ISSN (Print): 2476-8316
ISSN (Online): 2635-3490
Dutse Journal of Pure and Applied Sciences (DUJOPAS), *Vol. 4 No. 2 December 2018*

Assessment of Monthly Variation of Vegetation Activities in West Africa

***Sa'adu Abubakar Mafara[1], Muhammad Nuraddeen Danjuma[2] & Ibrahim Abdullahi[3]**
[1]Department of Preliminary Studies,
Abdu Gusau Polytechnic, Talata Mafara, Nigeria
[2]Department of Geography
Bayero University, Kano, Nigeria
[3]Department of Geography, Isa Kaita College of Education,
Dutsin-ma, Katsina State

Abstract
Vegetation plays important roles in the Earth's surface. It constitutes a vital source of energy, livestock fodder, construction and food materials, medicine and a number of indispensable ecosystem functions including atmospheric carbon sequestration and ground water recharge. Mapping vegetation activities is important and useful for environmental management, land use planning and/or policymaking support. The aim of this study is to assess monthly variation of vegetation in West Africa with a view to identifying responses of plants to seasons in the area. This study used bi-monthly NDVI3g dataset of 2000, 2005 and 2010 which was converted to monthly aggregates using the Maximum Value Composite method in order to further minimise the effects of cloud contamination using R software. Spatial and temporal analyses were made to examine the monthly variations of vegetation activity across the study area. The spatial mapping and temporal trend analysis were carried out using R software with aid of different library packages including raster, rasterVis, time series, and ncdf. This study found that marked association between NDVI and rainfall. For months with little or no rainfall (January through to April), NDVI is near zero especially in West Africa especially in Burkina Faso, Senegal, Mali and Niger Republic which are located latitude 15⁰N northwards. The temporal pattern also follows oscillating nature of rainfall arrival and cessation in the area as NDVI is seldom above 0.4 for most of the months except August and September which records up to 0.6. This can be linked to the high amount of rainfall received in June, July and August, which allow vegetation activity to rise. The lowest values of 0.1- 0.3 were found in October, November and December. This study recommended that major capacity building is needed through education to harness the new approaches and tools of monitoring vegetation variability for evidence-informed decision making, policy and practice in the area.

Keywords: Vegetation, Sahel, NDVI3g, rainfall

INTRODUCTION
West Africa is adversely affected by unprecedented environmental degradation particularly in savanna environments where the natural environment is perceived to be under greatest threat. Its sub-Saharan part has been one of the world's most water limited ecosystems (Kaptué et al., 2015) and this has strongly affected vegetation growth (Herrmann, Anyamba, and Tucker, 2005). This region has been the most devastated by the worst and lethal drought in recent history (Nicholson, 1995; Le Houérou, 2009). This resulted to four decades of studies on the intermittent effects of drought on vital components of the environment such

**Author for Correspondence*

as vegetation which lead to land degradation and deteriorate the area's natural state (Mbow et al., 2015).
In the region, the natural state of vegetation have been persistent affected since the drought of 1970s however, arguments emanates about re-greening (which probably weaken facts on the actual state of vegetation at local level) following the availability of time-series satellite data such as Normalised Difference Vegetation Index NDVI (Ecklundh, and Olsson, 2003; Fensholt, Langanke, Rasmussen, Reenberg, Prince; Mbow et al., 2015) and to some extent the success story of community conservation within sub-Saharan regions of Niger Republic (Reij et al., 2009). This calls for constant research on vegetation dynamics in the region using all available scales.

Changes in vegetation cover and/or productivity have been widely assessed using time series based satellite images vegetation index known as Normalized Vegetation Index (NDVI) which quantify vegetation change and degradation over time. Since 1970s several studies such Deering et al., 1975; Tucker, Dregne, and Newcomb 1991; Olsson, Eklundh, and Ardö, (2005); Landmann et al., 2014; Le et al., 2012; Knauer, Gessner, Dech, and Kuenzer, 2014; Walker et al., 2014; Zhang et al., 2014; Brandt et al. (2014) and Brandt, Tappan, Diouf, Beye, Mbow, and Fensholt, 2017 showed that vegetation in West Africa is still recovering from the driest years of the century. These works came to a conclusion that there is strong correlation between vegetation activities (using NDVI as a proxy) and rainfall although other factors like disturbance by urbanization and heavy livestock concentration (Li et al., 2004; Boschetti et al., 2013) are equally important.

The discrete nature of these works Barbosa, Huete and Baethgen, (2006) calls for also regional examination of the spatial heterogeneity of NDVI as well as its anomalies in West Africa. This is because in some locations such as Tahoua, Niger Republic there was relatively strong greening trends of up to 100% in the period 1982 to 1999 (Olsson, Eklundh, and Ardö, (2005) while Western Senegal, parts of Mali (Dardel et al., 2013), central and eastern Burkina Faso (Herrmann, and Tappan, 2013) and northern Nigeria showed strong browning down trends (Garba, 2008; Danjuma, 2017). The extent and degree of vegetation recovery or degradation in West Africa is still widely debated (Kaptué, Prihodko, Hanan, 2015), hence the results from the several small to regional scale studies presented here (that used satellite imagery and historical rainfall) are not enough to justify vegetation activities for the whole West Africa with confidence. This is due to fluctuating growth and a strong south to north declining trend of vegetation in the large parts of West Africa, (Knauer, Gessner, Dech, and Kuenzer, 2014), even the leading re-greening proponents of re-greening such as Brandt, Mbow, Diouf, Verger, Samimi, Fensholt, (2015) and Brandt et al. (2016) showed that the trends of annual vegetation growth in the region is not of sustained productivity but a mixture of improvement, gradual decline and disappearance of vegetation due to the conversion of grassland to agricultural land and the replacement of woody species by shrubs and grasses (Herrmann and Tappan, 2013; Sambou et al., 2016; Brandt et al. 2017; Danjuma, 2017).

