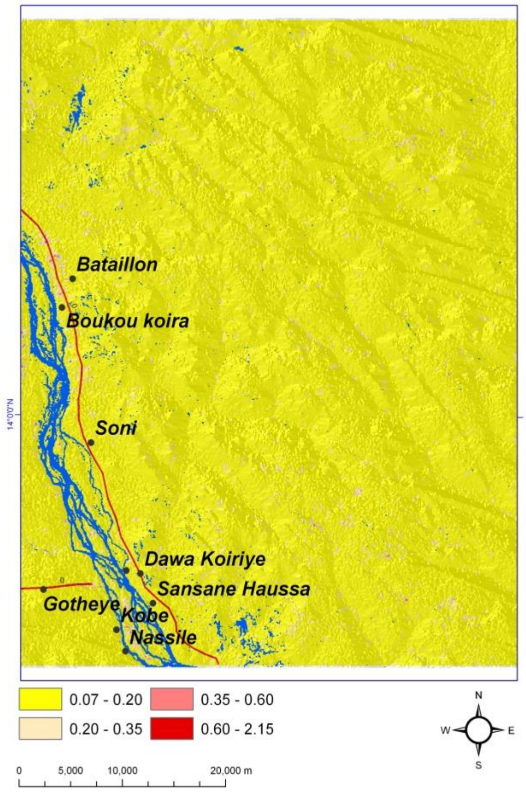

Figure 5.28: Degree of fragmentation rate from landsat TM image acquired in1989-09-17.

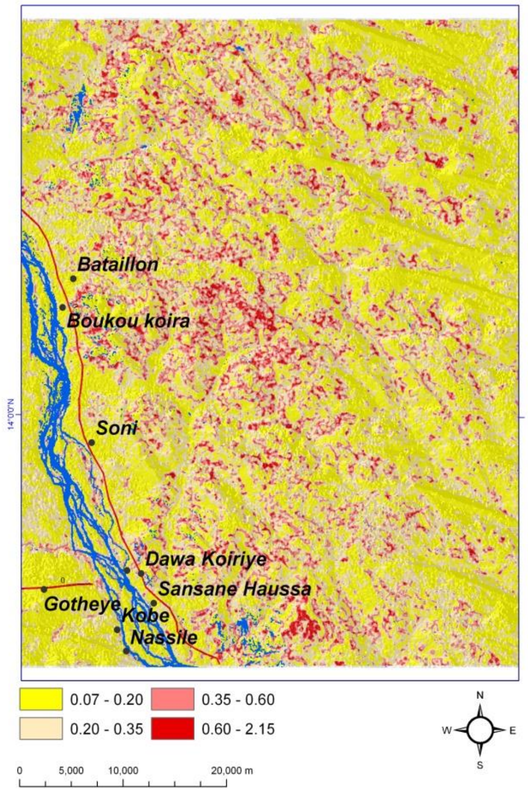

Figure 5.29: Degree of fragmentation rate from Landsat ETM +image acquired in 2001-09-18.

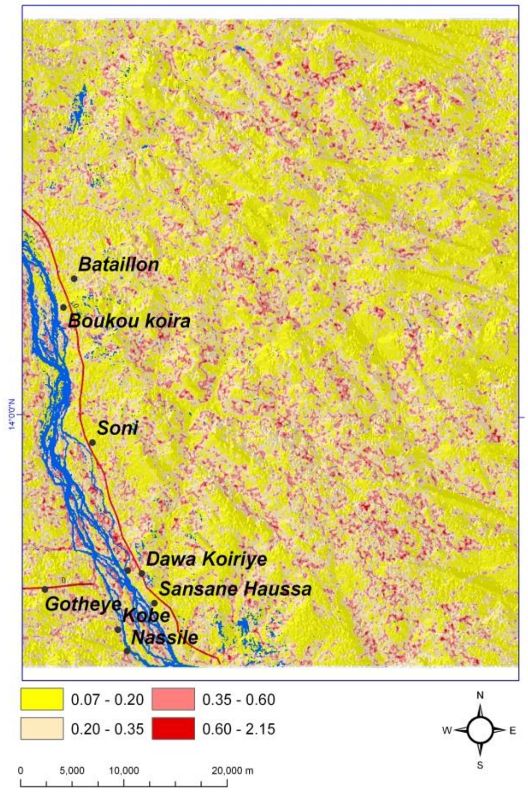

Figure 5.30: Degree of fragmentation rate from Landsat TM image acquired in 2007-09-27.

Landscape metrics

The analysis evidently exposes the state of landscape fragmentation over time. In 1973 the study area shows lower degree of fragmentation values, compared to 1989, 2001 and 2007. The spatial distribution of the degree of fragmentation indicates that the fragmented areas were increased considerably between 1989 and 2001 especially around the Niger River and the centre of the area of investigation (figures 5.28 and 5.29).

5.4.3 Changes in the Landscape Structure of the Study Area

This sub-section of the thesis was dealt with the changes in landscape structure with a special view on desertification. Due to the importance of landscape structure for desertification, it is essential to develop indicators for monitoring desertification at the level of landscape by combining a set of indicators. The indicator system, therefore, is composed of four landscape indicators: diversity of landscape (SHDI) fragmentation of landscape (MESH), irregularity of patches - the shape of different patches (LSI) and Mean Patch Area Index (.MPA).

From the maps (figures 5.31, 5.32 and 5.33), it can be observed that the landscape structure of the Tillabéry landscape has significantly changed over the 34 year study period. From visual interpretation of the landscape structure changes index, we can observe that the spatial distribution of high value of landscape structure changes seems a bit randomly distributed during the three different periods. But from 1973 to 1989 and 2001 to 2007 the high values of landscape structure change occurred in the centre and close to the main water body due to natural forces and human activities in this part of the study area. Again, the most extreme changes in the vegetation patch area were recorded in this part of the study area. The Tillabéry landscape was affected by development of agricultural lands and bare areas. The development of bare areas in fact eliminated the largest patches of vegetation cover, shortened patch shapes for all land cover classes and altered natural adjacencies of patch types within the landscape. This invariably affected the functionality of landscape. The density of agricultural land is an indication of increasing of population presence in the landscape. On the one hand, the landscape structure change index (1973-1989, 1989-2001 and 2001-2007) showed the highest level of change in the landscape with violet colour toward a more fragmented area illustrated by decreasingly larger patches and increasingly homogeneous land cover structure, more irregular patches.

Landscape metrics

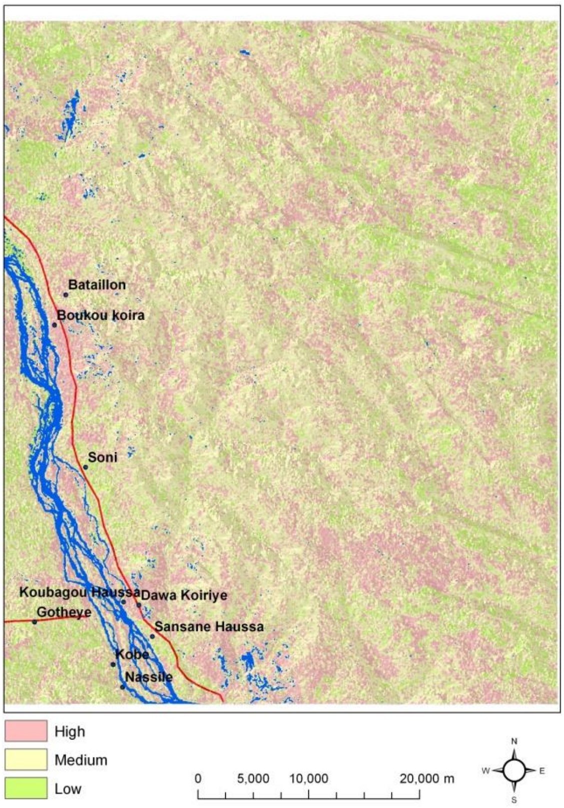

Figure 5.31: Landscape structure change from 1973 to 1989.

Figure 5.32: Landscape structure change from 1989 to 2001.

Figure 5.33: Landscape structure change from 2001 to 2007.

On the other hand, this index showed the lowest value of change in the landscape structure with yellow-green color in which the mesh index and diversity index continuously decreased over time, indicating the smaller risk of land fragmentation. These results validate the importance of vegetation cover in semi-arid Sahel to prevent negative changes of landscape structure. The mapping of changes in the landscape structure of the Tillabéry landscape has given good information about its disintegrating conditions.

Landscape metrics

Due to the significant increase of bare areas and a decrease in vegetation areas, particularly due to desert, the Tillabéry landscape has become more fragmented, less connected vegetation patches, lower diversity in landscape structure and lower productivity. Finally, the synthetic index of landscape structure can be successfully applied to the entire Sahel landscape.

5.4.4 Desertified Index

Desertification index was used to integrate and summarise the state of desertification in the study area. A three-step approach (amount and direction of change, velocity of change and change of landscape structure) based on Medalus methodological (Kirkby, 1998) framework was developed to characterise the change of desertification in the study area.

According to this model, the index of desertification (desertified index) has been grouped into 5 classes involved: Very high (DI) is a combination of high values of landscape structure index, signifying the conversion of shrubs to bare areas from amount and direction of change and increasing elements in the velocity of change. High (DI) is a combination of high values of landscape structure index, indicating the conversion of plateau vegetation to bare areas and increasing elements of velocity of change. Moderate (DI) is a different combination dominated by a simple combination of medium landscape structure values, depicting conversion of agricultural land to bare areas, and no change in the context of velocity. Low (DI) is a combination of low values of landscape structure index and no change in the context of amount, direction and velocity. Very low (DI) is a combination of low values of landscape structure index, decreased elements from velocity of change and positive changes from amount and direction of change.

Attribute information in percentage of the desertification land in the study area during the three different time intervals is shown in figure 5.34. During the time interval 1973 - 1989, the area of very high desertified land achieved 1.3% of the total area, of which high, moderate, low and very low desertified land were 6.21%, 30.5%, 36.6% and 25.39% respectively.

Desertified Index

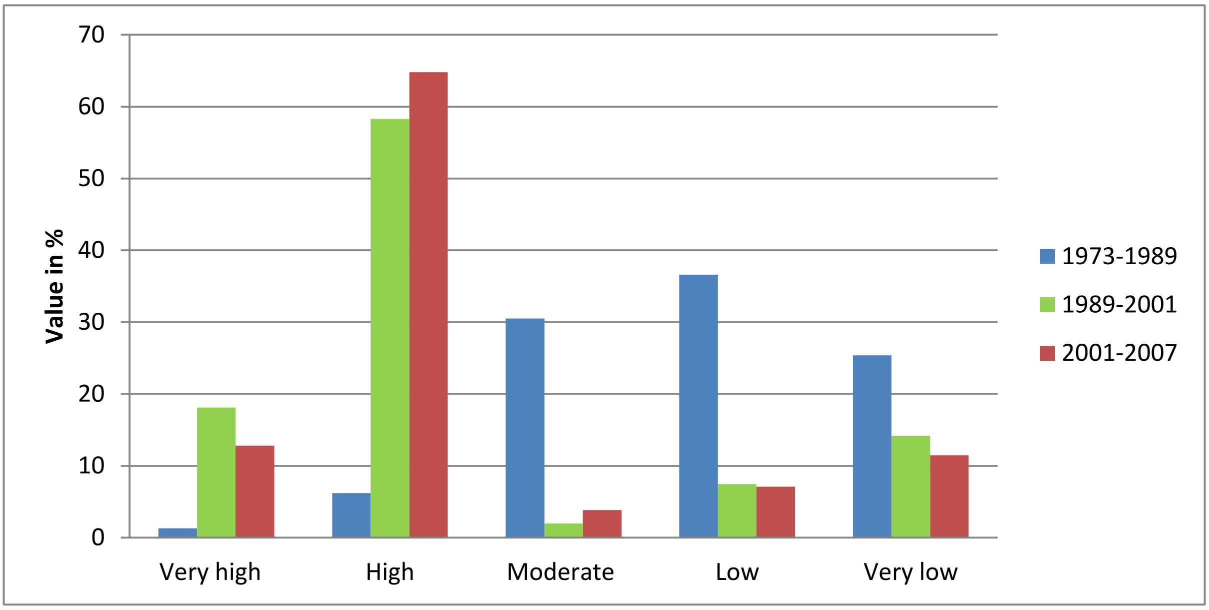

Figure 5.34: Area percentage of desertified land area during the intervals of 1973-1989, 1989-2001 and 2001-2007**.**

During the interval 1989 - 2001 the area of very high desertified land increased to 18.1% (56,283 ha) of the total land area, of which, high, moderate, low and very low desertified land areas were 58.29%, 1.98%, 7.43% and 14.2% respectively. By the interval period 2001 - 2007, the area of very high desertified land increased compared to the interval 1973 - 1989. This decreased slowly compared to the interval 1989 - 2001 which was 12.79% (39,785 ha) of the total land, of which high, moderate, low and very low desertified land areas were 64.82%, 3.85%, 7.1% and 11.44% respectively

On the one hand, the statistics point out that the very low and low for the type of desertification in three different intervals was highly decreased (very low: interval period 1973 - 1989, 1989 - 2001 and 2001 - 2007 were 25.39%, 14.2% and 11.44% respectively and low: interval period 1973 - 1989, 1989 - 2001 and 2001 - 2007 were 36.6%, 7.43% and 7.1% respectively).

On the other hand, the statistics indicate that the very high and high for the type of desertification in three different intervals was increased (very high: interval period 1973 - 1989, 1989 - 2001 and 2001 - 2007 were 1.30%, 18.10% and 12.79 % respectively and high: interval period 1973 - 1989, 1989 - 2001 and 2001 - 2007 were 6.21%, 58.29% and 64.82 % respectively). This result agrees with the findings of Amogu et al. (2010).

Desertified Index

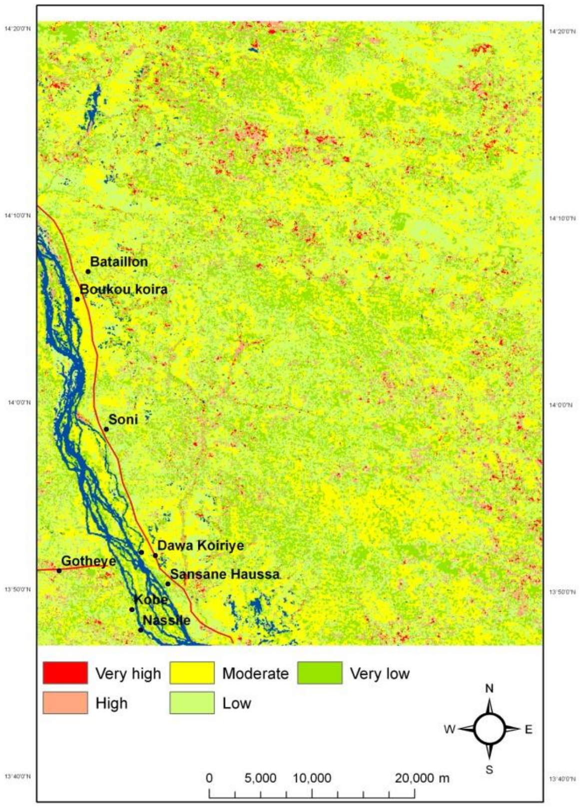

Figure 5.35: Spatial distribution of desertified land area during the interval of 1973 - 1989.

