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Dr. Mansour Mahamane
Eduardo Mondlane University of Maputo Mozambique

Dr. Volker Hochschild
Prof. Eberhard Karls University of Tuebingen Germany

Dr. Alfred Schultz
Prof. Eberswalde University for sustainable development

Jude Nkuo Kuma
Justus-Liebig University of Giessen Germany

Correspondence
Dr. Mansour Mahamane
Eduardo Mondlane University of Maputo Mozambique

Monitoring Desertification in the Tillabéry Landscape (Sahel Region) using Change Detection Methods and Landscape Metrics

Mansour Mahamane, Volker Hochschild, Alfred Schultz, Jude Kuma

Abstract
This paper seeks to investigate and monitor desertification processes by using remote sensing based change detection methods as well as landscape metrics approaches. The analysis of land use/cover between 1973 and 2007 was conducted using one Landsat Multispectral Scanner (1973-09-30) image, a Landsat Enhanced Thematic Mapper plus (2001-09-18) image and two Landsat Thematic Mapper (1989-09-29 and 2007-09-27) images. The results of these classifications revealed an increasing trend in desertification throughout the study period. A set of indices (Mesh Index, Landscape Shannon's Diversity Index, Mean Patch Area and Shape Index) were selected to investigate multi-temporal change in the Tillabéry landscape (Western Niger) an area affected by desertification. The results show that the landscape is highly fragmented, with a corresponding high number of patches with smaller patch sizes, indicating that the original landscape has been converted gradually into bare and desertified area. To further understand the trend and status of desertification in the Tillabéry landscape, a desertified index was developed.

Keywords: Change detection, Desertification, Landscape metrics, Tillabéry landscape (Niger)

1. Introduction

Human activities and natural factors operating in the Sahel have permanently changed the ecosystem by modifying the land use/cover potentials as well as the biodiversity of the landscape. Changes in the landscape are apparent and can also be perceived directly. They are associated with biodiversity losses (Tucker & Townshend, 2000) [17], negative socio-economic impacts, loss of soil quality, dramatic and unprecedented land use/cover dynamics, as well as climate change (Pielke *et al*., 2002) [11]. Several conservation and development studies have highlighted the predominant role played by desertification as a major factor in influencing land cover patterns in the Sahel, an issue that is also closely linked to demographic conditions in the area (Turner *et al*., 2007; Reenberg, 2012 & Van Vliel *et al*., 2013) [18, 13, 19].

Historically, the Sahelian ecosystem has proven to be very prone to undesirable weather conditions. Such is the case with the floods that occurred in 2007, 2008, 2009, 2012 and 2013 causing severe destruction to infrastructure, significant crop losses, leaving behind a degraded landscape. Sarr & Lona (2009) [15] reported that in Burkina Faso alone, a total of 9,300 ha of cultivated areas were destroyed in 2009. Likewise the droughts that occurred in 2010 caused significant losses in human life and livestock. The changing pattern between floods and droughts as observed between 2009 to 2012 shows how susceptible the Sahel is to extreme weather events. In the wake of such catastrophe, relieve efforts have often been slow to be mobilised. Such was the case during the famine of 1973 when lack of timely provision of resources led to the death of 200,000 people and 12,000,000 cattle (Glantz & Orlovesky, 1984) [4]. It is in the wake of the vulnerability of this ecosystem particular to climatic changes that it is primordial to understand desertification trends in the Sahel.

The fragile nature of the Sahelian ecosystem to climatic changes has led to the migration of many nomadic herders to other countries south of the area. All these challenges exacerbate the vulnerability of the population of the Sahel region (Mertz *et al*., 2011) [9]. Parry *et al*., (2007) [10] reported that rapid population growth, pervasive poverty, increasing urbanization and rural exodus, complex governance and chronic instability, lack of investment in education and public health, high sensitivity of key economic sectors to climate, fragile soils, and the lack of resilience makes the Sahel region and its population vulnerable to the projected increases in frequency, severity and the extent of land degradation. This paper aims to investigate and monitor desertification processes by combining change detection methods and landscape metrics. By providing spatio-temporal information on the nature of conversion of patch types. It also presents an overview of the sequential nature of landscape changes and as such, contribute in understanding the changing pattern in land use/cover in the Sahel.

