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SPATIO-TEMPORAL VARIATIONS OF TOP SOIL COARSENING AS A PEDO-GEOMORPHIC INDICATOR OF LAND DEGRADATION AND DESERTIFICATION STATUS IN A PART OF SEMI-ARID ZONE OF NIGERIA

[1]Ndabula, C., [1]Jidauna, G.G., [3]Oyatayo, K., [4]Iorkua, S.A., and [5]Iguisi, E.O.

[1]Department of Geography and Regional Planning, Federal University Dutsin-Ma, Katsina State
[2]Department of Geography, Ahmadu Bello University Zaria, Kaduna State, Nigeria
[3]Department of Geography, Kwararafa University Wukari, Taraba State, Nigeria
[4]Department of Geography, Benue State University, Benue State, Nigeria

Corresponding author: jidauna@yahoo.com/gjidauna@fudutsinma.edu.ng

ABSTRACT

Soil degradation is commonly mentioned as an indicator of desertification, not much is focused on specific form of soil degradation such as top soil coarsening which is rarely studied with respect to desertification. The major aim of this study therefore, is to assess the spatio-temporal patterns of top soil coarsening as a pedo-geomorphic indicator of desertification status (extent, rate and magnitude) in the semi-arid zone of Nigeria. This achieved using top soil grain size index (GSI) evaluated from remotely sensed reflectance of three (3) bands R, B and G of multi-temporal Landsat images (TM, 1987; ETM+, 2000 and OLI/TIR, 2015) and computed using a ratio algorithm. The multi-temporal sets of GSI (1987, 2000 and 2015) were generated from corresponding temporal Landsat images and top soil grain size sensitivity index (GSSI) was evaluated from the sensitivity analysis of the geometric mean of the three sets of GSI. Each of the temporal GSIs and the GSSI were segmented into five (Very High, High, Moderate, Low and Very Low) sensitivity to desertification areas. Result show that there is a generalized temporal trend of increasing intensity of top soil fine sand content or coarsening and hence desertification in the study area. Although the intensity varies among all the respective sensitivity areas mapped. For instance the highest intensity of 21.15% was recorded in the Very High Sensitivity Area, followed by Moderate (18.39%), High (17.50%), Low (12.82%) and Very Low (7.53%). The spatial extents of the distribution of top soil coarsening or fine sand content show a decline in the Very High and High Sensitivity Areas at annual rates of 1.46 and 1.39 km2 respectively, while in the Moderate, Low and Very Low Sensitivity Areas expansion at annual rates 1.17, 1.38 and 1.38 Km^2 respectively. Dynamic rate for the period (1987-2015) among sensitivity areas stood at Very High (3.56%), High (1.36%), Moderate (3.32%), Low (8.63%) and Very Low (43.74%). The single factor ANOVA analysis at 0.05 level of significance showed that there is significant variation in the change in top soil coarsening over the period (1987-2013) as well as among the various desertification sensitivity areas.

Key words: Desertification, Pedo-geomorphic, Indicator, Top Soil, Coarsening, Grain Size

INTRODUCTION

Desertification is a climate-related eco-geomorphic hazard and slow-onset disaster characterized by persistent exposure and sensitivity to adverse biophysical perturbations caused by both proximate and underlying biophysical and socio-economic factors resulting in land degradation mainly but not exclusively in arid, semi-arid and dry sub-humid areas (Ndabula, 2015). It also sustains a progressive shifting and conversion of the eco-geomorphic systems towards desert-like state. The cost (economic, technologic, and chronologic) of reversibility increases with the extent, rate and intensity of land degradation and desert-like state and becomes irreversible only if neglected to exceed a certain threshold to convert into desert landscape (Ndabula, 2015). Climatic conditions together with geomorphologic processes help to mould desert-like soil surface features in arid zones (Xiao et al., 2006). The identification of these soil features serves as a useful input for understanding the desertification process and land degradation as a whole (Shrestha et al,. 2005). Top soil coarsening is one of the most visible signs and symptoms of soil degradation and desertification in semi-arid lands

Top soil coarsening is one of the aspects of soil degradation that is not commonly studied especially with respect to desertification. Top soil coarsening is a form of soil degradation whereby there is the concentration of the top soil, of coarser sandy particles that would ordinarily be randomly distributed throughout the top soil. This occurs when the finer particles are removed by erosion (Xiao *et al*., 2006). Major causes include human activities such as over-grazing, over-cultivation and climatic factors such as high rainfall and wind storms intensities.

