DISENTANGLING THE EFFECTS OF CLIMATE AND LAND USE ON LAND DEGRADATION

A SYNTHESIS OF FIELD OBSERVATIONS AND THEORETICAL FOUNDATION

GEF-LAND DEGRADATION MONITORING PROJECT
DISENTANGLING REPORT

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Disentangling Report

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This report was produced as an output of the Global Environment Facility (GEF)-funded project "Enabling the use of global data sources to assess and monitor land degradation at multiple scales". The project aims to provide guidance on robust methods and a toolbox for assessing and monitoring status of land degradation using remote sensing technology.

For additional information on the project see http://vitalsigns.org/gef-ldmp.

The Land Degradation Monitoring Project is a collaboration of Conservation International, Vital Signs, the National Aeronautics and Space Administration (NASA), and Lund University.

ACKNOWLEDGEMENTS

This report benefited from support from many contributors whom we would like to acknowledge.

We express our sincere gratitude to **TRISTAN O. SCHNADER**, Senior Project Manager of the GEF-LDMP for coordinating this effort. Staff of the **CENTRE DE SUIVI ECOLOGIQUE (CSE)** in Dakar supported with planning and organizing fieldwork in Senegal as well as providing relevant data on a range of topics of interest in this report.

We are grateful for the support given by different people for field activities in the project countries. **DR. MAMADOU ADAMA SARR** and **COMMANDANT MOUSTAPHA SARR** for guided fieldwork in Senegal and provided advice and support in the writing of this document. **THEODORY THEONEST** and **JOSEPH MWALUGELO** kindly helped with organizing and guiding fieldwork in Tanzania, and in Kenya, **BENSON GUDU** did the same.

We are deeply grateful for **DR. HERBERT HAMBATI** of the University of Dar es Salaam as well as **DR. GEOFREY SOKA** of the Sokoine University of Agriculture for their insights on land use and land cover changes in Tanzania. Thank you **MR. HENRICK MARTIN** for providing information on the long history of land use changes in Kondoa.

SUMMARY

The aim of the report is to provide guidance on what variables to use for assessing land degradation. In principle the choice is between using a remotely sensed vegetation index in and of itself, here we have used the Normalized Difference Vegetation Index (NDVI), or using a combination of remotely sensed data and climatic data. We have approached this task in two ways, we have collected a set of ground reference points through field reconnaissance which illustrates both land degradation and land improvement. Data for these sites have been collected from the field, from satellite NDVI time series and from the CHIRPS spatial data base of daily rainfall and from the NDVI.

We have also systematically assessed the theoretical understanding of how vegetation dynamics are related to climate variables. There is strong evidence that NDVI integrated over a vegetation season can be used as a proxy for net primary productivity (NPP), and that trends in NPP can be used as a proxy for land degradation and improvement. Using a combination of NDVI and climate data offers the potential to disentangle the effects of land use and climate induced vegetation changes.

Badru Mugerwa downloads data from the climate station.
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We have tested both Rain Use Efficiency (RUE) and the modified RUE-based technique of Residual Trend Analysis (RESTREND). Even if the idea of using a combination of NDVI and rainfall data is sound, there are both practical and theoretical objections.

Firstly, the relationship between mean annual rainfall and plant productivity across biomes is well established, but that between annual rainfall and annual plant productivity is has not been properly investigated. Other theoretical objections are that the relationship between NPP and climate is not well understood, the shape and strength of the relationship differs between types of vegetation, soil characteristics, climate zones, and management, and finally, the relationship is highly variable in terms of time lag between climate and vegetation response. The practical objections are related to the reliability and spatial resolution of rainfall data. Even if there exist global data on daily rainfall the reliability is still a problem and there is a scale mismatch between the relatively high spatial resolution of 250 m of the NDVI data and the much coarser rainfall data of about 5-6 km of the CHIRPS data. The quality of the gridded rainfall data is also a concern.

Therefore, the recommendation from this study is to use the NDVI trends alone for assessing land degradation and improvement instead of combining them with rainfall data. This is at least the recommendation for assessing large areas such as a country and upwards. For more detailed studies however, the NDVI trend in combination with rainfall data as well as higher resolution data (and even ground data) for elucidating the processes responsible for land degradation and improvement are vital.

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I. INTRODUCTION

1. INTRODUCTION

Sub-Saharan Africa (SSA) is a very diverse region in terms of geomorphology, ecology, climate, culture, natural resource endowments, and even economic development [1]. Despite this diversity, the region has a number of features which find unity and a common sense of purpose in its development struggles. Key among these is the management of the region's natural resource base, and the use of these resources to support the economic, social and cultural development of its peoples. The sustainable management of natural resources in SSA has to contend with a number of challenges. These include the role of agriculture in the socio-economic development of the region, the changing demography of the region, competition for key resources such as water and land from major economic sectors as well as from external actors, and the challenge of climate variability and change.

As human populations grow, their demands for food, fiber and fuel from nature increases and, in many cases, contribute to changing the structure and functioning of natural environments. In SSA, many cases of such human interactions with nature are putting pressures on environmental systems and, in some cases, degrading the structures and functioning of these systems. Land degradation refers to "any reduction or loss in the biological or economic productive capacity of the land resource base. It is generally caused by human activities, exacerbated by natural processes, and often magnified by and closely intertwined with climate change and biodiversity loss" [2]. Land degradation in its diverse forms is a problem that has been plaguing many parts of the world over a long period. The cause of land degradation may be different from one place to another, as well as may also vary over time, even in the same ecosystem. For example, land clearing and deforestation are the most common causes of degradation in tropical and sub-tropical forested regions.

In agroecosystems with poor farming practices (such as shifting cultivation without adequate fallow periods, poor or no soil conservation measures, cultivation of fragile lands, unbalanced fertilizer use), the depletion of soil nutrients is a common driver of land degradation. Overgrazing by livestock is a common cause in savannah drylands [3]. Other causes include urban sprawl and commercial development, as well as land pollution including poorly managed industrial waste disposal. The relationship between human use of land and natural ecosystems and how this can affect the functioning of such systems has been has been a topic of scientific interest for a long time. In his book entitled Collapse, *How Societies Choose to Fail or Succeed*, Jared Diamond illustrates how such relationships can lead to the collapse of ecosystems if proper care is not taken [4].

Given the importance of the phenomenon of land degradation, interest in assessing and measuring it has been growing in recent decades. Vegetation health is one of the key indicators that have been agreed upon for assessing and monitoring land condition [5]. Over the years, the normalized difference vegetation index (NDVI) [6] has gained recognition as a reliable proxy of vegetation condition. NDVI has been used for studies of land degradation at different scales [3, 7-9]. The potential of using vegetation and associated indices as proxies for land degradation has come a long way. These efforts have benefited from developments in Earth Observation (EO) science over the last few decades. Developments in EO in the last four decades have led to an unprecedented ability to observe the earth from space [10]. Our increasing ability to monitor and assess the status of and changes in the natural and man-made environments means that we can measure land use changes and proxies of land health on a near real-time basis. As satellite data has become more available, in increasing quantities, and at no or very low cost, EO has also become an increasingly attractive approach for undertaking such assessments.

The growing appeal of EO-based methodologies for monitoring land condition demands the development and use of better and more reliable tools for accomplishing such tasks. It also demands a better understanding of the ecological processes that determine major land dynamics. To achieve sustainable long-term planning of natural resources management, a holistic understanding of land use and land cover dynamics is essential. All-inclusive approaches can contribute to better understanding and addressing challenges associated with major shifts in land use, changing pressures on land resources, and fluid regimes of land governance.

Such understanding provides insights into processes and outcomes of land use and land cover change dynamics, and enlighten stakeholders at different levels on key aspects of the vulnerability of natural resources to environmental and human pressures. Hence, in addition to detecting and monitoring changes in using EO methodologies, there is need to incorporate societal structures as well as individual and even collective behavior that determine land uses and hence land cover. These social components and dynamics have implications on the structure and function of the biophysical sub-system, the environment feedbacks, and ecosystem service provision.

This report outlines results of applying a set of tools and methods developed to facilitate the assessment of vegetation conditions at local levels and country scales. Within the context of the project[1] under which this report is written, the *trends.earth* toolbox was developed to implement existing methodologies for assessing and monitoring vegetation condition.

This report therefore focuses more on the methodological applications of the toolbox, especially the process and outcomes of combining data analyses from using this toolbox with local and regional level quantitative and qualitative methodologies. One of the goals of the project was to examine the viability of the implementation of these methodologies in understanding land degradation (using the *trends.earth* toolbox).

In this report, we address the following issues: (1) re-examine our current understanding of critical elements associated with the use of vegetation as a proxy for land improvement or degradation. Specifically, the relationship between precipitation (as well as other key climatic variables) and net primary production was revisited. This was done by drawing on the literature of major studies in the fields of ecology, remote sensing, and related sciences. (2) Assess vegetation dynamics (using the toolbox, in combination with ancillary high-resolution imagery data, as well as qualitative data collected in-situ) to examine the potential of relating vegetation changes and observed land cover dynamics to results of analysis based on EO data and methodologies.

[1] Enabling the use of global data sources to assess and monitor land degradation at multiple scales. https://www.conservation.org/gef/projects/Pages/NDVI.aspx

II. SOURCES OF DATA AND METHODS

2. SOURCES OF DATA AND METHODS

To develop a much more nuanced and comprehensive understanding of the factors that contribute to land degradation, as well as on how these factors play out on the ground, it is important to make use of interdisciplinary approaches. This is not a simple task, as attempts at interdisciplinary research often resulted in multidisciplinary research being undertaken, with practice and results bound in traditional disciplinary confines [11]. In this study, we recognize the multi-dimensional and multi-scalar nature of both the underlying and proximate triggers of land degradation.

Theoretically, the multi-dimensional aspect of land degradation can be understood in terms of the relationship between key sectors of society associated with the causes of the phenomenon, as well as being impacted by its effects. The multi-scalar feature of land degradation draws mainly from its methods of assessment. At the broad scale, remotely sensed data sources and methods could be used to assess the extent of degradation of some land resources. For example, showing the changes in forested land or increases in the area of any land resource characterized as degraded. At the local or field scale, on-site observation and other field methods may be used to monitor indicators which can help identify land parcels undergoing reductions in soil quality (such as sheet or rill erosion) – and hence identifying processes of degradation.

The approach employed in this study has therefore been varied, to reflect the recognition of the multi-dimensional and multi-scalar nature of the problem of land degradation.

Key approaches include the use of remotely sensed data, analysis of maps, field study involving observations, validation of remotely sensed data and the administration of semi-structured questionnaires to generate new data.

2.1 ASSESSING NDVI TRENDS AND CONCENTRATIONS OF HOT AND COLD SPOTS OF VEGETATION ACTIVITY

The practice of using satellite remote sensing data and methods to identify hotspots of vegetation activity (increasing trends of NDVI) and cold spots of land degradation, as a cost-effective means of screening large geographical areas that may require urgent or more in-depth investigations is increasingly becoming common. For example, this method has been used to identify potential locations of land degradation in Italy [12], and to assess vegetation dynamics in the Middle East and North Africa (MENA) region [13]. Analysis of hot and cold spots of vegetation activity was done using single band GIMMS MODIS Terra & Aqua NDVI 8-bit 9x9 degree tiles covering Senegal, Uganda, Tanzania, and Kenya. The data is mapped to a global 180W to 180E, 90N to 90S Lat-Lon grid with a spatial resolution of 0.00225 x 0.00225 degrees (~250-meter).

These were 8-day composite images in GeoTIFF format. A discontinuous mosaic dataset of the tiles was created, so that each resulting tile represented the image of an individual day in the data collection. Mosaic datasets permit the storage, management, viewing, and query of small to vast collections of raster and image data. It also streamlines the processing of multiple datasets.

Mosaic datasets have advanced raster querying capabilities and processing functions and can handle datasets that are both continuous and discontinuous (as is the case with this data where Senegal does not adjoin other East African countries studied in this project). This permits the assembly of the data in a single containing holder while keeping track of their temporal uniqueness – hence enabling the ability to place them on a time series stack. The mosaicked data was then stacked to form a continuous time-series of 8-day composites from day 57 in 2000 to day 361 in 2016.

Two sets of analysis were performed on the raw stacked NDVI series. The first was the linear trend analysis which maps the slope coefficient of an ordinary least squares (OLS) regression between the values of each pixel over time resulting in an output of the rate of change per time step (in this case, changes over each of the 8-days). The hot and cold spots of vegetation activity were identified by computing the z- and p-values and confidence levels of the spatial clustering of NDVI trend values resulting from the ordinary least squares (OLS) regression. In this computation, a high z-score and small p-value indicate a spatial clustering of high values while a low negative z-score and small p-value indicates a spatial clustering of low values. More intense clustering are determined by higher (or lower) the z-score, while a z-score near zero indicates no apparent spatial clustering. The use of 'hotspots' and 'cold spots' is increasingly popular as a method for identifying potential areas of attention in land degradation research. Thiombiano and Tourino-Soto [1] used 'hot spots' and 'bright spots' status and trends of land degradation in Africa.

Classical seasonal decomposition using moving averages was used to filter and break down a time series into constituent elements. Such elements include the underlying trend (pattern which denotes the long-term increase or decrease in the data), seasonal element (the pattern which portrays the influence of seasonal factors on a series), and the noise element (random behavior, not explained by the trend of seasonal element).

The decomposition of time-series into seasonal, trend and irregular components was achieved using the R package called decompose[2]. This package removes the seasonal effect from a time series and provides a clearer illustration of the trend in the dataset. The seasonally adjusted time-series can then be used to detect anomalies, while the random noise can be used to detect anomalies and outliers.

The Breaks For Additive Season and Trend (BFAST) algorithm[3] is another resource available as an R package. It was developed by Verbesselt and others [14, 15]. BFAST is used to detect and characterize abrupt changes within the trend and seasonal components of time-series.

BFAST uses piecewise linear models to fit the time series data and detect structural changes (breaks) in the fitted data [14, 15]. Greening and browning trends were computed using greenbrown[4], an R package developed by Forkel et al. [16]. This package is made up of a group of functions for analyzing trends and trend changes in gridded time series data such as from satellite imagery. In this context, "greening" indicates positive trends in vegetation greenness, while browning indicates negative trends. The greenbrown package offers three options [16]: one in which the trends are calculated on the annual aggregated time-series (AAT); the other is based on a seasonal trend model (STM) in which harmonics are fitted to the seasonal time-series to model the seasonal cycle, and then calculate trends based on a multiple linear regression; and the last in which the first seasonal cycle in the time-series is removed and the trend is calculated on the remainder series (Seasonal Adjusted).

Trends.earth was used to identify areas of significant vegetation changes, as well as perform residual trend analysis (RESTREND) in the NDVI datasets. RESTREND is used to disentangle the influence of climate on vegetation (Wessels et al. 2007). The climatic variable used in trends.earth to perform RESTREND for this project was rainfall, hence isolating non-climatic effects on the NDVI signal – effects that can possible be linked to mainly to human activity. The Climate Hazards Group InfraRed Precipitation (CHIRPS) with Station data is rainfall dataset was used in the RESTREND analysis . It spans 50°S-50°N (all longitudes); covers the period 1981 to near-present; has a 0.05° spatial resolution with in-situ station data to create gridded rainfall time series for trend analysis[5] (Funk et al., 2015).

[2] A full description of the suite of functions and their implementation can be found her: https://stat.ethz.ch/R-manual/R-devel/library/stats/html/decompose.html

[3] More information on BFAST as well as links to documentation and examples can be found here: http://bfast.r-forge.r-project.org/

[4] The greenbrown package is published under the GPL-2 license (GNU Public License). http://greenbrown.r-forge.r-project.org/

2.2 COLLECTION OF FIELD DATA

There were two reasons for carrying out field observations and obtaining other field data using semi-structured interviews. One was to understand the type and nature of human activities that were taking place in identified zones of interest. The second was to validate the results derived from remote sensing analysis of satellite imagery on the area – assess why the NDVI signal for the location was what it is. This exercise sought to close one of the major gaps in processes of using vegetation dynamics as proxies to understand land degradation trends. While ground-based validation of satellite-derived indices of vegetation activity tends to be an established practice [17, 18], relating the dynamics of vegetation activity obtained through remote sensing methods to human activity over time is not very common.