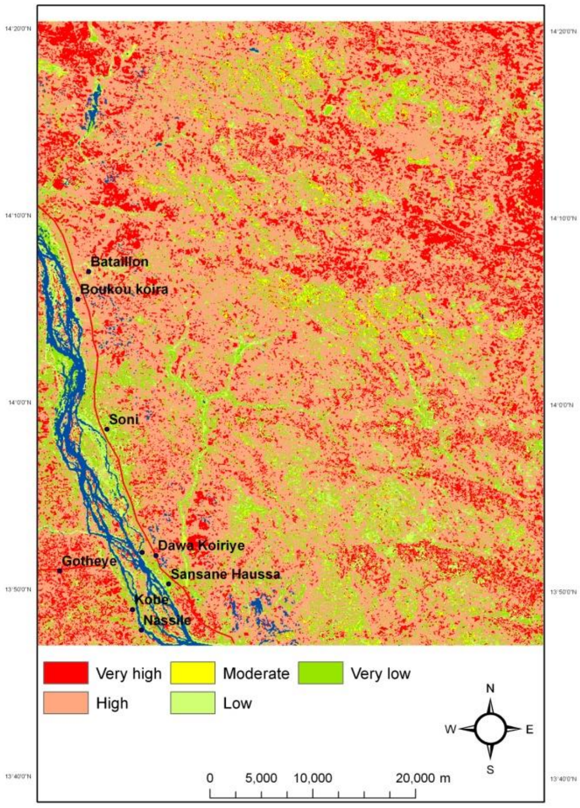

Figure 5.36: Spatial distribution of desertified land area during the interval of 1989 - 2001.

From Figure 5.35 very high areas of desertification developed from the northwest towards the centre of the landscape. This shows the spatial distribution of desertification during the 16 years from 1973 - 1989. The landscape is slightly influenced by desertification as displayed in the map, it can be observed that the changes for very high and high rates of desertification are concentrated more in the north and south-east of the study area.

Another important class worth highlighting is the dominance of moderate, low and very low desertified index during this period (1973 – 1989). These findings were in line with the result of the % LAND, where shrubs increase from 22.78% in 1973 to 29.34% in 1989 caused by greater planting activities. The shrubs later decreased from 1989 to 2007 caused by human activities and climate change and aggravated by political instability.

Desertified Index

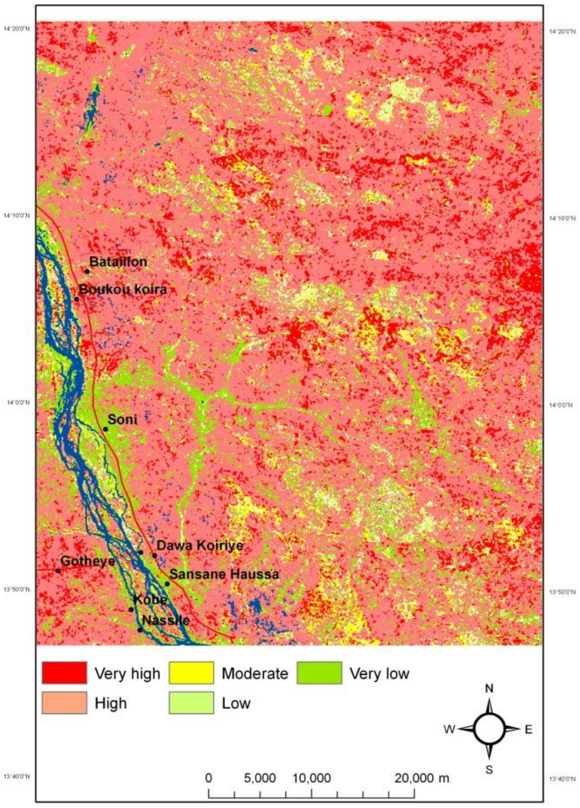

Figure 5.37: Spatial distribution of desertified land area during the interval of 2001-2007

The figures 5.36 and 5.37 indicate the spatial distribution of desertification during the 12 years period from 1989 - 2001 and during the 6 years from 2001 - 2007 respectively.

The areas, highly influenced by desertification are shown in these maps. The period from 1989 - 2001 and 2001 - 2007 shows a tremendous increase in high and very high rates of desertification. Amogu et al. (2010) report that the strong increase in bare and degraded soil from 1993 to 2007 was caused by land use changes, in overgrazing, increase in crop area and in wood harvesting.

5.4.4.1 Desertification Index Verification from the Knowledge of Local Residents

Interviews were conducted with local residents of 10 villages. The villages are Sansane Haoussa, Mele Haoussa, Gotheye, koulbagou Haoussa, Lossa, Guega Kado Babagadey Koira, Kabay, Boukou and Gouria. The respondents were individuals or groups of people between 35 - 75 years old, from whom important information was obtained about the land cover history of the Tillabéry region. The outcomes from these interviews were divided into three major categories: (i) Land degradation; (ii) Land productivity and (iii) Land availability.

I. Land Degradation

The respondents pointed out that vegetation cover has declined in the study area. Form figure 5.38, the results obtained revealed that 100% of the respondents reported that the problem of land degradation on the field could be perceived because of decreasing of yield over time, increasing desertification, the presence of more wadis, glacis and koris and the movement of sand to water bodies (Niger River and lakes). The majority of the respondents agreed that the variability of the rainfall events, erosion, and drought were the reasons for a declination of vegetation cover. Another important factor mentioned by respondents was increased population and mismanagement of land cover.

The respondents mentioned that the deterioration of vegetation cover forces the nomads to move longer distances to search for fodder. It has been noted that since recently some nomads have shifted to a sedentary life style. The survey also indicated that the people employed several methods to improve and increase land productivity such as crop rotation, terracing, tree planting, agro forestry, rock barricades, “Zai”, Deme-Lune, sand dune fixation and application of organic and inorganic fertilizers. This demonstrates that the respondents’ practices are a reasonable reaction to changing conditions and a desire to preserve their natural resources. These activities contribute significantly to the expansion of bright spots as reported by FAO (2002).
The results from the interviews are in line with the satellite images of the desertification and land degradation of this study concerning the development of bare areas, wadis and the deterioration of the vegetation.

Furthermore, the respondents pointed out that the change in vegetation cover incorporates change in plant type, density, disappearance of species and the emergence of new vegetation species in the study area. Malan Saley Issa Marabou of the Sausane Haoussa village acknowledged the disappearance of some medicinal plant species (*Momordica balsamina L, Tephrosia lupinifolia DC. and Bauhinia rufesens L*.). Also most villagers mentioned rare or disappearance of some food (*Hyphaene thebaica, Lannea microphylla Engl. and Adansonia digitata L*.) and forage plant species (*Balanites aegyptiacus, Corchorus tridens L. and Leptadenia hastata*).

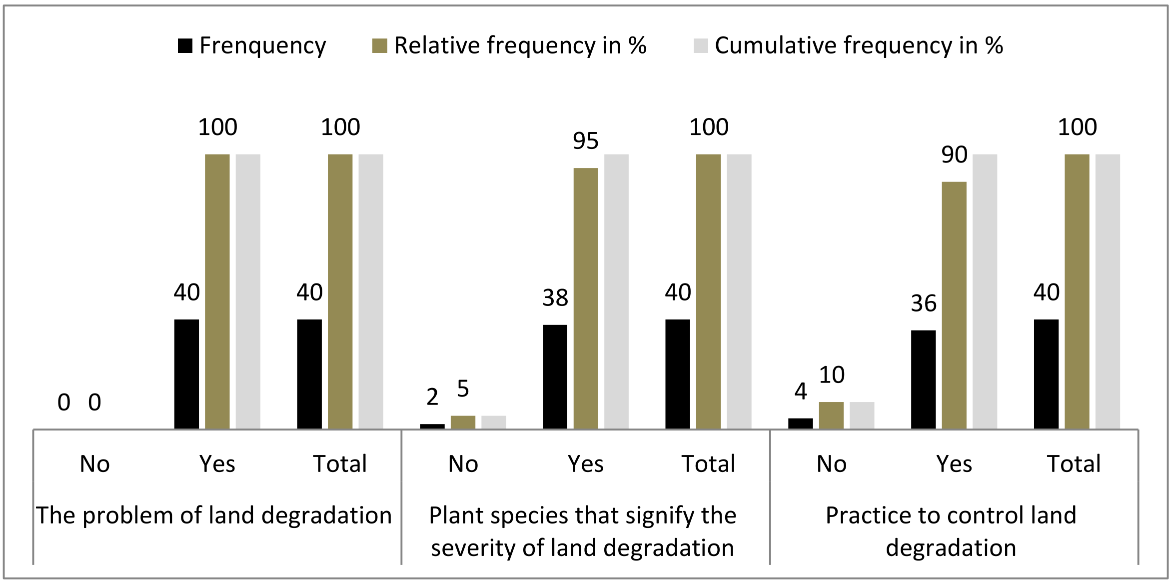

Figure 5.38: Summary of local residents answers concerning land degradation.

95% of the respondents said that some of the new weed species signified the severity of land degradation like *Striga hermonthica* and *Striga asiatica*. In fact, these species have become invasive in certain parts of the study area. De Groote et al. (2005) reported that Striga is a particular problem in the landscape with low moisture and where the soil fertility is eroded. The respondents also pointed out that surface water (river and lake) is affected by water Hyacinth. It has been noticed that the depth of groundwater has drastically changed (i.e. increased the depth of water table thereby very limited amount of water). They responded also that new species such as *Acanthospermun hispidum* and *Centrus biflorus* occupied now large areas especially in the northern part. This result indicated that the vegetation cover in this study area changed during the study period.

Figure 5.39: Striga spp indicating a reduction of soil fertility. Close to the Niger river in the southern area of study.

Figure 5.40: Water Hayacinth making Niger river useless for navigation and agricultural production and affecting biodiversity.

II. Land Productivity

100% of the respondents noted the loss of land productive capacity during the last 37 years as a result of soil erosion by wind and water, which results in soil infertility and drought. This type of land degradation occurring in this area is confirmed by Aubreville (1973) and FAO (2002). The reduction of crop productivity, leading to long-term decline in agricultural yields, vegetation biomass and biodiversity are caused by desertification. McCarthy et al. (2001) reported that these changes reduced the ability of the land to support people, often igniting an exodus of farmers to urban areas. This result validates the soil degradation investigation. Some respondents (92.5%) mentioned that some of the new species (*Centrus biflorus* and *Acanthospermun hispidum*) are good indicators for a decline in soil fertility. Also the farmers reported drought as one of the important reasons for a desease in biodiversity and land productivity.

Verification and Validation

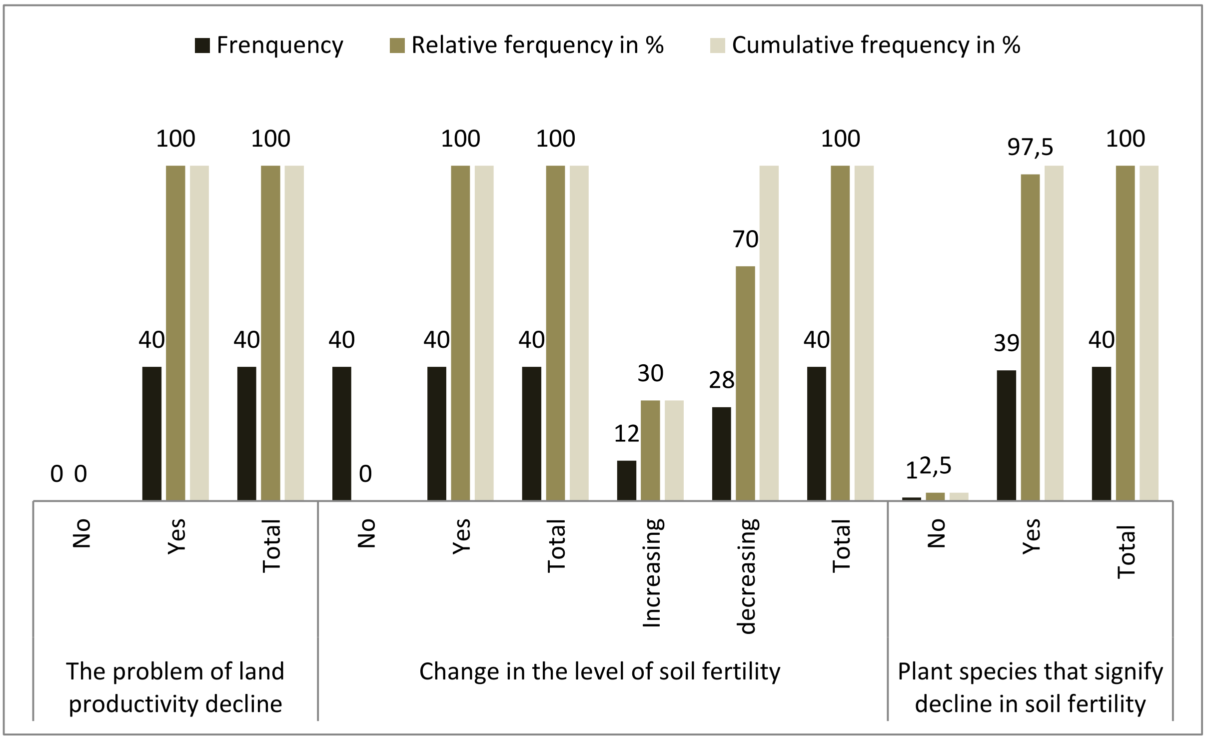

Figure 5.41: Summary of local residents answers concerning land productivity.

In the Sahel region, the soil fertility is one of the most limiting factors of land productivity; more than 95% of the soils are loam and pose a great challenge to food security. The farmers used two traditional methods for improving soil fertility: fallow and the application of organic and inorganic fertilizers. Bationo et al. (1998) reported that the combination of organic and inorganic fertilizers appears to be the best panacea for restoring the nutrient balance, improving crop yield and increasing rural incomes.

Desertification has significant connotation to soil fertility, principally water-retention capacity, organic matter content, pore space and base caution content. The results from the figure showed that 95% of the respondents used organic fertilizers on the farms, while 5% did not. Also 45% of the respondents used inorganic fertilizer and 55% did not.

According to the respondents, 12% of the farmers used NPK (Nitrogen, Phosphorous and Potassium), 4% urea and 2% SSP (Single Super Phosphate). NPK and urea are the two most common types of fertilizers used by farmers in this area and showed that NPK and urea were suitable fertilizers for the production of most food crops in the study area. Also, most villagers mentioned the low application of inorganic fertilizer among the people in the study area because of lack of sufficient knowledge about inorganic fertilizer application, inadequate supply and distribution system of fertilizers and weak purchasing power.

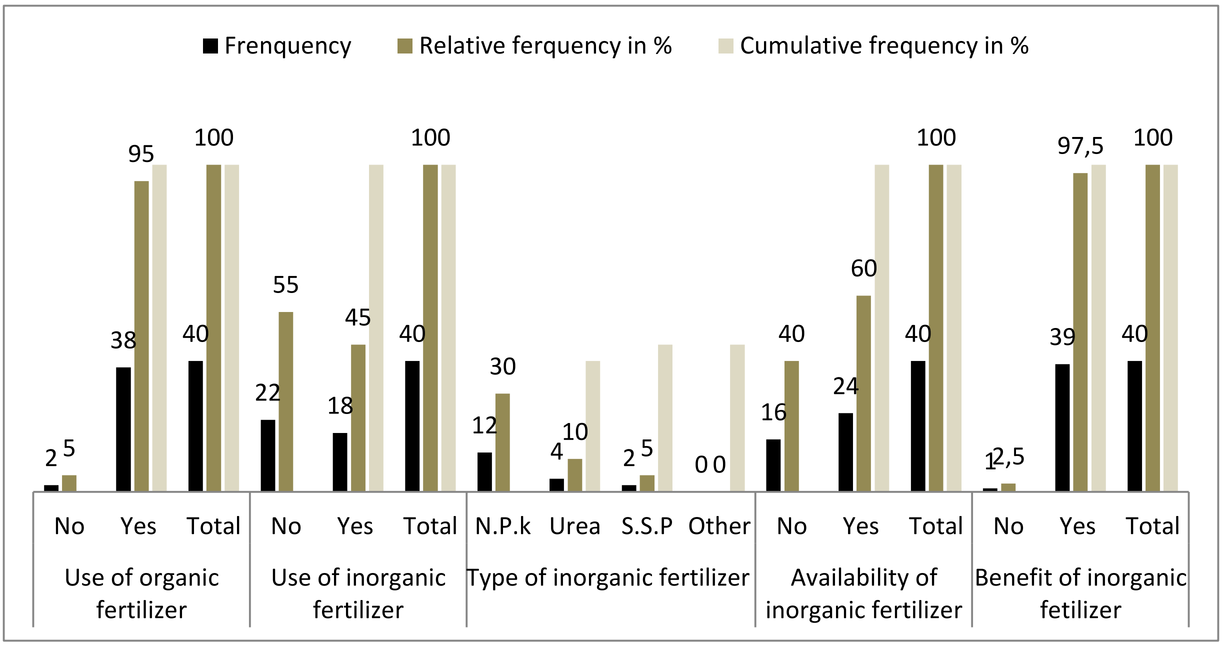

Figure 5.42: Summary of local residents answers concerning soil fertility.