Among the few studies of top soil coarsening as an indicator of land degradation and desertification (Su *et al*., 2004; Xiao *et al*., 2006; Wang *et al*., 2006; Wang *et al*., 2008; Hongyan*et al*., 2008;and Macchiato *et, al*., 2008). Soil particle size distribution is one of the most important physical attributes in soil systems (Hillel *et, al*., 1980). Particle size distribution characterizes the soil texture and other physical properties such as the movement and retention of water, solutes, heat and air and thus changes in soil grain size distribution greatly affects soil fertility (Su *et, al*., 2004). It is on the basis of this that Su *et, al*. (2004) and Xiao *et, al*. (2006) posited that changes in top soil grain size distribution was useful parameter for monitoring soil degradation and desertification process. Wang *et, al*. (2006, 2008) showed that landuse has considerable influence on particle size distribution. Hongyan*et, al*. (2008) had examined both climatic and anthropogenic influences on top soil distribution in semi-arid east Asian, steppe using four environmental/human activity factors; mean annual temperature (MAT), mean annual precipitation (MAP) and human disturbance index (HDI) and landuse/landcover (LULC).Major causes of topsoil coarsening include overgrazing and over cultivation which tend to accentuate both wind and water erosion (FU et al., 2002) which entrenches finer soil particles thereby increasing concentration of coarser sand particles in the top soil.

The focus on examining top soil coarsening among other aspects of soil degradation is increasingly important in view of its diverse implications on other aspects of soil fertility. It is generally reported that Soil Organic Carbon (SOC) content is negatively correlated with coarse sand percentage implying that reduction of soil fertility is linked to top soil coarsening (Liu etal., 2007). Soil degradation due to topsoil coarsening results in soil compaction and reduction in primary productivity of the soil (Noy-Meir, 1973). Xiao et al., (2006) found that in inner Mongolia the GSI has a positive correlation with fine sand content. The more severe the desertification, the coarser the topsoil grain size composition (ie coarse grains >2mm). top soil coarsening also affects soil bulk density.

MATERIALS AND METHODS

Study Area

The Sudano-sahelian ecological zone of Nigeria has its southern boundary crossing latitude 12^{o}N on the western frontier to latitude 10^{o}N 30' on the eastern frontier, extending to latitude 14^{o}N as the northernmost boundary (Kowal and Knabe, 1972; Mortimore, 1989). The generally low lying relief plains of the Chad Basin is geologically a sedimentary formation, but the Yobe axis of the study area principally comprises crystalline and sedimentary rocks, underlain by basement complex rocks. The climate is semi-arid with wide seasonal and diurnal temperatures. A long dry season is followed by a single short wet season. The high intensities rainfalls and strong Harmattan (NE easterly) trade wind are the dominant geomorphic agents influencing the fluvial and aeolian processes respectively to account for this semi-arid geomorphic landscape pattern. The soils of Borno-Yobe vary in color, texture, structure, physic-chemical and other essential characteristics. Fig3.1.2.4 reveals the distributin of soil. Vertisols (dark heavy clay soils (firkin)) dominate the flat plains close to Lake Chad and most parts of wetlands and floodplains. Regosols found mainly in the sand dunes are shallow with weakly developed profiles. The vegetation is dominantly of sudan and sahel savanna and is characterized by sparse shrubs, grasses and woody trees.