In Senegal, the sampling sites were chosen based on three criteria. The first criteria was to achieve representativeness in the diversity of agro-ecological communities and land-use practices. Hence sites were selected from the Niayes; Northern Groundnut Basin; the Sylvopastoral Zone; Eastern Senegal and Upper Casamance; and Lower and Middle Casamance. Second, the samples had to represent major zones of hot and cold spots of vegetation activity identified. Thirdly some sites were included in the samples to make use of the rich time-series data that has been collected and archived by our collaborating institution in Senegal. Tanzania is a very large country, with an area of over 945000 km2 (the 13th largest in the world). It is also vastly diverse, with over seven major agro-ecological zones divided into tens of sub-zones. Here, the samples were chosen to represent four of the seven major agro-ecological zones (arid lands, semi-arid lands; northern highlands; and plateaux). Major areas of hot and cold spots were also identified for sampling, as were areas characterized by the dominance of particular land use practices (for example, plantation forestry, commercial sisal, grazing, and others). In Kenya and Uganda, the sample sites were purposefully sampled. The reason for this expert-based sampling approach was to target and investigate specific land uses and their influences on the NDVI trends. In Kenya, the three locations selected include: a farming valley that has undergone substantial transformation owing to increased population growth; a rice cultivation scheme that has undergone substantial periods of opportunities and challenges associated with management; and a gully system is described as the biggest in east and southern Africa. In Uganda, a valley of concentrated small-holder annual cropping; and a section of private forestry development were investigated.

Information on the history of land use on sample sites was obtained from key informants and local experts on land use and land cover changes in such locations. Key informants were mainly local persons living in the nearest communities to such sample points, in most cases undertaking activities that affect or have affected land use or land cover changes on the sample sites. Where possible, information from both key informants and experts was integrated to understand land use and land cover dynamics in the area. Questions focused on the types of land uses that have been practiced on sample sites over the last decade and a half, and the reasons for changes in these land uses. Questions were also asked on the scale of such land uses changes and their effects on the local environment as perceived by the interviewee. Care was taken to identify the changes in land uses and the periods during which such changes occurred as further off-field analysis would involve identifying such changes in the profiles of satellite-derived vegetation activity. This questionnaire-derived data had three main goals: (1) Identify the land-uses that are associated with identified trends in satellite-derived vegetation trends for sample locations; (2) Identify land-uses that are related to observed land conditions; and (3) relate the land condition and the vegetation trend data to local perceptions of land degradation.

[2] A full description of the suite of functions and their implementation can be found her: https://stat.ethz.ch/R-manual/R-devel/library/stats/html/decompose.html

[3] More information on BFAST as well as links to documentation and examples can be found here: http://bfast.r-forge.r-project.org/

[4] The greenbrown package is published under the GPL-2 license (GNU Public License). http://greenbrown.r-forge.r-project.org/

[5] More information on how to install and use Trends.earth for the analysis of vegetation dynamics can be found here: http://trends.earth/docs/en/documentation/before_installing.html

III. REASSESSING OUR THEORETICAL FOUNDATIONS

3. REASSESSING OUR THEORETICAL FOUNDATIONS

If we are interested in human-induced aspects of land degradation we should try to disentangle the effects of ecological dynamics and land use practices. The ecological dynamics are closely related to climatic variations and time is a crucial but tricky dimension. The remote sensing literature often assumes a straightforward relationship between vegetation dynamics and climate variability, and sometimes only rainfall. Proceeding from the ecological literature, however, the interannual variation of primary production is not well understood. Therefore a critical limitation to such disentangling is a lack of understanding of the inherent interannual variability of vegetation dynamics [19-23]. Many ecologists agree that temperature and precipitation are prime drivers of NPP [22, 24]. This has, however, been challenged by recent studies based on theoretical insights from Metabolic Scaling Theory [25]. Michaletz et al [26] found that climate has little direct effect on NPP. After controlling for plant age and stand biomass, temperature and rainfall did not explain any of the variation of NPP in a study of 1247 woody plant communities globally. On the other hand, climate controls NPP indirectly through plant age and standing biomass [26]. Even if the results and methods of the Michaletz study were criticised [27] their findings are to some extent confirmed by the observed ecosystem resilience of biomes to variations in rainfall [28, 29].

A further level of complexity is added when management changes are considered. The combined effect of climatic variations and human-induced pressure are poorly understood [30] and highly complex [31] [32]. In a recent study across a climatic gradient in West Africa (from annual rainfall of 1200 mm in Ghana to 600 mm in Burkina Faso) Guuroh et al. [33] tested a range of potential explanatory variables for predicting various ecosystems services with a focus on forage provision and the regulation of soil erosion. The results show that rainfall (accumulated over the season) is indeed an important driver of above ground biomass (AGB), but explained only 38% of the variance. For other ecosystems properties, rainfall was not the dominant driver, and aridity (i.e., the long-term climatic conditions) were almost negligible (Figure 1). In essence, these results also confirm the resilience to climatic variations of these ecosystems.

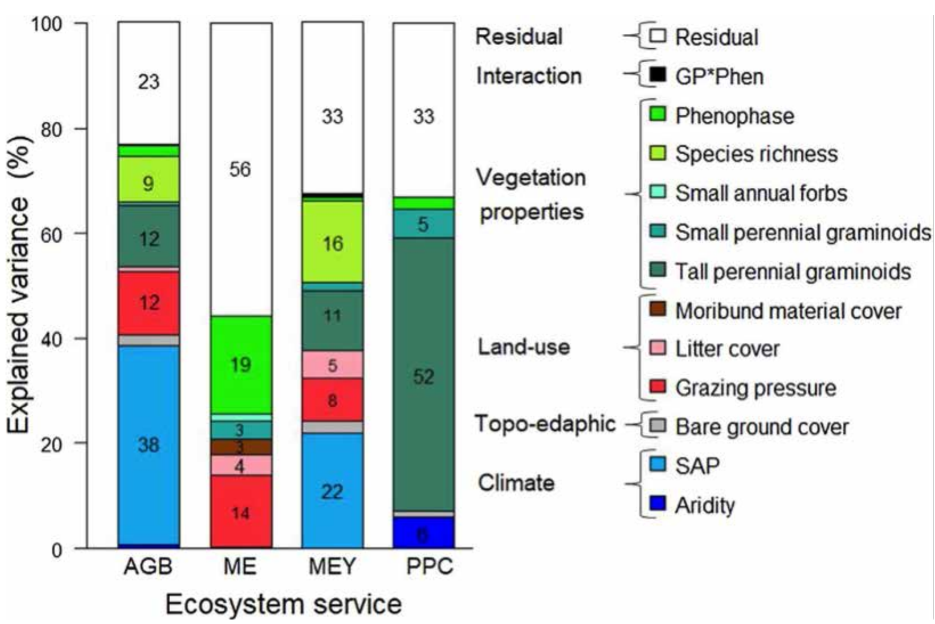

Figure 1. Variance explained by biophysical and land-use predictors in linear mixed-effect model. SAP=Season's accumulated precipitation, GP=grazing pressure, Phen=phenophase; AGB=aboveground biomass, ME=metabolisable energy, MEY=metabolisable energy yield, PPC=perennial plant cover. [33]

In an attempt to quantify two key factors for ecosystem stability of grasslands, resistance to drought and recovery after drought, Ruppert and others [30] used a large cross-continental database of long-term ecological experiments, totaling over 4400 years of observations. They tested effects of drought intensity on several characteristics: grazing intensity, biome (grassland, shrubland, savannah), and dominant life history (perennial or annual). The results showed that the most important factor was dominant life history, with perennial vegetation being more drought resistant while annual vegetation showed stronger post-drought recovery. The scientific support for the utility of aggregate proxies of land degradation, such as above-ground biomass (or above-ground net primary production, ANPP), and rain use efficiency (ANPP / rainfall, RUE), is ambivalent. From the above, it is clear that there is a lack of scientific knowledge about the determinants of vegetation dynamics. Nevertheless, many remote sensing studies assume that RUE is a useful indicator of degradation. Interestingly enough, many studies also postulates that rainfall drives vegetation dynamics even if their own studies are evidence of the opposite. Fensholt [34] for example state the "it is beyond doubt that the productivity of the semi-natural grasslands of the Sahel is to a considerable extent controlled by precipitation' [34, p. 665].

In summary, the problems of using the rain-use efficiency approach are many:

Rainfall influences vegetation dynamics in different ways across biomes and across species. As shown by several studies above, ANPP might for some biomes be indirectly driven by antecedent rainfall over several years [26, 28, 29] while the direct impacts on ANPP might be negligible [26]. This will cause problems for assessing how rainfall and ANPP interact at the landscape level. The rainfall – ANPP relationship varies across biomes, soil and vegetation types. For example, woody versus herbaceous and annual versus perennial, will respond differently to rainfall [20].

Most of the studies above are valid for woody vegetation, but also herbaceous vegetation composition seems to be responsive to rainfall regimes in a similar way [29]. In Tunisia, vegetation on loamy soils responded much more to drought conditions than other soils [35].

The rainfall – ANPP relationship varies across eco-climatic zones [32, 36]. Rainfall is a stronger driver of ANPP in drylands [37] than in more humid areas [21]. However, all biomes seem to converge to a common RUE, corresponding to 3.6 kg DM/ha/year/mm of annual rainfall, during the driest year for each biome [21], a value which is very similar to what Le Houerou suggested (4kg/ha/year/mm rainfall). Rain-use efficiency is often assumed to be a conservative measure, i.e., it is constant over time for a given biome in the absence of any non-climatic stressor. There are often substantial time lags between rainfall anomalies and vegetation response [38]. A strong legacy effect has been demonstrated by Anderegg, Schwalm [39] by which droughts may influence (reduce) the ANPP during a period of 1-4 years post drought. This legacy effect seems to be particularly strong in drylands [39].

The relationship between mean annual rainfall and plant productivity across biomes is well established [40]. However, the relationship between annual rainfall and annual plant productivity is much weaker [38, 41]. In some studies based on remote sensing, the authors may have misunderstood the relationship between rainfall and ANPP. The most commonly quoted source of the concept Rain Use Efficiency is Le Houerou who worked extensively on methods and theories for estimating range productivity in drylands [40, 42, 43]. He noted a strong correlation between mean annual rainfall and plant productivity, on average 4 kg dry matter / ha and mm rainfall [42, 43]. Similar empirical studies had been conducted earlier with very similar results [44].

It is important to note that both Le Houerou and Cook & Sims highlighted that the high correlation was between mean annual rainfall (or in some cases mean seasonal rainfall) and plant productivity, and they stressed that the relationship between annual rainfall and annual plant productivity was much weaker [42, 44], which has been confirmed in later studies [38, 41]. In a study of LTER sites across the US and Latin America, Huxman and colleagues [21] found that ANPP was more strongly correlated with the maximum temperature and the ANPP the previous year than with annual rainfall for the most productive sites, while ANPP was most strongly correlated with annual rainfall for the least productive sites. Other studies suggest that precipitation is one of several drivers of ANPP [33].

The Silonay community is working together to plant a mangrove forest taht will protect the ecology and their future.
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IV. TRENDS.EARTH AND VEGETATION DYNAMICS IN PROJECT COUNTRIES

4. TRENDS.EARTH AND VEGETATION DYNAMICS IN PROJECT COUNTRIES

4.1 SENEGAL

The vegetation dynamics in Senegal follows patterns of vegetation greening that have been reported over the western part of the Sahel. This phenomenon has been observed in the region since the 1980s, after ‘the great Sahelian drought’ of the 1960s and 1970s [45-47]. In the Sahel region of Senegal, an increase in satellite observed greenness is attributed to an increased tree cover associated with changes in post-drought rainfall [48]. Notwithstanding this generally positive vegetation trends, there are some areas of the country in which negative vegetation trends stand out, in most cases as patches in an otherwise positive vegetation trend landscape (see Appendix, Senegal).

Many of such negative trends are found in the Casamance region in which a number of socio-economic and political factors combine to determine land use and land cover changes. These factors include: demographic growth, immigration, the declassification of protected areas, the Casamance conflict, poor land management, and the illegal exploitation of wood resources associated with cross border criminality. In Linguere, patches of negative vegetation trends are associated with heavy grazing and poor grazing land management, while conserved areas (such as the Great Green Wall), and managed grazing areas (such as the Réserve Sylovo-pastoral de Barkédji Dodji and the Réserve Sylovo-pastoral de Six Forages) show generally positive vegetation trends (Figure 2). The agricultural system plays a determining role in the distribution of vegetation trends in certain regions of Senegal. This is the case in the northern regions (especially region of Saint Louis) where areas of annual crops tend to be associated with declining vegetation trends (Figure 2). These include farmlands producing annual crops such as rice, (the country’s a staple food crop), as well as large-scale tomato and onion farms. Generally positive trends are observed in farms engaged in the largescale production of perennial crops, such as sugarcane.

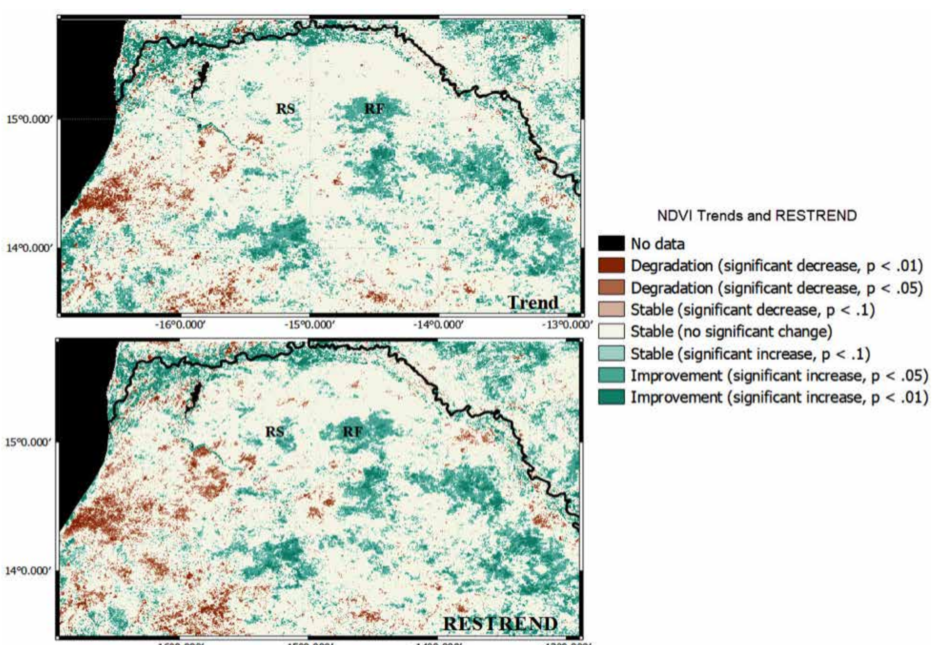


Figure 2. Vegetation dynamics in northern Senegal, showing NDVI trends and RESTREND values for the northern region of the country. Positive trends of vegetation are observed when the influence of rainfall is accounted for (RESTREND). Derived from MODIS 250 meter resolution and the CHIRPS dataset, and covers the period 2000-2015.

When the influence of rainfall is removed from the NDVI trends, a clear pattern of greening is observed in more areas of north central Senegal. Most of the areas manifesting greening are close to the valley of the River Senegal and are associated with the strong practice of agriculture in this zone.
Away from the valley of River Senegal, much of the greenness is associated with conservation activities, chiefly the Réserve Sylvo-Pastorale des Six Forages (RS) and the Réserve Sylvo-Pastorale de Faune du Ferlo Nord (RF). The Great Green Wall – extending from Widou (east of Louga) into Matam is also contributing to the greenness (also see Appendix, Senegal). The picture inset is a view inside the Réserve Sylvo-Pastorale des Six Forages.

In Senegal (as with most areas of the Sahel) land degradation is a result of a combination of climatic and anthropogenic factors of land management and resource use. Drought and diminishing rainfall constitute the two main climatic factors contributing to land degradation in the region [49]. Anthropogenic factors contributing to land degradation include forms of land use and land management practices, frequency and severity of the exploitation of natural resources (such as woody biomass for fuel and fodder, land and water for agriculture), overgrazing, and population growth [50, 51].

Agricultural practice is an important feature in Senegal, as its influence on land degradation goes well beyond land use and the management of existing farmlands. It includes the expansion of agriculture into new lands, some of which are marginal lands, which affects vegetation cover and renders the land more vulnerable to forces of land degradation. In Senegal, the expansion of agricultural land, especially for groundnut cultivation, has contributed to shorter fallows in savanna landscapes of the center and north of the country [49]. Grazing pressures have also been increasing in the country as the livestock population has been increasing. For example, the population of cattle increased by 43%, from 1,960,000 in 1961 to 3,481,126 in 2014, while sheep increased by 78%, from 1,100,000 in 1961 to 4,996,406 in 2006 [52].

In the southern regions of Senegal (the Casamance), a number of politico-historical and socio-economic factors work in unison to determine the evolution of land use and land cover in the region (Figure 3). These include demographic growth, immigration, the declassification of protected areas, the Casamance conflict, poor land management, and the illegal exploitation of wood resources associated with cross border criminality. In the 1980s, there were rapid population movements into these areas as farmers searched for new lands for the cultivation of groundnuts.