III. Land Availability

Agricultural production is considered as the fundamental economic system. The real economic dimension of a farm is given by the size of the available land. The respondents explained that the present agricultural production is largely a subsistence systems, based on *Pennisetum glaucum L*. (millet) and *Sorghum bicolour L*.(sorghum) associated with cash crop such as *Vigna Unguiculata L*.(cowpea), *Arachis hypogeae L*.(groundnuts) and *Sesamun indicum L*.(sesame). The majority of respondents said that the cash crops were the main drivers of vegetation change in the study period.

The interview data also showed that a majority of the respondents had large family sizes (about 5 -16 members). According to the respondents in the villages, 34.50% and 82.5 % of the farmers had their farm holdings ranging 1-3 ha in the period respectively from 1963 to 1973 and 1973 to 2010. This shows that small-scale farmers in the study areas have increased.

Figure 5.43: Farmer in millet production near the village of Gouria, Tillabery region, shows the low yield level during 2011.

Figure 5.44: Loss land by water erosion.

Table 5.14: Farm size of the farmers in the study areas (after and during the study period).

Size of the farm(ha)	% respondents 1963-1973	Size of the farm(ha)	% respondents 1973-2007
1-3	34.50	1-3	82.50
4-6	22.00	4-6	5.00
6-10	20.00	6-10	10.00
11 and above	23.50	11 and above	2.50

The decline in available cultivable land area per household compared with a fast-growing population signifies extreme vulnerability of the inhabitants of the Sahel region. IRAM (2006a) reported that the decline in the agricultural field size is in many places accompanied by a reported loss in soil fertility, with a resulting low output from these fields. A very small proportion (2.5% from 1973 to 2007) of the farmers had large farm sizes; this may be attributed to the fact that they had enough money and political power for the procurement and management of their farms.

5.4.4.2 Validating Desertification Index by using Geographically Weighted Regression

There are several studies that provide independent data for validation. The techniques used in this thesis differ substantially from previous techniques that focused on descriptive statistics, whereas this thesis makes use of geostatistics by employing external validation of desertified index using geographically weighted regression (GWR) model. This was undertaken between desertified index from 2001 to 2007 as dependent variable and ground truth data as explanatory variables (land cover). Geographically Weighted Regression investigation was carried out using an adaptively defined kernel with a bi-square function in which the bandwidth was determined by minimisation of the Akaike Information Criterion (AIC) (Fortheringham et al. 2002). It is important to mention that the value displayed in figures 5.45, 5.46 and 5.47 were created using Ordinary Kriging and summarise the results derived from geographically weighted regression.

Figure 5.45 shows the spatial distribution of the intercept which had a range of 0.1 to 0.7. The higher values are distributed mainly northern-east and southern-west in the study area while median values are mainly found in the middle and close to the river, where very low desertified land area is observed. Low values are mainly northern-west and southern-east, where very high and high desertified land areas are recorded. This parameter decreases in order from very low desertified (shrubs land), to low desertified (grassland), to moderate, to high and to very high.

Verification and Validation

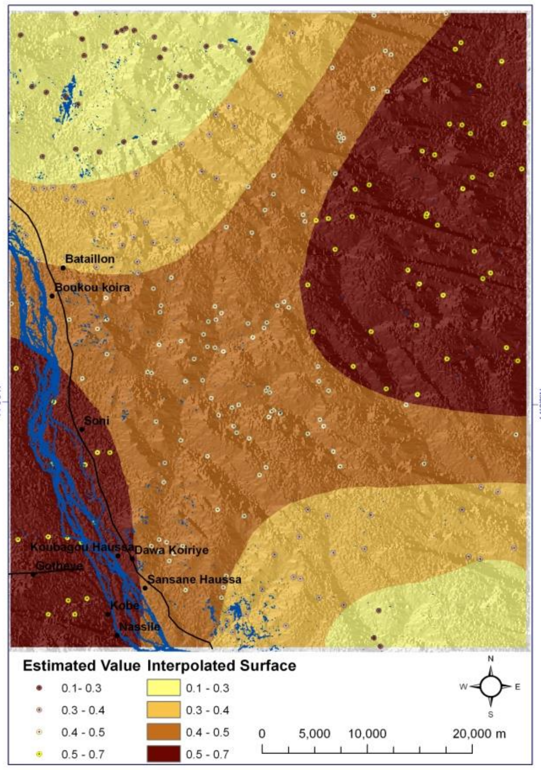

Figure 5.45.: Estimated value and corresponding interpolated surface by GWR model - Intercept

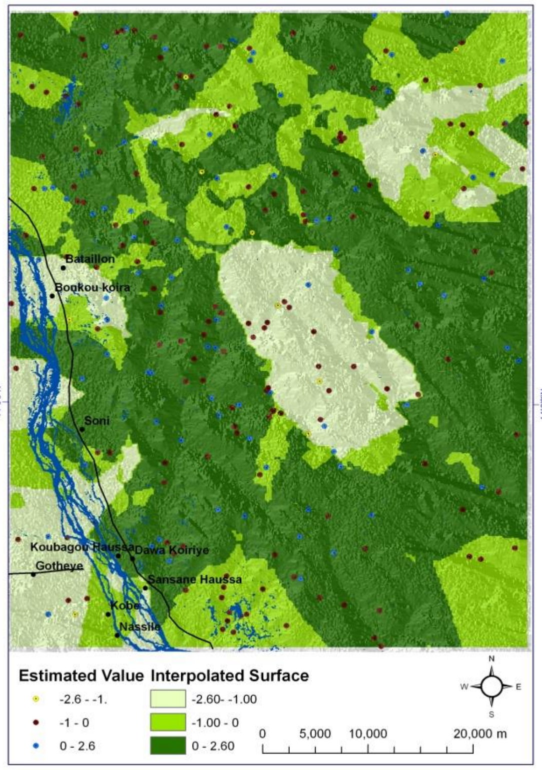

Figure 5.46: Estimated value and corresponding interpolated surface by GWR model-Residual

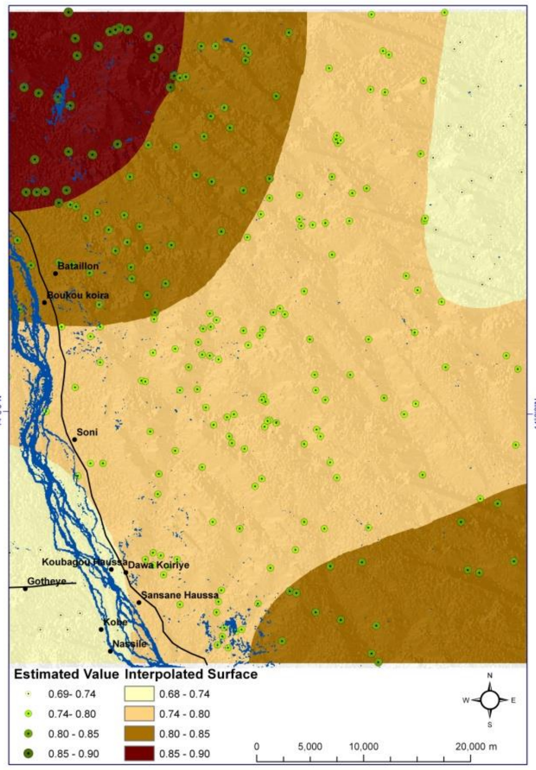

Figure 5.47: Estimated value and corresponding interpolated surface by GWR model - The local R^2

The spatial distribution of residuals (see figure 5.46) shows negative and positive values, the residuals are an indicator of overestimation and underestimation respectively.

In general, the area which had the local R^2 between 60-72% has the negative residuals, which suggest that the model overestimates the real values. In contrast, the areas that had the local R^2 between 80-90% also had positive residuals, revealing the tendency of the model underestimation.

Verification and Validation

One of the important spatial distributions obtained from GWR is the spatial variation in the goodness-of-fit statistic, local R^2, shown in figure 5.47. It shows that the goodness-of-fit, measured by coefficient of determination, R^2 value, varies from 0.69 to 0.90. The spatial distribution of the local R^2 shows significant spatial variation with lower values in the southern-west and northern east.

Higher values were found in the northern west that demonstrates a strong relation between desertified index and field measurements (R^2 between 0.85 - 0.90) for land cover and soil structure. Therefore, the northern west area of Tillabéry landscape had the highest basic level of bare area (very high and high desertified land). Here semi-desert and desert vegetation cover dominates.

6 Assessing Soil Erosion Risk

To combat desertification, it is indispensable to understand soil erosion processes in the Sahel zone. The objective of this section was to develop a simple model that uses soil texture data from the field and DEM parameters to predict soil texture map. Also, this section assesses soil erosion research in the Sahel region, illustrated by a case study from Tillabéry landscape. The RUSLE and USPED were used to achieve one of the additional secondary objectives of this thesis.

6.1 Soil Texture

Soil texture is influenced by drainage condition, permeability, and water holding capacity. Otherwise, it directly affects the porosity of the soil and long-term soil fertility. Wischmeier & Smith (1978) reported that soil texture determines the soil erodibility and affects the risk of soil erosion. Therefore the knowledge of soil texture is essential for studying soil erosion. The TreeNet Model (Salford Systems Implementation, cf. Friedman, 1999) was used to assess the spatial distribution of soil texture.

6.1.1 Influence of Independent Parameters on the Soil Texture Processes (Rankings of important variables)

Topography elements are parameters affecting the type and distribution of soil texture. The quantification of the relationships between topographical elements and soil texture was done in this part. Using TreeNet Model technique, an estimate of important topographical parameters in relation to different soil structure elements is presented in figure 6.1. The results show that there is a relatively strong relation between soil structure distribution and topographical parameters.

Assessing soil erosion risk

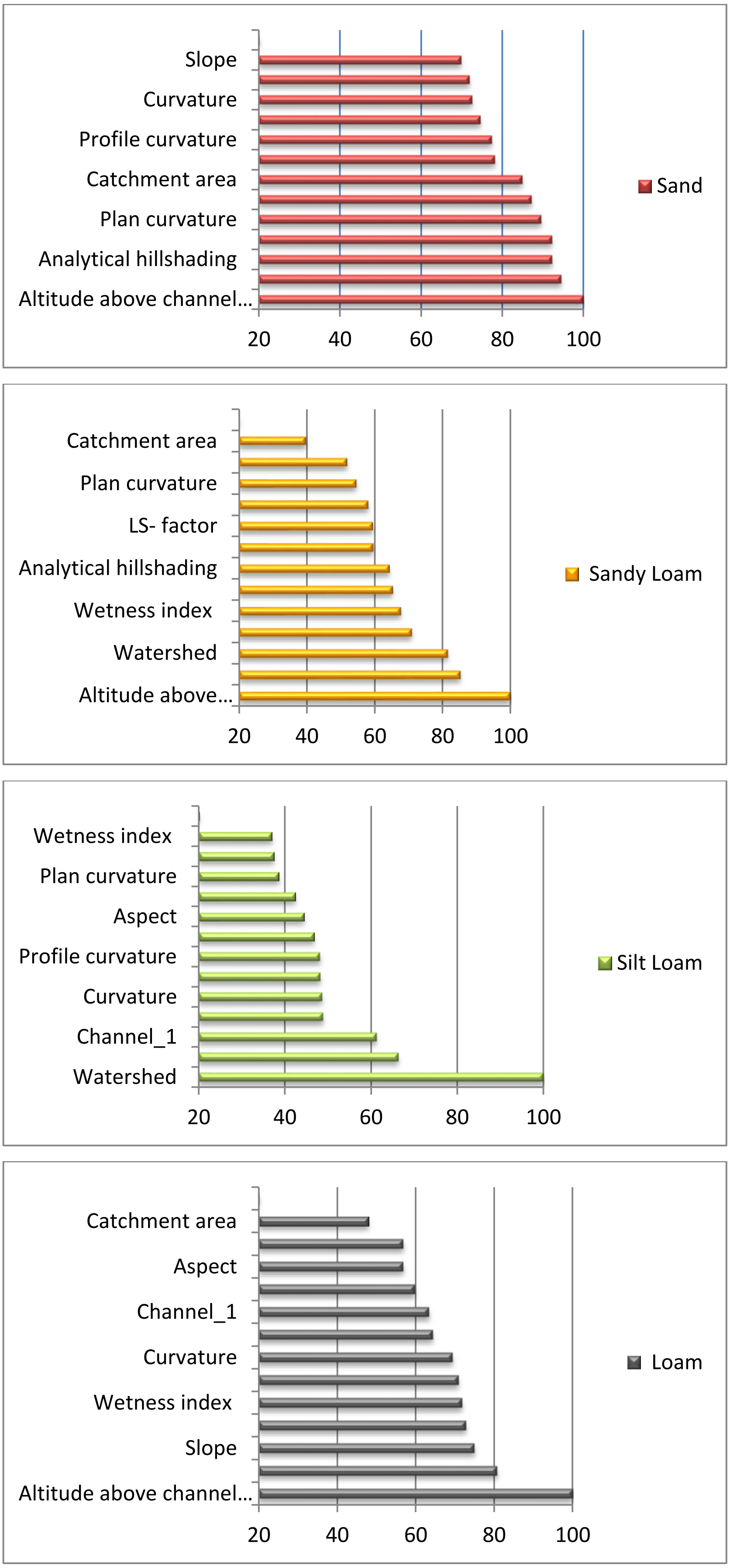

Figure 6.1 : Ranking of the importance variable related to soil texture content regionalization derived from the model.

The global picture is the following: Altitude (100.00%) has the highest value for soil structure models. Watershed (88.28%), Channel network (76.00%), Profile curvature (74.98%), Plan curvature (73.97%), Wetness index (72.49%), Analytical hillshading (72.01%), Curvature (70.54%), Aspect (66.34%), and LS-factor (64.63%) are apparently important as well. Also all other variables achieved score values of 6.15% to 56.46% and their influence cannot be neglected. Sand content displayed the highest score with Altitude (100.00%) and Channel network (94.48%), whereas Loam content had the highest score with Altitude (100.00%) and Plan curvature (82.72%). Wilcke et al. (2008) argued that there is a strong dependence of soil texture on Altitude, articulated by a good positive correlation between Altitude and Sand content but a negative correlation concerning Clay content. Altitude above Channel network was the most important predictor for Sandy loam, Loam and Clay loam in the study area due to erosion and deposition processes.

6.1.2 Model Performance Evaluation and Cross Validation

Receiver operating characteristic (ROC) curve was used for characterizing the model performance. The value of ROC is between 0 and 1. In the worst case scenario, the ROC value can be no less than 0.5 and the best can be close to 1(Lasko et al., 2005).

For the ROC analysis, the true positive rate is plotted on the Y axis and the false positive rate is plotted on the X axis. The figure 6.2 illustrates the error tradeoffs available with a given model and describes the predictive behavior of the six classifiers, independent of class distributions. The most reliable soil texture predictor was loam and sand (0.981 and 0.983 respectively).