Because of uncertainties regarding use of the currently available field data (traditionally collected at small spatial and temporal scales and vary in their type and reliability) for predicting regional changes, this study used high resolution satellite imagery (GIMMs NDVI3g) to assess monthly variation of vegetation in West Africa on both spatial and temporal scales with a view to identifying annual average, annual maximum and minimum increments and estimate vegetation response to seasons in the area. This study is imperative because there is the need to determine the condition of vegetation of this fragile region with a high temporal and spatial resolution data to detect local vegetation change which is still contestable in the findings of some contributors such as Reij et al. (2009) and opponents of land degradation Behnke and Mortimore (2016).

STUDY AREA

West Africa is located between latitude 4°N and 20°N and longitude 17°W and 15°E (Figure 1). The area is approximately 6,140,000 km^2, roughly about one-fifth of the African continent. It is situated between the arid and semi-arid regions of the Saharan desert in North Africa, and humid tropical savanna in the equatorial West Africa down to the Atlantic coast to the south.

Climate of the area is predominantly tropical, with the majority of the continent having mean temperatures above 21° celsius for nine months of the year. The primary determinant of precipitation in Africa is the air movement surrounding the Inter-Tropical Convergence Zone (ITCZ) and associated equatorial trough (Griffiths, 2005). In simple terms, winds are pushed out from two sub-tropical high pressure belts toward the equator, where they meet and force air and moisture upward. This upward movement cools the air, forcing the moisture out as precipitation. The mean temperature in the hottest and coldest months of the year varies little for most of West Africa (Le Houérou, 2009).

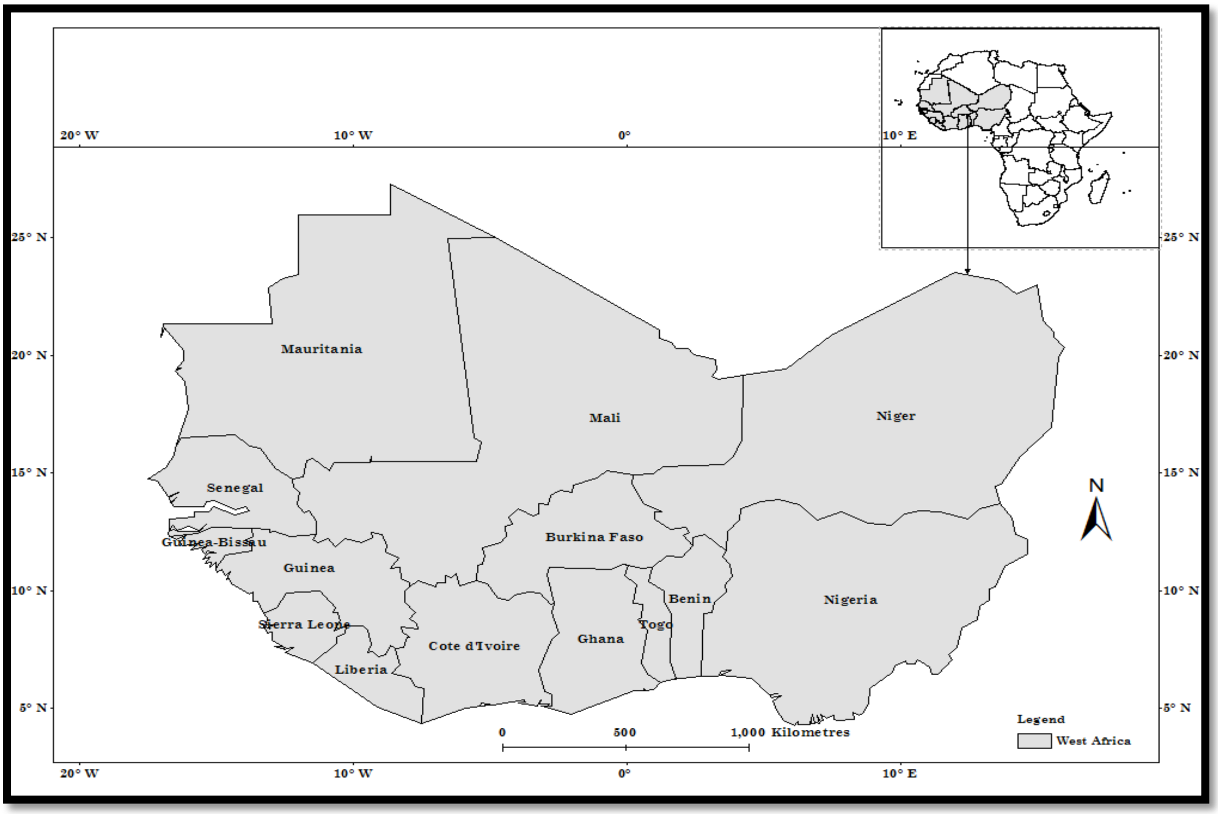

Figure 1: Map of the West Africa

Most of the flora and fauna found in West Africa today descended from plant and animal species that were present on the continent when it separated from other land masses during the breakup of Gondwanaland, roughly 150 million years ago (Le Houérou, 2009). Africa's pattern of vegetation zones largely mirrors its climate zones. Areas with the greatest rainfall have the greatest volume of biomass or primary productivity (Stock, 2004). Commonly found trees in the area include *Hyphaene thebaica, Parkia biglobosa, Adansonia digitata, Faidherbia albida, Tamarindus indica, Borassus aethiopum, Prosopis africana, Balanite aegyptiaca* and *Acacia nilotica.* Exotic species include *Acacia senegalensis*, *Azadirachta indica, Cassia siammea, Dolonix regia,* and *Eucalyptus camaldulensis.*

Land degradation is the dominant problem of West Africa today. Land degradation and desertification in particular result from both human activities and climatic variability. It has been reported that more than one-quarter of Africa's arid and semi-arid lands are degraded (White et al., 2000) due to soil erosion, loss of soil nutrients, pollution, or salinization (Darkoh, 1996).