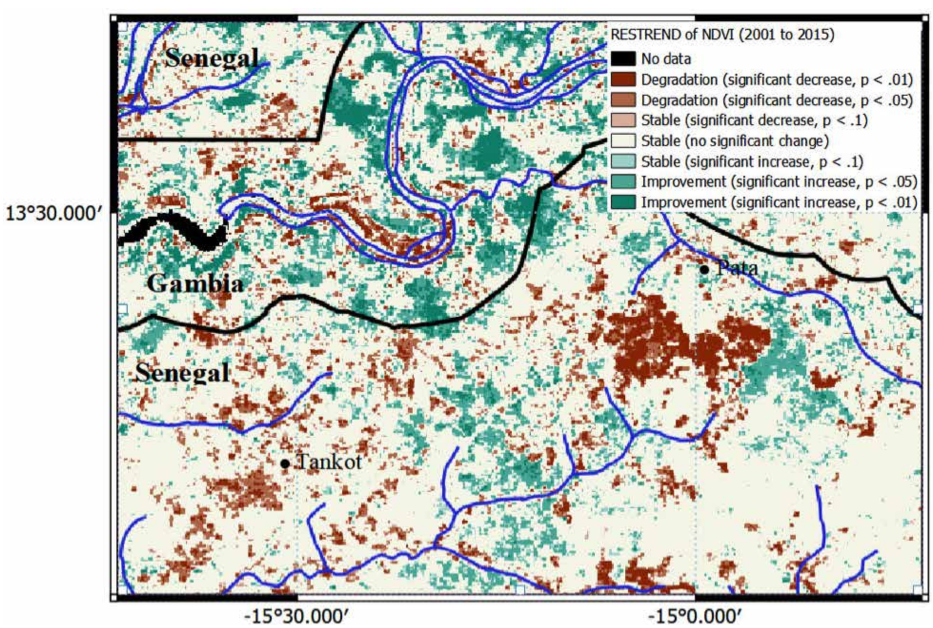


Figure 3. The border between Senegal and southern sections of the Gambia. On the ground, the negative trends of NDVI along the border is said to be associated to cross border illegal exploitation of forest resources. Away from the border, new farms abound and explain some of the negative trends. Derived from MODIS 250 meter resolution, and covers the period 2000-2015

The high rates of deforestation along the border with Gambia (see Figure 3) is therefore both a result of the combination of factors that started building up since the 1980s, but also a result of the relatively porous border between Senegal and the Gambia. This ease of travel between the two countries is exploited by criminal elements to harvest forest products that serve fuel and timber markets in both countries.

4.2 TANZANIA

Tanzania is a big country, with a diverse range of climatic zones ranging from arid lands to wetter highland areas to coastal and lake zones, and an elevation range from 0 to 5,898 meters above sea level. This diversity of climatic and altitudinal profiles therefore impacts the effects of climate change will vary across the country [53].

In the last century, Tanzania demonstrated some of the most glaring cases of the potentially negative consequences of land cover changes and the resulting degradation that may ensue, with districts such as Kondoa and Dodoma serving as infamous cases [54-56]. Previous studies have identified some of the major drivers of land cover changes in Tanzania to be agricultural expansion, overgrazing, demand for forest products, increasing crop prices and lack of proper land governance [57]. Understanding the relationship between land use and land cover changes and their impacts on land degradation has been a national level priority [58, 59]. A number of land covers show generally positive NDVI tendencies. The annual cost of land degradation in Tanzania is estimated at about USD 2.2 billion – about 10% of the gross domestic product of the country [60]. These include: (i) Areas under legal protection (especially those with active enforcement of protection laws with onsite patrols) such as national parks and game reserves.

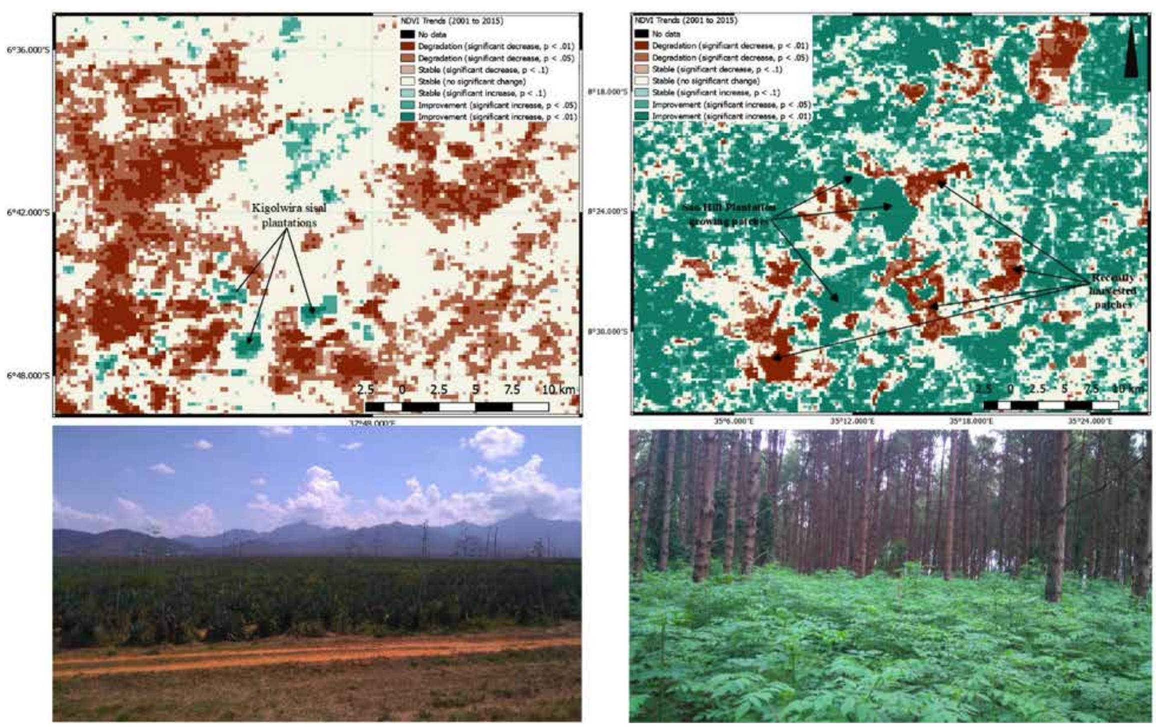


Figure 4. 'A' indicates trends of NDVI for Kigolwira and the eastern outskirts of Morogoro. The positive trends of NDVI for sisal plantations stand out against the backdrop of negative or non-significant trends of the surrounding landscape. 'B' shows vegetation dynamics for the Mafinga region. These residual trends of NDVI show a generally positive picture of vegetation activity compared to many regions around big towns in Tanzania. Many factors contribute to the vegetation dynamics in this region. Areas occupied by the Sao Hill Plantations show positive trends for growing tree crop areas and negative trends for recently harvested areas. The NDVI data is derived from MODIS 250 meter resolution and the CHIRPS dataset, and covers the period 2000-2015

Examples include the Rungwa, Kigosi and Moyowosi game reserves. This is also generally the case with conserved areas under community protection. It should be noted that while general tendencies of positive vegetation trends exist in this land use class, there are also patched of negative or no significant trends that can be found in this land cover class. (ii) Forest plantations under different ownership regimes (Figure 4) – individual, communal, and state owned. These plantations tend to have planting-harvesting cycles ranging from eight to twenty years depending on the ownership regime.

State plantations tend to have longer harvesting cycles than individual or communally owned plantations, which intend have longer cycles than individual plantations. Previous studies have reported on the potentially beneficial effects that the regenerating on former agricultural land, as well as the establishment of forest plantations, can have on biodiversity services and ecosystem services [61]. (iii) Sisal (Agave sisalana) is a perennial crop that yields a stiff fiber used for a variety of purposes. It was introduced in Tanzania in the late 19th century by the German East Africa Company and has continued to be an important factor of land use in the country. This crop has a lifespan of 7-10 years during which time it will produce 200-250 thick green leaves of 1.5 – 2 meters in length. The plantations are usually large and show up consistently as spots of positive vegetation trends on the landscape (Figure 4); (iv) Areas where there is a tight coupling of food crop production, agroforestry, and livestock rearing.

There are other land uses that tend to show generally negative trends of vegetation activity. These include: (i) Regions dominated by grazing as the main socio-economic activity, especially in places that have witnessed an increase in the number of grazers over the recent past (Figure 5); (ii) Areas in which the practice of annual cropping of either food or commercial crops dominate (especially when there is little coupling with other livelihood practices such as agroforestry and livestock rearing); (iii) Areas of active vegetation clearing (forests or savanna woodlands) for new farmlands, or for the exploitation of environmental resources such as biomass for wood fuels or for the production of charcoal (Figure 5).

Long term drivers have exerted pressure over large area generating declining vegetation trends in the center of the country – the area extending into the districts of Dodoma, Kiteto and Morogoro (between Gairo and Mkoka, see Figure 6).

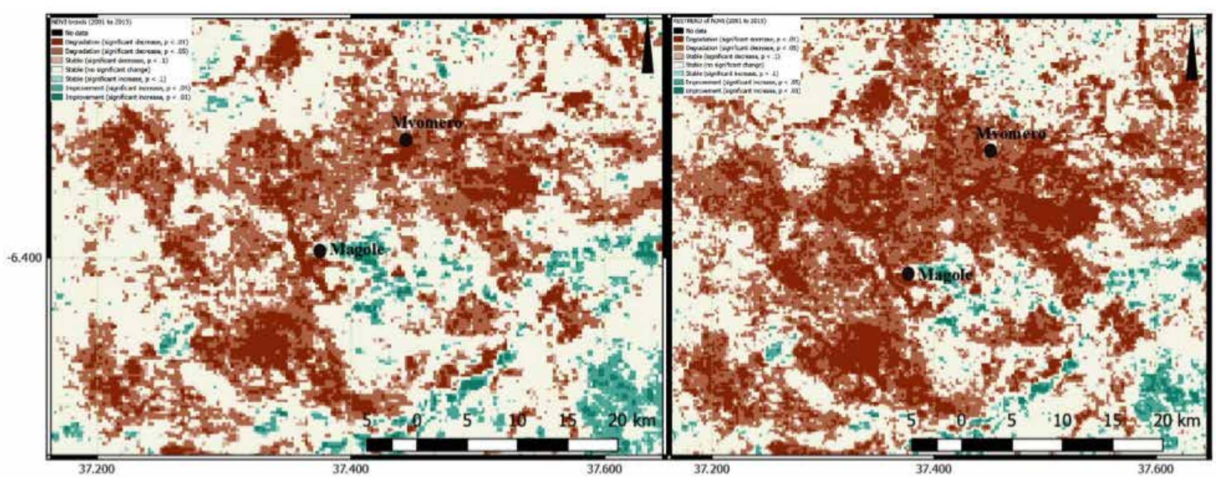


Figure 5. NDVI dynamics in and around Mvomero, Tanzania. The residual trend shows an increase in locations with negative vegetation trends. This is attributed to rapid deforestation and an increase in the numbers of livestock in the region. The reforestation is undertaken to expand farmlands and tree-cutting for wood fuels and the production of charcoal to meet rising demand in surrounding urban centers. Derived from MODIS 250 meter resolution and the CHIRPS dataset, and covers the period 2000-2015.

These pressures started with government-encouraged movements since the 1970s into an area that was basically wilderness before this time. The policy of villagization in 1974 was meant to bring people into communities or population centers that would permit the government to be able to serve them with social amenities such as water, schools, health centers, etc. (see the works of Shao [62] and Kikula [63] on the implications of villagization on the natural environment and ecological balance). Today, natural population increase is contributing to increased pressure on environmental resources of the region.

The declining vegetation trends are associated mainly with fuelwood harvesting, charcoal production, crop cultivation, and overgrazing (Figure 5 and Figure 6).

Fuelwood harvesting and charcoal production are important businesses which have been increasing over the years owing to demand by the growing population of Tanzania [58]. The rapid population growth is accompanied by a high rate of urbanization which adds demand for fuel and food from the peripheral area. Charcoal provides most of the energy used for cooking by the urban population in Tanzania. An increasing population means an increase in demand for food. The increase in food demand increases demand for arable and grazing land in rural areas, and urban peripheries to produce food to meet high demand from both rural and urban populations [58].

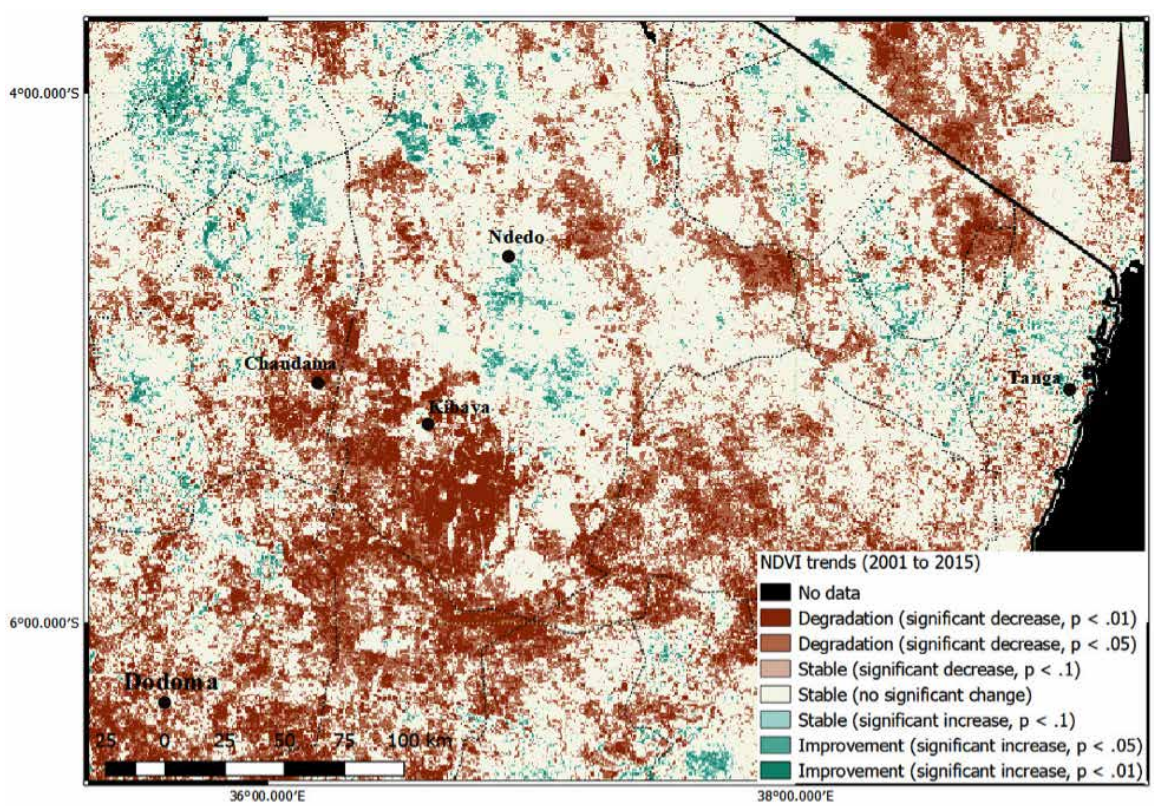


Figure 6. The region around Gairo and Kibaya where current trends in vegetation dynamics are associated with a complex mosaic of politico-historical and socio-economic events in Tanzania's recent past. Challenges in this region include overgrazing, drought, cutting down of wood for firewood, illegal lumbering and charcoal production. Severe droughts in this region usually occurs every 10 years. Recent droughts have occurred in 1964, 1974, 1984, 1994, 2004, 2014. Local people report that such droughts tend to occur roughly10 years. The NDVI data is derived from MODIS 250 meter resolution and covers the period 2000-2015.

V. LAND USES, LAND COVER AND THEIR INFLUENCES ON NDVI TRENDS

5. LAND USES, LAND COVER AND THEIR INFLUENCES ON NDVI TRENDS

Factors contributing to the type and speed of land use changes vary from one place to another, and may also vary over time. They can be divided into two categories – underlying factors, and immediate factors [64-66]. Underlying factors that contribute to land use changes have been described as macro-level interactions contributing to local outcomes, and they operate some distance away from the landscapes they affect [65]. Lambin, Turner [65] see these factors as important, as they have the potential of amplifying and attenuating local drivers of land use change.
These include changes in demography, levels of economic growth, socio-cultural, technological, and political factors [64, 65].

At the local level such underlying factors may manifest as pressures on natural resources resulting from population increases, degrees of political representation and the accountability of political representatives, levels of social protections available to local populations, as well as the availability and reliability of legal representation. Immediate factors (also described as proximate) are human activities (land uses) that directly affect the environment, connect the changes in land cover and land use [67]. Immediate factors are determined by local levels of technology, local livelihoods, local environmental constraints, the level of organization of local institutions with regards to managing environmental resources, access to information on natural resources management, and other presures that determine local interaction with the natural environment.