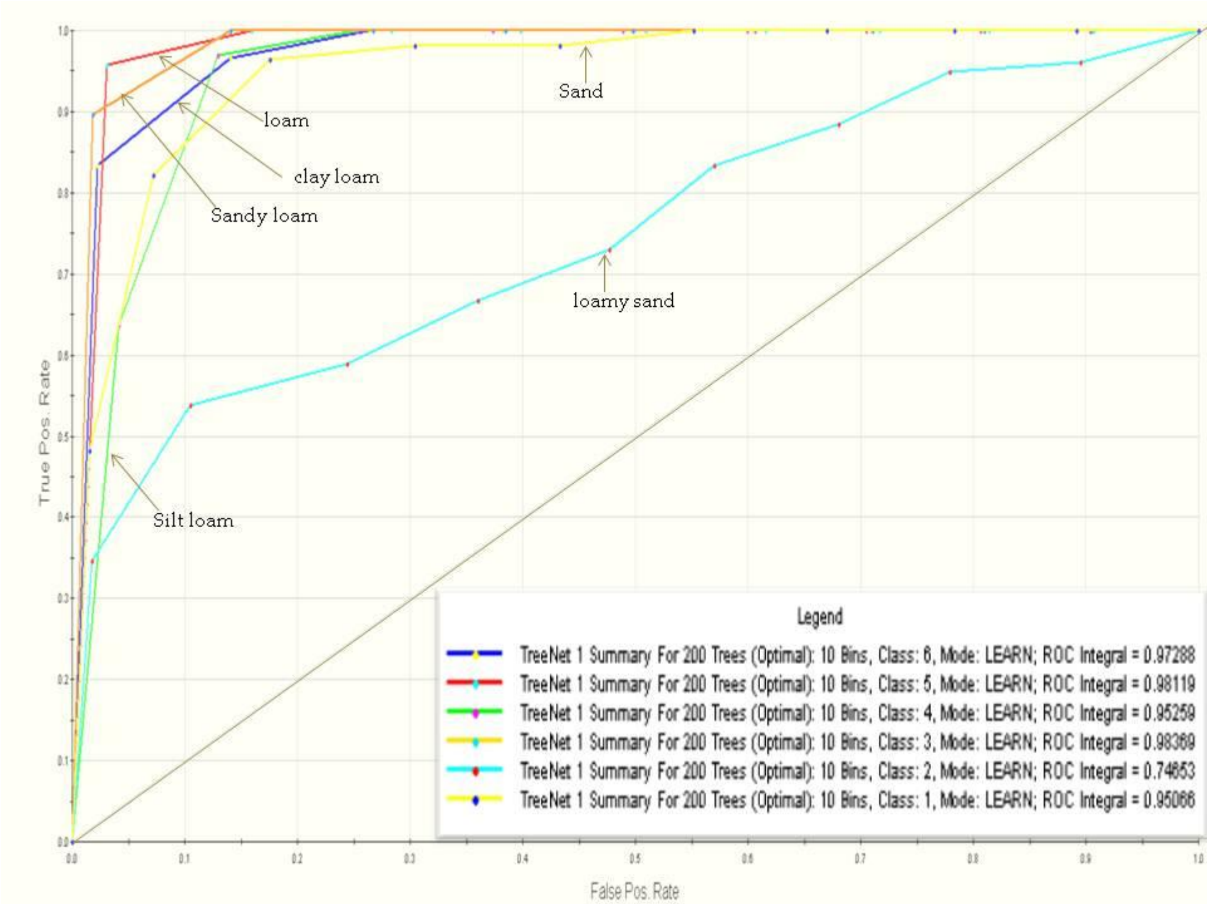

Figure 6.2 : The Receiver Operating Characteristic (ROC) curve for each soil class.

Table 6.1: Prediction success from ten-fold cross validation (total 250 samples)

Class	Samples	Percent correct
Sand	56	77.84
Loamy sand	78	39.74
Sandy loam	29	89.66
Silt loam	33	87.88
Loam	24	95.83
Clay loam	30	90.00
Average		80.88
Overall % correct		**72.80**

The prediction errors for the spatial texture of the topsoil in the study area were quantified by a ten-cross validation method (see table 6.1 and 6.2). The model had an accurate classification rate of 72.80% by ten-fold cross validation. The result from cross validation is unsuitable because there are not enough data sets but when the data sets are large, the model validation becomes particularly attractive.

Table 6.2: Misclassification

Class	N cases	N misclassified	Pot. error	Cost
Sand	56	10	17.86	10.00
Loamy sand	78	47	60.25	47.00
Sandy loam	29	3	10.34	3.00
Silt loam	33	4	12.12	4.00
Loam	24	1	4.17	1.00
Clay loam	30	3	10.00	3.00

6.1.3 Soil Texture Map

The scoring process of the entire data set of Tillabéry landscape allowed constructing a map showing the spatially distributed soil texture potential for each class. Soil texture plays a very important role not only for soil fertility, but also for soil stability, water retention capacity and soil biodiversity. Figure 6.3 shows how the soil texture is spatially distributed in the study area. Soil texture estimation provides a better view of erosion and desertification processes. The map reflects the high importance of topography parameters for soil texture distribution. Also the model detected for the following terrain attributes a very high prediction potential for soil texture: Altitude above Channel network, Watershed, Channel network, Profile curvature, Convergence index, Plan curvature, Wetness index, Analytical hillshading, Curvature, Slope, Aspect and LS-factor.

Therefore, the result suggests that topography elements were important in determining the spatial distribution of soil texture. This can be explained that all terrain attributes influenced soil texture considered in this investigation due to erosion, transport and deposition processes. This study has demonstrated that loam (63.91%) was the dominant soil texture, suggesting that the study area tends to have high soil loss. The map shows that silt loam was found close to Niger River and seasonal water bodies.

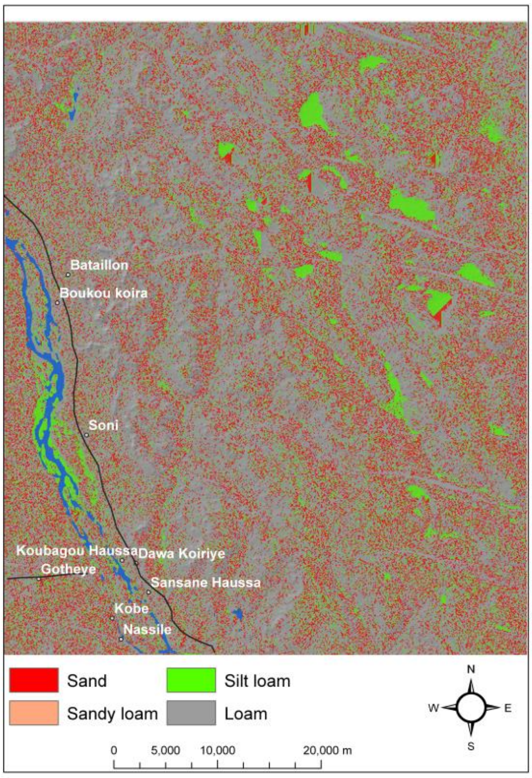

Figure 6.3: Predicted soil texture for the topsoil layer (0-30 cm).

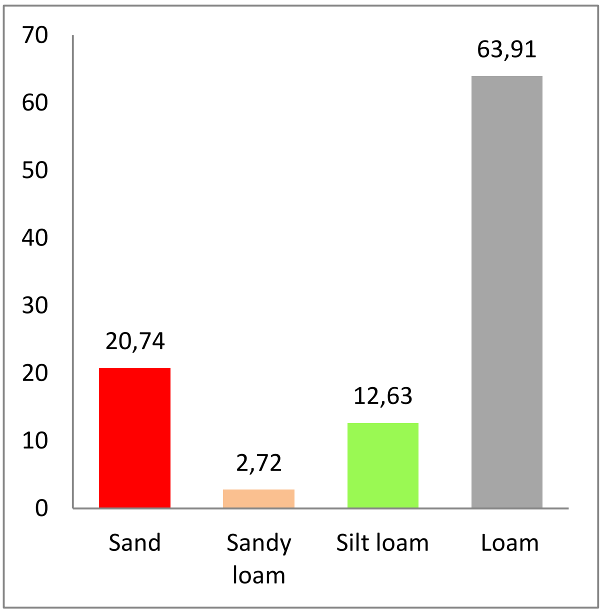

Figure 6.4: The percentage of soil texture predicted.

This result shows that the spatial distribution of soil texture in the study area depends on the wind regime. Sandy soil distribution is indicated by the activity of aeolian processes and act with dry wind direction (October–April) that move northeast and rainy season wind direction (May-July) that move west through the Sahel in the same time. In addition, the upper part of the study area is mostly dominated by loamy soils under the influence of aeolian. In general, the study showed that the spatial distributions of soil texture are influenced by the topography elements and aeolian activities in the Sahel region.

6.2 A Comparison between the Two Soil Erodibility Factor Models

The soil erodibility assessment is an important step to understand the soil quality and susceptibitility to erosion and to predict soil loss. The first model was expressed by the relation proposed by Renard et al. (1997) based on the percentage of respective soil texture classes and geometric mean diameter. The second model was computed by the relation given by Torri et al. (2002) based on the percentage of silt plus very fine sand, percentage of sand, percentage of organic matter and soil texture.

The K given by the Renard et al. (1997) equation (noted K factor **without** organic matter) in the study area is estimated to vary from 0.02 to 0.25 t ha h /ha MJ mm (see chapter 4). These results are fully in accordance with the K value published by Natural Resources Conservation Service (NRCS) soil survey and are well compatible with other studies carried out in Sahel region. The second, K given by Torri et al. (2002) equation (noted K factor **with** organic matter) value ranges between 0.005 to 0.050 t ha h /ha MJ mm. Results are in agreement with the study carried out by Vaezi et al. (2010) that indicates that estimate K values using only soil texture data are higher than the estimated ones based on soil texture and soil organic matter. Organic matter reduces the susceptibility of the soil to detachment and increases infiltration and consequently affects soil erodibility, which decreases runoff. The K factors were supposed as the dependent response variables in the model and different topographic information as the independent predictor response variables.

6.2.1 Response Variable

Table 6.3: Misclassification for learn data.

Response variable	K factor without organic matter				K factor with organic matter			
	N cases	N misclassification	Pot error	Cost	N cases	N misclassification	Pot error	Cost
Class 1	14	1	7.14	1	-	-	-	-
Class 2	22	9	40.91	9	23	3	13.04	3
Class 3	4	0	0.00	0	17	7	41.18	7

Table 6.4: Misclassification for test data.

Response variable	K factor without organic matter				K factor with organic matter			
	N cases	**N misclassification**	**Pot error**	**Cost**	**N cases**	**N misclassification**	**Pot error**	**Cost**
Class 1	14	7	50.00	7	-	-	-	-
Class 2	22	16	72.73	16	23	9	39.13	9
Class 3	4	3	75.00	3	17	14	82.35	14

Class 1 (0.02-0.2 t ha h /ha MJ mm) Class 2 (0.20-0.25 t ha h /ha MJ mm) Class 3 (0.25-0.40 t ha h /ha MJ mm)

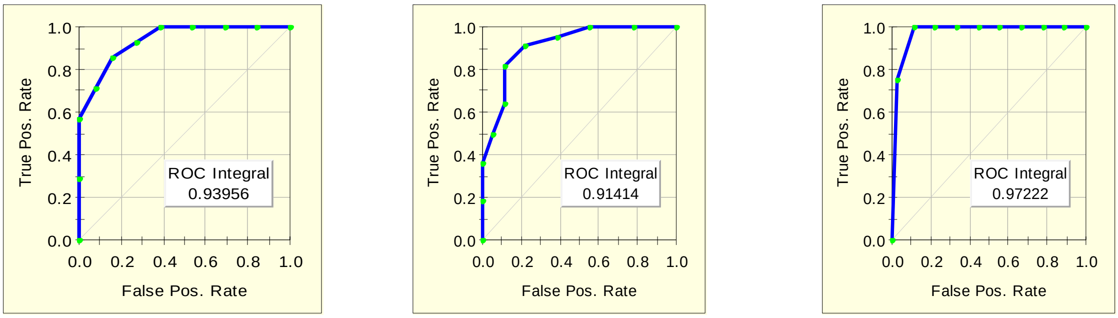

Figure 6.5 : ROC curves for each K factor class data set without organic matter data (learn data set).

Class 2 (< 0.015 t ha h /ha MJ mm) Class 3 (0.015- 0.050 t ha h /ha MJ mm)

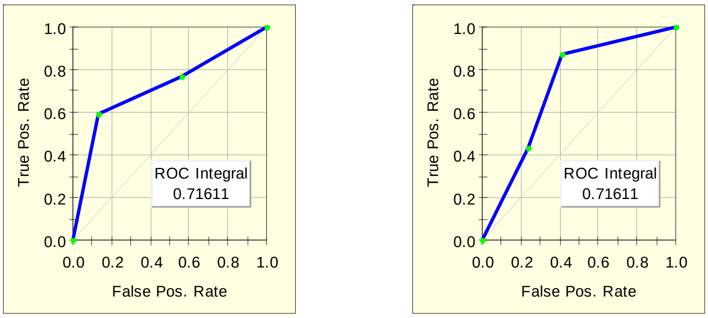

Figure 6.6: ROC curves for each K factor class data set with organic matter data (learn data set).

Tables 6.3 and 6.4 summarize the statistical criteria for the misclassification for learn and test data for the two models. In order to estimate and compare the overall prediction skill of the two models, receiver Operating Characteristics (ROC) curves was used (figures 6.5 and 6.6). The highest prediction is connected to the K factor **without** organic matter (ROC integral greater than 0.9 for all classes). The average value of the ROC integral for the entire K factor **without** organic matter indicates an excellent performance of the model and this approach gives the most accurate results compared to K factor **with** organic matter approaches.

6.2.2 Predictor Parameters

To predict the erodibility factor (**with** and **without** organic matter) 13 independent parameters, revealing the terrain attributes were used. The terrain attributes influence soil processes and affect the properties of the soil (Behrens et al., 2010) but also directly affect soil fertility (Zhang et al., 2011). It was chosen to quantify the role played by topography elements in the spatial distribution of the K factor.

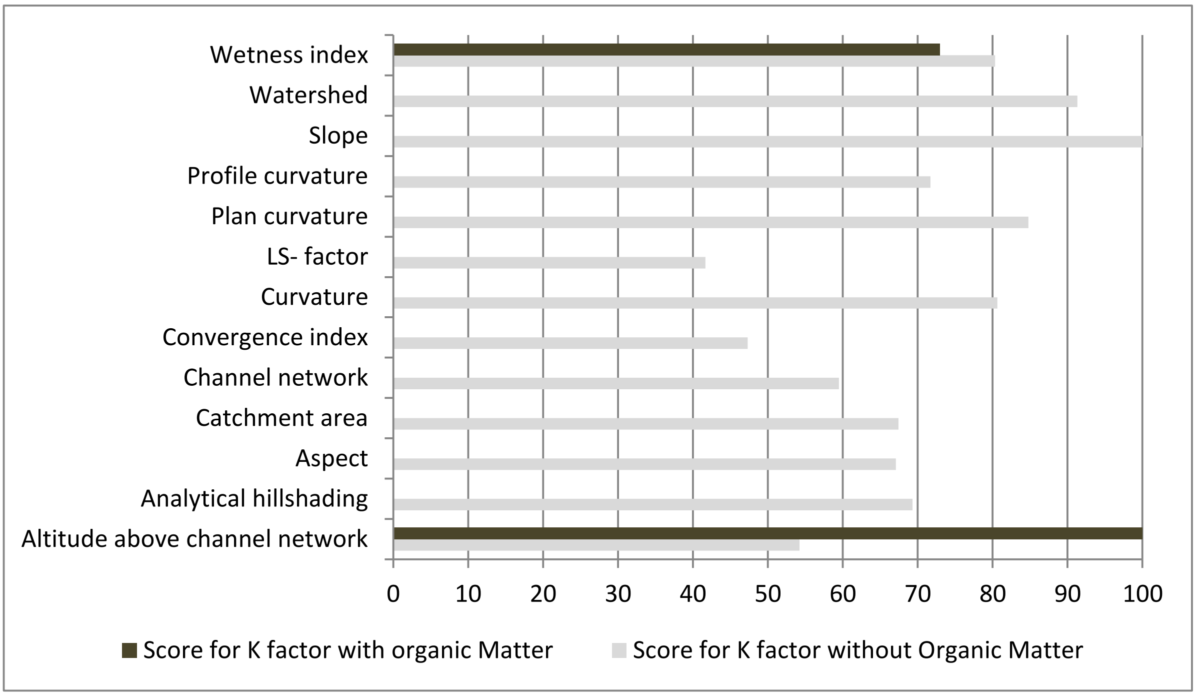

Figure 6.7: Variable importance in % for the predictive variables.