MATERIALS AND METHODS

This study used NDVI as an indicator of vegetation greenness. This index reflects vegetation growth because it is closely related to the amount of photosynthetically absorbed active radiation (Anyamba and Tucker, 2005; Kogan, 2005). It is also sensitive indicator of the interannual variability of rainfall (Pinzon and Tucker, 2014). The Global Inventory Modelling and Mapping Studies (GIMMS) 3rd generation (NDVI3g) dataset for the African continent was used. The data is an improved version of the previous GIMMS NDVI and is processed using an adaptive Empirical Mode Decomposition (EMD) (Pinzon et al., 2005). The EMD is used to find and remove artefacts from the NDVI time-series including solar zenith angle, trends associated with orbital drift, discrepancies in the AVHRR data among sensors due to their differences, and other factors that introduce non-linear and non-stationary effects to the dataset.

In contrast to the previous version, the new dataset covers the period of July 1981 to December 2012 with a bi-weekly temporal and 8km spatial resolution (Pinzon and Tucker, 2014). The effect of sensor change that affected the quality of the AVHRR sensor is significantly reduced in the new GIMMS NDVI3g. This study was limited to January 2000 to December 2010 due to data availability. The data was sourced from NOAA-AVHRR instruments onboard sensor 7, 9, 11, 14, 16, 17, 18 and 19.

The NDVI3g dataset comes with the different quality flags and only flag 1 which is a good value was used for this study in order to restrict the analysis to the most reliable NDVI values (Xu et al., 2013). The bi-monthly data was converted to monthly aggregates using the Maximum Value Composite (MVC) method (Holben, 1986) in order to further minimise the effects of cloud contamination. The data was later projected to the WGS 1984 coordinate system, cropped and extracted using R software. Spatial and temporal analyses were made to examine the monthly and annual changes of vegetation activity in the study area. Spatial mapping and temporal trend analysis were carried out using R software with aid of different library packages including raster, rasterVis, time series, and ncdf. The analysis with R was found to be the most suitable when compared to other remote sensing software due to network common data format.

RESULT AND DISCUSSION

Spatial Variation of Monthly NDVI in West Africa

As a surrogate of temporal primary productivity and representation of average level of vegetation growth within a year, (Jackson, Banner, Jobbagy, Pockman and Wall, 2002), spatial NDVI was used to assess the pattern of monthly vegetation variations in the area.

Figures 2, 3 and 4 respectively, shows the spatial pattern of monthly NDVI in West Africa for the year 2000, 2005 and 2010. As evident in all the figures, NDVI pattern follows fluctuation of rainfall in most parts of Northern West Africa and the Sahelian region of the area. In months with little or no rainfall, NDVI is near zero especially in Northern countries such as Burkina Faso, Senegal, Mali and Niger Republic which are located above latitude 15⁰N. Spatial pattern of NDVI was low during the months of January through to April in West Africa. However, with arrival of rainfall in the month of May in most parts of West Africa, NDVI activity tends to pick up and increase rapidly up to the month of November. This study found that the highest value of monthly NDVI is in the months of September and October in all the years. Philippon et al., (2005) showed that water is the main limiting factor for vegetation growth throughout the Sub Saharan Zone, which means that photosynthesis mainly takes place during the wet season. This finding also corroborates Traore, Ladmann, Forkuo and Traore (2014) who noted that the spatial distribution of vegetation in Bani River Basin in Mali is largely related to cumulative (annual) rainfall and the length of the rainy season, which varies along the eco-climatic gradient. Vegetation patterns on a landscape scale are determined by localized climatic variations in Mali and Niger (Dardel et al., 2013).