In local environments, these immediate drivers are manifested as degrees of grazing pressures, demand for forest products, type of agricultural system, access to markets for agricultural products, food prices, land tenure systems, and the importance and effectiveness of local common initiative groups. Major factors contributing to the distribution of NDVI trends in the study locations include: fuelwood harvesting and charcoal production; overgrazing; monocultures of perennials; differences in farming systems; conservation activities; deforestation; reforestation of formerly deforested areas; and politico-historical conditions.

5.1 AGRICULTURAL LAND USES

The agricultural sector in SSA accounts for about 65% employment of its working population [68, 69]. In rural areas, agricultural employment could be as high as 90%. Despite the importance of this sector to the economy of the region, investments in agriculture remain low and positive developments in productivity remain patchy and weak [68].
This limited attention given to agriculture has led to a number of general characteristics in this key economic sector. The gaps between potential and actual yields for major food crops remain large in many countries, agricultural technology among smallholder farmers remains quite rudimentary, infrastructural development in support of agriculture is limited, and reliance of food production on rain-fed systems remains high [70, 71]. The results of this under-performance of the agricultural sector are many. One major outcome is the existence of an agricultural system that produces far less than its optimal capacity [70, 71]. About a quarter of people in Sub-Saharan Africa are undernourished. Given the high reliance on rain-fed production, food production systems and security are vulnerable to climatic variation [72]. Over the last two decades, the region has witnessed an increase in the reliance on imports to substitute for local food production deficiencies. Perhaps one of the most important outcomes of the practice and performance of agriculture in sub-Saharan Africa is the rapid land use and land cover changes associated with increased production.

The increase in agricultural production being experienced in the region is as a result of more land being brought under cultivation, and not a result of increases in yields per unit area cultivated [70]. This contributes to large changes in land use and land cover in the region, as well as puts pressure on land resources. The changes in land use and land cover, together with the implications of such changes on ecosystem services compound pressures already brought about by other land use demands in the region, chiefly from rapid demographic growth, a rising middle class, and changes in dietary patterns [73].

5.1.1 FARMING PRACTICES AND LAND MANAGEMENT

In some cases, farming practices can have a clear imprint on the NDVI signal that makes the area in which farming is practiced easily identifiable against the backdrop of other land uses. Intensive cultivation of annual crops in smallholder farming systems are an example of the types of farming practices that may stand out in their NDVI profile relative to other land uses in a landscape.

In Figure 7, the valley bottom (and its tributaries) is relatively wetter than the surrounding landscape, and supports smallholder annual crop production more intensely than its surroundings (Figure 7A). By combining the history of land use (using key informant interviews), the type and distribution of land cover (from Figure 7A and C), with the trends of NDVI (Figure 7B), an inference can be made on the causes of the significant negative trends of NDVI identified in the valley. Such trends are unlikely to be the effect of climate, as they affect only the valley where a specific type of land use is being undertaken. The types of land use and land management are likely to be the culprit for such significant negative trends.

5.1.2 MONOCULTURES OF PERENNIALS

Monocultures of perennials tend to be associated with positive NDVI trends than surrounding farmlands or non-farmed areas being used for other economic purposes (see Figure 8 and Figure 4). In terms of land degradation, this tendency towards positive vegetation trends has to be seen within the context of other implications for cultivating largescale monocultures on any landscape.

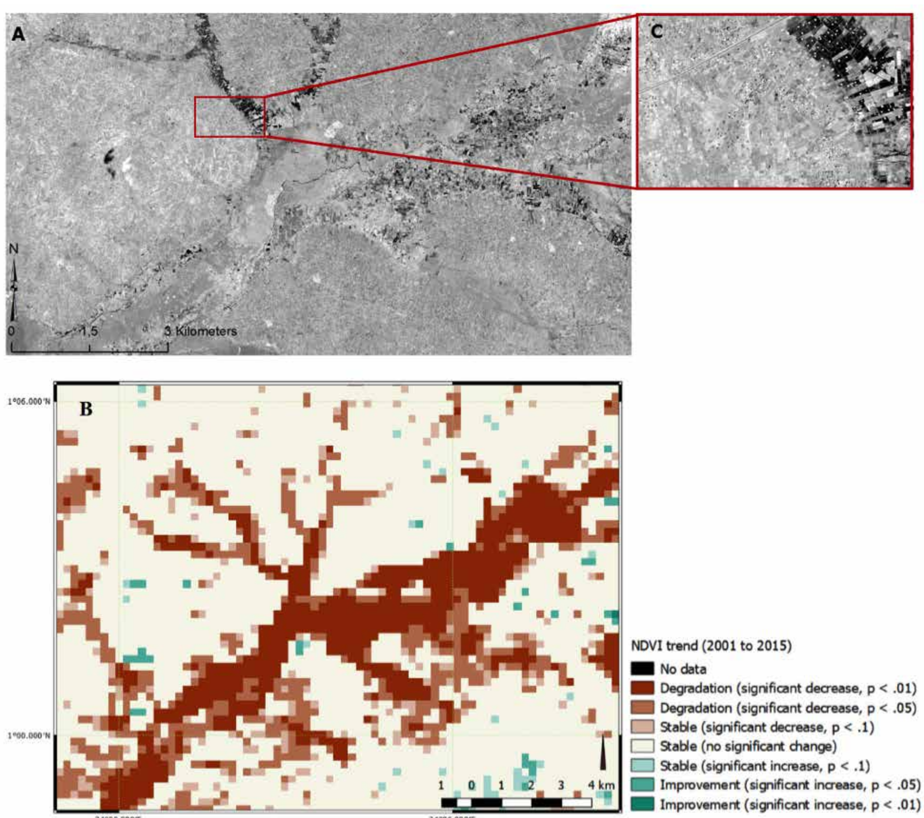


Figure 7. Section of a heavily cultivated valley in Mbale, Eastern Uganda. The image includes a broader view of a section of the valley (A); NDVI trends for the section, showing a close relationship between and areas cultivated and negative trends (B); and an inset showing a closer view of the intensity of land use for smallholder agriculture in the region (see NDVI trends for a location inside the farming area, Appendix-Uganda). The NDVI data is derived from MODIS 250 meter resolution and covers the period 2000-2015. Image source: DigitalGlobe, Inc. Licenced under NextView.

Monocultures of perennials may deplete selective nutrients from the soil, rendering it less useful for other forms of crop production. Monocultures do not favor developments in biodiversity, and ecosystem services associated with biologically diverse landscapes [74]. An increase in NDVI activity resulting from the development of monocultures may not necessarily indicate improvements in land condition overall. However, one must note that monocultures may be contributing to the social and economic well-being of communities that engage in them. The cultivation of perennial monocrops tends to be associated with the use of greater inputs of material and technical resources for the development of these crops. This contributes to generally healthy vegetation stands in the plantation of monocultures, and is reflected in the NDVI signal that is received from such cultivation systems. These signals generally tend to stand out or be distinct from that of the surrounding area (Figure 8).

Figure 8A shows NDVI profiles of two areas of sisal cultivation in an area between Dar es Salaam and Morogoro, as well as smallholder cultivation systems adjacent these perennial mono-cropping systems. Greater technical and resource inputs into the sisal monocrops sustains higher and relatively stable NDVI signals. Adjacent smallholder food farms on the other hand, do not benefit from these inputs of technical and material resources. Some perennial monocrops tend to be managed in ways that leave a clear impression on the vegetation signal from such systems. An example of the cultivation and harvesting of trees in plantations for lumber. Where harvesting is done by clear-cutting of designated parcels, the signal is unmistakable in the NDVI profile.

Figure 8B shows NDVI trends for different parcels of managed forest plantations in Mafinga. The impact of human activities (planting and harvesting) in systems such as these tends to be clearly imprinted into the NDVI record. The times when different parcels are harvested is clearly illustrated by a vertical downward drop of the NDVI signal followed by a gradual increase as the portion of land is seeded and begins regrowth.

In Senegal, gum arabic tree (Acacia senegal) is a naturally occurring tree species that serves a variety of valuable economic and ecological functions in local livelihoods and environments, and as a consequence is preferred for plantations (Figure 9).

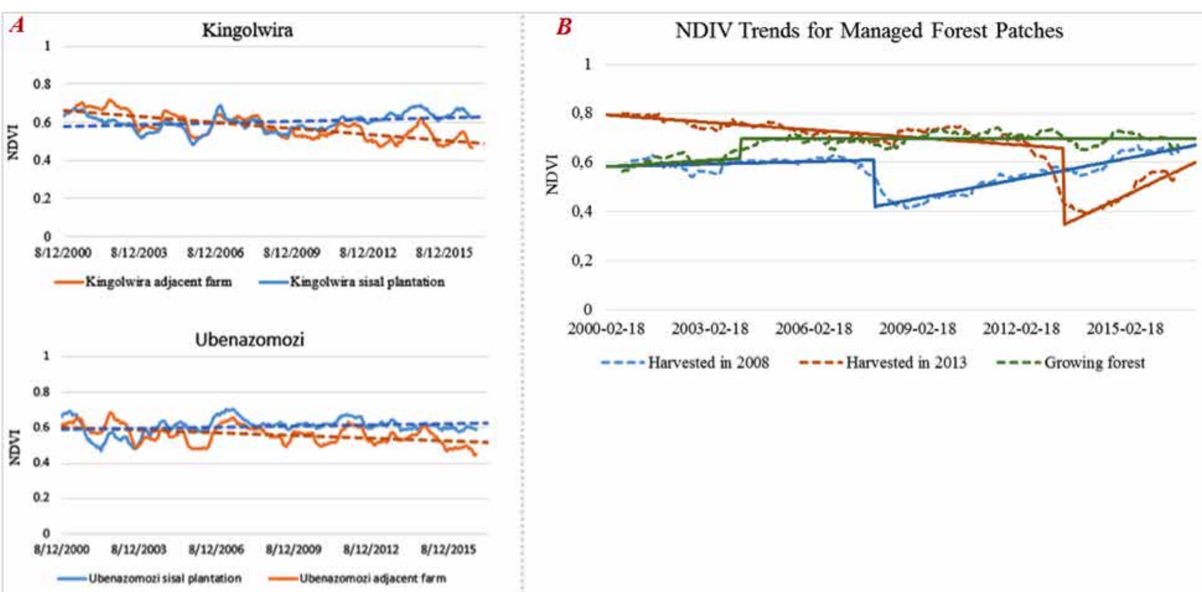


Figure 8. NDVI profiles for perennial monocrops stand out and can be easily identified: A: Comparing NDVI profiles for perennial monocrop plantations (sisal) and adjacent smallholder farmlands in Kingolwira and Ubenazomozi. NDVI tends to decrease in smallholder farming systems compared to nearby monocrop plantations. B: NDVI profiles for forest patches and BFAST trends indicating different management activities - a patch that was harvested in 2008, one harvested in 2013, and another unharvested. The harvested profiles are akin to what may be observed in a clear-cut unmanaged forest.

This tree provides fodder for livestock, fuelwood for local communities, and shade for both livestock and people. Its extensive lateral root system reduces soil erosion by surface runoff and wind, common in most parts of the country. Given its numerous economic and environmental benefits, it is one of the most preferred species of perennials for associating with both food production and pastoral systems. It also has a range of non-traditional uses in the pharmaceutical and food industries, and hence its cultivation in large-scale plantations is increasingly becoming a common practice in Sudano-Sahelian countries. These plantations are associated with environmental benefits that are reflected in the performance of NDVI (see vegetation trends in a plantation of Acacia Senegal, Appendix – Senegal).

5.1.3 DIFFERENCES IN FARMING SYSTEMS

The cropping systems encompass all practices and the organization of farm production that make a particular unit unique from the other. Reckling et al. (2016) include the rotation, management activities (tillage, inputs, harvesting etc.) and production orientation (arable, mixed or forage) in the definition of cropping system. Different types of cropping systems can have different impacts on the environment. For example, an a study evaluating effects of introducing legumes into crop rotations found that the environmental impact was lower for cropping systems with legumes that for those without legumes in the rotational cycle [75]. The types of crops cultivated, as well as the ways in which agriculture is practiced can have an influence on the trends of vegetation in an area. Some farming systems support the presence of continuous vegetation cover.

These farming systems tend to have mixed cultivation patterns and/or coupled production systems - systems that integrate crop production with agroforestry and/or livestock production. Production systems that integrate food crop production and agroforestry, for example, tend to manifest positive trends in NDVI. Research by Maitima, Mugatha [76] observes that farmers who grow many crops conserve native plant species better than those who grow only one crop. Production systems with a weak or no coupling of crop, agroforestry, and livestock systems may at best show limited positive trends in NDVI, or even negative trends. This is especially the case for smallholder farming systems where annual crops dominate the production system.

Examples from northern and central Tanzania exemplify the effects of differences in cropping systems on the vegetation signals (Figure 10).

Figure 9. A plantation of Acacia Senegal

It was observed that in general, areas in which there is a tight integration of crop-livestock-agroforestry systems tend to be associated with the practice of intercropping, multiple cropping and relay cropping. In these cropping systems, the soil is constantly protected from the elements and the land is covered by vegetation year-round. The importance of multiple cropping systems in biodiversity conservation and soil protection has been well studied and reported [77-79]. NDVI in areas practicing these forms of agriculture tends to be positive. This tends not to be the case with cropping systems that leave the land uncultivated or unprotected from the elements for relatively long periods of the year. Monocultures of food crops and practices of one-season cultivation (without cover crops in the non-agricultural seasons) are examples of cropping systems that are associated with declines in NDVI. Around Karatu, soil conservation initiatives have been well received by many of the largescale wheat farmers of the region.

The people of the region have been sensitized on the need for soil conservation, agroforestry, etc. Most of the positive vegetation trends around Lake Eyasi are areas of recent growth of acacia. The areas of negative vegetation trends around Lake Eyasi is associated to the cultivation of onions (Figure 10). The cultivation of onions leaves the farm bare over long periods. Between Lake Eyasi and Lake Manyara, most of the activities there are agro-pastoral with some areas that have adopted zero grazing.

5.2 NATURAL RESOURCES USE AND MANAGEMENT

Competition for land resources, such as arable land, water, and biomass, between major development sectors in sub-Saharan Africa is on the rise. The manner in which this demand will be met in a number of key land-based sectors is crucial: agriculture; water; and energy.

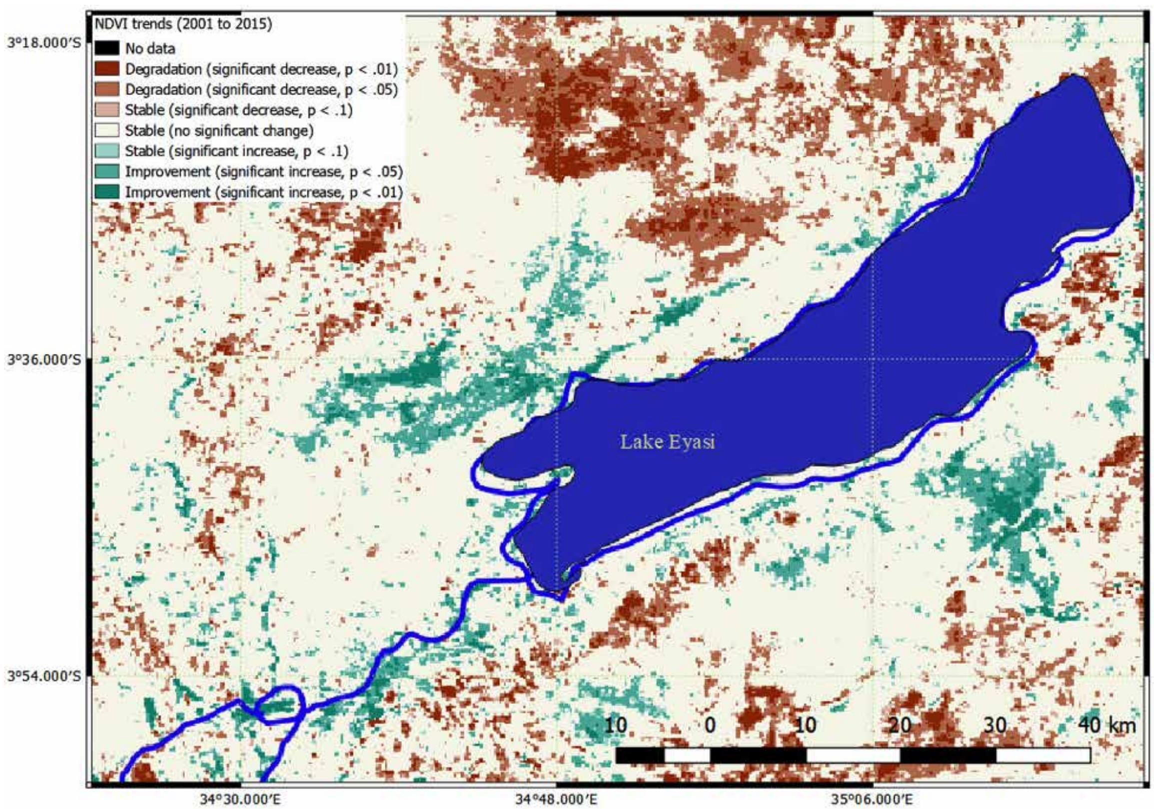


Figure 10. The areas of positive vegetation trends west and southwest of Lake Eyasi are associated with a tight coupling of crop production, livestock keeping, and agroforestry. Derived from MODIS 250 meter resolution data, and covers the period 2000-2015.