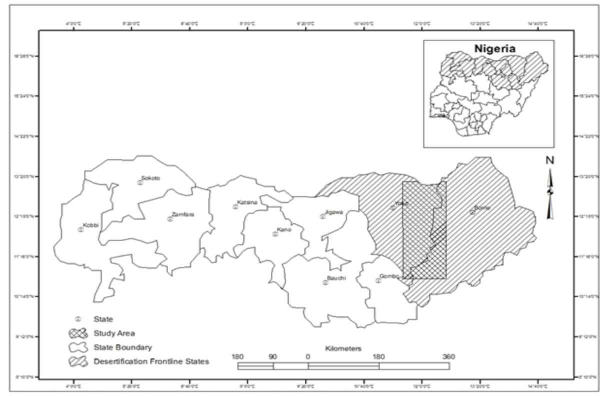


Fig 1: Desertification Frontline States Showing the Study Area Source: Ndabula, 2015

Data Type and Sources

Multi-temporal Satelite images (landsat.TM, 1987, ETM$^+$, 2000 and OLI/TIR, 2015) were downloaded from the GLCF. The selection of images was based on availability and systematic sampling at an approximate 15 year interval. Also the use of only Landsat images is based on the fact that when selecting RS data for change detection application, it is important to use images of the same sensor, radiometric and spatial resolution and near acquisition dates in order to minimize effects of external sources such as sun angle, seasonal and phenological differences. First of all, optical images of high resolution were preferred over microwave, since most of the biophysical indices require information that are captured in the Visible, NIR and Thermal bands. High resolution Landsat.TM, Landsat.ETM and Landsat.OLI/TIR provided better spectral, spatial and radiometric properties for extraction and computation of biophysical indices especially of vegetation and soil conditions,

Image Preprocessing Techniques

In most cases it is preferable to convert satellite image data to physical quantities such as Surface or Top of Atmosphere (TOA) spectral radiance and reflectance, before using the data to interpret the landscape. It is the surface or TOA spectral reflectance that is characteristic of a particular surface type. The objective of image pre-processing was to prepare image bands for reliable and accurate information extraction of landscape biophysical characteristics, which depends heavily on using physically derived quantities from satellite images. The pre-processing was performed on band x band basis.

- Band x Band radiance and reflectance correction using ENVI software using landsat metadata as contained in the USGS handbook user guide that came with the images.
- Band x Band resampling of the multi-temporal data sets of landsat images in ArcGIS software
- Band x Band mosaicing and subseting of the study area in Erdas imaging software

The following pre-processing operations were performed in the order below

- Conversion of calibrated Digital Numbers (DNs) to radiance
- Dark Object Subtraction (DOS)
- Conversion of radiance to reflectance values
- Conditional enforcement of positive values
- Reprojection

- Mosaicing
- Subsetting

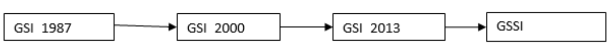
Conversion to surface or top of the atmosphere (TOA) radiance
LandSat images used in this study were not in the original USGS GeoTIFF with metadata format. Hence, conversions of Qcal –to- Lλ were not automatically computed in GIS software. For landSat data not in the original USGS GeoTIFF with metadata format, conversion of Qcal $_{-to-}$ L_{λ} need to be manually computed. Two methods were used, depending on the scene calibration data available in the header file(s). The two methods and formulas have been adapted from USGS (2001) Landsat handbook. Preliminary field reconnaissance was conducted to aid image interpretation

Evaluation and mapping of top soil grain size index (GSI) and sensitivity index (GSSI)
Top soil grain size index computes the ratio of three (3) bands R, B and G. Top Soil Grain Size Index (GSI) for the three multi-temporal landsat datasets were first evaluated and mapped using the algorithm developed by (Xiao *et al*., 2006)

GSI= (R - B)/(R + B+ G) ……………….. (1)

Where, R = band3, G = band2, B = band1, NIR =band4 for landsat TM amdETM+ and R = band4, G = band3, B = band2, NIR = band5 for landsatOLI/TIR

The GSSI was then evaluated and mapped from the geometric mean of the three GSI datasets
GSSI= $\sum(GSI\_87 + GSI\_2000 + GSI\_2013)^{1/3}$.