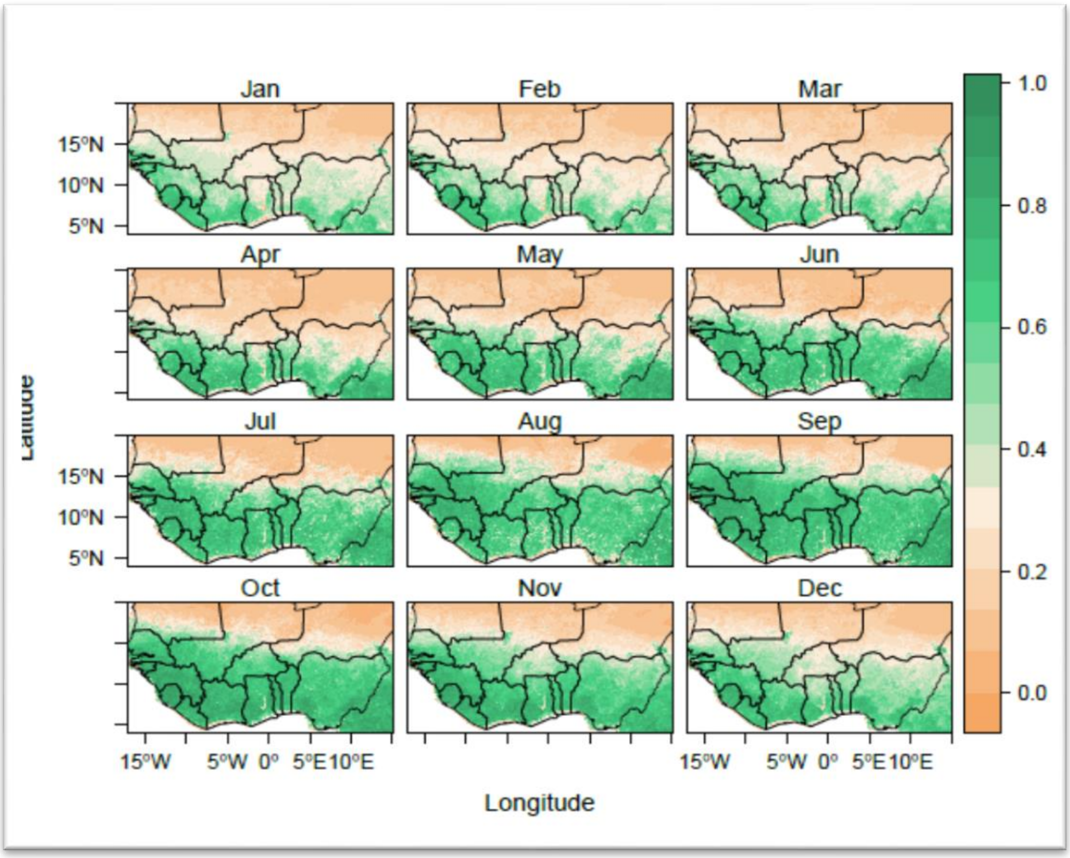

Figure 2: Monthly Variation of NDVI in West Africa in 2000

Spatially, year 2000 has witnessed an intermittent vegetation activity as with most times in West Africa. Generally, areas on latitude 12⁰N and 15⁰N covering northern Nigeria, Republics of Niger, Mali and Burkina faso (southern part is our interest) recorded relatively low NDVI value of 0.2 to 0.3 in the year 2000 in January to April (Figure 2). NDVI value of 0.5 to 0.6 recorded in June to November areas between latitude 12⁰N and 15⁰N almost constantly show low value indicated that vegetation activities surged up with the onset and stability of raining season in the area. This justifies the mainstream predictions relating phenological activities of vegetation in West Africa with rainfall. Semi arid northern Nigeria, the whole of Niger, pocket of southern Mali, and Burkina faso have NDVI value below 0.5 in

May and this presented relatively weak vegetation activity which could emanate from delay in the onset of rainfall in the area.

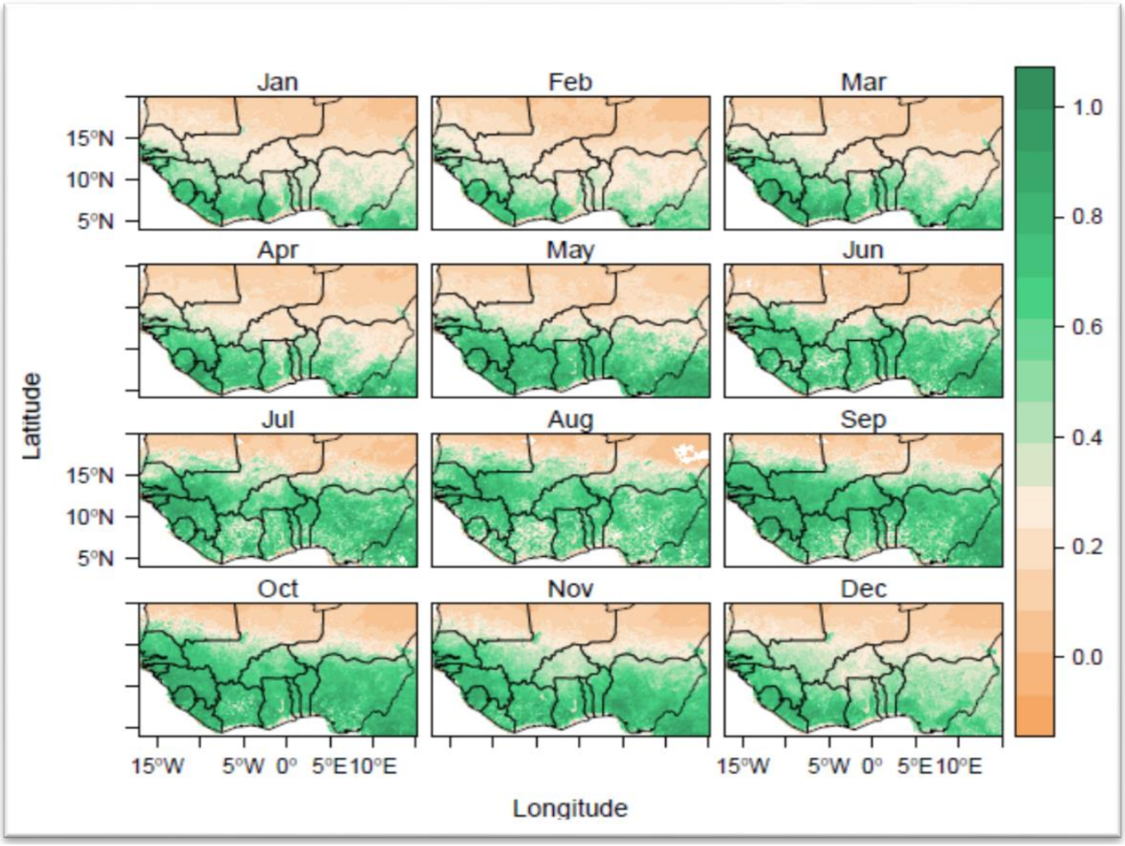

Figure 3: Monthly Variation of NDVI in West Africa in 2005

In 2005, vegetation pattern was generally especially over Sudan Savanna region of West Africa between 7^{0}N to 11^{0}N covering an area from southern Mali to Northern Nigeria. However, there were intermittent result as follows: areas on northcentral Nigeria to and parts of Republics of Niger and Burkina faso between latitude 8^{0}N and 14^{0}N obtained NDVI value of 0.2 – 0.3 in January to April in 2005. Vegetation activities picked up in most of northern Nigeria, southern Niger and Mali (latitude 11^{0}N and 14^{0}N) in May 2005. This continues in June and subsides by November with NDVI values of 0.5 and 0.6 in most places at the southern tips of the region.