The production of bioenergy feedstock is becoming another key driver of land use and land cover changes in SSA. A clear shift from fossil-based petrochemicals has been observed, and bio-based systems of energy production are seen as an inevitable mid-term future of energy production and consumption [80]. Fischer et al. (2009) estimate that land used for biofuel feedstock may increase from current 25 million ha to between 45 and 70 million ha by 2030. The demand for food crop agricultural land will therefore be further compounded by demand for land to increase the production of bioenergy and other industrial crops. It must also be noted that many of the large-scale land investments that have been made in SSA to meet this demand for bioenergy are not intended for local consumption.

With a population of about 1.2 billion in 2016, Africa is the second-largest and second most populous continent on earth. The population of sub-Saharan Africa is projected to reach two billion by 2050[6], and rise to nearly four billion by 2100 (UN Department of Economic and Social Affairs 2013).

It must be noted however that growth rates are not uniform throughout all the 54 countries of SSA. Rates vary from as low as <1% in Mauritius, Reunion and Seychelles, to >3.5% in Equatorial guinea and Niger [81]. Despite the overall high rate of population growth (of about 2.5% average for the region), SSA currently has a relatively low population density of about 46 people per square kilometer mile, which puts it behind 145 persons per km2 in Asia, 172 in western Europe, and a global average of 58 [81]. As populations grow and incomes increase, it is forecast that 70% more food production will be required globally, and up to 100% more in developing countries (relative to 2009 levels) to meet demands by 2050 . These developments will increase demand for key natural resources (land, water, and others), with the potential of having major impacts on the natural environment [66, 73]. Laurance, Sayer [82] foresee major impacts on tropical forests and semi-arid environments, with huge implications for biodiversity and their associated ecosystem services. This will contribute in increasing the footprint of agriculture – a main socio-economic activity in the region.

Figure 11. Fuelwoods are not only an energy source. Their sale as is, as well as the production and sale of charcoal is a means of livelihood for many households. The area of deforestation is north of Kibaya (Lat: -5.180450, Lon: 36.543504). Charcoal and firewood is sold along roads, and is bought both in wholesale and by families, many of which are destined for use in big cities of the region.

6 Key messages from: The State of the World's Land and Water Resources for Food and Agriculture http://www.fao.org/nr/solaw/main-messages/en/

5.2.1 FUELWOOD HARVESTING AND CHARCOAL PRODUCTION

Wood fuels are the single most important source of renewable energy on the globe, providing about 6% of the global total primary energy supply. The FAO reports that more than two billion people depend on wood energy for cooking and/or heating, particularly in households in developing countries. This makes wood fuels the most decentralized energy in the world, representing one-third of the global renewable energy consumption. It is the backup energy option for societies at any socio-economic level. Populations will switch easily back to wood energy when encountering economic difficulties, natural disasters, conflict situations or fossil energy supply shortages, and depend on the harvesting and sale of wood energy products as an economic activity (Figure 11).

The use of fuelwood as an energy source is a common phenomenon in much of sub-Saharan Africa. Even in areas where there is electricity, the consumption of fuelwood and charcoal persists, as it contributes to cutting down the overall energy bill of households and small businesses.
Much of the fuelwood harvested is used for cooking in both rural areas and many urban centers. Fuelwood harvesting is one of the main contributing factors to deforestation in the region. Trees outside recognized forests do also contribute to the supply of fuelwood, highlighting the importance of non-forest resources. Recognized forests in this case may include conserved forests, forests set aside by local communities for a range of uses, and forests that are not being exploited either because of distance or because of other barriers. Studies have reported fuelwood harvesting to be an important contributor to deforestation, mainly in some situations in Africa where deforestation is associated with wood extraction (Geist and Lambin 2002). The disadvantage of using fuelwood is that with increased demand, its consumption will contribute to deforestation or overexploitation of vegetation resources – with potential of contributing to land degradation. It must be noted however that firewood and charcoal are renewable energy resources if produced and harvested in a sustainable manner.

The impact of using wood fuels on the NDVI profile depends on the length of period of observation, the speed and intensity of fuelwood harvesting. When fuelwood harvesting is not controlled, there is potential for harvesting to be rapid and in some cases intense. This can lead to steep declines in vegetation cover and the NDVI profile (see the effects of fuelwood harvesting on the NDVI curves of Kipogoro and Niktiku in Tanzania, Appendix). In the case of Tankon in southern Senegal, there is the illegal harvesting of wood, chiefly for timber.

Figure 12. Selective harvesting of desired tree species outside Tankon, Casamance region of Senegal.

Hence harvesting is selective for desired species, not clear-cut (Figure 12). The resulting NDVI curve continues to show minimal increases as new trees in this patch of forest grow to fill spaces in the harvested patches.

5.2.2 DEFORESTATION

Deforestation is one of the most important processes of land cover change in all case studies. In Tanzania, it is reported throughout the country. In Senegal, the process is also widespread, even though more common in the southern and the eastern regions. It is widely reported in Northern and northeastern Uganda. In Kenya, it is seen as one of the main forms of land cover change in the northwestern and southwestern regions of the country. The drivers vary from one region to another, even within national borders. For example, the environmental history of particular locations determines whether such areas will be strong suppliers of wood fuels [83].

However, four major drivers are common to all case studies at the local level, and associated to smallholder livelihood practices: demand for farming land; demand for energy resources (fuelwood or wood for charcoal production); clearing of forests to make room for pest-free livestock rearing environments; and clearing of land for habitation.

In many cases, when forests are clear-cut for agriculture (Figure 13a), the farming land is left without sufficient vegetation cover for protection from the elements. Hence, erosion can occur and lead to topsoil being blown away by wind from one area to another, or transported by surface water into river systems. In cases where the agriculture practiced is mainly smallholder annual crops, the soil may have to be tilled every year, a process that can further accelerate the land's susceptibility to soil erosion. Where intact, unmanaged forests still exists, agricultural producers move on, clear more forest and continue the cycle of soil loss.

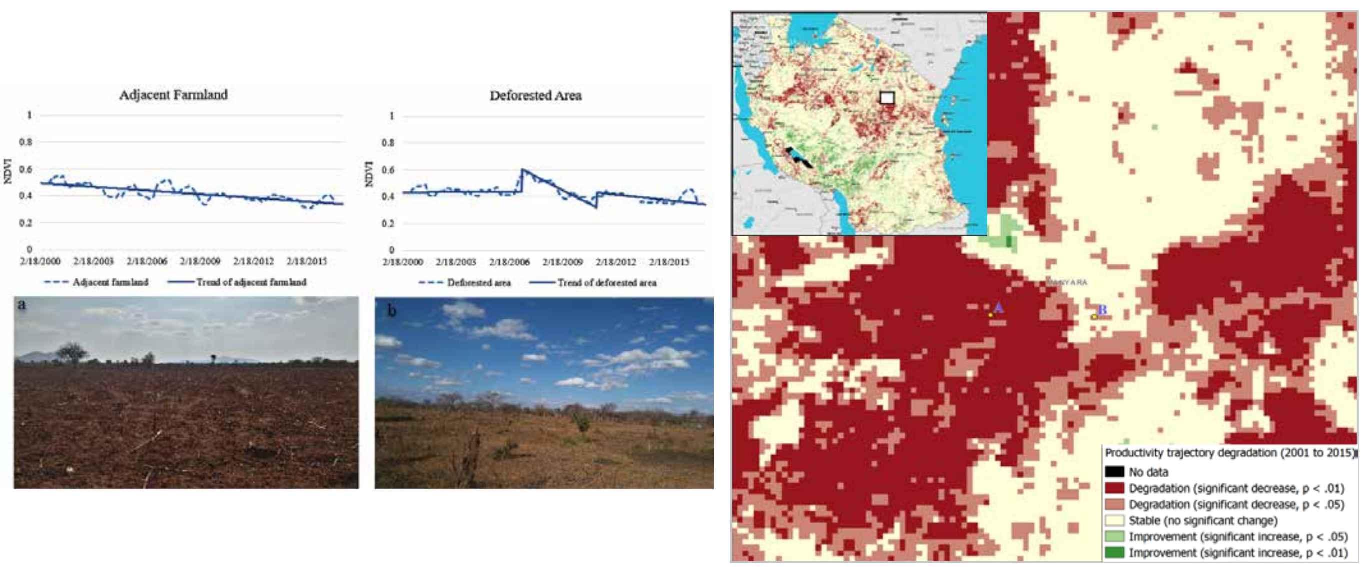


Figure 13. NDVI trends for a farmland that was established in 1996 (a: Lat: -5.15179, Lon: 36.512488), and an area near the farmland that is suffering from recurrent deforestation for firewood and charcoal production (b: Lat: -5.152712, Lon: 36.554285). Note the steady decline of trends for the farmland. While the formerly forested land shows a decline in NDVI trends, periods of excessive cutting occurred in 2009, and the most recent episode in 2016.

The speed and effectiveness of deforestation will determine the nature of its imprint on the NDVI curve. The decrease in NDVI could be sharp and steep in cases of a clear-cut over a short period, or gradual, such as when local communities are gradually exploiting the forest for its tree resources until the forest cover is lost. In the former case, the intention may have been to clear the land. This can be the case when the intention is to create space for agriculture. Some communities clear extensive areas around their living grounds to rid the area of potential disease vectors that may affect their livestock. This is the case with animal grazers of the Sukuma ethnic groups. In the latter case, the intention may not necessarily be to clear the land, however the over-exploitation of the vegetal resources leads to the area being deforested (Figure 13b). The removal of vegetation in an area rids the soil of its protective layer against elements of erosion. These barren, unprotected surfaces become vulnerable to water and wind which can lead to the loss of the top, most fertile layers of soil. In dry environments, this process leaves behind the less-biologically-active lower-soil-layers, which are often of little productivity.
When the search for habitation land is one of the key drivers of land clearing, the impact may extend well beyond the immediate locations that become habitable.

Figure 14 shows the rapid population growth in Bududa, Uganda over a ten-year period, and the implications of the surrounding vegetation cover (Figure 15). Besides the direct impact of vegetation clearing for habitable land that is captured by the NDVI signal, the impact on environmental resources (forest resources harvested by the local population) is also captured by the NDVI times-series. In Figure 15, the sharp declining trends of NDVI along the fringes of a forest in the immediate outskirts of the habitation area indicates rapid deforestation by the growing population of the area.

5.2.3 REFORESTATION OF FORMERLY DEFORESTED AREAS

The process of deforestation, as well as the fate of deforested land in all four case studies, have close similarities. Fuelwood harvesting and charcoal production are some of the leading contributors to deforestation in Kenya, Tanzania, Senegal and Uganda. These activities rid the original forest of its valuable tree resources, leaving the land no longer useful as a potential for fuelwood supply and charcoal production. In most cases, the deforested land is then either converted to agricultural use.

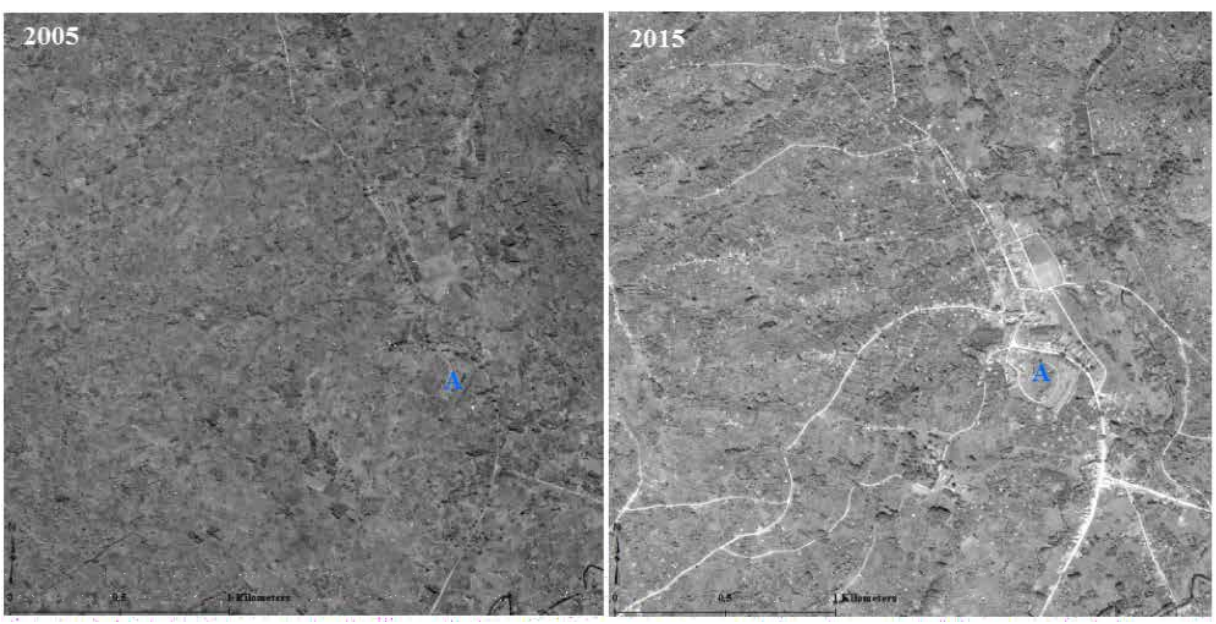


Figure 14. Population growth, land use and land cover changes contributing to declining vegetation trends in Bududa, Uganda. The town center in both image is indicated by “A”. Image source: DigitalGlobe, Inc. Licenced under NextView.

When the land is cultivated over a period of years, the fertility declines and the area is abandoned as a wasteland and can potentially regenerate to forest (see some of the main contributing factors to positive and negative vegetation trends in the Mafinga area of southern Tanzania, Figure 16). In cases where the population had no agricultural interest, the land is simply abandoned and new land with fuelwood and charcoal resources is sought. The regeneration of forests in such abandoned lands is sometimes not very straight forward. This is the case when the processes of deforestation and/or eventual cultivation of the land were associated with soil degradation. It can also be the case when the land continues to suffer from recurrent disturbance, as bushes emerging from the forests land are further harvested for the uses of local populations.

Reforestation is the reestablishment of forests either through natural processes or through human intervention by seeding and planting trees. Reforestation may contribute to land improvement through protection of the soil from erosion, improvement in biodiversity, as well as through other ecosystem services.

Reforestation may especially be beneficial to local ecosystems if the species being introduced are native to the ecosystem or do not negatively affect the ecosystem. Formerly degraded lands may exhibit positive trends in NDVI as vegetation naturally recolonizes these areas. This is a situation that was also observed in many locations in Senegal (an example is Pata in southern Senegal, see Appendix). The causes of vegetation decline and possible degradation may have been deforestation, fuelwood harvesting, charcoal production, or even overgrazing. In these cases, positive trends in vegetation activity may exists even when some forms of land degradation are still manifesting. For example, vegetation trends may be increasing even as some forms of soil erosion continue to affect the land. The recovery of such degraded lands may be long, and determined by a range of post-harvest management techniques applied to the land [83].

5.2.4 CONSERVATION ACTIVITIES

Increasing vegetation trends in areas of conservation may indicate improvements in land condition, as conservation contributes to different aspects of ecosystem improvement.