2. Methods

2.1 Study Area

The study area is located in Western Niger in the core of the Sahel in the department of Tillabéry and includes parts of the wide valley of the Niger River (Fig. 1). Annual precipitation ranges from 300 – 400 mm (see Fig. 1). This area is dominated by sand and loam soil (Mahamane 2015). It is very infertile and poses enormous challenges for agricultural production. Desertification and land degradation are amongst the major challenges faced by inhabitants of this area.

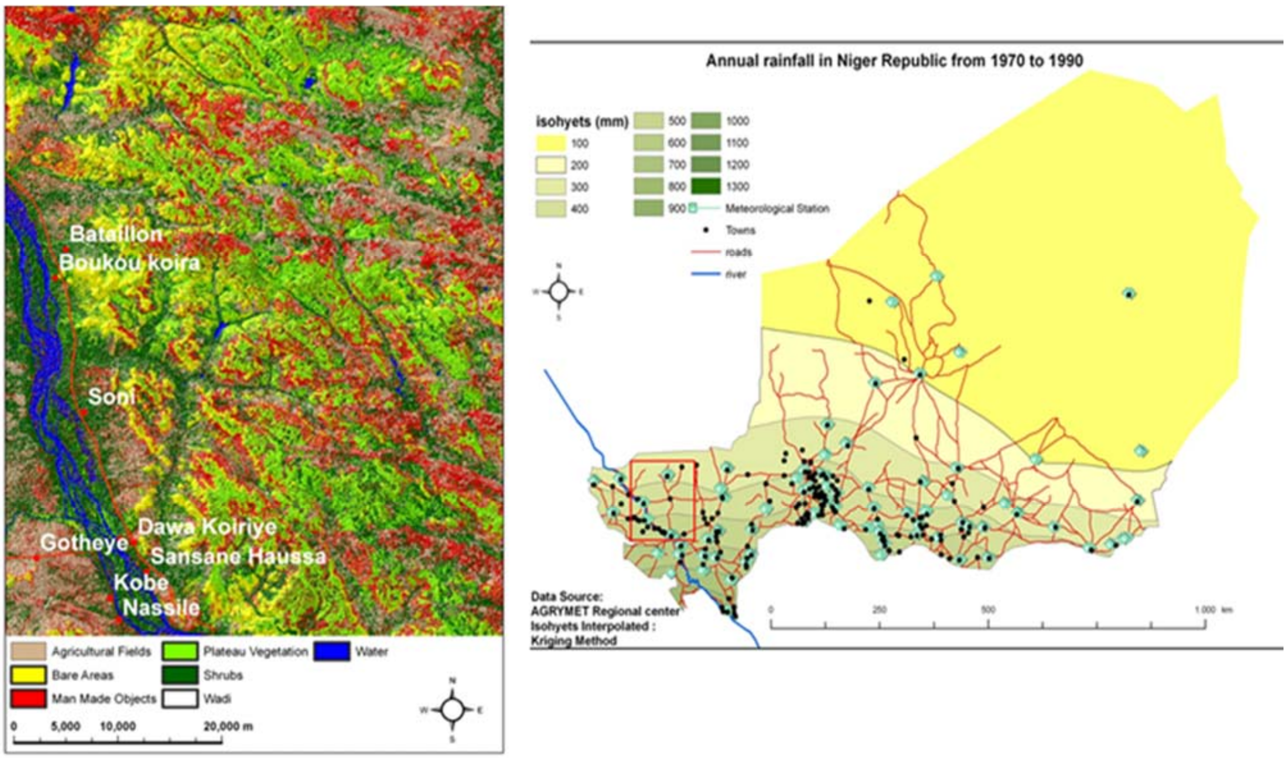

Fig. 1: Location of the study area in Niger, showing different types of land use/cover in 2001.

2.2 Data and Method

The paper seeks to answer the questions projected in Fig. 2. In answering these questions, it combined change detection method and landscape metrics, so as to and provide a scientific understanding of the phenomenon of desertification.