The multi-temporal sets of GSI (1987, 2000 and 2013) are generated from corresponding temporal landsat images and GSSI from the sensitivity analysis of the geometric mean of the three sets of GSI that have been generated in raster map format.
GSSI= $\sum(GSI\_87 + GSI\_2000 + GSI\_2013)^{1/3}$

All the GSI and GSSI raster maps were classified into vulnerability classes using natural breaks (Jenks, 1967; 1977) to reveal spatio-temporal patterns based on hierarchical organization in the landscape. The extent, rate and intensity of change were computedusing the landuse/landcover change structures approach suggested by Wang *et, al* (2010) and applied by Ndabula*et al.,*2013).

Annual rate of conversion or change (L) was computed using the logarithmic approach of Landis (2001).

- Annual rate of conversion or change (L) was computed using the logarithmic approach of Landis (2001).
  $L=10(\log(U_{bi}-U_{ai}))/T$ …………………………(2)

Where;
L= Rate of conversion or change
U_{bi}= Areal extent of landcover at the beginning of study
U_{ai}= Areal extent of landcover at the end of study
T= period between the beginning and the end
NB: this logarithmic approach according to (Landis, 2001) gives better estimates than the direct approach that divides rate of change by time (U_{bi}-U_{ai}/T)

- Landcover/landscape Change Intensity Index (Ti): the extent of a particular landcover change divided by total land area (B) in the study period. It can be used to compare the strength of land use change or potential trends (Wang, 2010). It measures landcover change in the breadth and depth and thus a good measure of magnitude or intensity of landcover change.

$T_i = (U_{bi}-U_{ai})/B$…………………(3)

T_i = intensity of the landcover change in the study period.
U_{ai} = Areal extent of landcover at the beginning of study
U_{bi} = Areal extent of landcover at the end of study
B = total areal extent of study area

- Landcover/landscape Dynamic Index**:** This is the rate of change of landcover type within a certain period of time (Wang, 2010)

$$K = \frac{U_{bi} - U_{ai}}{U_{ai}} \times \frac{1}{T} \times 100\% \text{ ………………………..(4)}$$

K = Built-up dynamic index for landcover within study period.
U_{ai}= Areal extent of landcover at the beginning of study
U_{bi} = Areal extent of landcover at the end of study
T = study Period.
NB: This approach differs from rate of growth used in (a) above

RESULTS AND DISCUSSIONS
According to Xiao *et al*, (2006) top soil grain size has a positive correlation with fine sand content. Where higher values represent higher finer rather than coarser sand content and hence decreasing top soil coarsening and lower values less finer and coarser sand content and hence increasing top soil coarsening and thus desertification. Higher values towards 1.0 signify high fine sand content and hence high tendency of top soil coarsening while negative values or nearly 0 represent water or dense vegetation. Top soil coarsening or increasing fine sand content may result from the gradual loss in clay and silt likely due to water or wind erosion.
Results revealed in Figs 1a, 1b, 1c and 1d indicates inter annual temporal increasing trend as seen in the values of GSI; In 1987 (-0.143 to 0.456), 2000 (-0.107 to 0.497) and 2015 (-0.079 to 0.515). the upper limit positive values has been increasing steadily from 0.456 in 1987 to 0.497 in 2000 and 0.515 in 2915 signifying increasing top soil coarsening. This implies that the analysis of sensitivity areas leaves the northernmost Very High, High and Moderate higher sensitivity areas as increasing top soil coarsening. On the other hand the lower negative values have been decreasing steadily from -0.143 in 1987 to -0.107 and -0.079 in 2015 signifying increasing vegetation regeneration and recovery from desertification especially in the Low and Very Low sensitivity areas to the south of the study area. However, the GSSI which seeks to show long term mean values revealed values in the range of -0.084 to 0.420 hence top soil coarsening is caused by short term changes in land surface conditions such as climatic variations, vegetation changes and human activities such as grazing and cultivation.
From Figs 2a, b, c, and d and the respective Tables 1a, 1b, 1c and 1d all show that there is a generalized temporal trend of increasing intensity of top soil fine sand content or coarsening and hence desertification in the study area. Although the intensity

varies among all the respective sensitivity areas mapped. For instance the highest intensity of 21.15% was recorded in the Very High Sensitivity Area, followed by Moderate (18.39%), High (17.50%), Low (12.82%) and Very Low (7.53%). These inter annual spatio-temporal patterns of change in intensity can be attributed to short term climatic variations such as seasons, dry spells, and droughts. Also human activities such as grazing, cultivation that reduce vegetation cover are at the root of these desertification dynamics.