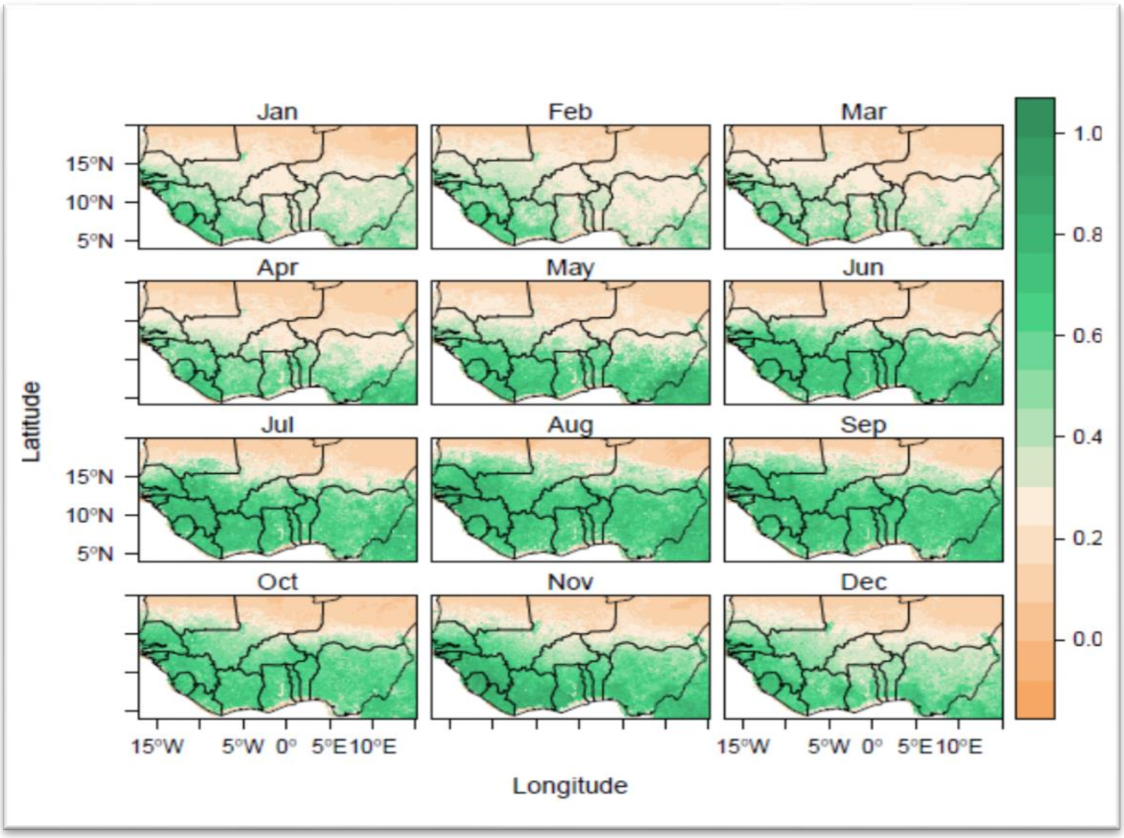

Figure 4: Monthly Variation of NDVI in West Africa in 2010

Spatial patterns of NDVI for the year 2010 which is also closely related to the pattern of rainfall distribution in West Africa (Figure 4). As can be seen, most sub-Saharan West African countries show a decrease in the NDVI values particularly, between 8^{0}N to 15^{0}N. The spatial trends shows constant greening between 4^{0}N to 7^{0}N includes countries of Benin, Cote d'ivoire, Ghana and Ivory Coast while areas around northern Nigeria, Niger and Mali on latitude 12^{0}N to 15^{0}N showed NDVI value 0.2 to 0.3 over most periods except July to October.

Temporal Variation of NDVI in West Africa

NDVI has been successfully applied to research on temporal trends and variation in vegetation distribution, productivity and dynamics, to monitor habitat degradation and fragmentation, and the ecological effects of climatic disasters such as drought or fire.

This study used monthly measures based from the NDVI time-series to assess vegetation dynamics at regional scale between 2000 and 2010 (Figure 5, 6 and 7) which represent temporal variation of monthly NDVI for the year 2000, 2005 and 2010 respectively. The temporal pattern of vegetation in West Africa follows the oscillating nature of rainfall onset and cessation in the area. Hence months with high amount of rainfall tends to have high value of NDVI and vice versa.

Temporal Variation of NDVI in 2000

Figure 5 showed that the NDVI is within 0.1-0.6 for most of the months in the year 2000. However, the pattern occasionally changes especially in the month of October, November and December. This is probably can be linked to the high amount of rainfall received in the previous months of June, July and August, which allow vegetation activity to pick up within the proceeding months.

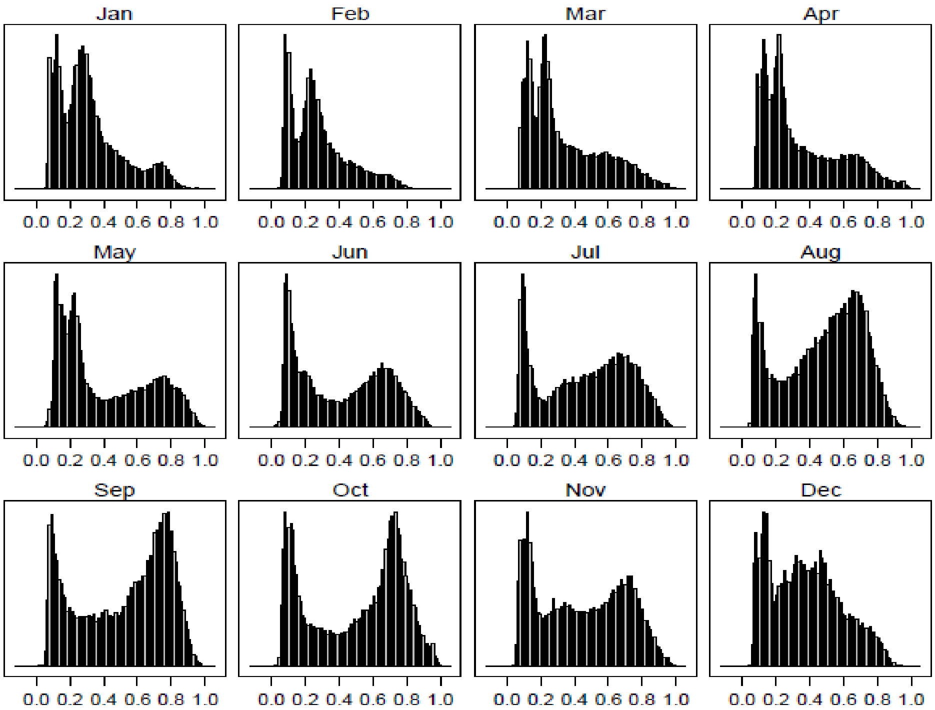

Figure 5: Temporal Variation of monthly NDVI in West Africa in the year 2000

Temporal Variation of NDVI in 2005

Figure 6 showed temporal variation of monthly NDVI value for the year 2005. As in the Figure, low NDVI between 0.0-0.6 was recorded between the months of January to May. However, the trends in August to 0.7 thereby reflecting a positive increase in the density of green cover from the month due to high amount of rainfall that can support primary productivity in the area.