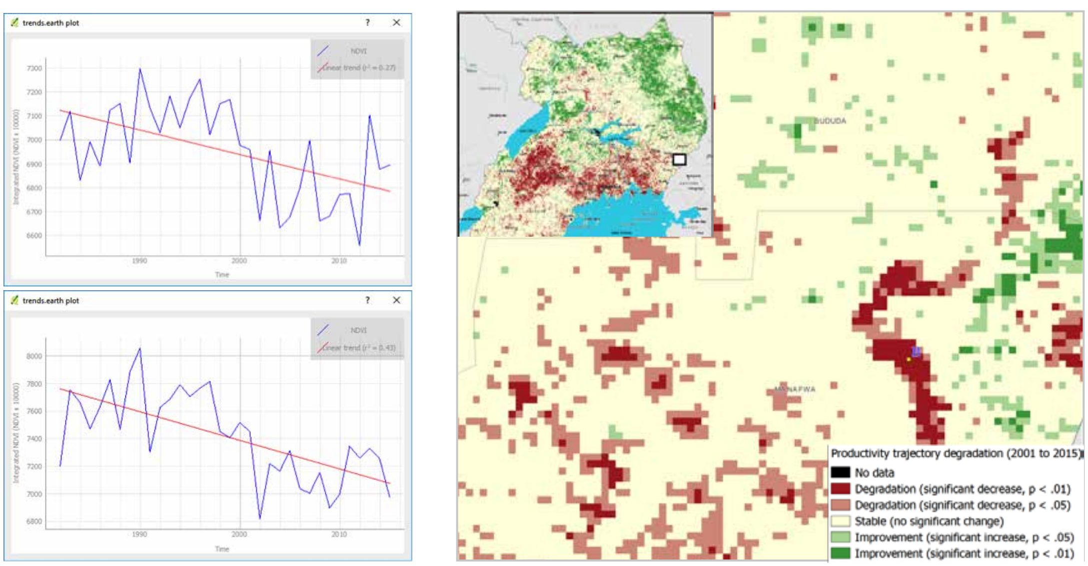


Figure 15. The impact of population growth and demand for resources in Bududa. Significant deforestation has been experienced at the forest edge closest to the town area. 'A' indicates the town center that has developed and expanded over the last decade (Lat: 1.0006, Lon: 34.3169); and 'B' indicates the significant decline in NDVI indicating deforestation at the edge of a forest outside the inhabited area (Lat: 0.9616, Lon: 34.3964). 'A' indicated in both images in Figure 14 correspond to 'A' in this figure. The degrading forest edge is not covered by the latter image. Derived from MODIS 250 meter resolution data, and covers the period 2000-2015.

In Senegal for example, protected zones such as the area occupied by the Great Green Wall (Figure 17), and sylvo-pastoral reserves exhibit positive inter-annual vegetation trends (see Figure 17, and also see NDVI trends inside the Great Green Wall, Appendix-Senegal). Nonetheless, not all areas that are under conservation experience positive trends in NDVI, or are witnessing improvements in land condition. A number of factors may contribute to the absence of positive trends in NDVI or the lack of improvements in land condition include overgrazing from within the conservation spaces. These include overgrazing by wildlife (protected animal species), illegal grazing by local livestock herders, bushfires, fuelwood and timber exploitation, etc. In some cases, conservation efforts align with local livelihood structures to create systems that contribute to positive vegetation signals observed in the area.

5.2.5 MANAGEMENT OF GRAZING LANDS

One of the most common pressures on land in arid and semi-arid areas within the countries analyzed is overgrazing. Overgrazing refers to grazing by livestock or wildlife to the point where the grass cover is depleted, leaving bare, unprotected patches of soil (OECD 2001). Overgrazing is not only a feature of areas of high human population density [3], as livestock keepers can move their animals to areas that a quite remote from human settlements. It occurs when vegetation or pasture is repeatedly removed from land and is not given enough time to recover. The main causes of overgrazing in both Tanzania and Senegal are generally similar. Overstocking implies a situation where a piece of land is intensively stocked with more animals that the site can support for a grazing season. Overstocking is a problematic aspect of the development of the livestock sector in Tanzania – which has ranked the 11th country globally in terms of cattle inventory, with over 25.7 million heads of cattle (1.67% of the global total).

Senegal ranks 63rd in the world with about 3.4 million heads[7]. While the densities are variable countrywide, some areas support more cattle numbers than others. There is also the lack of proper livestock and pasture management.

Major contributors to *positive vegetation trends* in Iringa: (a): A strong culture of agroforestry practice by small, and medium-holder agriculturalists; (b): The presence of large-scale producers of forest products such as the Sao Hill Plantations; (c): the regeneration for formerly defrosted areas. Conservation is also carried out in forest reserves in the region. Contributors to *negative vegetation trends* include: (d): Harvesting of forest plantations by producers; (e): New cases of deforestation for agriculture and other land uses.

Figure 16. Contributing factors to vegetation dynamics in Mafinga and surrounding areas.

Figure 18 illustrates how this limited management can lead to certain areas being severely overgrazed. Climatic factors such as drought and the decline in precipitation have the potential of contributing to overgrazing by limiting the growth and survival of vegetation used as pasture. This then leads to more cattle depending on less pasture and the pasture being overgrazed. While overstocking and overgrazing can be seen as a case of livestock numbers exceeding the capacity of the land to sustain them, some ethnographic scholars question the idea that pastoralist do not achieve a balance with their environment but routinely overstock and overgraze [84].

Ellis and Swift [84] argue that the relationship between traditional livestock keepers and their environment was one of dynamic equilibrium – in which cycles of pasture abundance and decline played a role in determining this equilibrium. Other factors include the use of fire to clear the land towards the end of the rainy season – to boost the upshot of tender fresh grasses in the rainy season (according to grazers interviewed). Indeed, the frequent use of fires for land clearing in savanna regions benefit grasses and suppress the recruitment of mature woody plants [85], thereby making open pasture land available for grazers. These factors, in association with high-intensity rainstorms, and in some cases steep topography renders the soil susceptible to erosional degradation. In Tanzania, some of the major regions where overgrazing plays an important role in land degradation include Shinyanga, Simiyu, Tabora, Maasailand, and Mbulu.

In Senegal this is common in the central and northern regions of the country. Overgrazed regions in arid and semi-arid environments tend to offer little in terms of woody biomass. Most harbor grasses during the brief rainy seasons that is rapidly depleted, leaving a more or less barren landscape through the dry season. While many of the locations examined showed clear signs of sheet, rill and gully erosion, their associated NDVI profiles tended to show no significant trends (see the profiles of two examples in Tanzania, Figure 18 and Figure 19). The absence of significance in the NDVI trends can be explained by the dearth of vegetation in these locations.

Figure 17. Inside the Great Green Wall.

[7] World Cattle Inventory: Ranking of countries (FAO) and Industrial food animal production (IFAP)

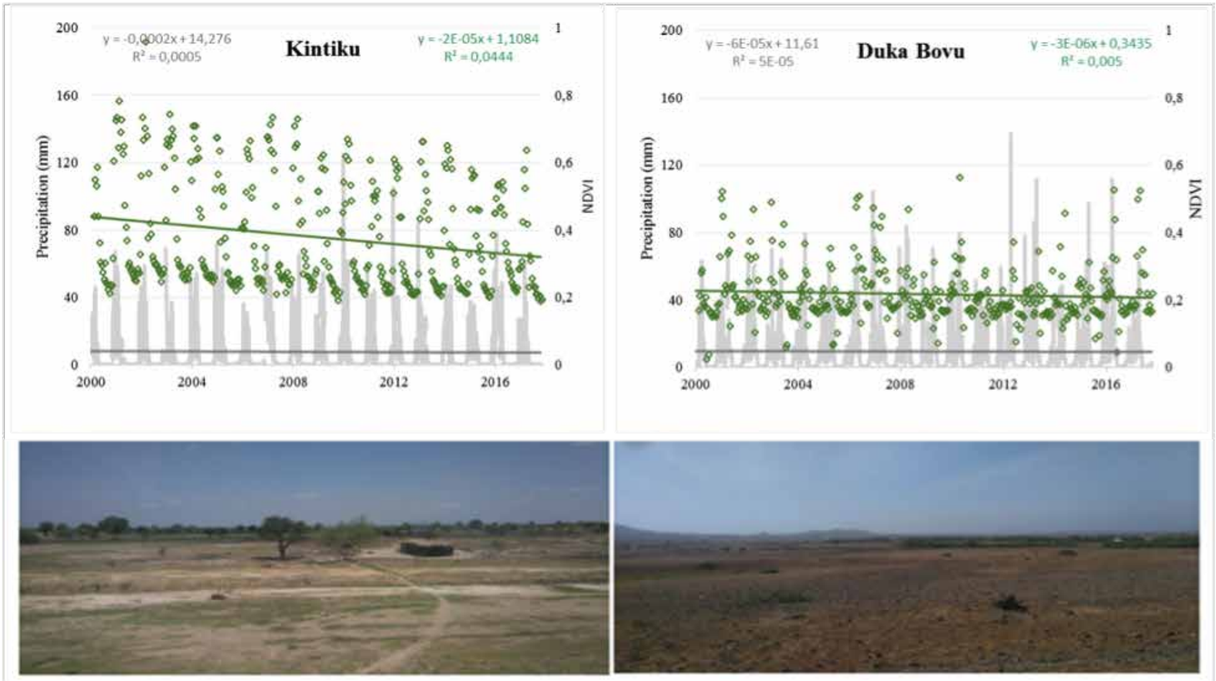


Figure 18. Very limited vegetation cover in two predominantly pastoral areas in Tanzania Kintuku (a) and Duka Bovu (b). Declining vegetation trends in Kintiku signify ongoing tree-cutting to make room for livestock rearing and provide fuel. Much of the vegetation in Duka Bovu has already been cleared, hence there is limited vegetation to contribute to the NDVI profile in many zones of the area (see NDVI profiles of Kintiku and Duka Bovu, Appendix-Tanzania). Precipitation is in grey and NDVI in green.

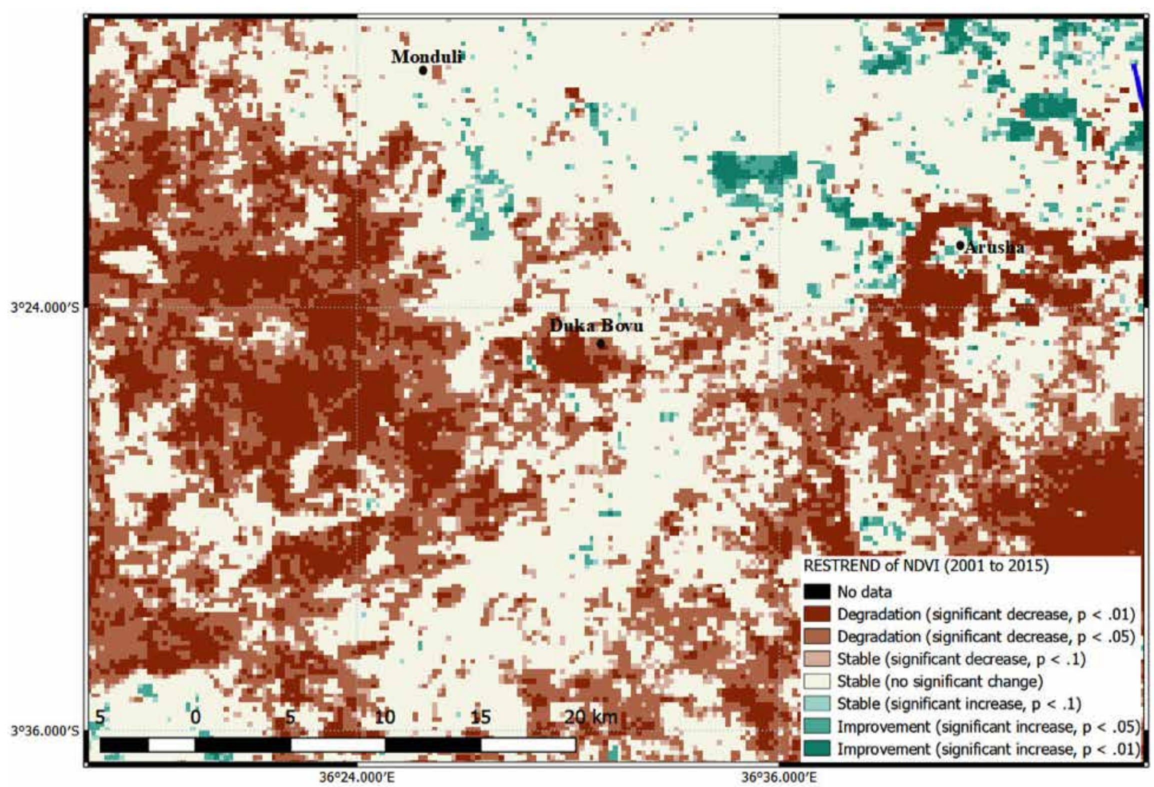


Figure 19. Residual trends of vegetation in Duka Bovu, Tanzania, corrected for the influence of precipitation. While some of the areas in and around this community (located west of Arusha City) do not show significance in the trends, much of it shows signs of suffering from degradation through processes of sheet and gully erosion (see Figure 18). Derived from MODIS 250 meter resolution and the CHIRPS dataset, and covers the period 2000-2015.

VI. TREND TYPOLOGIES AND INTERPRETATION

6. TREND TYPOLOGIES AND INTERPRETATION

The typologies of NDVI trajectories observed in the case studies are summarized in Figure 20. These typologies can be divided into four groups based on a combination of land cover and land use (Figure 20), as well as based on land cover condition (Figure 21).

A- ANNUAL VERSUS PERENNIAL CROPS: Differences were observed in NDVI trajectories between annual and perennial crops (Figure 20A). Annual food crops of both subsistence systems (maize, sorghum, beans) and market-oriented production systems (onions, carrots and potatoes) tended to have declining NDVI trends in the four pilot countries analyzed, although neutral or positive trajectories could be found in annual crops under certain conditions (e.g. high input agriculture). On the other hand, perennial crops such as gum Arabica (in Senegal) and sisal (in Tanzania) showed generally positive NDVI tendencies.

B- LEVELS OF CROP-LIVESTOCK-AGROFORESTRY INTEGRATION: When crop production is integrated with agroforestry and livestock keeping, positive trends of NDVI tended to be common (Figure 20B). The tighter the level of integration of crop production, agro-forestry, and livestock keeping the more the tendency towards positive NDVI trends we observed. Stable NDVI trends were common in areas where livestock keeping is extensive, characterized by large herds, and where woody biomass was visibly absent. These are areas where there is limited integration of crop production and agroforestry with livestock keeping. In these conditions, grasses that emerge and grow during the rainy seasons are systematically grazed by the large animal populations, with no significant effect on the vegetation profile of the region (also see Figure 18).

C- MANAGED VERSUS UNMANAGED GRAZING: Managed grazing[8] can be observed in National parks and game reserves where the vegetation is protected for grazing by protected animals. While this is possible on land set aside by communities for their grazing needs, the tendency is for these lands to be overgrazed based on the well-known theory of 'tragedy of the commons.' In managed grazing scenarios the NDVI trend tends to manifest a more or less continuous cycle of declines and recovery which in the long-term may sustain a stable trend - with no significant positive or negative tendencies (Figure 20C). In unmanaged conditions however, the NDVI trends decline until it finds a stable equilibrium at a low level of the initial curve height (Figure 20C). Trends in unmanaged grazing areas may also appear as stable low profiles in the data analyzed is collected after the profile already reached its low, and stable point (as explained in 'B' above).

D- WOODLANDS IN NATURAL VERSUS HUMAN PRESSURES: Based on the origin of the pressures (natural or man-made) experienced by woodlands, the typology of NDVI profiles is similar to that of managed versus unmanaged grazing. Natural pressures on woodlands are best observed in protected environments where human activities directly contributing to changes are minimized, such as national parks and game reserves. Overgrazing by herbivores would therefore constitute such natural pressures. The NDVI profile tends to be characterized by longer, slower periods of vegetation decline, followed by recovery, and then further decline (Figure 20D). Herbivores will move to areas of better vegetation when good sources in other grazing areas are limited, provided the size of the conservation area relative to animal densities permit the existence of other areas of better grazing lands. On the other hand, woodlands experiencing human pressures (even when protected) tend to have shorter cycles of decline and recovery. This is the case with woodlands that are kept aside by local communities for the harvesting of wood fuel. Here 'mature' trees are harvested as soon as they can be used either as wood fuel or for charcoal production.

[8] Managed grazing describes a variety of closely related systems of forage use in which ruminant and non-ruminant herds are regularly and systematically moved to fresh rested areas (in a controlled manner) with the intent to maximize the quality and quantity of forage growth 86. Undersander, D., Pastures for Profit, a guide to rotational grazing. 2015, USDA-NRCS. University of Minnesota extension service. In unmanaged systems on the other hand, grazing areas are not nested and the drive is not predominantly to maximize the quality and quantity of forage growth, but rather to provide feeding for animals on a short-term basis.