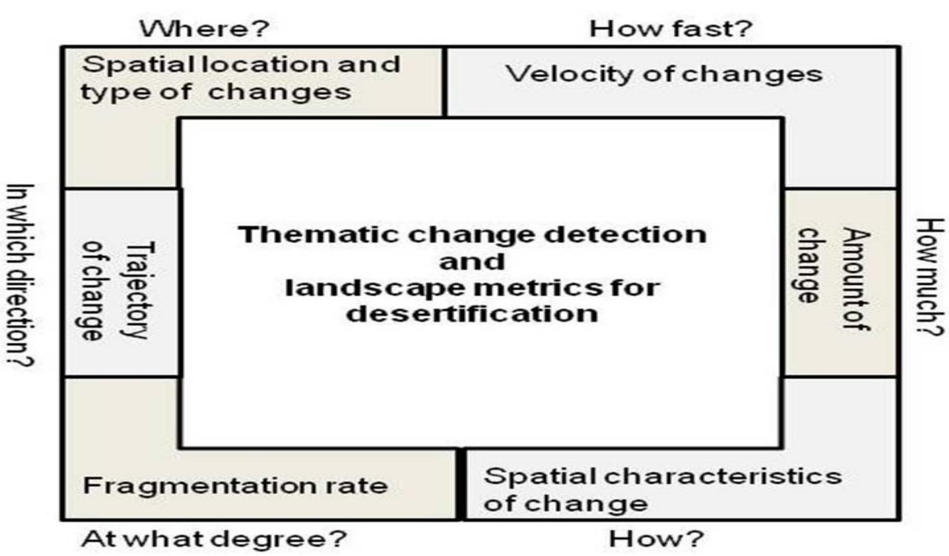

Fig. 2: Quantitative data presented by combining change detection and landscape metrics method

In capturing spatio-temporal change in the Tillabéry landscape, focus was made on the indices that can capture landscape diversity, fragmentation and the irregularity of patches. In this regard, Li *et al*. (2004) [6] provided a useful guide. Therefore the following combined index for landscape structure (LS) was applied:

$$LS = f(M_{eff}, MPA, LSI, SHDI) \qquad 1$$

Where M_{eff} represents the Mesh index, $SHDI$ is the Shannon's Diversity Index, MPA is the Mean Patch Area, and LSI is the Shape Index at the landscape level.
The *LS* is dominated by the Mesh Index due to its high value. Since the above mentioned formula does not reflect changes but rather displays the spatial information of landscape structure, the change detection method was used to express the landscape structure change (*LSC*) index.
Three variables were chosen including: location, amount and direction of change, velocity of change, and landscape structure change. The arithmetic means of the three variables were calculated for the final desertified index (DI) according to formula (2). A low pass (7x7 kernels) filter was applied to all the layers for noise reduction:

$$DI = f(ADV, V, LSC) \qquad 2$$

Where DI represents the desertified index, ADC is the amount and direction of change, V is the velocity of change, and LSC is the landscape structure change. The Mesh Index, Landscape Shannon's Diversity Index, Mean Patch Area and Shape Index were selected at the landscape level.
Maps of DI were prepared, and based on this model, the index values were grouped into five classes, ranging from very high to very low defined as follows:

- Very high (DI) combines high values of landscape structure change – conversion of shrubs to bare areas as a result of the amount and direction of change and increasing elements in the velocity of change.
- High (DI) combines high values of landscape structure change – conversion of plateau vegetation to bare areas and increasing elements in the velocity of change.
- Moderate (DI) is 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) combines low values of landscape structure change and no change in the context of the amount, direction and velocity.
- Very low (DI) combines low values of landscape structure change – decreasing elements in the velocity of change and positive changes from amount and direction of change.

3. Results and Discussion

The results from the various landscape matrices show that the land use/cover of the Tillabéry landscape have undergone significant changes from 1973 to 2007. Major losses in vegetation were noted, whereas bare areas and wadi also expanded in all directions and agricultural lands also increased. These changes can be ascribed to the combined effect of human impact (land use changes, over-grazing, increase in crop area and increase in wood harvesting) and climate change (decrease in rainfall events).