The spatial extents of the distribution of top soil coarsening or fine sand content show a decline in the Very High and High Sensitivity Areas at annual rates of 1.46 and 1.39 km2 respectively, while in the Moderate, Low and Very Low Sensitivity Areas expansion at annual rates 1.17, 1.38 and 1.38 Km^2 respectively. Dynamic rate for the period (1987-2015) among sensitivity areas stood at Very High (3.56%), High (1.36%), Moderate (3.32%), Low (8.63%) and Very Low (43.74%).

In Table 1a it can clearly be seen that inter annual patterns among sensitivity areas tend to fluctuate in some cases while in others they reveal a steady pattern. For instance, in the Very High, Moderate and Low sensitivity areas they pattern is erratic fluctuations among the years under review, while in the High and Very Low sensitivity areas steady expansion has been observed.

The study went further applied the Top Soil Grain Size Sensitivity Index (GSSI) to examine mean extents and rates of top soil coarsening among the sensitivity areas. Results indicated mean extents are as follows; Very High (1618 Km^2), High (7266 Km^2), Moderate (13154 Km^2), Low (6017 Km^2) and Very Low (2517 Km^2).

Top soil coarsening as observed in this study may have resulted from loss of fine grain fractions due to human activities such as over-grazing and over-cultivation through erosion and also an increase in coarse grain fractions by climatic changes. This study disagree in part with the report of Abubakar et al (1999) which said there was no top soil coarsening. However it agrees in the aspect of increasing regeneration of vegetation and thus top soil coarsening since in the southern parts were decreasing GSI values of negative to zero values signifies vegetation increase.

Post analysis field corroboration observed this phenomenon mostly on badlands where either due to over-grazing, or over-cultivation the top soil compaction has resulted in hard panning of soil surface. These areas have shown very clear visible signs of poor or reduced primary production or decline in vegetation cover as posited by Noy_Meir (1973). Primary production in arid and semi arid regions is higher on coarse texture soils, than on fine texture soils, but when top soil coarsening sets in primary production declines. The post field description of state of the various classes which was supported with laboratory analysis of fine sand content which is has positive correlation with top soil coarsening (Xiao et al., 2006)

CONCLUSION

This study successfully showed that the use of fine sand content or top soil coarsening using evaluated from remote sensing or satellite data is a convenient, reliable means of studying desertification in space and time. The generalized trend is that there is an increasing rate, extent and intensity of fine sand in the top soil of the study area which signifies desertification.

Efforts towards combating desertification should be focused on specific forms of desertification such as top soil coarsening which has multiple effects on other aspects of soil fertility. Areas undergoing top soil coarsening were observed in the field to also correlate with badland (paved soil surfaces with very scanty short thorny shrubs. It also leads to reduction in soil organic carbon. GSI is also positively correlated to other soil physical parameters such as bulk density, soil moisture holding capacity and soil organic carbon. Therefore, loss of fine sand content or increasing coarser sand content in the top soil is very detrimental to soil fertility and productivity. Both wind and water erosion are adduced as the probable processes accounting for top soil coarsening. Therefore, the green belt project is seen as one major way of combating top soil coarsening and thus desertification in the study area.

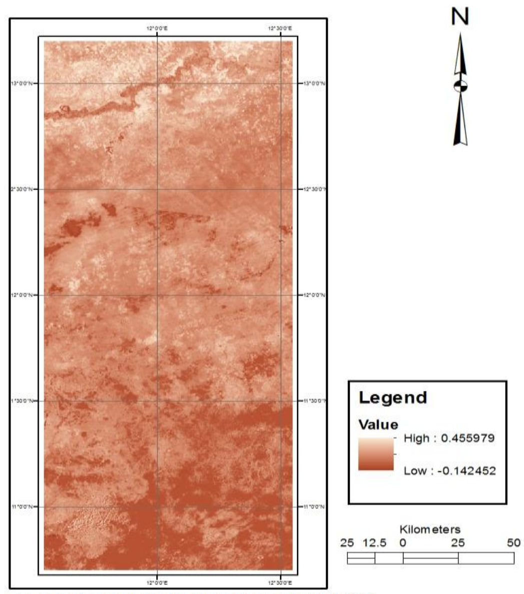


Fig 1a: Top Soil Grain Sise Index (GSI 1987)