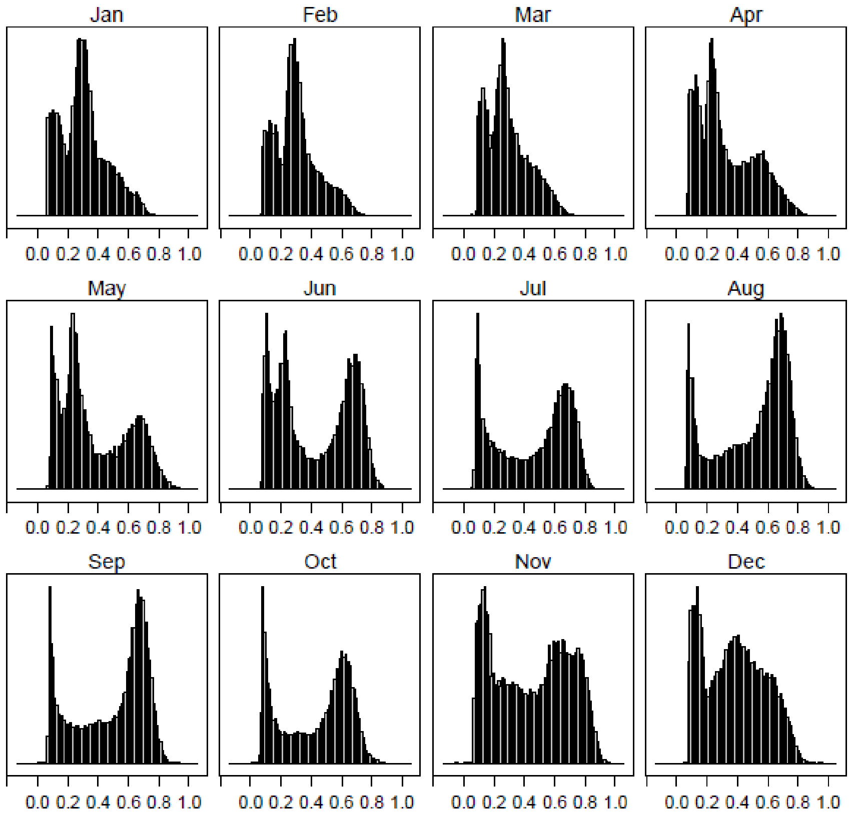

Figure 6: Temporal Variation of monthly NDVI in West Africa in the year 2005

Temporal Variation of NDVI in 2010

Figure 7 showed temporal variations of monthly NDVI values for the year 2010. It showed the highest value of NDVI was recorded in the months of August and September while the lowest was in October. This is because of onset of rainfall which increased seasonal trend of vegetation and potential contribution of herbaceous growth due to the increase in water.

Empirical evidences on vegetation dynamics in Africa have shown nuanced picture with both declines and increases since 1930s. Despite its unique location at biological crossroads in the continent, the West Africa will lose its great diversity, much of which are as a result of the region's fragility. Findings of this study showed that vegetation cover change has been, and still is a problem that needs to be critically evaluated especially in northern parts which is climatically at the margin.

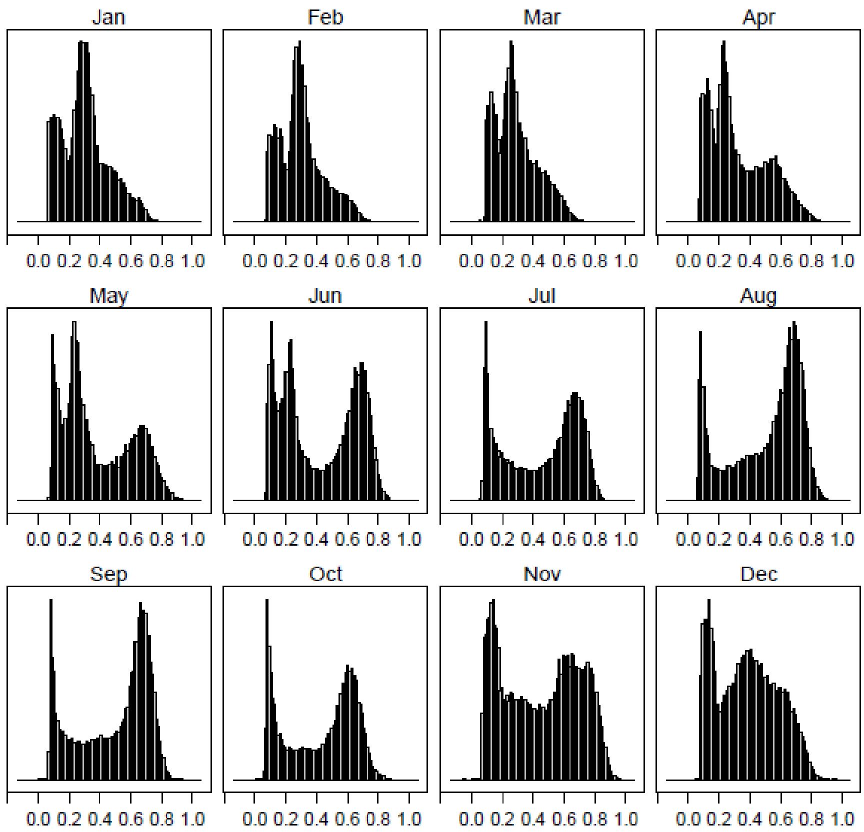

Figure 7: Temporal Variation of monthly NDVI in West Africa in the year 2010

Conclusion

Vegetation changes play a critical role to ecosystem stability in the West Africa hence this study showed that with availability of vegetation proxies such as NDVI; a new opportunity for researchers to understand the dynamics of vegetation activity is possible. Therefore, spatial and temporal trend analyses carried out in this paper has shown the potentials of NDVI data in understanding changes of vegetation in West Africa as well as its anomalies. The conclusion is that NDVI (vegetation activity) follows pattern of rainfall because months with high rainfall recorded high values while the rest.