3.1 Change detection

The change detection technique was adopted to map and analyze the spatial location, amount, direction and velocity of change in the context of desertification processes. The result showed a negative trend of 29% and 35% for the periods from 1973 to 1989 and 2001 to 2007 respectively (see tables 1 and 2). 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 is 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.
From the velocity of change model, two categories were characterized that show a trend in the direction of deterioration (rapidly and slowly increasing) and two categories with a trend in the direction decreasing (rapidly and slowly decreasing) desertification. Nevertheless, it should be noted that the spatial distribution of areas subjected to a state of rapidly increasing desertification are in the northern part of the study area and the velocity of change for areas vulnerable to desertification is randomly distributed during the first period (1973 – 1989). The strong rapidly increasing state of desertification from 1989 to 2001 was caused by land use changes associated with overgrazing, increase in crop area and in wood harvesting. The results of the change detection method are revealed in Fig. 3 (A and B). This illustrates the changes from 1973 – 1989 and 2001 – 2007. The northern part of the study area shows drastic changes in vegetation cover whereas the vegetation around the Niger River is comparatively more stable. Increases of bare areas, wadi and agricultural fields constitute the major dominant change in the study area.
The areas subjected to desertification are characterised by an increase in bare areas and wadi and a decrease in vegetation cover. Table 1 show that more than 29% of the area changed. The greatest change is the conversion of vegetation areas to bare areas. The period (1989 – 2001) shows significant increase in bare areas, an important factor that affects the landscape in this area. In that regard, the greatest conversion was from shrubs to bare areas (10%). Plateau vegetation equally decreased by 6% to the benefit of bare areas.
The spatial distribution of the gains in bare areas from vegetation cover are more concentrated in clustered patches in the north, the centre and in the southeast. Shrubs lost 8% of their surface area to agricultural fields. It is worth pointing out that a total of 20% of features that are considered to be deterrents to desertification were converted to bare areas and wadi during this period.

Table 1: 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 2: 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**

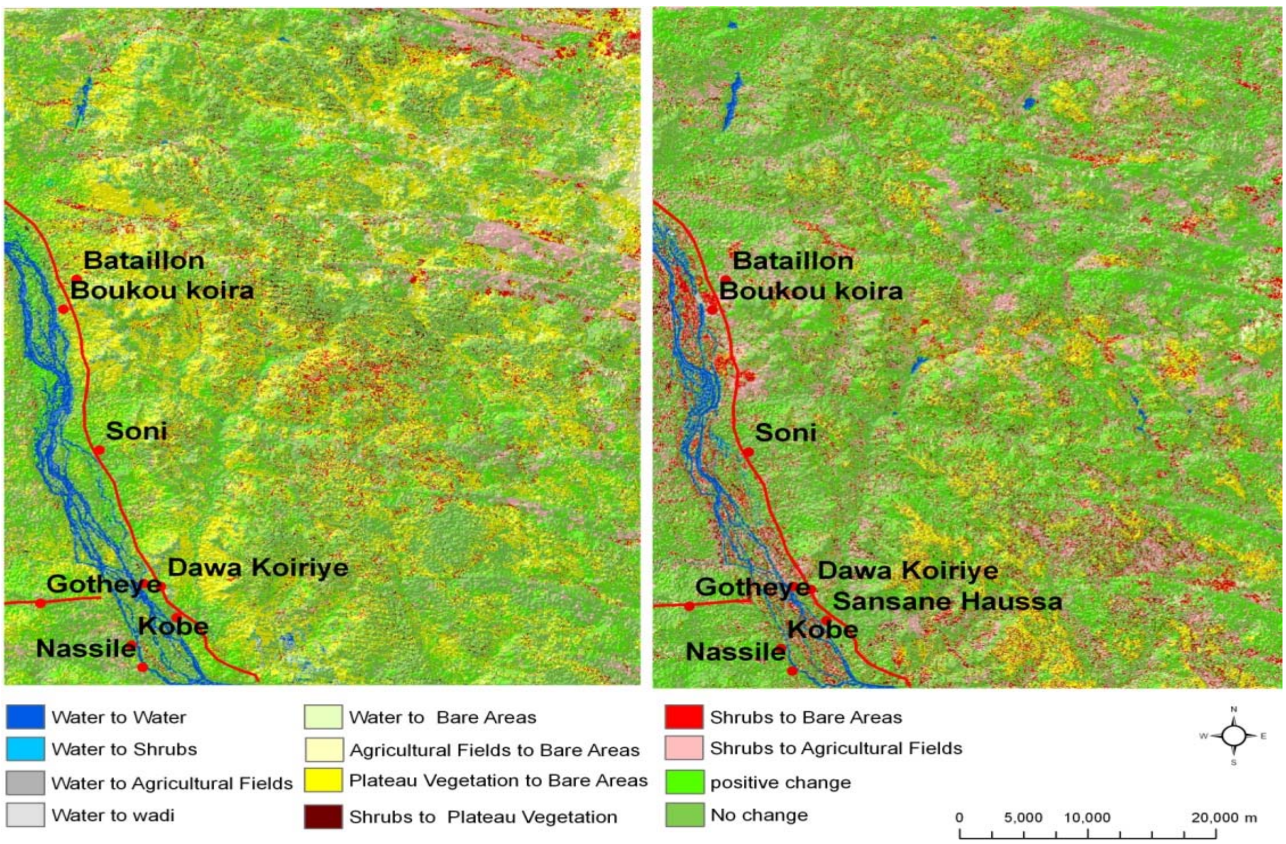

Fig 3: Land cover change detection map 1973 –1989 (left) and 2001–2007 (right) for Tillabéry and its environs.