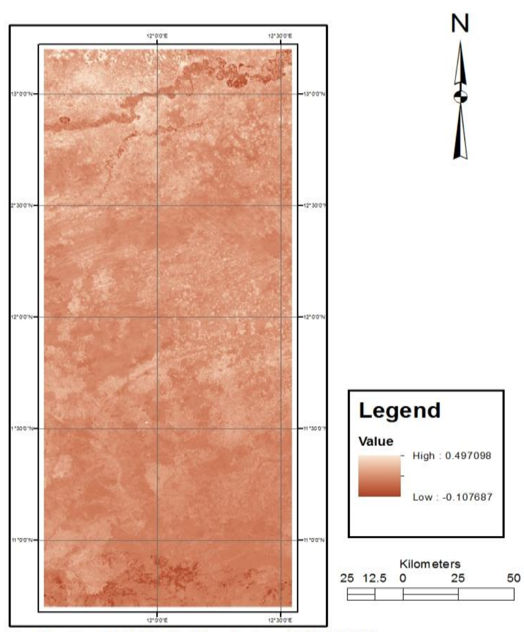


Fig 1b: Top Soil Grain Sise Index (GSI 2000)

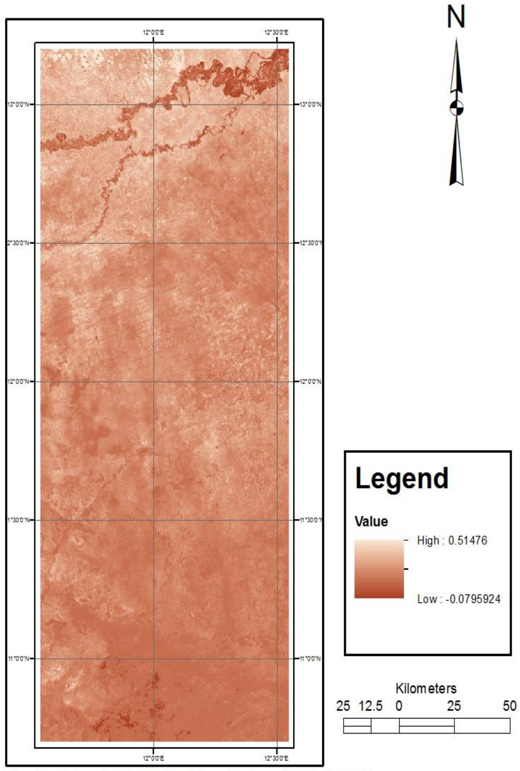


Fig 1c: Top Soil Grain Sise Index (GSI 2015)