Four major trajectories of NDVI were observed in the study locations based on land cover condition. High stable NDVI trends were observed in mature forests in places such as national parks and mature forest plantations. In mature forest plantations, these high stable trends were achieved after years of increasing NDVI (Figure 21a). In cases where the data collected for the analysis covered a relatively short period of time relative to the age of that portion of plantation, the trend may not show the period of growth of the plantation before attaining the stable trend. Increasing trends were observed in areas recovering from deforestation; patches of young forestry plantations; tight integrated practice of crop-livestock-agroforestry production; or the existence of perennial crops (Figure 21b). Declining trends (Figure 21c) tended to be associated with lands under long-term practice of annual cropping. This may indicate declining nutrient or other crop growth support conditions in soils. Low stable trends of NDVI tended to be associated with areas of heavy grazing, seen in semi-arid regions of the cases studies (Figure 21d).

While these typologies summarize observations in the study locations, to apply them in other cases studies, a number of considerations are necessary. The length of the data record may determine whether the analyst observes a portion of the expected profile or its entirety. By summarizing the data over a large geographical area, aspects of the typology may be dissolved. Also, changes in land cover over the study period of may contribute to variations in expected NDVI profiles.

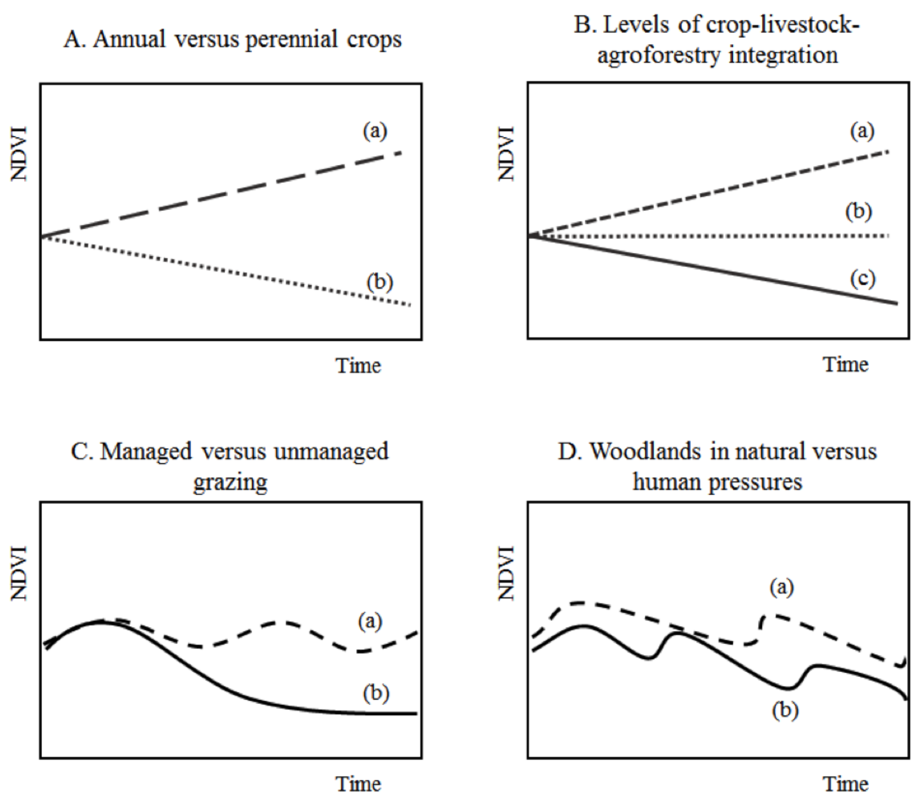


Figure 20. Category of typologies of NDVI trajectories observed in the case studies based on land use and land cover.

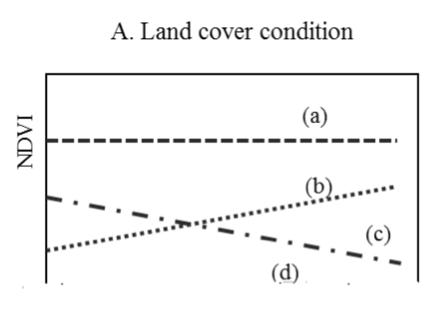


Figure 21. Typology of NDVI profiles based on land cover condition.

VII. IMPORTANT CONSIDERATIONS

7. IMPORTANT CONSIDERATIONS

7.1 DIFFERENTIATING BETWEEN VEGETATION TRENDS AND STATUS

A trend refers to the direction and rate of change in a condition from one period to another. This rate can be negative, positive, or even absent, in which case the change in that condition may be described as having no trend, or being stable. The use of trends to understand changes in the condition of different variables has been applied in many fields of earth resources studies. The analysis of trends has been found to be especially useful in the assessment and monitoring of natural resources, as well as in forecasting and scenario assessments of resource management options. The interpretation of trends, especially when using such interpretations to make a one-to-one relationship with other biophysical changes can be tricky, and in some cases downright problematic. In the case of vegetation trends, increases do not always mean improvements in landscape productivity or health.

Examples of these can be drawn from forest plantation monocrops where high values of normalized vegetation indices may hide the lack of biological diversity, or the depletion of certain groups of nutrients supporting the growth of such monocrops relative to others. Vegetation trends are a lagging indicator of a combination of environmental controls on vegetation performance (for natural ecosystems) and management effectiveness (in managed systems). Even then, geography plays an important role in interpreting the contributions of natural processes and management when analyzing vegetation trends. For example, in managed vegetation systems in semi-arid climates, neither a declining trend in the dry season nor an increasing trend in the rainy season can be used to interpret the role of management.

Land status refers to the condition of the land at a given point in time. The condition of the land can be assessed based on what the land is used or not used for (keeping in mind that healthy intact ecosystems that are not used for any direct economic profit-making are important for a range of services to both the natural and human worlds). Land condition therefore determines how much ecosystem services the land can provide, as well as its resilience to shocks, and disturbances associated with providing these services. Land condition has the potential of affecting livelihoods, and guiding decisions on actions that may be taken to restore the functioning of the land and associated benefits derived from it. Land condition can therefore be affected negatively by natural processes such the presence and frequency of extreme climate events, droughts, or extreme rainfall; as well as human factors such as types and processes of land use.

The land potential is determined by the intactness and efficiency of it biogeochemical cycles (energy, nutrient, water, etc.). Vegetation plays a key role in the functioning and efficiency of these cycles. Undisturbed land will offer ecosystem services in optimal quality and quantity for that ecosystem. On the other hand, the more disturbed the land, the less the suite of ecosystem services it can offer. It is therefore possible to assess the status by assessing its condition, based on the quantity and quality of ecosystem services it offers. It must be noted that the condition of the land can be assessed in light of the potential of a land to provide a specific service or set of services. For example, we can look at land condition based on its suitability for grazing, food crop production, biodiversity conservation or a combination of different land uses. It is important to assess the condition of land based on identified land use(s) because theoretically, a piece of land is capable of supporting many different types of land uses, many of which may not be of interest to the investigator. By comparing the land's condition at any given period to what that land can potentially offer in terms of ecosystem services, we can determine the status of the land. Such a comparison can also give us a estimation of how much productivity has been lost.

To understand how land condition can be used to benchmark that status of the land, the Australian Government developed a framework for grazing land management that details indicators for assessing land condition. The ''ABCD Land Condition Framework for Grazing'' serves to identify whether their land condition is improving, stable or deteriorating (Figure 22).

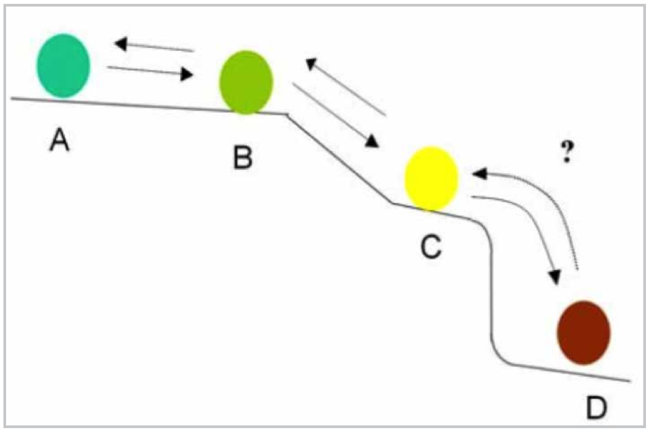


Figure 22. The "Rolling Ball of Land Condition." The steeper the incline the harder it is to get the ball back up the slope. This diagram illustrates the susceptibility of land condition to deteriorate, and how much effort is required to revert the land condition to the previous state. When land is in 'D' condition it is almost impossible to get it back to 'C' condition without spending a lot of money. Even then, returning it to 'C' may not be possible (source: Phelps [87].

It has four condition levels (A – D). Land in A condition is considered to be in the best condition, while land and D is in the condition the worst. Land in A condition maximizes natural processes such as rainfall infiltration and pasture production and reduces runoff, and soil and nutrient loss to support grazing. Land in D condition may have a general lack of perennial grasses and/or have severe scalding or erosion resulting in a hostile environment for plant growth. Woody weed thickets may also cover part or most of the area.

7.2 REFLECTION ON THE CHOICE OF DATA PRODUCTS TO SUPPORT ASSESSMENTS

One of the characteristics of satellite remote sensing is the diversity spatial, temporal and spectral resolutions. These diverse spatial, temporal and spectral resolutions can be limiting factors for the utilization of satellite images for certain applications. Technical constraints limit the relationship between spatial and spectral resolutions for satellite remote sensing systems. High spatial resolutions are associated with low spectral resolutions and vice versa. Hence, systems with high spectral resolutions tend to offer medium or low spatial resolutions. Compromises therefore must be made between different resolutions depending on the applications envisaged for the acquired data. Both the spatial and spectral resolutions of satellite imagery determine the extent to which these products can be used to assess and monitor processes of land degradation. Land use, land cover changes and land degradation occur at different spatial scales [88]. The choice of the earth observation product used to assess and monitor land degradation processes should depend on the spatial extent of the physical land degradation processes being studied. This means that to arrive at a robust analysis, there is need for some prior understanding of the type and physical characterization of the land degradation processes being investigated before the choice of the earth observation products and tools to assess and monitor them are determined. This calls for careful considerations when deciding what data products may be useful for the assessment and monitoring of land degradation processes and country level.

Consideration should be given to the potential for the existence of different forms of land degradation whose assessment may not be possible or suitable using a single dataset or method. It also highlights that importance of complementing assessment methodologies and procedures with field observations at different stages.

This should be done at the initial stages when deciding the types of data and methodologies to be used, and later on, for the validation of the results derived from remotely sensed data and earth observation methods. It therefore follows that at a country level, and even at regional and some sub-regional levels different datasets may be required for the assessment and monitoring of land degradation.

The choice of datasets to be used should ideally be determined by the type and characteristics of land degradation processes.

7.3 UNDERSTANDING OF GROUND CONDITIONS

The usefulness of vegetation as an indicator of environmental conditions has long been recognized [89-91]. Notwithstanding this recognition, caution is needed when using vegetation in the assessment of land condition. An illustration of the need of such caution can be shown using the undesirable changes in floristic composition caused by the encroachment or invasion of landscapes by non-native species in pastoral agro-ecological landscapes. The proliferation of such plants may signal positive trends in the NDVI record, while their presence on the ground may not be associated with positive outcomes. In pastoral communities, such an invasion may lead to declines in native pasture species or sown species that are relied on by local livestock keepers for animal keeping. To local communities in savanna grasslands, such an invasion indicates a degradation of the local environments, even though the vegetation signal may indicate positive trends in the vegetation signal. Hence, while being a useful indicator of some ecological processes and human activities on the landscape, the trend of vegetation is not an answer to all questions regarding land use and land cover dynamics.

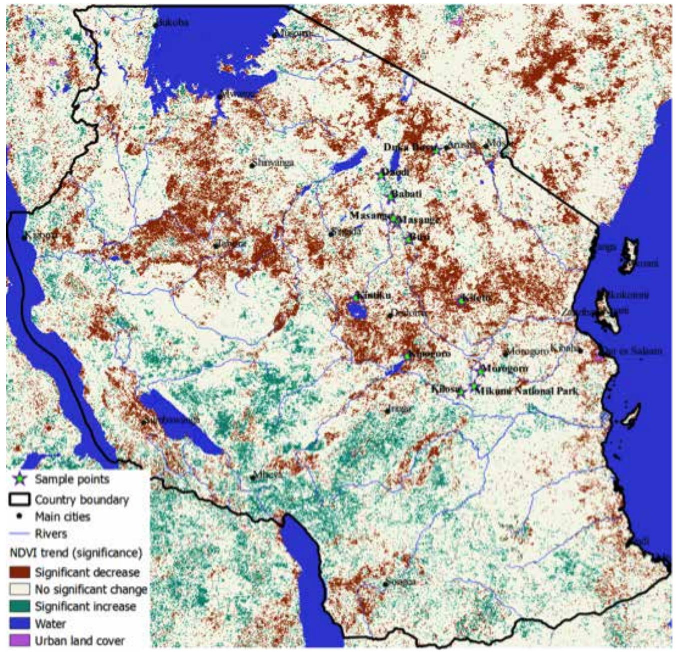
Vegetation trends should therefore ideally not be used as a single indicator of land use and land cover dynamics, as well as their associated outcomes – land degradation or improvement. Another need for understanding ground conditions has to do with the interpretation of vegetation trends in general. There are many cases in which changes in vegetation trends associated with types and goals of land management may be difficult to discern using vegetation profiles alone. Interpreting such changes as qualifiers of vegetation health may therefore be misleading.

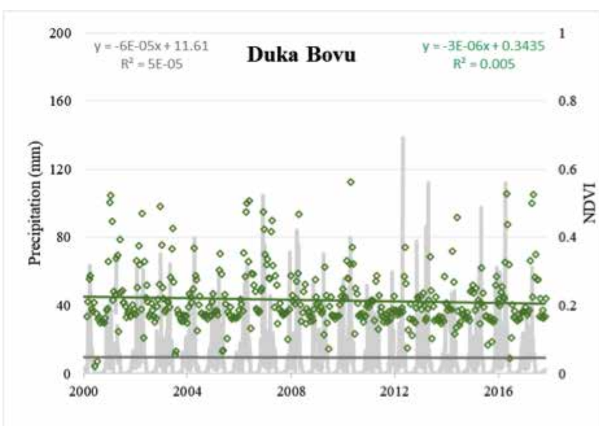
For example, declining NDVI trends may be associated with specific individual or societal desires. Hence, understanding these trends in the light of natural environmental factors (even when they point in the same direction, and may correlate as drivers) can be misleading.

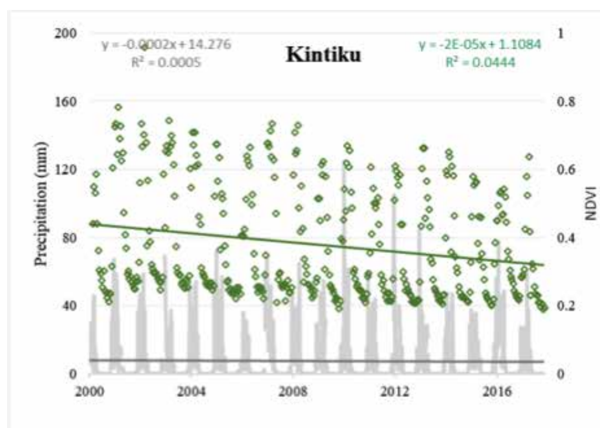
The length of period of investigation of vegetation trends has to be undertaken over periods of time which permit the detection of changes that are short-term and those that are long-term changes. Short-term vegetation changes may be associated with natural phenomena such as flood events, fire and volcanic activity, or human activities such as changes in grazing pressures, changes in farming systems and crop types [92, 93]. If these changes are negative, it may indicate that the observed trend may not necessarily be towards irreversible land degradation. Long-term changes on the other hand may be associated with changes in key determinants of vegetation growth such as inter-annual climatic variation and climate change [92, 94] and changes in the availability of plant nutrients. Where such long-term trends are negative, it may indicate a tendency towards land degradation of a more permanent nature.