During the period 2001 – 2007, the greatest changes were recorded by agricultural fields. It made a total increase of 13%, 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 study area (see Fig. 3 right). From Tables 1 and 2, one can observe that agricultural fields, bare areas were gradually increasing during the different intervals of the study. Bare areas increased by 7%, being gains from plateau vegetation and shrubs. Desertification in this area is characterised by an increase in bare areas and wadi, as well as a decrease in vegetation cover.

3.2 Landscape Metrics for Monitoring Desertification Phenomena

Landscape metrics were computed and estimated for the 34 year period at two different scales and with different input parameters. A set of indices that represent the composition and configuration of landscapes were selected with a special focus on desertification. In this section the capability of individual metrics to quantify landscape structure will be investigated in the context of desertification.

3.2.1 Composition Metrics - Diversity Metrics

Diversity metrics are derived from information theory and involve the use of indices such as Patch Richness (PR) and Shannon's Diversity Index (SHDI) (Margalef, 1958) [8]. SHDI increased from 1.17 in 1973 to 1.49 in 1989, but then declined slightly (see table 3) between 1989 and 2007. This reflects a reduction in evenness, as the landscape became dominated by larger patches of a few land cover type. During the entire study period the Shannon´s Evenness Index (SHEI) value is high (close to 1), implying that the study area is not dominated by a single land cover type.

The SHEI increased from 0.73 in 1973 to 0.92 in 1989 and later decreased slightly from 0.92 in 1989 to 0.78 in 2001. The increase in the values of SHEI and SHDI during 1973 – 2001 can be attributed to the emergence of a river corridor and an increase in the breadth of the corridor over the years, resulting in an increase in the number of landscape elements. Patch Richness (PR) increased from 1973 to 2007 due to an increase in landscape elements (more classes), which means a decrease in biodiversity as well as nutrient storage (soil degradation) and storm water retention in the study areas. The decline in nutrients shows decreasing trends in soil fertility and affects the food security in the study area. This is a major contributing factor in conflicts between farmers and pastoralists (Coe and Foley (2001) [2].

Throughout the study period, the Simpson's Diversity Index (SIDI) indices are high (close to one) this is an indicator that the study area is not dominated by a single land cover type. Modified Simpson's Diversity Index (MSDI) increased slightly from 1973 – 1989 and declined slightly from 1989 – 2007. The MSIDI and the SDI both increased from 1973 – 1989 and decreased slightly from 1989 – 2001. The increase in diversity and in evenness during 1989 – 2001 can be attributed mainly to the existence of a river corridor and an increase in the size of the corridor over the years which led to an increase in the number of landscape elements.

Further interpretation of the land cover diversity processes can be done by evaluating and comparing maps of Shannon's Diversity Index (SHDI) at landscape level using a moving window approach (60 m radius). These maps (Fig. 4) show the spatial distribution of diversity in the study area for the years 1973, 1989, 2001 and 2007. The vegetation cover is characterized by high diversity index values. Bare areas exhibit low diversity index values. From 2001 – 2007, large sparsely vegetated areas that have been severely degraded are characterized by low diversity index values. The Diversity Index therefore is a sensitive indicator of desertification