A comparison of variable importance for the prediction of both K factors (K factors **without** organic matter and K factor **with** organic matter) presented large differences (figure 6.7). On the one hand, slope (100%), Watershed (91.3%), Plan curvature (84.79), Curvature (80.62%) and Wetness index (80.34) are the first important factors in the variable importance for K factor **without** organic matter. On the other hand, there are 2 important variables for K factor **with** organic matter, which are played important role in the model prediction (Altitude above channel network and Wetness index). Unfortunately, K factor **with** organic matter is difficult to predict (poor model performance for test data) due to low amount of data, consequently accurate results. Ließ et al. (2011) explained that “poor model performance is most probably caused by the small size of the dataset”. In addition, model performance might be related to the size of the study area (Ziadat, 2005). Finally both K factors were computed using Co-Kriging model with wetness index as independent variable.

6.2.3 Spatial Variability of Soil Erodibility Factor (K) of the RUSLE and USPED Model

Two approaches for spatial distribution models have been evaluated. The results showed that the approach of K factor **without** organic matter provides the most accurate result according to AUC values in Tillabéry landscape using TreeNet model. A comparison between the soil erodibility factor K values with considering organic matter and **without** organic matter value showed that the K value **with** organic matter were from 4 to 5.56 times smaller than the soil erodibility factor **without** organic matter.

Therefore, spatial distributions of the two models' K values were different. The K value **without** organic matter had the highest (0.20 to 0.25 t ha h /ha MJ mm) value close to river and seasonal water bodies indicating deposition of suspended load consisting of silty loam textures (see figure 6.3).

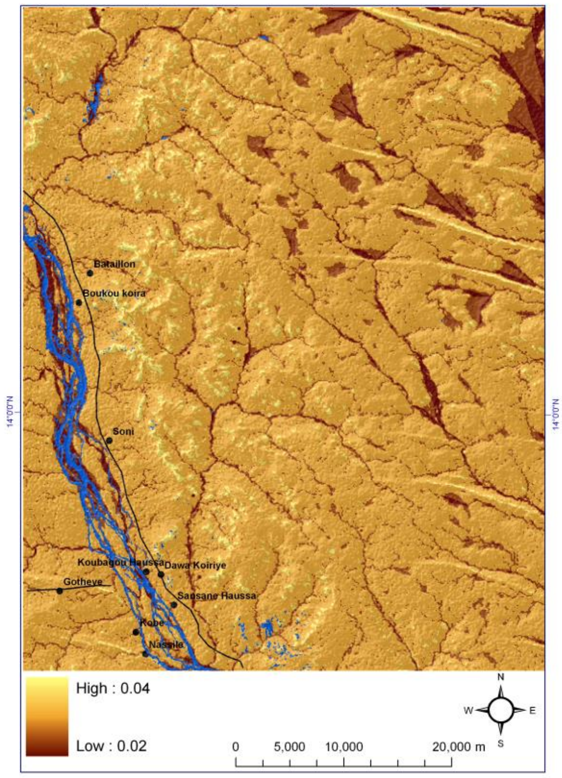

Figure 6.8: Spatial variations map of soil erodibility with organic matter using Co-Kriging.

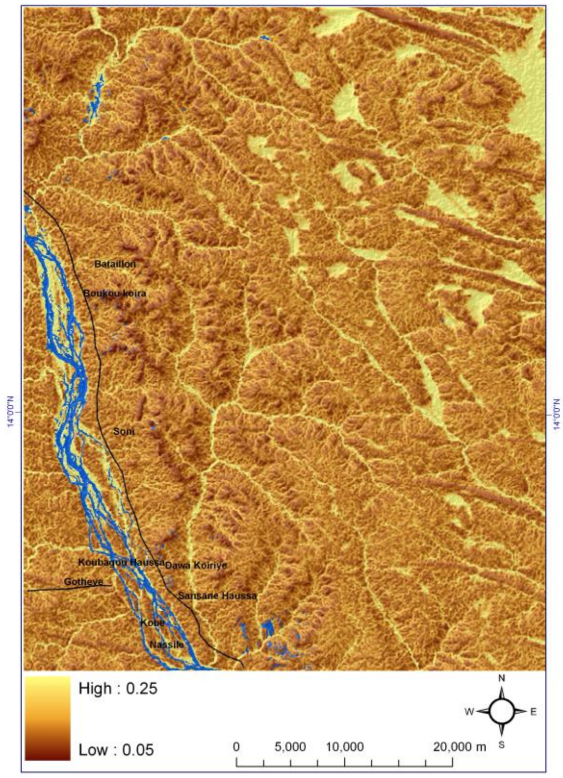

Figure 6.9: Spatial variations soil erodibility map without organic matter using Co-Kriging.

Moderate values are randomly distributed, where the texture is covered by loam soil. Therefore, lowest values are more concentrated in the center of the study area (0.05

t ha h /ha MJ mm), where the soil texture is dominated by coarse textured soils such as sandy soil. These soils are easily detached and have low runoff potential. Weesies (1998) reported that fine-textured soils have low K values (0.05 to 0.15 t ha h /ha MJ mm) and loam has moderate K values (0.25 to 0.45 t ha h /ha MJ mm). These results confirm the spatial distribution of soil texture modeled by TreeNet (see figure 6.3).

The K value **with** organic matter recorded the highest value in the center and south-east, while the moderate values were randomly distributed in the study area and cover the sandy soil texture and agricultural lands. The results indicated that the lowest values are a small part of the areas where the shrubs land are the dominant land cover class with high organic matter. Therefore, this work showed that the use of the K factor **with** organic matter would lead to an underestimation of the amount of soil erodibility in the study area, but confirms the importance of organic matter in semi-arid Tillabéry to prevent soil degradation from water erosion. The results found from the use of the K factor **without** organic matter were more representative to the field observation.

6.3 Spatial Distribution of Soil Loss using RUSLE

The spatial distribution maps of sheet and rill erosion in Tillabéry landscape from 1973 to 2007 are shown in figures 6.10, 6.11, 6.12 and 6.13 based on K factor without organic matter and soil loss based K factor with organic matter was taking under consideration. The result is displayed in 90 x 90 meter grid cells.

The erosion is classified in different classifications. Wichmeier and Smith (1978) reported that the maximum tolerable soil loss (12 t/ha year) is described as “the maximum level of soil erosion that will permit a level of crop productivity to be sustained economically and indefinitely”. In this study, the K factor, LS factor and P factor values were constant and R factor and C factor values were changed according to scenario settings. The results of this analysis demonstrated that rill and sheet erosion during the study periods increased along side the K factor models.

Mean annual soil loss values are presented in figures 6.10, 6.11, 6.12 and 6.13 from 1973 to 2007 and they range from 0 to 140 t/ha year. The highest values (greater than 50 t/ha year) of soil loss were recorded in an infinitesimal amount in the center of the study area in 1973 and increased with time in the study area for both models. It should be noted that the zone of intensive rill and sheet erosion is situated in the study area with loamy texture soils, bare soil areas and with a slope greater than 7%. Analysis of the RUSLE model series (1973, 1989, 2001 and 2007) shows that the moderate rill and sheet erosion (30-50 t/ha year) increased and this increase was closely related to an increase of bare area (desertification) in the study area.

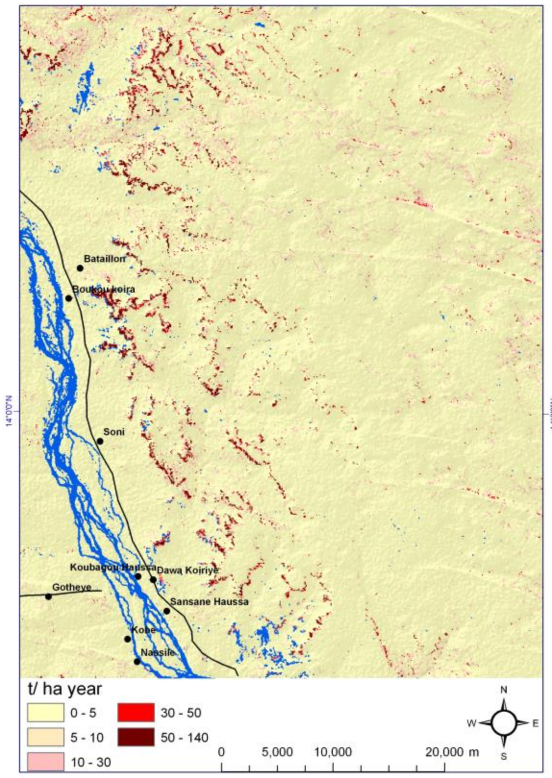

Figure 6.10: Spatial distribution of soil loss based on K factor without organic matter in 1973.

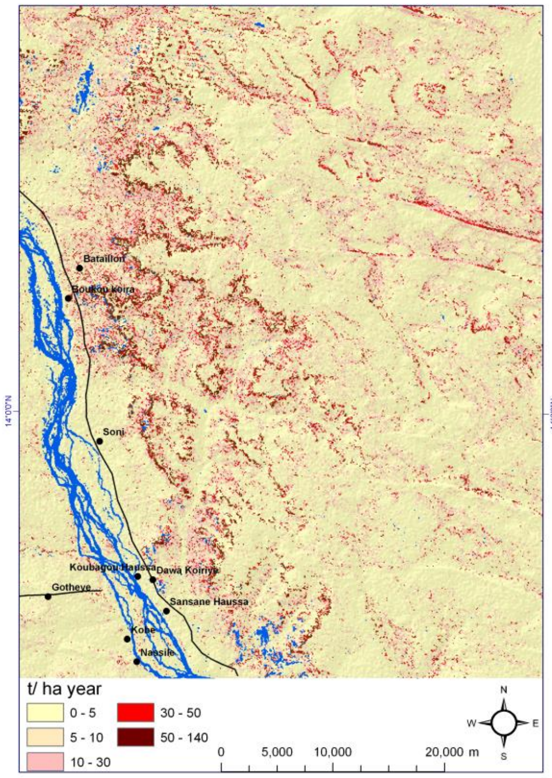

Figure 6.11: Spatial distribution of soil loss based on K factor without organic matter in 1989.

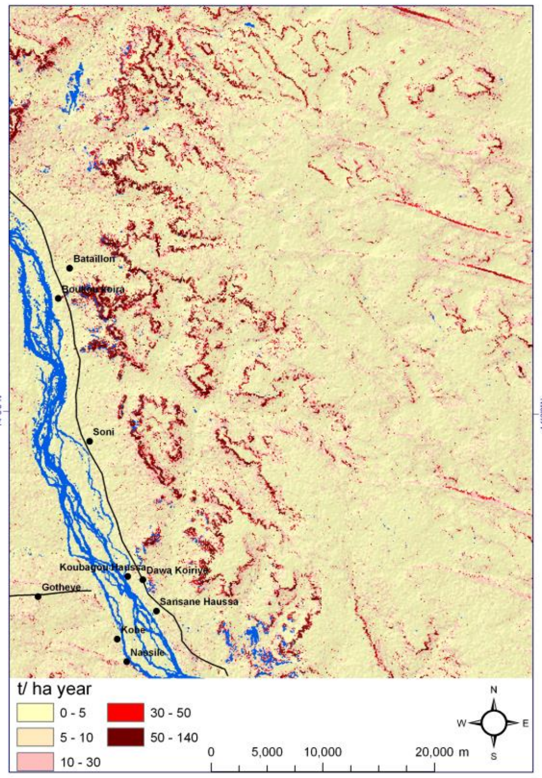

Figure 6.12: Spatial distribution of soil loss based on K factor without organic matter in 2001.

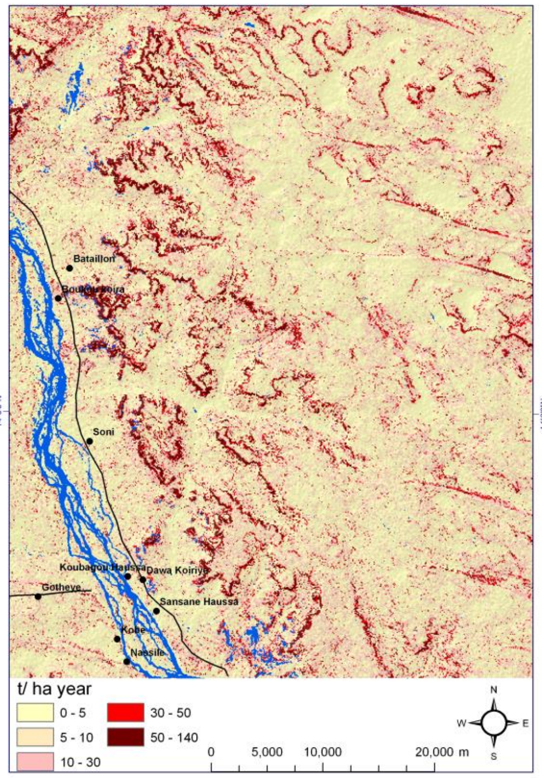

Figure 6.13: Spatial distribution of soil loss based on K factor without organic matter in 2007.

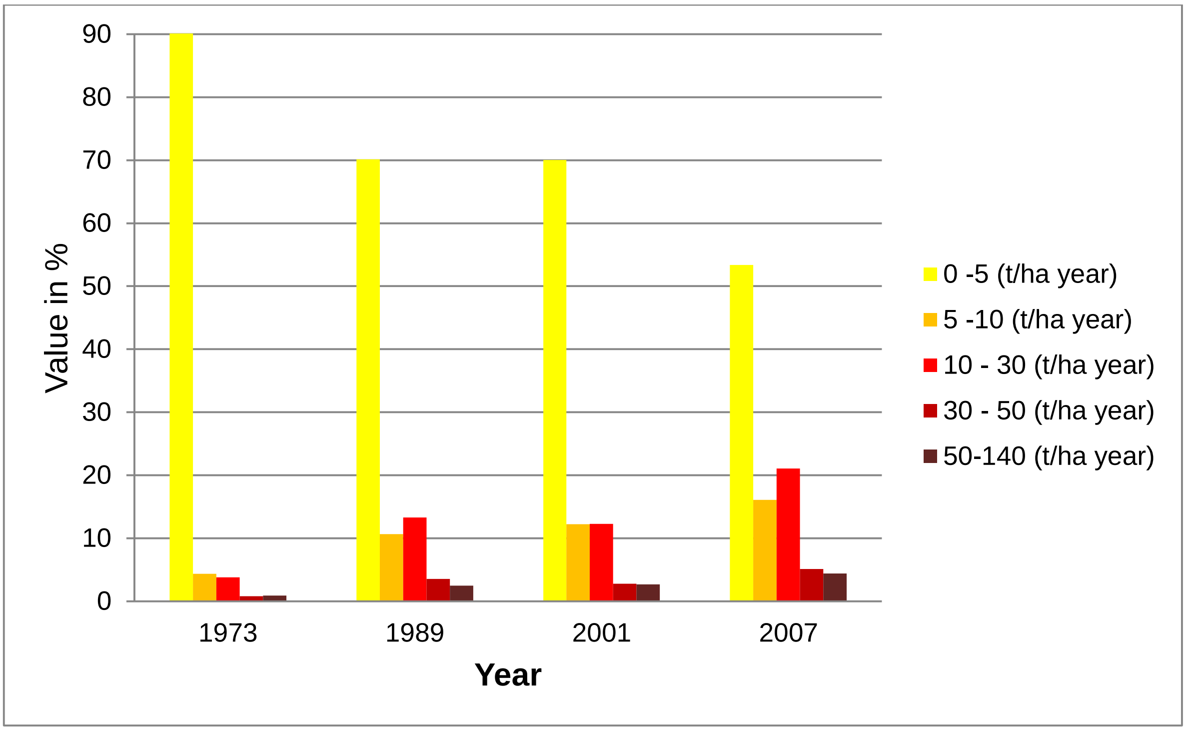

Figure 6.14: Comparison of soil loss (based on K factor without organic matter) rate (t/ha year) per % of surface affected by rill and sheet erosion in the study area.