Recommendations

1. Long-term monitoring of the study area is recommended using both remote sensing and field observations to enhance the understanding of broad-scale changes in vegetation and the possible relationship between such changes and ecosystem resilience.

2. There is need for a major capacity strengthening initiative to enhance peoples' awareness to utilise new science approaches and tools of monitoring vegetation variability for evidence-based decision making, policy and practice in the area. This can be achieved through a regional body that will provide manpower and training to students and researchers in West Africa to harness remote sensing opportunities for environmental management.

REFERENCES

Anyamba, A. and Tucker, C. J. (2005). Analysis of Sahelian vegetation dynamics using NOAA-

AVHRR NDVI data from 1981–2003. *Journal of Arid Environments,* 63**,** 596-614.

Barbosa, H.A., Huete, A.R. and Baethgen, W.E. (2006). A 20-year study of NDVI variability over the Northeast Region of Brazil. *Journal of Arid Environments*, 67: 288- 307.

Behnke, R.H. and Mortimore, M. (2016). *The End of Desertification?. Disputing Environmental Change in the Drylands* (eds). Spiekermann-Verlag Berlin Heidelberg

Brandt, M., Romankiewicz, C., Spiekermann, R. and Samimi, C. (2014). Environmental Change in Time Series – An Interdisciplinary Study in the Sahel of Mali and Senegal. *Journal of Arid Environments*, 105: 52–63. doi:10.1016/j.jaridenv.2014.02.019.

Brandt, M.; Mbow, C.; Diouf, A.A.; Verger, A.; Samimi, C.; Fensholt, R. (2015). Ground- and satellite-based evidence of the biophysical mechanisms behind the greening Sahel. *Glob. Chang. Biol.*, 21:1610–1620.

Brandt, M., Hiernaux, P., Rasmussen, K., Mbow, C., Kergoat, L., Tagesson, T., Ibrahim, Y.Z., Wélé, A., Tucker, C.J., and Fensholt, R. (2016). Assessing woody vegetation trends in Sahelian drylands using MODIS based seasonal metrics. *Remote Sensing of Environment*, 183: 215–225

Brandt, M., Tappan, G., Diouf, A., Beye, G., Mbow, C. and Fensholt, R. (2017). Woody Vegetation Die off and Regeneration in Response to Rainfall Variability in the West African Sahel. *Remote Sens.*, 9:39; doi:10.3390/rs9010039

Boschetti, M., Nutini, F., Brivio, P. A., Bartholomé, E., Stroppiana, D. and Hoscilo, A. (2013). Identification of Environmental Anomaly Hot Spots in West Africa from Time Series of NDVI and Rainfall. *ISPRS Journal of Photogrammetry and Remote Sensing*, 78: 26–40. doi:10.1016/j.isprsjprs.2013.01.003.

Dardel, C., Kergot, L., Heirnaux, P., Mougin, E., Grappa, M. and Tucker, C.J. (2013). Re-greening Sahel: 30 years of Remote Sensing Data and Field Observations (Mali, Niger). *Remote Sensing of Environment,* Vol. 140:350-364

Deering, D.W., Rouse, J.W., Haas, R.H. and Schell, J.A. (1975). *Measuring Forage Production of Grazing Units from Landsat MSS Data*. 10th International Symposium on Remote Sensing of Environment, 2: 1169-1178

Ecklundh, L. and Olsson, L. (2003). Vegetation index trends for the African Sahel 1982–1999. *Geophysical Research Letters*, 30(8):1430.

Fensholt, R., and Sandholt, I. (2005). Evaluation of MODIS and NOAA AVHRR Vegetation Indices with in situ Measurements in a Semi-Arid Environment. *International Journal of Remote Sensing*, 26 (12): 2561–2594. doi:10.1080/01431160500033724.

Fensholt, R., Nielsen, T.T. and Stisen, S. (2006). Evaluation of AVHRR PAL and GIMMS 10day composite NDVI time series products using SPOT4 vegetation data for the African continent. *International Journal of Remote Sensing,* 27**:**2719-2733.

Fensholt, R., Rasmussen, K., Nielsen, T.T. and Mbow, C. (2009). Evaluation of earth observation based long term vegetation trends — Intercomparing NDVI time series trend analysis consistency of Sahel from AVHRR GIMMS, Terra MODIS and SPOT VGT data. *Remote Sensing of Environment,* 113**:**1886-1898.

Fensholt, R., Langanke, T., Rasmussen, K., Reenberg, A., Prince, S.D., Tucker, C., Scholes, R.J., Bao Le, Q., Bondeau, A., Eastman, R., Epstein, H., Gaughan, A.E., Hellden, U., Mbow, C., Olsson, L., Paruelo, J., Schweitzer, C., Seaquist, J. and Wessels, K. (2012). Greenness in semi-arid areas across the globe 1981-2007: an Earth Observing Satellite based analysis of trends and drivers. *Remote Sensing of Environment,* 121: 144-158.

Garba, S.S. (2008). *Assessment of Land Cover Change in North Eastern Nigeria*. A thesis submitted to the School of Applied Science in partial fulfilment of the requirements for the award of the degree of Doctor of Philosophy of the University of Cranfield, UK

Gates, D.M. (2012). *Biophysical ecology*, Courier Corporation.

Griffiths, J.F. (2005). Climate of Africa. **In**: John E. Oliver (ed). (2006). *Encyclopedia of World Climatology*. Springer, Berlin

Herrmann, S.M.; Anyamba, A. and Tucker, C.J. (2005). Recent trends in vegetation dynamics in the African Sahel and their relationship to climate. *Glob. Environ. Chang.*, 15:394–404.

Herrmann, S.M. and Tappan, G.G. (2013). Vegetation impoverishment despite greening: a case study from central Senegal. *J. Arid Environ.*, 90:55–66.

Holben, B.N. (1986). Characteristics of maximum-value composite images from temporal AVHRR data. *International journal of remote sensing,* 7**:**1417-1434.