Table 3: 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

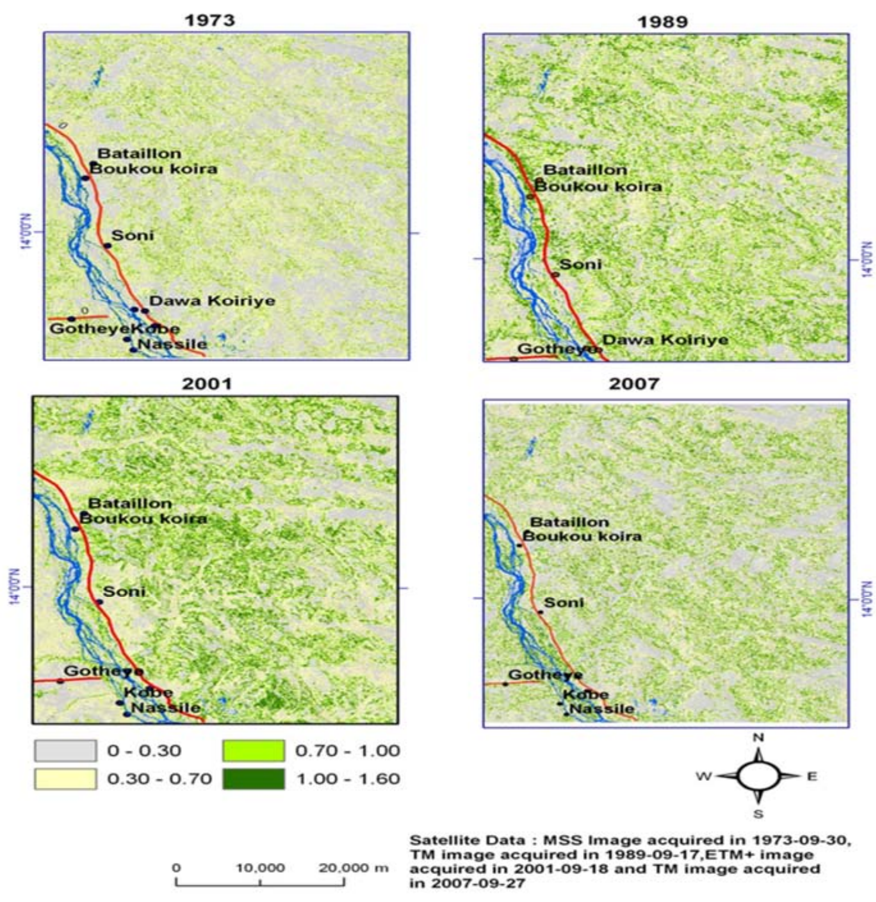

Fig 4: Shannon diversity Index

3.2.2 Desertified Index (DI)

Using the DI, a three-step approach (amount and direction of change, velocity of change and change of landscape structure) was developed to characterize the change of desertification in the study area. Attribute information in percentage of the desertified land in the study area during the three different time intervals is shown in Fig. 5 and Fig. 6. The landscape is slightly influenced by desertification as displayed in the map. Changes denoting very high and high rates of desertification are concentrated more in the north and southeast of the study area.

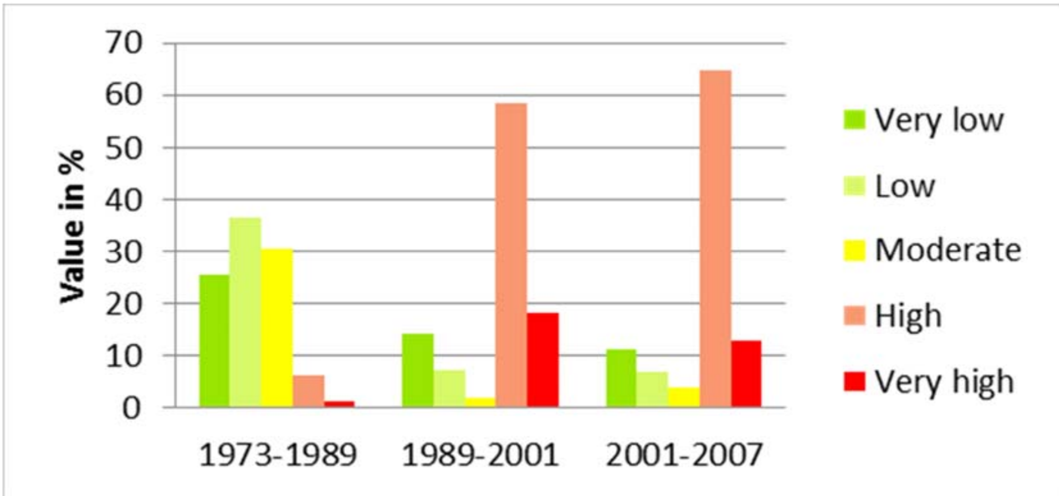

Fig 5: Percentage of desertified classes during the intervals of 1973 – 1989, 1989 – 2001 and 2001 – 2007. The increase in severe land degradation classes is obvious.