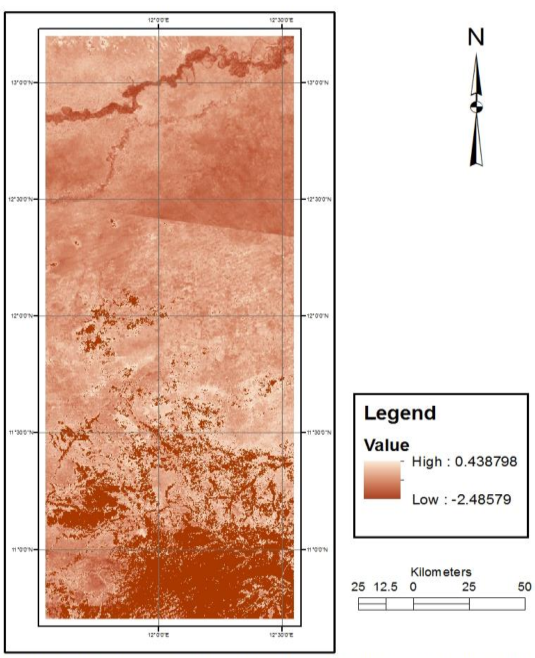


Fig 1d: Top Soil Grain Size Sensitivity Index for the Period (1987-2015

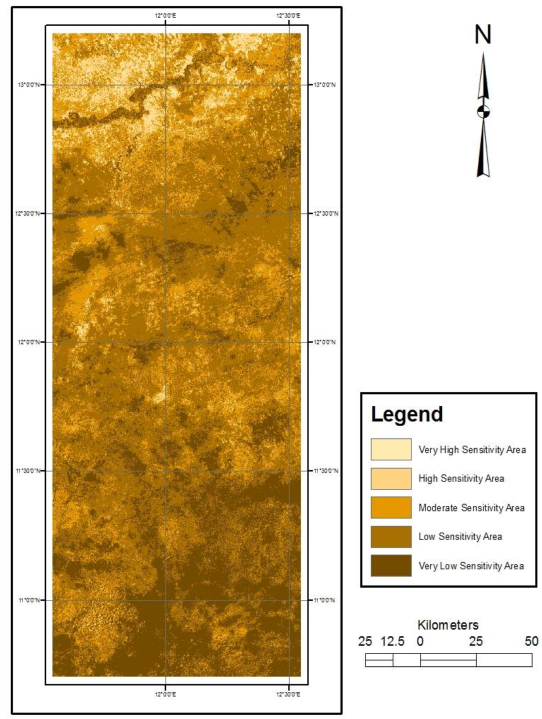


Fig 2a: Top Soil Coarsening SensitivityAreas (1987)

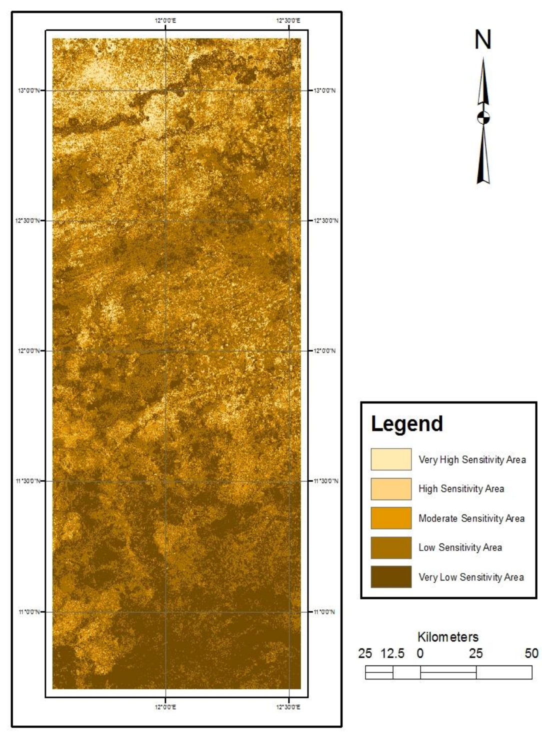


Fig 2b: Top Soil Coarsening SensitivityAreas (2000)

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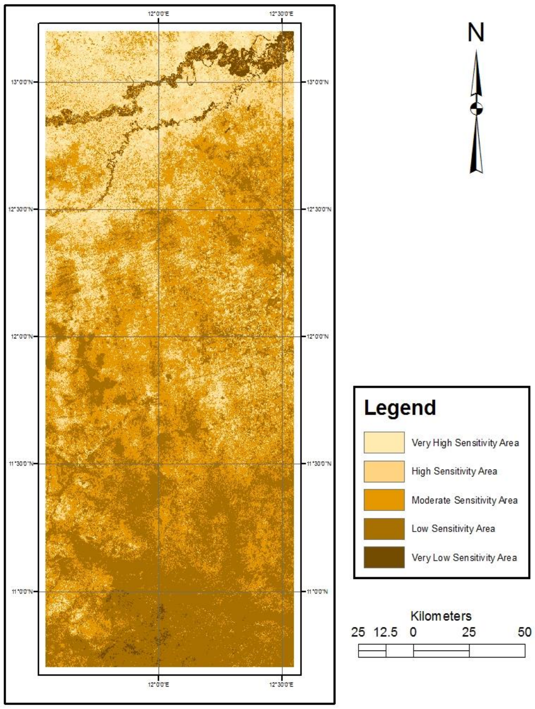