These results clearly show the existence of interactions between the slope, land cover and soil texture. Soil loss increases are higher with the first model because of high values in K factor. Both models indicate a low erosion risk close to the river and southwestern part of the study area but show high erosion in the upper lands. By comparison of both models it can be noted that the rill and sheet erosion area reveal high values for both methods (50-140 t/ha year), which implies that rill and sheet erosion play an important role in land degradation and desertification in the Sahel region.

On the one hand, sheet erosion is more concentrated in the north east of the study area, dominated by agricultural lands and grasslands. This can be explained by the fact that in the Sahel region, sheet erosion is associated with animal and agricultural production activities which accentuates compaction of the soil and the destruction of vegetation cover. On the another hand, the spatial distribution of rill erosion is more concentrated around the centre and close to major water bodies This is due to the fact that rill erosion in the Sahel region is connected with areas with high altitude (centre of the study area) and with silt loam soil type (close to major water bodies).

Figure 6.15: Sheet erosion shown in the north east of the study area dominated by grasslands.

Figure 6.16: Rill erosion shown in the centre of the study area.

6.3.1 Comparison of Soil Erosion Scenarios under Rainfall options between two K Factors.

If landscape is degrading by rill and sheet erosion, it is essential to determine the spatial distribution of rill and sheet erosion after a certain period of time under changing climatic conditions. To achieve this goal, scenario analysis is a common method and valuable tool to assess the impact of today`s decisions on the future development of resources. Scenarios are a consistent portrait of possible future. Kahn & Wiener (1967) defined scenario as ”hypothetical sequences of events constructed for the purpose of focusing attention on causal processes and decision points”. The rainfall erosivity for time period 2070 in Tillabéry area using future precipitation predicted from Had CM3 mode under A2 emission scenario (Alcamo et al., 2003 and IPCC, 2000) was used. It gives useful information on erosion risk in a changed climate condition. Figure 6.17 and 6.18 illustrate the expected future trend of soil erosion for the Tillabéry landscape up to 2070.

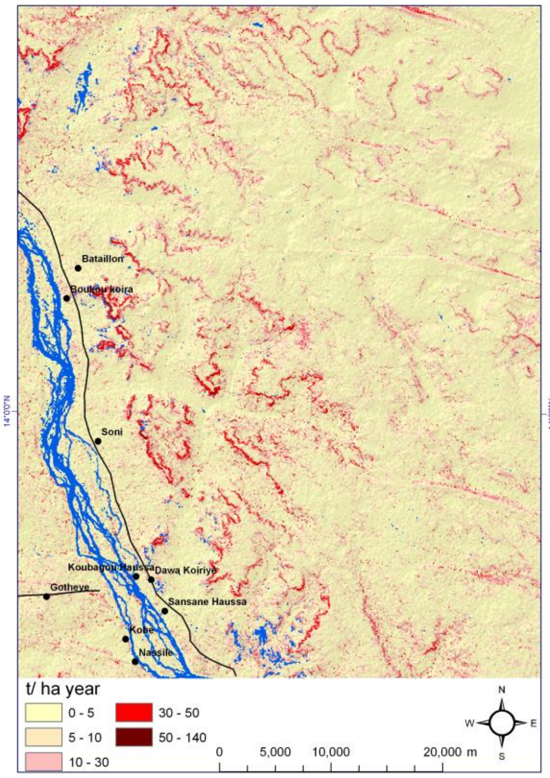

Figure 6.17: Simulated changes in soil erosion risk scenarios in 2070 (Tillabéry I) with organic matter.

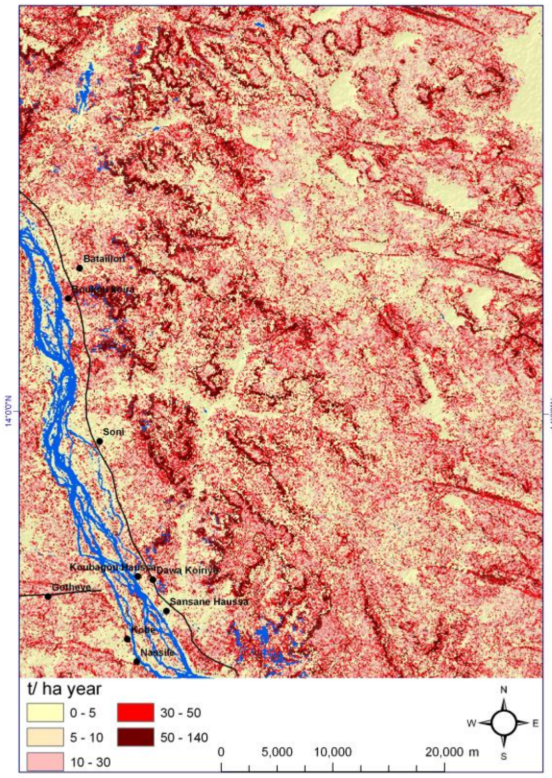

Figure 6.18: Simulated changes in soil erosion risk scenarios in 2070 (Tillabéry II) without organic matter.

Figures 6.17 and 6.18 show the spatial development of soil erosion up to the year 2070 under two scenarios (Tillabéry I and Tillabéry II).

Tillabéry I is a simulated change in soil erosion risk for the scenarios based on rainfall erosivity till the year 2070 in the Tillabéry area using future precipitation predicted from Had CM3 model under A2 emission scenario based on K factor **with** organic matter. **Tillabéry II** depicts a simulated change in soil erosion risk for the same area based on rainfall erosivity until 2070 in the Tillabéry area using future precipitation predicted from Had CM3 model under A2 emission scenario (Alcamo et al., 2003 and IPCC, 2000) based on K factor **without** organic matter.

In the both scenarios (Tillabéry I and II), an increase in the soil erosion is observed. In Tillabéry I, no risk of erosion is in the flat zones of the Niger River Basin. In the Tillabéry II, the higher erosion risk (greater than 50 t/ha year) is visible. As such, these changes affect the rest of the classes. The spatial distributions of soil erosion scenarios between the two scenarios have a close relationship in general (Figures 6.17 and 6.18). The area with a high erosion value with Tillabéry I may likely have a high erosion value with Tillabéry II. The spatial distribution of area with high erosion value with Tillabéry II show a concentration in the middle parts of the Tillabéry landscape, where as the distribution of erosion with Tillabéry I are concentrated in the northeastern part of the study area, precisely close to the Niger River.

6.4 Spatial Pattern of Soil Erosion and Soil Deposition Simulated by USPED Model.

The spatial pattern of soil erosion and deposition was simulated with the USPED (Unit Stream Prediction Erosion Deposition Process, Mitasova et al., 1996) model to demonstrate the magnitude and spatial variability of soil loss and accumulation and to identify the most severely affected areas in Tillabéry landscape using land use /land cover for the four years 1973, 1989, 2001 and 2007. To determine C factors, the precipitation data, from 1973 to 2007 were taken into consideration to calculate R factor values. K factor **without** considering organic matter is the same as used in the RUSLE model. However, the topographic component was computed by combining the Profile and the Tangential curvature, Upslope contributing area, Aspect and Slope. In the model output, erosion and deposition areas are shown by negative and positive signs respectively. The maps obtained using USPED model were divided in the following classes as suggested by De Rosa (2005):

- -5 to -0.1 (t/ha year): erosion
- -0.1 to 0.1 (t/ha year): stability
- 0.1 to 5 (t/ha year): deposition or sedimentation

The results show that high soil erosion was observed and predicted on convex landscape positions and soil deposition was observed and predicted on concave landscape position and confirm the results obtained from the RUSLE and desertified analysis. During the four different years (1973, 1989, 2001 and 2007), simulated soil erosion/deposition maps show a low amplitude of simulated values. Indeed, the soil loss values range between 0.1 and 5 t/ha year and deposition values show similar amplitudes in the study area. These values can be elucidated by the specific terrain parameter of the Tillabéry landscape, where areas that have a low slope gradient, produce low soil loss rates and low accumulation.

Assessing soil erosion risk

The soil erosion/ deposition maps show that most of the study area is very stable with very low soil loss (0 - 0.1 t/ha year) rates and very low deposition (0 – 0.1 t/ha year) in 1973 (see figure 6.20). Erosion has a significantly lower spatial coverage in 1973 and covers an area with slope greater than 7% and was increased during the study period but the area prone to erosion was the same as 1973. Such increase in erosion zone is caused by a reduction of shrub and grassland, created desertification and affected landscape stability. This means that rill and sheet erosion has led to or will lead to land degradation, decreased soil productivity and deterioration of the soil and water quality if no conservation methods are applied. The USPED model highlights area that was potentially affected by water erosion. So erosion areas could be well-known in a short period of time using this model.

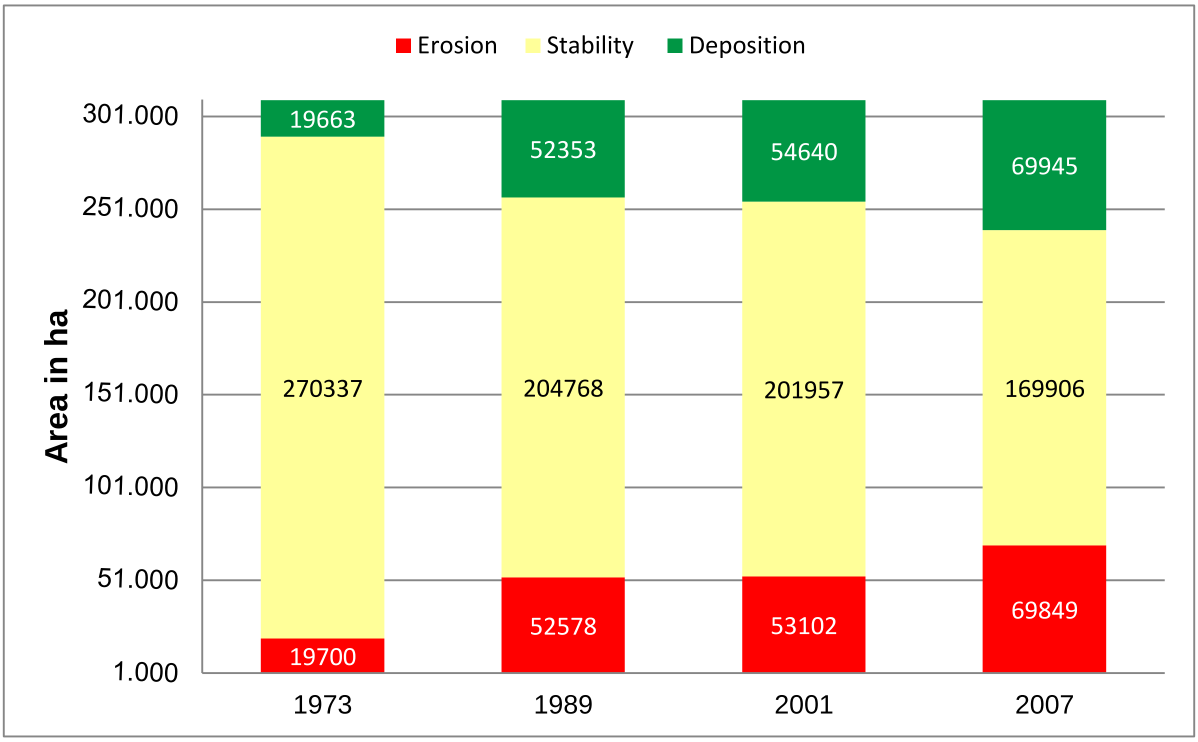

Figure 6.19: Soil erosion and deposition simulated with the USPED during the study period.

Assessing soil erosion risk

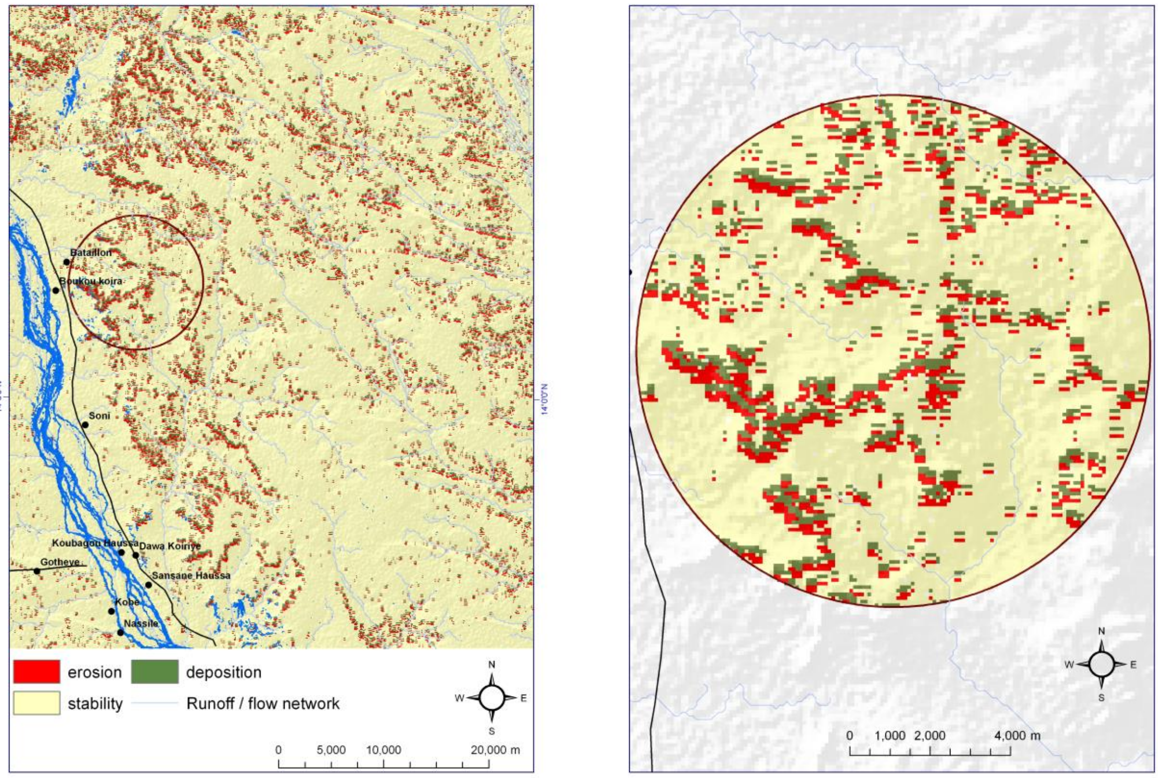

Figure 6.20: Spatial distribution of simulated soil erosion and soil deposition by USPED model for the study area in 1973.

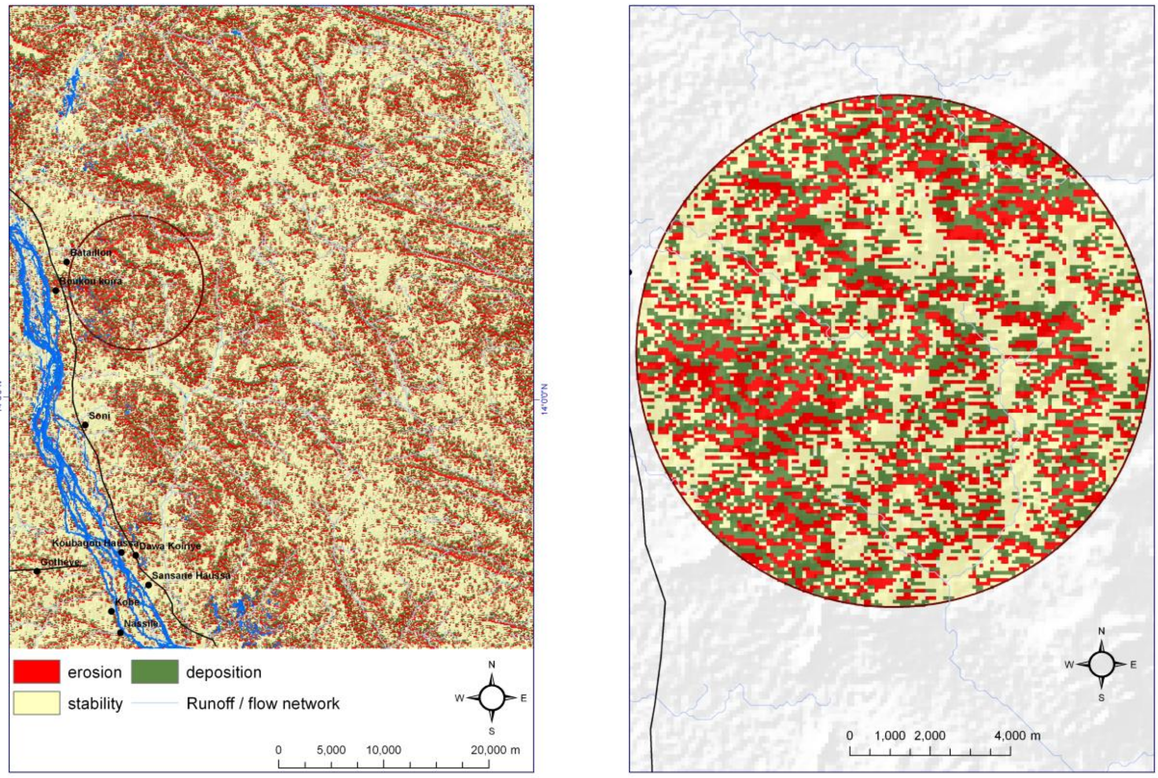

Figure 6.21: Spatial distribution of simulated soil erosion and soil deposition by USPED model for the study area in 2007.