Another important class worth highlighting is the dominance of moderate, low and very low DI during this period (1973 – 1989) caused by an increase in planting activities. Shrubs later decreased from 1989 to 2007 caused by human activities and climate change, aggravated by political instability. The periods from 1989 – 2001 and 2001 – 2007 showed a tremendous increase in high and very high rates of desertification.

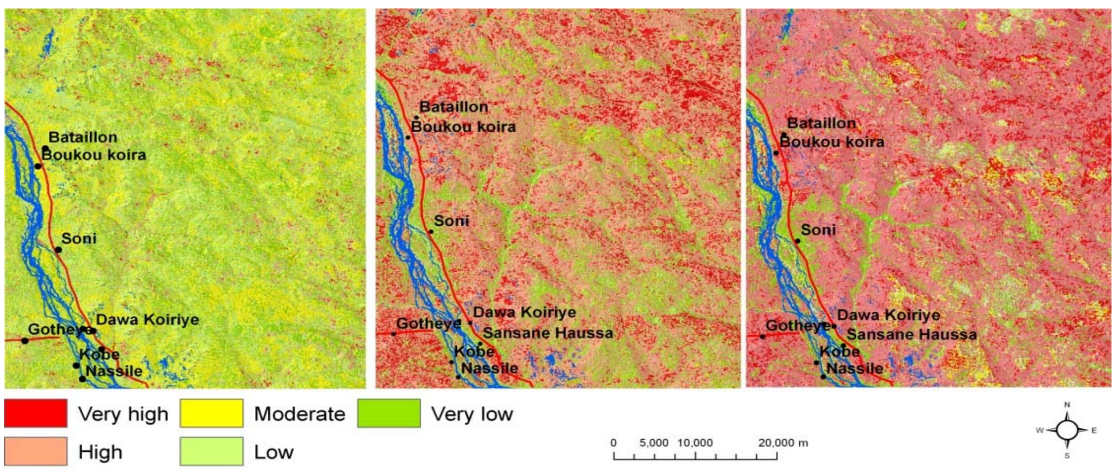

Fig 6: Spatial distribution of desertified land area during the intervals of 1973 – 1989 (left), 1989 – 2001 (middle) and 2001 – 2007 (right).

On the one hand, the statistics point out that the very low and low classes of desertified land area decreased greatly in the three different intervals (very low: interval periods 1973 - 1989, 1989 - 2001 and 2001 - 2007 25%, 14% and 11% respectively. Data for the low: interval periods 1973 - 1989, 1989 - 2001 and 2001 - 2007 were 36%, 7% and 7% respectively). On the other hand, the statistics indicate that the very high and high classes were increased in the three different intervals (very high: interval period 1973 - 1989, 1989 - 2001 and 2001 - 2007 were 1%, 18% and 12% respectively and high: interval period 1973 - 1989, 1989 - 2001 and 2001 - 2007 were 6%, 58% and 64% respectively). These results agree with the findings of Amogu *et al*. (2010)

4. Conclusions

This paper demonstrates that by combining a change detection technique and landscape metrics additional information is generated in understanding the process of desertification in the Tillabéry landscape. The DI provides an efficient method of locating, postulating the trajectory, quantifying the amount, and determining the velocity, composition and configuration of the areas in which desertification occurs. This makes it a valuable index in understanding spatio-temporal changes on disturbed landscapes. The DI further shows that the area of desertified land has increased during the study period. This increase is profound in areas of high altitude, which are found mostly in the middle of the study area due to high iron concentration in the soil, low soil infiltration rates, low organic matter content in the soils, shallow soils and the intensive collection of wood for fuel, furniture and general household demands.

Finally, the DI also serves as an index to categorize trends in decortication and provides a useful tool to guide policy makers identify urgent areas to intervene in land management. Some general recommendations for managing the area include: (1) where high sensitivity to desertification was identified close to shrub patches, tree planting activities should be conducted in order to increase the connectivity and diversity of the landscape, as well as to reduce the fragmentation and irregularity of shrub patches. Local species such as *Acacia senegal, A. laeta, Commiphora africana, Balanites aegyptiaca* should be used in reforestation activities due to their high tolerance to thrive on marginal lands in the Tillabéry landscape and also due to their ability to improve soil fertility while lowering water demand. (2) Water harvesting around the Niger River should be strictly supervised to allow the river to fight encroaching sand (3) Sensitization of local residents on farming practices that foster re-greening is vital in order to combat desertification and land degradation in the Tillabéry landscape.

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