Fig 2c: Top Soil Coarsening SensitivityAreas (2015)

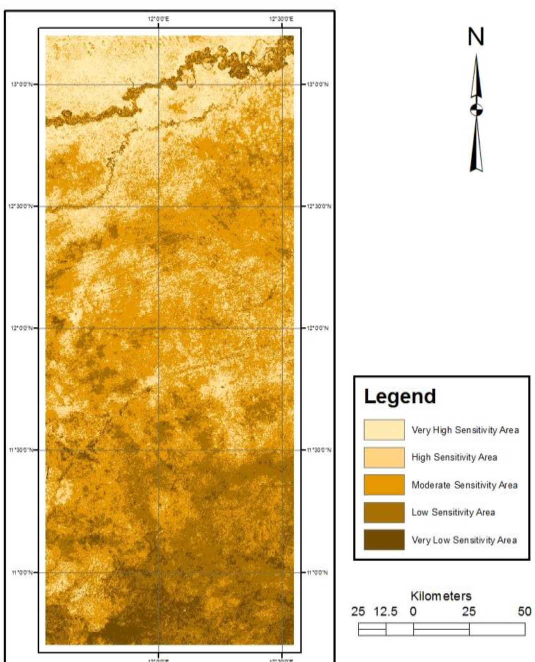

Fig 2d: Top Soil Coarsening SensitivityAreas for the Period (1987-2015)

Table 1a: Spatio-temporal patterns of Top Soil Coarsening Sensitivity Areas (Based on GSI and GSSI analysis) in the study area

Class of Sensitivity Area (SA)	Extent of i^{th} class of SA in km^2 1987 (Uai)	Extent of i^{th} class of SA in Km^2 2000	Extent of ith class of SA in Km^2:2015 (U_{bi})	Extent of ith class of SA in Km^2 based on GSSI	Change in extent of i^{th} SA in Km^2 for study period (U_{bi}-U_{ai})	Annual Rate of change of i^{th} SA in Km^2 (Li)	Change intensity index for i^{th} class of SA for the study period (T_i) in %	Dynamic index for i^{th} class of SA in % for the study period (K_i)	proportion of contribution by i^{th} class of SA for the study period (A_i)
1-Very high	6939	9693	516	1618	-6423	-1.46	21.15	3.56	-0.012
2-High	14984	12899	9668	7266	-5326	-1.39	17.50	1.36	0.051
3-Moderate	6482	5448	12069	13154	5587	1.17	18.39	3.32	0.326
4-Low	1736	1817	5631	6017	3895	1.38	12.82	8.63	0.094
5-Very low	201	516	2487	2517	2286	1.38	7.53	43.74	-0.517
Total Area	30373	30373	30373	30373					

Source: fieldwork, 2015

Table 1b: Post Field Analysis and Description of Top Soil Coarsening Sensitivity Areas (Based on GSSI)

S/N	Sensitivity Class	Location	GPS	Description
1	Very high	Babangida Kalalawa	12º7'22"N; 11º45'37"E 11º55'44"N; 11º51'31"E	Dorminantly bare sandy areas with fine sand content > 45%,
2	High	Kalalawa Lawanti	11º55'34"N; 11º50'46"E 11º37'59"N; 11º37'35"E	Scattered thorny shrubs areas with fine sand content <45-30%
3	Moderate	Lawanti Dabalam	12º38'36"N; 11º40'47"E 12º3'45"N; 11º38'27"E	Dorminantly thorny shrubs areas with fine sand content <30-25%
4	Low	Allagarno Shegau	11º55'34"N; 11º38'20"E 12º55'34"N; 11º38"20"E	Dominantly Scattered woody savanna areas with fine sand content <25-20%
5	Very low	Gabai Allagarno	11º57'44"N; 11º38'20"E 11º55'55"N; 11º37'55"E	Water bodies, wetlands and forested areas with fine sand content <20%

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