The deposition zone is limited to the Niger River prone to accumulation and close to the runoff network as a result of the change in slope gradients. The figures 6.20 and 6.21 show a clear correlation between erosion affected zone and bare areas with gradients greater that 10%. There are areas in the center part of the study area in 1989, 2001 and 2007 which show high erosion rates and in 1973 low erosion rates because in this period these areas were generally more densely covered by shrubs. Compared to 1973, the stability area decreased by 100,431 ha in 2007 (figure 6.21). The increasing of sediment was observed during all the study period due to the climatic change, development of agricultural and bare areas. This expresses ongoing desertification.

To reduce soil erosion in the study area is more efficient than to deal with removing sediment from Niger River, which is extremely costly and difficult in Sahel region.
Investigating of soil erosion/deposition in the Tillabéry landscape can actually be seen as an original step to achieve information about the spatial distribution of soil erosion and sediment deposition within the area. In addition, the figures could be applied to identify adequate position for implementing land conservation assessment. Also, the results show that slope and land cover are the most important factors influencing soil erosion in the study area, which point out at the same time that the good land management practices have a controlling effect on soil loss.

7 Process Intensities and Dynamics in the Affected Areas

As Whitford (1992) asserted, soils are an essential resource that must be healthy for the rest of the ecosystem to remain diverse and productive. Therefore, a decline in soil quality (degradation) can have adverse effect on the ecosystem by causing a diminution in biomass productivity and environment moderation capacity (Lal et. al., 2004). Given that soil is a non-renewable resource, it is straightforwardly degraded by soil mismanagement and land misuse (Lal, 1997a).

Although land degradation is a global phenomenon, the Sahel region can be said to have more than a fair share of this problem. In the course of the field work, many different types of soil degradation were observed, such as: wind and water erosion, reduction of soil fertility, alkalinity and salinity. In this section, the process intensities of land degradation and the dynamics of affected areas are investigated.

Soil erosion is a universal problem associated with desertification, loss of soil productivity and development of unproductive land (bare area). Desertification is a fundamental and increasing environmental issue in the Sahel region. In view of this, there is a need for better understanding of the relations between affected area of soil erosion and desertification.

Water erosion affected areas rating equal or higher than 30 t/ ha year were considered as severely affected zones. These affected areas were grouped into two classes: high (between 30- 50 t/ ha year) and very high (between 50 to 140 t/ ha year) (see figure 7.1). In order to investigate the relations between desertification and erosion, the outputs of two affected areas from desertified index and water erosion computed from RUSLE model based on K factor without organic matter were overlaid. This approach provides information on rill and sheet erosion and desertification for the study area and will be useful for future monitoring of land degradation.

Process intensities and dynamics

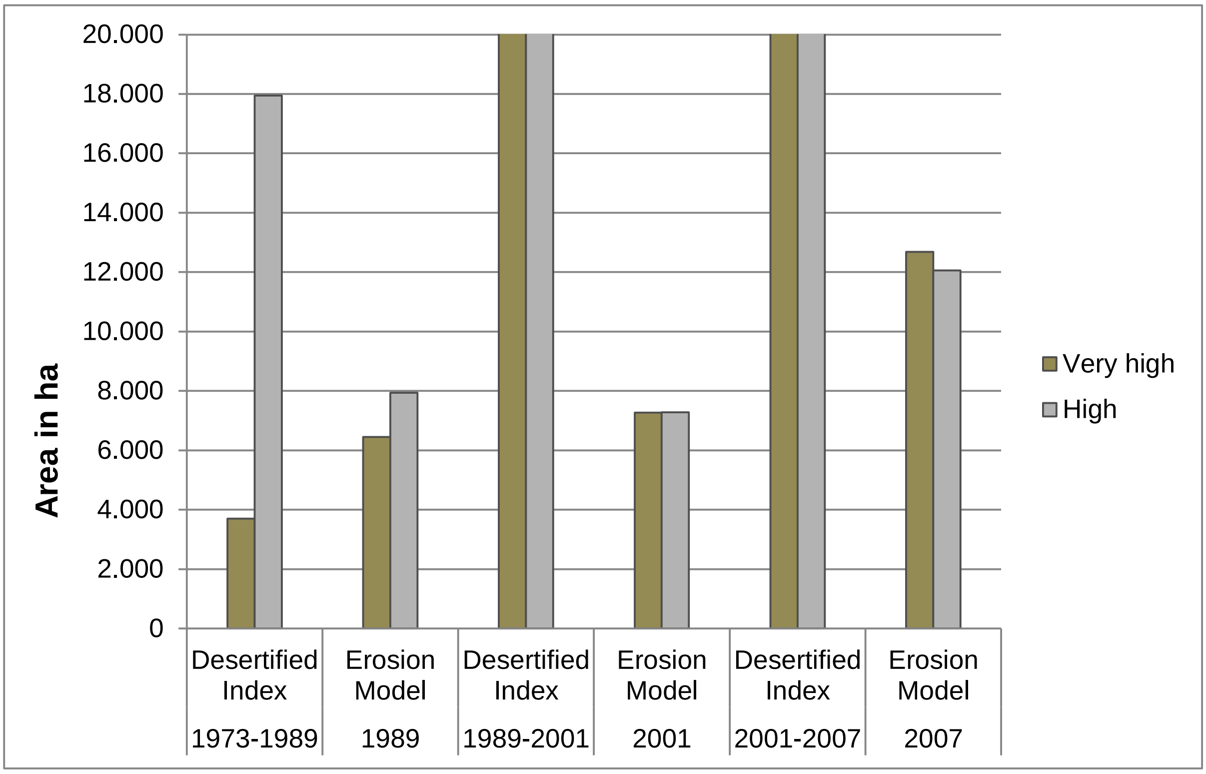

Figure 7.1: Comparison of study area according to the desertified affected area and Erosion magnitude affected area.

The comparative analysis showed that, during 16 year period (1973 - 1989), the study area was not affected by erosion and desertification due to considerable natural vegetation cover. In this period, the total desertified and water (rill and sheet) erosion affected areas were 21,651 ha and 14,396.ha respectively out of the 312,345 ha landmass of the study area.

The largest desertified area appeared mostly during the period 1989 - 2001, caused by a decrease in natural vegetation cover. During the same period, the erosion increased slightly comparative to the speed of the desertified index (see figure 7.2). The period 2001 - 2007 was dominated by an increase in areas both affected by erosion and desertification. This confirmed that the reduction of vegetation cover affected the velocity of soil erosion. In this period, the land area affected by land degradation due to water erosion is estimated at 24,746 ha and 245,258 ha according to the desertified index (figure 7.1). Areas affected by erosion are shown in the centre part of the study area whereas desertified affected areas appear to be randomly distributed.

Process intensities and dynamics

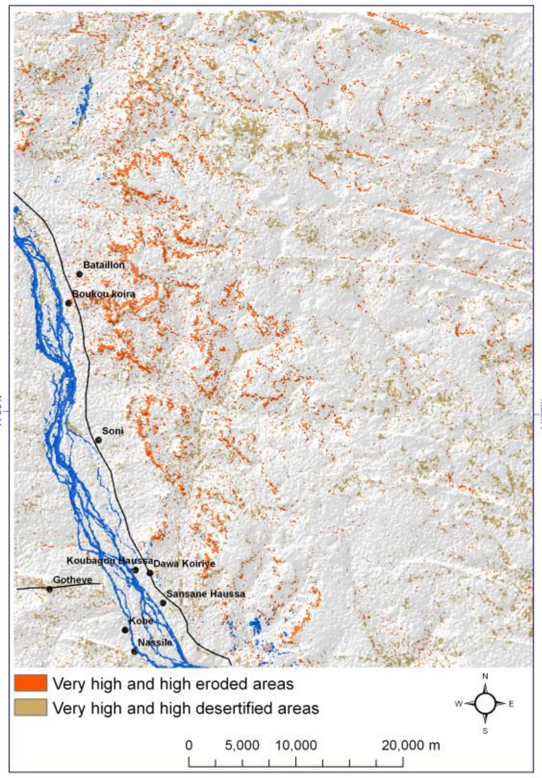

Figure 7.2: Spatial distribution of the dynamics and intensities of desertification over the period 1973-1989 and areas affected by rill and sheet erosion in 1989.

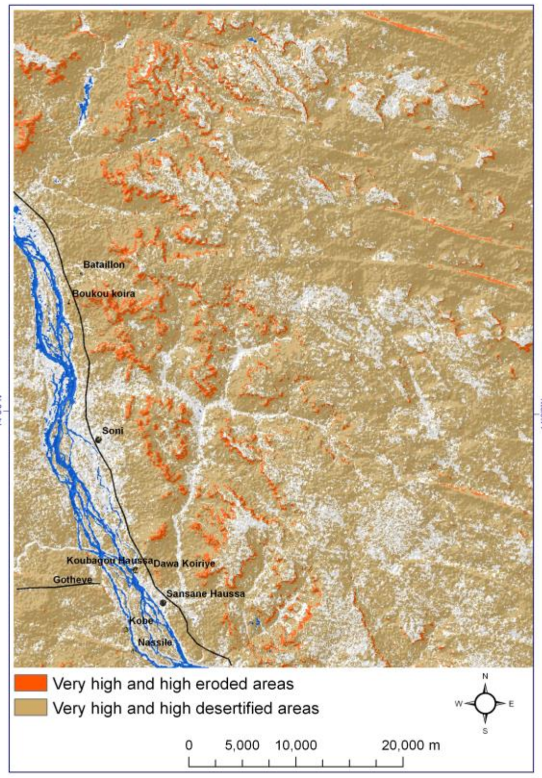

Figure 7.3: Spatial distribution of the dynamics and intensities of desertification over the period 1989-2001 and areas affected by rill and sheet erosion in 2001.

The results of desertified and erosion affected areas show the spatial-temporal dynamics and intensities of desertification and erosion processes. The figure 7.2 shows the spatial distribution of the dynamics and intensities of desertification over the period 1973 - 1989. The high and very high erosion affected areas were distributed especially at high slope position with a low infiltration and high runoff capacity. But the high and very high desertified areas were noted especially at areas with bare soil (laterite soils) in this period. During this period, areas affected by erosion were associated only with topographic factors due to high vegetation cover.

Figure 7.4: Picture of lateritic soil.

The very high and high eroded areas denoted in figure 7.5 depict areas that are affected by very high levels of soil erosion and a simultaneous high level of desertified index. These areas represent “hotspots” where the land is seriously affected by land degradation. The dominant soil types in these spots are laterites, associated with low levels of infiltration, low organic content, highly compact and a presence of ion oxide presence (see Figure 7.4).

Process intensities and dynamics

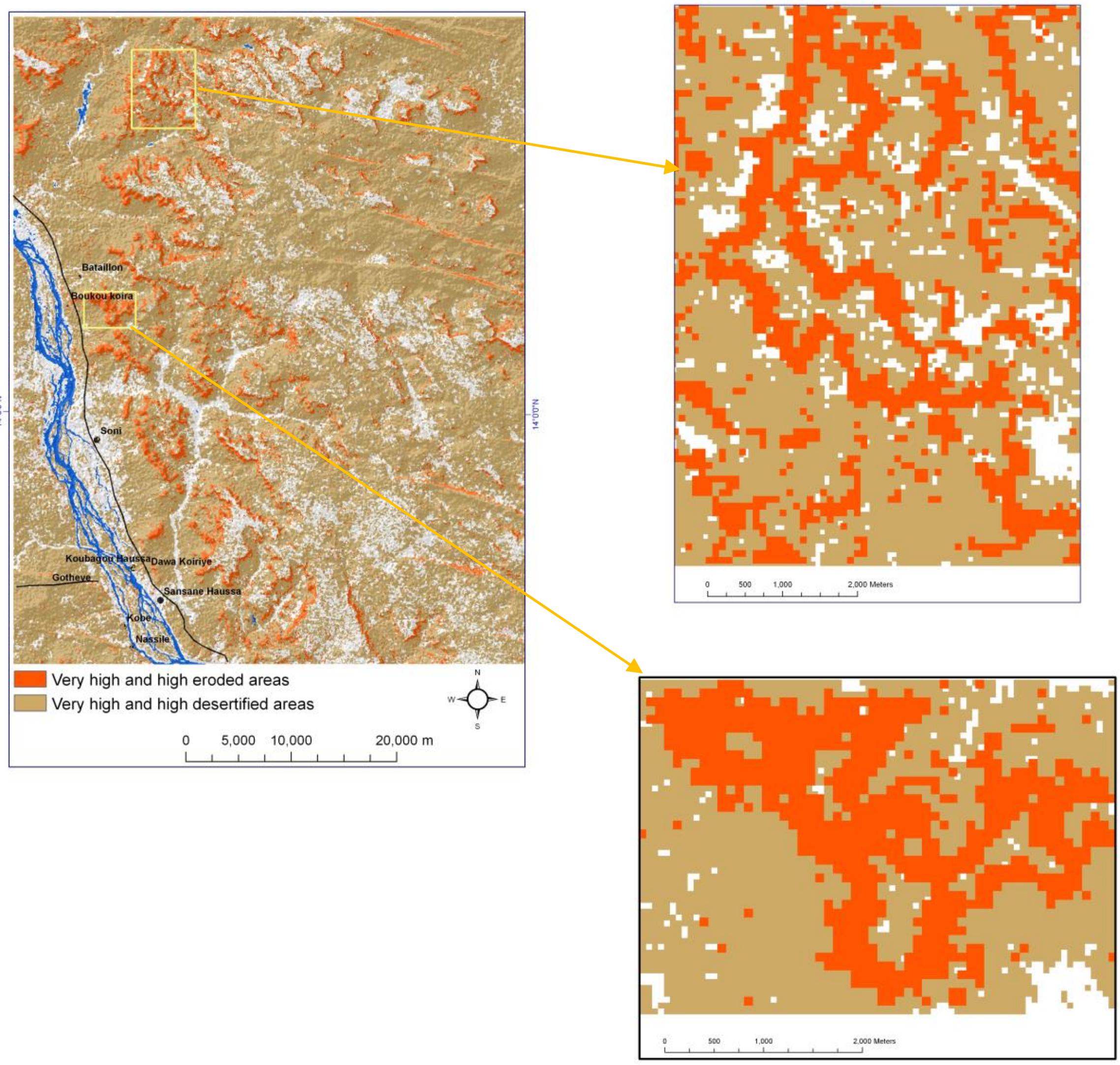

Figure 7.5: Spatial distribution of the dynamics and intensities of desertification over the period 2001-2007 and areas affected by rill and sheet erosion in 2007.