Huete, A., Liu, H., Batchily, K. V. and Van Leeuwen, W. (1997). A comparison of vegetation indices over a global set of TM images for EOS-MODIS. *Remote sensing of environment,* 59**:**440-451.

Jackson, R.B., Banner, J.L., Jobbágy, E.G., Pockman, W.T. and Wall, D.H. (2002). Ecosystem carbon loss with woody plant invasion of grasslands. *Nature,* 418:623-626.

Jensen, J.R. and Im, J. (2007). Remote sensing change detection in urban environments. *Geo-Spatial Technologies in Urban Environments.* Springer.

Knauer, K., Gessner, U., Dech, S. and Kuenzer, C. (2014). Remote sensing of vegetation dynamics in West Africa. *International Journal of Remote Sensing*, 35:17: 6357-6396, DOI: 10.1080/01431161.2014.954062

Kogan, F.N. (2005). *NOAA/AVHRR satellite data based indices for monitoring agricultural droughts*, New York: Oxford University Press.

Kaptué, A.T., Prihodko, L. and Hanan, N.P. (2015). On regreening and degradation in sahelian watersheds. *Proc. Natl. Acad. Sci. USA*, 112, 12133–12138.

Landmann, T. and Dubovyk, O. (2014). Spatial analysis of human-induced vegetation decline over eastern African using a decade (2001-2011) of medium resolution MODIS time-series data, *International Journal of Applied Earth Observation and Geoinformation,* 33:76-82.

Le Houérou, H.N. (2009). *Bioclimatology and Biogeography of Africa.* Berlin Heidelberg: Springer-Verlag

Le, Q.B., Tamene, L. and Vlek, P.L.G. (2012). Multi-pronged assessment of land degradation in West Africa to assess the importance of atmospheric fertilization in masking the processes involved. *Global Planet. Change*, 92–93:71–81.

Li, J., Lewis, J. Rowland, J., Gray Tappan, G. and Tieszen, L.L. (2004). Evaluation of Land Performance in Senegal Using Multi-Temporal NDVI and Rainfall Series. *Journal of Arid Environments,* 59 (3): 463–480. doi:10.1016/j.jaridenv.2004.03.019

Mbow, C., Brandt, M., Ouedraogo, I., de Leeuw, J. and Marshall, M. (2015). What Four Decades of Earth Observation Tell Us about Land Degradation in the Sahel? *Remote Sensing,* 7**:**4048-4067.

Nicholson, S. (1995). Sahel, West Africa. *Encyclopedia of Environmental Biology*, Volume 3, 261-275

Olsson, L., Eklundh, L. and Ardö, J. (2005). A recent greening of the Sahel – trends, patterns and potential causes. *Journal of Arid Environments*, 63:556-566

Reij, C., Tappan, G. and Smale, M. (2009). Agro-environmental Transformation in the Sahel. Another Kind of Green Revolution'. *IFRRI Discussion Paper 00914*, 2020 Vision Initiative, International Food Policy Research Institute, Washington, DC

Sambou, A., Theilade, I., Fensholt, R. and Ræbild, A. (2016). Decline of woody vegetation in a saline landscape in the Groundnut Basin, Senegal. *Regional Environmental Change*.

Myneni, R.B. and Hall, F.G. (1995). The interpretation of spectral vegetation indexes. *Geoscience and Remote Sensing, IEEE Transactions on,* 33**,** 481-486.

Nemani, R.R., Keeling, C.D., Hashimoto, H., Jolly, W.M., Piper, S.C., Tucker, C.J., Myneni, R. B. and Running, S.W. (2003). Climate-driven increases in global terrestrial net primary production from 1982 to 1999. *Science,* 300**:**1560-1563.

Philippon, N., Mougin, E., Jarlan, L. and Frison, P. (2005). Analysis of the linkages between rainfall and land surface conditions in the West African monsoon through CMAP, ERS-WSC, and NOAA-AVHRR data. *J. Geophys. Res.* ,110:D24115.

Pinzon, J., Brown, M. E. and Tucker, C. J. (2005). *EMD correction of orbital drift artifacts in satellite data stream*, World Scientific Publishing Co Pte Ltd.: Singapore.

Pinzon, J. and Tucker, C. (2014). A Non-Stationary 1981–2012 AVHRR NDVI3g Time Series. *Remote Sensing,* 6**:**6929-6960.

Stock, R. (2004). *Africa South of the Sahara: A Geographical Interpretation.* Guilford Press, New York

Traore, S.S., Landmann, T.,Forkuo, E.K. and Traore, P.C.S. (2014). Assessing Long-Term Trends In Vegetation Productivity Change Over the Bani River Basin in Mali (West Africa). *Journal of Geography and Earth Sciences*, Vol. 2 (2):21-34

Tucker, C.J., Dregne, H.E. and Newcomb, W.W. (1991). Expansion and Contraction of the Sahara Desert from 1980 to 1990. *Science*, 253 (5017): 299–300. doi:10.1126/science.253.5017.299.

Tucker, C., Pinzon, J., Brown, M., Slayback, D., Pak, E., Mahoney, R., Vermote, E. and El Saleous, N. (2005). An extended AVHRR 8-km NDVI dataset compatible with MODIS and SPOT vegetation NDVI data. *International Journal of Remote Sensing,* 26**:**4485-4498.

White, R.P., Murray, S. and Rohweder, M. (2000). *Pilot Analysis of Global Ecosystems: Grassland Ecosystems*. Washington, D.C.: World Resources Institute. Available at: http://www.wri.org/biodiv/ pubs_description.cfm?pid=3057

Wessels, K.J., Prince, S.D., Malherbe, J., Small, J., Frost, P.E. and VanZyl, D. (2007). Can human-induced land degradation be distinguished from the effects of rainfall variability? A case study in South Africa, *Journal of Arid Environments,* 68:271-297.

Zhang, J., Niu, J., Bao, T., Buyantuyev, A., Zhang, J. and Zhang, X., (2014). Human induced dryland degradation in Ordos Plateau, China, revealed by multilevel statistical modeling of normalized difference vegetation index and rainfall time series. *Journal of Arid Land*, 6 (2) 219-229.