The periods from 1989 - 2001 and 2001 - 2007 (figure 7.3 and 7.5) show that both high and/or very high desertified and erosion affected areas were increased. The results suggest that human disturbance and topographic factors led to increase of affected areas. Figures 7.2, 7.3 and 7.5 provide helpful information for the planning process, which allows to identify how desertified trends and water erosion are spatially distributed during a 34 years period and indicating the more affected areas (deserts and hot spots). The areas affected by both processes created extensive challenges to human welfare (agricultural and animal production), biodiversity and water resources of this area. This issue requires active conservation management in order to reverse this negative evolution of the landscape.

8 Summary, Conclusion, Limitations and Further Research

8.1 Summary

The project presented in this thesis addressed and explored concepts and methods to assess desertification and land degradation processes in the Sahel area, particularly in the Tillabéry area in Niger. The methodology developed in this project provided powerful techniques by the integration of remote sensing and Geographical Information Systems analysis in order to examine the environmental changes that took place over a period of thirty four years in the Tillabéry area.

Particularly, the landscape metrics approach which was applied in the Tillabéry area that is prone to land degradation and desertification is a pioneer effort in this direction in the Sahel region. Previous desertification research topics have focused on the current desertification such as Iranian Deserts Classification (Ekhtesasi & Mohajeri, 1995) and Medalus (Kosmas et al., 1999). However, desertification investigations have rarely been combined with historical issues and landscape structure.

The Tillabéry area was selected for this study due to four reasons: (1) The area is prone to political instability and increasing population aggravated by low levels of education, (2) Desertification is the most serious environmental problem in this area, (3) It is located at the core of the Sahel, being a very representative and sensitive area of Sahel region and (4) It includes part of the important Niger River valley.

The results describing the effects of desertification and land degradation may be divided into five broad categories. Firstly, the secondary data was used to describe the relationship between spatial data and landscape processes and functions in the context of desertification and land degradation. This system gives an overview of the spatial data that are needed and might be useful to describe and analyse any landscape and it equally throws light on the accuracy that is needed and recommended and how and from which sources they may be obtained.

Secondly, the change detection technique provided information concerning the location, amount, direction and velocity of change. Two different change detection models were applied - change detection matrix to capture the direction, amount of change and image differentiation of land use / cover to measure the velocity of change.

Thirdly, the application of landscape metrics provided reliable results in the context of desertification investigation. The findings of the 20 selected indices at landscape and class level are capable to emphasize ongoing processes. Simoniello et al. (2006) reported that the landscape metrics are capable to highlight ongoing processes not only in relation to forests dynamics, that are already widely proven, but also for land cover severely affected by degradation processes such as badlands and gullies (e.g. Stream Power Index).

Fourthly, the change detection results (location, direction, amount and velocity) were combined with landscape metrics (landscape structure index) in order to develop a desertified index in the study area as suggested by Simoniello et al. (2006). Combining the above two techniques provided information on the nature and causes of desertification trends and land degradation processes in the study area in the years 1973, 1989, 2001 and 2007. The desertified index enables to distinguish between the spatial distribution of the contemporary state of desertification and the trend of desertification.

Finally, analyses of water erosion based on two different K factor models (with and without considering organic matter) were carried out. These results confirmed the importance of organic matter content in the Sahel region to prevent land degradation from water erosion. So, the process intensities of land degradation and the dynamics of affected areas were investigated.

8.2 Conclusions

8.2.1 Conclusions Concerning Change Detection Result

Remote sensing data was used to improve the scientific knowledge of desertification processes in Sahel region. The result of the land use / land cover analysis for the study area was derived using standardised digital remote sensing classification techniques employed on Landsat scenes dated, September 1973, September 1989, September 2001 and September 2007. A hierarchical level II land use and land cover classification involved shrub land, water, agricultural, wadi, bare areas and plateau vegetation.

Standardised accuracy assessment measures were used. The accuracy assessment showed that the land use and land cover maps were 83%, 91%, 92% and 90% for the 1973, 1989, 2001, and 2007 images respectively. For land use / land cover 2007, field data was used as reference data and for land use / land cover 1972, 1989 and 2001, tool from ERDAS IMAGINE was developed the references data. The patterns of land use / land cover are changing rapidly in the Tillabéry area. Significant losses in vegetation were noted, whereas bare areas and wadi have expanded in all directions, and agricultural land has also increased. This change can be ascribed to the combined effect of human impact (land use changes, over-grazing, increase in crop area and increase of wood harvesting) and climate change (scarcity of precipitation).

The change detection technique was adopted to map and analyse the spatial location, amount, direction and velocity of change in the context of desertification and land degradation processes. The result showed a negative trend of 29%, 34% and 35% for the years 1973 to 1989; 1989 to 2001 and 2001 to 2007 respectively. The directions of negative change in the study area are denoted by the conversions of shrubs to bare areas, shrubs to agricultural lands and shrubs to plateau vegetation. Another perspective of negative change represented by the conversions of water to bare areas, water to wadi and water to agricultural lands. The conversions of plateau vegetation to agricultural lands, plateau vegetation to bare areas and agricultural lands to bare areas signify another category of negative change.

Limitations and Further Research

Also, from the velocity of change model, two classes were characterised that show a trend in the direction of deterioration (rapidly and slowly increasing), and two classes with a trend in the direction decreasing (rapidly and slowly decreasing) desertification.

Nevertheless, it should be noted that the spatial distribution of rapidly increasing of desertification state in the northern part of the study area and the velocity of land desertification is randomly distributed during of the study period. It coved 25,245 ha, 22,8616 ha, and 203,733 ha respectively 1973 to 1989, 1989 to 2001 and 2001 to 2007. The strong rapidly increasing of desertification state from 1989 to 2001 was caused by land use changes, in overgrazing, increase in crop area and in wood harvesting.

8.2.2 Conclusions Concerning Changes in Landscape Metrics

During the period of 34 years from 1973 to 2007, twenty landscape metrics were computed and estimated at two different scales and with different input parameters. The land use / land cover in the context of desertification were identified and the investigation of possible causes was discussed. Results showed that 1989 marked the beginning of a steady increase in vegetation fragmentation and an increase in bare areas and degraded lands.

Besides this, the most important driving force of landscape change in the study area were human activities such as land use changes, overgrazing, and increase in crop area and an increase in wood harvesting. This deterioration reduced the ability of landscape to resist the desertification.

The vegetation fragmentation index was found to be a reliable approach for recovering the vegetation ecosystem and the function of vegetation fragments can be improved by encouraging natural regeneration and taking under consideration the size and shape of vegetation patches. This method will improve the connectivity of vegetation patches and the resistance to external disturbances (increasing of bare area). Desertlinks (2005) argued that the larger and connected ecosystems are the best for biodiversity conservation and for protecting landscape from soil erosion and desertification than the smaller and more isolated ones.

In many cases, fragmentation of water bodies also revealed signs of a decrease in flow of the Niger River over time. This can largely be attributed to agricultural uses, scarcity of precipitation and the movement of sandy soils (by water and wind). Besides, the landscape structure change index applied in this project, allowed for a better understanding of past and current ecological conditions in the Tillabéry landscape. It is, in fact, a reliable approach to develop environmental management strategies.

The result from landscape structure change index showed that the Tillabéry landscape has become more fragmented, less connected vegetation patches, lower diversity in land cover and consequently lower productivity. The results confirm that the landscape metrics approach can be used as indicator to support land managers in decision making to combat desertification.

8.2.3 Conclusions Concerning the Desertified Index Model

This thesis demonstrated that combining a change detection model and a landscape metrics model is a powerful approach to develop a desertified index. It supplied efficient means of locating, postulating the trajectory, quantifying the amount, determining the velocity, composition and configuration of the areas in which desertification occurred. This makes it an effective decision support tool for sustainable land management in the Sahel region. The desertified index showed that the general area of desertified land has increased during the study period. These increases are profound in areas with high altitude, which are found mostly in the middle of the study are (hotspots) due to high iron concentrations in the soil, low soil infiltration rate, poor organic matter content of soils, shallow soils and the intensive collection of wood for fuel and furniture and general household demands.

The results from the interviews are in agreement with the desertified index results of the thesis. This is particularly the case regarding the bare areas and the deterioration of vegetation cover. In order to perform the best validation of the desertified index, field data were needed and a geographical weighted regression was undertaken between the desertified index (2001-2007) as dependent variable and ground truth data as explanatory variables. The results obtained showed a satisfactory agreement between the two variables.

Finally, the desertified index has achieved the main objective of this thesis, in terms of providing a reliable tool for categorising the trend of decortications and to develop strategies for accomplishing a sustainable land management of the study area. Some general recommendation for managing the area could be given: (1) where high sensitivity to desertification was identified close to shrub patches, plantation activities in collaboration with local residents was required in order to increase the connectivity and diversity as well as to reduce the fragmentation and irregularity of shrub patches. The species to be used should be the local species such as *Acacia Senegal, Acacia laeta, Commiphora africana, balanites aegyptiaca* and others due to their high resistance to local conditions and their ability to improve soil fertility and low water demand. (2) Water management systems should be improved around the Niger River, and an urgent need to promote sustainable ecological practices.

8.2.4 Conclusions Concerning Soil Loss, Process Intensities and Dynamics of Affected Areas

The relationship between a set of topographic attributes, soil texture and different K factors for soil erosion assessment were investigated by using TreeNet model in order to improve our understanding regarding the soil degradation in the Sahel region and to build up a soil model for the study area. A set of topographic attributes (independent variables) were investigated, which allowed for a better understanding of the major driving factors that influence the spatial distribution of soil texture and erosion processes in the Sahel region. The results show that the altitude above the channel network and the wetness index are the important factors that play a dominant role in the spatial distribution of soil texture because of their direct impact on run off and transportation processes.

Soil texture output provided excellent predictive performance, confirming that the TreeNet model was an effective tool. But, the output of K factors provided a bad predictive performance (test data set) due to the limited amount of soil sampling (low sample size). Therefore Co-Kriging was used in estimating the K factors in the case of limited available data.

RUSLE and USPED models have shown a realistic evolution of soil loss distribution during all the study period and confirm the need to continue the investigation of soil erosion processes by using data mining tools in the Sahel region. Puerta et al. (2008) reported that soil loss by soil erosion is often pointed out to play a major role in the desertification process. Both soil erosion scenarios (based on future precipitation predicted from Had CM3 mode under A2 emission scenario) output show greater soil erosion in 2070 in the study area. The scenario based on K factor **without** considering the organic matter has been revealed as the one with the highest erodibility.

The present thesis confirms the importance of organic matter in influencing soil erosion prediction and also as a useful instrument in planning soil degradation control practices. Therefore, reducing soil erosion is more efficient than to deal with removing sediment and sandy soil from the Niger River, which is costly and difficult in the Sahel region.

8.3 Limitations and Further Research

The accepted limitations associated with the applied approach are the following ones:

- Classification confusion caused by overlapping spectral response of some surface features and also lack of recent cloud-free image
- Low quality of the MSS image used and the problem connected with differences in sensors, mainly the spatial resolution
- Insufficient climatic, agricultural statistics and socio-economic data
- The results of thematic change and landscape metrics greatly depend on the accuracy of the classification of the land cover and land use classes derived from the satellite images. A number of errors may exist on land cover and land use data and the data may amplify the error
- One main problem in interpreting landscape metrics is that the landscape elements have to be delineated from each other in patches, which may be difficult and arbitrary in some types of landscape
- Another limitation in interpreting landscape metrics is the scale and the spatial resolution of the data. These limitations were taken into account with vigilance when comparing results from different periods of the study

Limitations and Further Research

- Inaccessibility and lack of security in some locations of the study area during the field work
- ASTER DEM was found to have a higher resolution, but was not used due to the vegetation reflectance in the images

The following issues should be further investigated in future research studies

Repetition of the investigation in other sites of the Sahel region was needed and transferring the methodology to the whole Sahel region. These approaches will require a big amount of data. For this reason, low resolution (MODIS or MERIS) or moderate resolution (LDCM or SENTINEL-2) could be used, because the methodology of the desertified index also works with low resolution. However, the desertified index is most transferable to semi arid region with the vegetation conditions similar to Sahel region.

But future research would much more benefit from high and very high resolution images for desertified index, at regional level such as GeoEye-1, QuickBird and IKONOS or multisensoral data. This would produce more reliable results. Another method that could contribute to the enhancement of the desertified index performance is the combination of radar and optical satellite data (data fusion) for the parameterisation of different land use / land cover. Above all, our understanding of desertification patterns needs to be further developed by involving further research. First of all, this includes more research in the behaviour of landscape structure indicators at other sites than the Sahel region, and second is the integration of socio- economic parameters in the methodology of desertified index needed.

Finally, erosion (RUSLE and USPED) models are prone to further research. Further studies must be focused on trying to improve the soil erosion processes by using data mining tools in the Sahel region. However results indicate that the greater number of sampling sites and using higher quality DEM derived from LIDAR/RADAR and TanDEM-X are needed in order to improve the result of the soil model.

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10 Appendice

Questionnaire to assess desertification and land degradation in Tillabery area

Name of village: ________________________________

I. Land degradation:

1. Do you perceive the problem of land degradation on your field?

   i. yes_______

   ii. no________

2. if yes, what features lead you to believe that such problem exists ?

   i.____

   ii.____

3. Do you observe appearance of plant species that signify the severity of land degradation

i. yes_______________

ii. no________________

4. If yes, what are the names of these species?

Local Name	Scientific Name
i.__________________	______________________
ii.__________________	______________________

5. Do you use Kind of practice to control land degradation

   i. yes____

   ii. no_____

6. If yes, which of the following technique do you practice?

   i. crop rotation

   ii. terracing

iii. windbreaks

iv. vegetative and crop cover

v. tree planting

vi. agro forestry

vii. other (specify)____________________

II soil Fertility and land productivity

7. Do you perceive the problem of land productivity decline on your cultivated land?

i. yes______

ii. no_______

8. if yes, has it been:

i. increasing_________

ii. decreasing_________

iii. unchanged_________

9. What features leads you to believe that such problem exists?

i.____

ii.____

10. Do you observe change in the level of soil fertility on your cultivated land?

i. yes __________

ii. no___________

11. if yes, has it been increasing or declining?

i. increasing

ii. declined

12. if increasing or declining what are the major reasons?

i.____

ii.____

13. Do you observe appearances of plant species that signify decline in soil fertility?

i. yes __________

ii. no___________

14. if yes, what are the names of these species?

Local Name Scientific Name

i.______________ ____________________

ii.______________________ ______________________

15. if yes, which of the following practices do you use?

i. use of organic fertilizer

ii. use of inorganic fertilizer

iii. intercropping

iv. crop rotation

v. agroforestry

vi. others(specify) ______________________

16. if you use inorganic fertilizer, what kind of fertilizers do you use?

____

17. How much do you pay for 50 kg of fertilizer?

____

18. Has your fertilizer use increased, decreased, or remained the same?

____

19. What are the reasons for this change?

i.____

ii.____

20. Does investment in fertilizer use benefit you ?

i. yes

ii. no

21. Is fertilizer available in your village?

i. yes

ii. no

22. How often have you experienced drought and famine in this area?

i. once in 2 years_______

ii. once in 4 years_______

iii. other (specify)_______

23. What measures do you take in times of famine and drought?

i. ____

ii. ____

iii. ____

iv. ____

II. Land availability

24. How many people live in your house?________

25. What is the total area of your cultivated land?

____________________Ha

26. Are you cultivating all your land?

i. yes________

ii. no_________

27. if no , what are the reasons?

____

28. Has the size of your cultivated land changed?

i. yes

ii. no

29. if yes, has it:

    i. increased

    ii. decreased

    iii. same

30. If it has decreased, what are the reasons?

____

____

31. How do you solve this problem?

____

32. if your cultivated land has expanded, is the newly cultivated land as productive as the previous one?

    i. more productive______________

    ii. less productive_______________

    iii. same ________________________

33. Do you grow trees on your farm?

i. yes

ii. no

34. If yes, for what purposes?

    i. building materials_____ tree type _________

    ii. fuel wood_____________ tree type_________

    iii. fodder________________ tree type_________

    iv. increase soil fertility ____ tree type_______

    v. fruits__________ tree type_______________

    vi. Windbreaks_____ tree type_______________

    vii. shades__________ tree type_______________