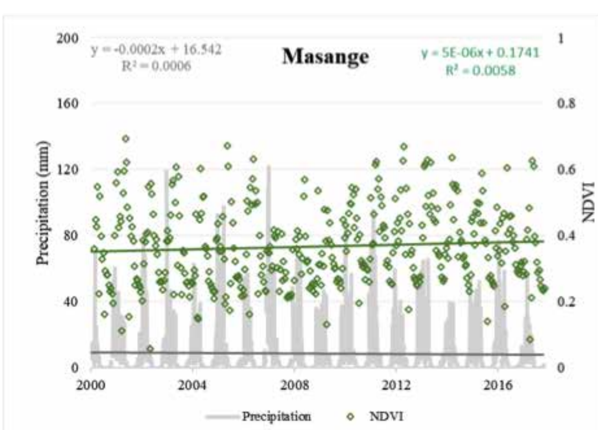
APPENDIX - SAMPLE LOCATIONS FOR SPECIFIC COUNTRIES

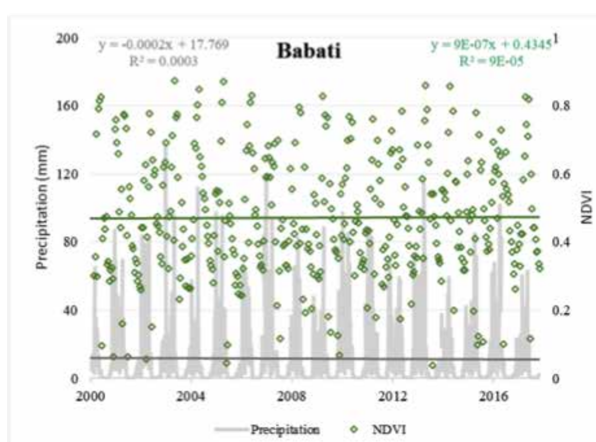
7.4 TANZANIA









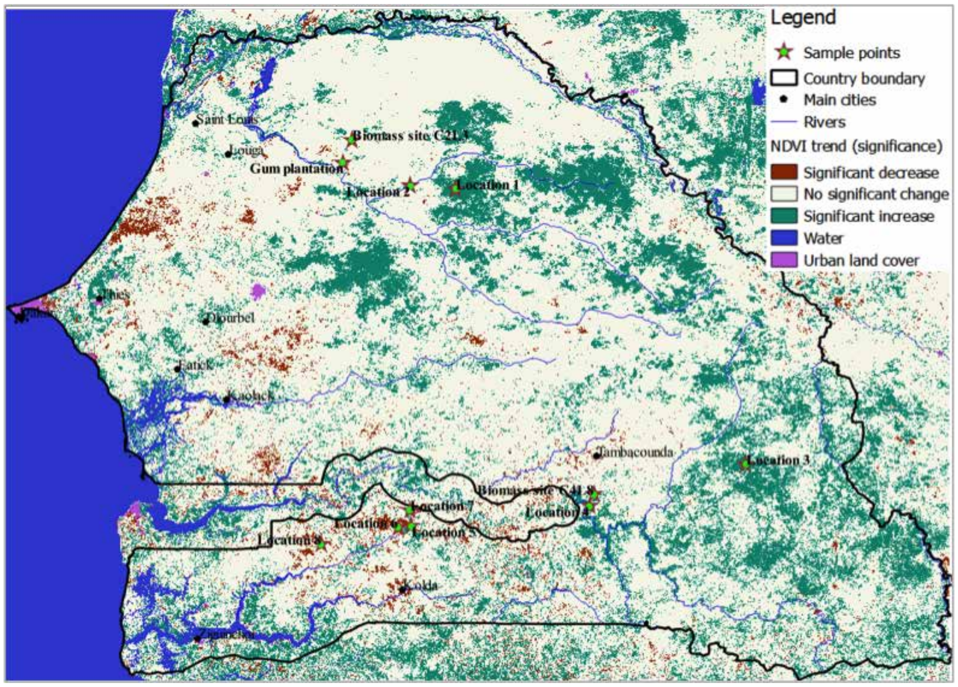


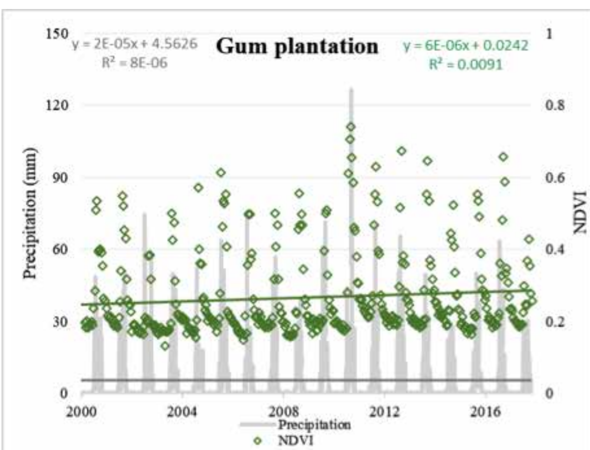
LAT, LON	GROUND DATA
LOCATION 1 -6.861266, 36.030675	**Kipogoro:** These are low land and semi-arid areas of central Tanzania which receive small amount of rainfall annually. The areas are extensively dominated by shrubs vegetation with few scattered trees. Livestock keeping is highly practiced compared to farming in the area. Over grazing leaves the soils bare and exposed to erosion. Notice the almost complete lack of smaller trees, as such growth is suppressed by grazing animals. The nearby forests and bushes are cut down for fuelwood and the production of charcoal.
LOCATION 2 -5.884957, 35.165022	**Kintiku:** Landscape dominated by pastoralism. The main animals kept by almost all households in this region are sheep, goats, donkeys, horses, and cows. The grass is kept short by overgrazing with the bare ground visible in large areas. Signs of sheet and rill erosion by way of visible grass roots, exposed tree roots, and exposed subsoil or stony soils are common. Evidence of charcoal harvesting is borne by the existence of bags for charcoal stacked along major roads for sale. The source trees must be coming from the hinterlands, as there is an almost complete lack of smaller trees. The forests and bushes provide material for both fuelwood and the production of charcoal.
LOCATION 3 -3.824444, 35.588111	**Daudi:** Smallholder agricultural landscapes integrated with agroforestry. Livestock keeping is not extensive. The area is in escarpment of the Rift Valley stretching from Babati, providing diverse climatic and agro-ecological conditions for farming and agroforestry. The region receives adequate rainfall annually. Mixed cropping including both annual and perennial crops along with zero grazing is tight. Farmers intentionally retain trees around their farms and houses for various purposes explaining some of the positive trends in NDVI observed.
LOCATION 4 -7.452038, 36.913637	**Kilosa:** Poor farming practices leave the soil exposed to erosion most of the year. Valleys occupied by perennial crops, chiefly bananas and some fruit trees.
LOCATION 5 -3.410265, 36.504028	**Duka Bovu:** The area is located in the lower land and leeward of Mount Meru settled by Maasai who are engaging in livestock rearing. Naturally, the area is dominated with grass (grassland) with very sparse trees. During the dry season the area is heavily overgrazed, and suffer serious erosion during early rains.
LOCATION 6 -4.190796, 35.750032	**Babati:** Smallholder agricultural landscapes. There is a tight integration of crop production, livestock keeping and agroforestry. The area is in the Rift Valley, providing diverse climatic and agro-ecological conditions for farming and agroforestry. It receives adequate rainfall annually. Mixed cropping including both annual and perennial crops along with zero grazing is tight. Farmers intentionally retain trees around their farms and houses for various purposes explaining some of the positive trends in NDVI observed.
LOCATION 7 -4.55137 35.78094	Masange and Busi are two geographically related agricultural communities in the same agro-ecological zone in the Kondoa District of Tanzanai. **Masange:** The cropping system with a close integration of food crop production, agroforestry and livestock production. Animals are fed crop residues from farms, and manure from animals is used almost exclusively to fertilize crop production. Main food crops cultivated include maize, peas, vegetables, and sunflowers. Trees grown include mangoes, avocadoes, Senna siamea, (locally known as Mjohoro), and other agroforestry species. Nurseries of these trees are evident in many parts of the community. Animals are mainly cows, goats, donkeys and some chicken. There is evidence of some limited land degradation processes such as gullying. Local populations report no cases of water scarcity for household use, as water is harvested from the adjoining mountain and delivered through standing pipes into homesteads. Nonetheless, the effects of climate changes and variability on agriculture are reported. The evidence given is that they used to grow two cycles of maize a year, and another crop in between. However, given changes in climate, this is no longer possible. Also yields per acre have reduced for maize from about 15-20 bags (100 kg per bag) to about 5 bags per acre.

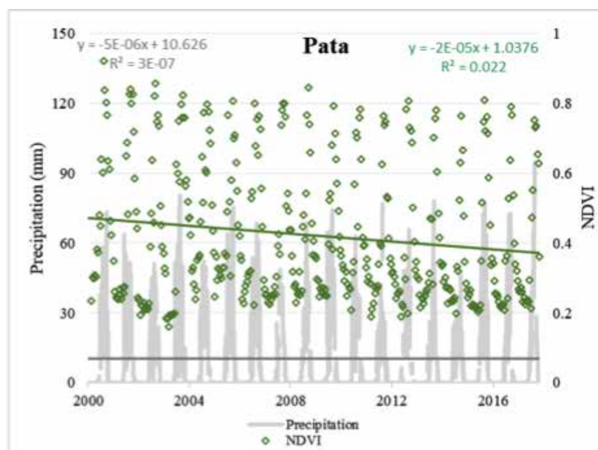
CONTINUED

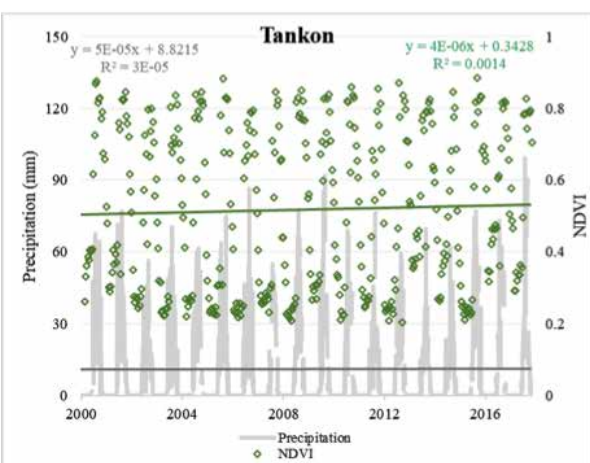
LAT, LON	GROUND DATA
LOCATION 8 **-4.90808,** **36.05024**	**Busi:** Main crops cultivated are millet, sunflowers, cassava, and peas. Cropping is very seasonal with long periods of the year in which the land is not cultivated. Agroforestry is not a common practice. Even though there is animal grazing, this practice is extensive and not integrated into the system of crop production. The bare land during the non-cropping season, clear signs of overgrazing, and signs of sheet and gully erosion suggest poor land management.
LOCATION 9 **-7.3588** **37.1449**	**Mikumi National Park:** An area of conserved woodland that is experiencing deterioration in vegetation. On the ground, evidence of loss of vegetation cover is signified by patches of bare ground and heavily grazed grasses. Key factors associated with the decline in vegetation cover are a higher population of herbivores, and the generally dry conditions of the part (as it harbours no surface hydrographic networks).
LOCATION 10 **-7.109** **37.2522**	**Morogoro:** A valley dominated by smallholder farmers cultivating both subsistence food crops (such as maize, beans, and vegetables), as well as market crops (chiefly tomatoes). Farms are small, and the cultivation of market garden crops demand the use of inputs such as pesticides and fertilizers. Most household food crops are cultivated without external inputs. Local communities report experiencing yield declines over the years, and associated these with declining soil fertility.
LOCATION 11 **-5.925401** **36.93099**	**Kiteto:** The chief culprits are overgrazing and forest exploitation for charcoal production. While the area has harboured livestock throughout its history, these populations of livestock and people have steadily increased over recent years. Much of the charcoal produced is used to meet energy demand in far-away urban centres such as Dodoma, Arusha and even Dar es Salaam.

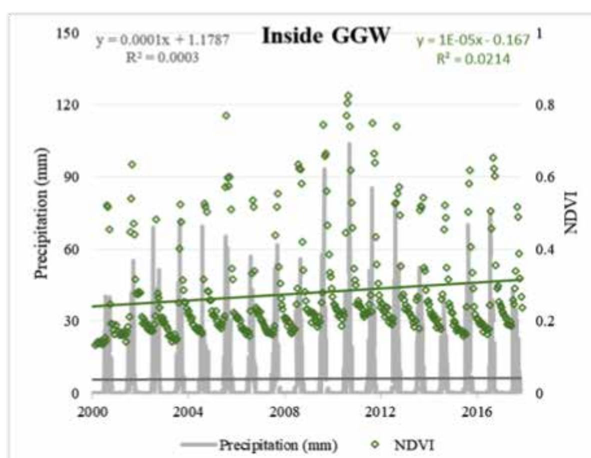
7.5 SENEGAL


Legend
Sample points
Country boundary
Main cities
Rivers
NDVI trend (significance)
Significant decrease
No significant change
Significant increase
Water
Urban land cover
Saint Louis
Louga
Biomass site C21.3
Gum plantation
Location 2
Location 1
Thies
Diourbel
Fatick
Kaolack
Tambacounda
Location 3
Biomass site C41.8
Location 7
Location 4
Location 8
Location 5
Location 6
Kolda


Gum plantation
y = 2E-05x + 4.5626
R² = 8E-06
y = 6E-06x + 0.0242
R² = 0.0091
Precipitation (mm)
NDVI
Precipitation
NDVI


Pata
y = -5E-06x + 10.626
R² = 3E-07
y = -2E-05x + 1.0376
R² = 0.022
Precipitation (mm)
NDVI
Precipitation
NDVI


Tankon
y = 5E-05x + 8.8215
R² = 3E-05
y = 4E-06x + 0.3428
R² = 0.0014
Precipitation (mm)
NDVI
Precipitation
NDVI


Inside GGW
y = 0.0001x + 1.1787
R² = 0.0003
y = 1E-05x - 0.167
R² = 0.0214
Precipitation (mm)
NDVI
Precipitation (mm)
NDVI

LOCATION	GROUND DATA
LOCATION 1 15.52235, -14.59847	**Réserve sylvo-pastorale de Barkedji Dodji:** This reserve was put in place since 1956. Its status has made it less exposed to clandestine activities that contribute to deforestation, and given it relative protection. Conservation is therefore a key feature of vegetation dynamics in this area. The vegetation is in good condition, with limited evidence of tree-cutting, more abundant undergrowth, and less evidence of soil erosion. Positive vegetation trends reflect the abundance of woody plant species.
LOCATION 2 15.54251, -14.89421	**Dodji, between the Réserve sylvo-pastorale de Rhadar and Réserve sylvo-pastorale de Barkedji Dodji:** This area borders asylvopastoral reserve, but outside the protected zone. Human activities that contribute to vegetation dynamics in this location include grazing and fuelwood harvesting. Despite its closeness to a conserved area, the constant exposure of this area to human utilization is reflected by the greater number of breaks in the vegetation trend. Vegetation resources are harvested (by animals and people) leading to their decline, and their eventual regrowth, before another cycle of harvesting. This figure contrasts with the more or less steady trend, marked by less profound breaks of vegetation in conserved sylvopastoral zones.
BIOMASS SITE C2L3 15.84419, -15.27750	**Réserve sylvo-pastorale de Six Forages:** This area is relatively well preserved and located inside the Réserve Sylvopastorale des Six Forages. While the area is preserved, it still accommodates managed grazing, hence limiting the potential for increasing trends in NDVI. Onsite observation reveals little evidence of physical signs of land degradation in the form of rills, gullies and sheet erosion. The NDVI trend shows a relatively steady profile with substantial increases in 2006 and 2011.
GUM PLANTATION 15.69570, -15.33500	**Plantation of Acacia Senegal south of Barkedji:** From February 1999 to September 2003, Asila Gum Company produced nurseries and planted 6,545,000 gum trees in the various rural communities of the department of Linguère. This plantation of Acacia Senegal is one of the investments in this venture. The profile of vegetation activity shows the establishment of the plantation in this area in 2000, as well as good vegetation performance in 2010 and 2011 boosted by better than average rainfall in the region during these years. The NDVI profile shows a steady increase with substantial positive changes in 2006 and 2011 as observed for most undisturbed vegetation in the region.
LOCATION 3 13.71985, -12.70072	**Gangali:** This location is in an area of low population density, where nucleated settlements are the norm. Vegetation resources closest to the settlements therefore tend to be used up more than resources further away from settlements. Resources that are further away from settlements, such as the ones in this location, do benefit from some protection from constant exploitation, by virtue of their distance from human settlements. The increasing trend of NDVI and very few breaks indicate minimal disturbance of the vegetation.
LOCATION 4 13.44429, -13.72415	**Tambacounda:** This area is within a relatively dense gallery forest on the bank of River Gambia. The presence of forest in this zone is supported by natural suitability of the area, benefiting from rich sediment deposits brought in by the river and the constant supply of water for all-year-round vegetation growth. This area is also conserved by local communities, thereby limiting the exploitation of its forest resources. The natural suitability of the area for vegetation growth and its preservation from human disturbance is reflected in the increasing and relatively steady profile of NDVI.
BIOMASS SITE C4L8 13.52080, -13.69530	**Gouloumbou Forest:** Some areas of protected forests may still suffer from some sort of exploitation. This is the case with portions of the Gouloumbou Forest. While the classification of this forest offers it relative protection, some forms of human activities may still contribute to vegetation dynamics. In this case, man-made bushfires, and the illegal exploitation of forest resources are some of the contributing factors to downward shifts in the vegetation trends in 2003, 2007 and 2014 as shown in the NDVI profile.

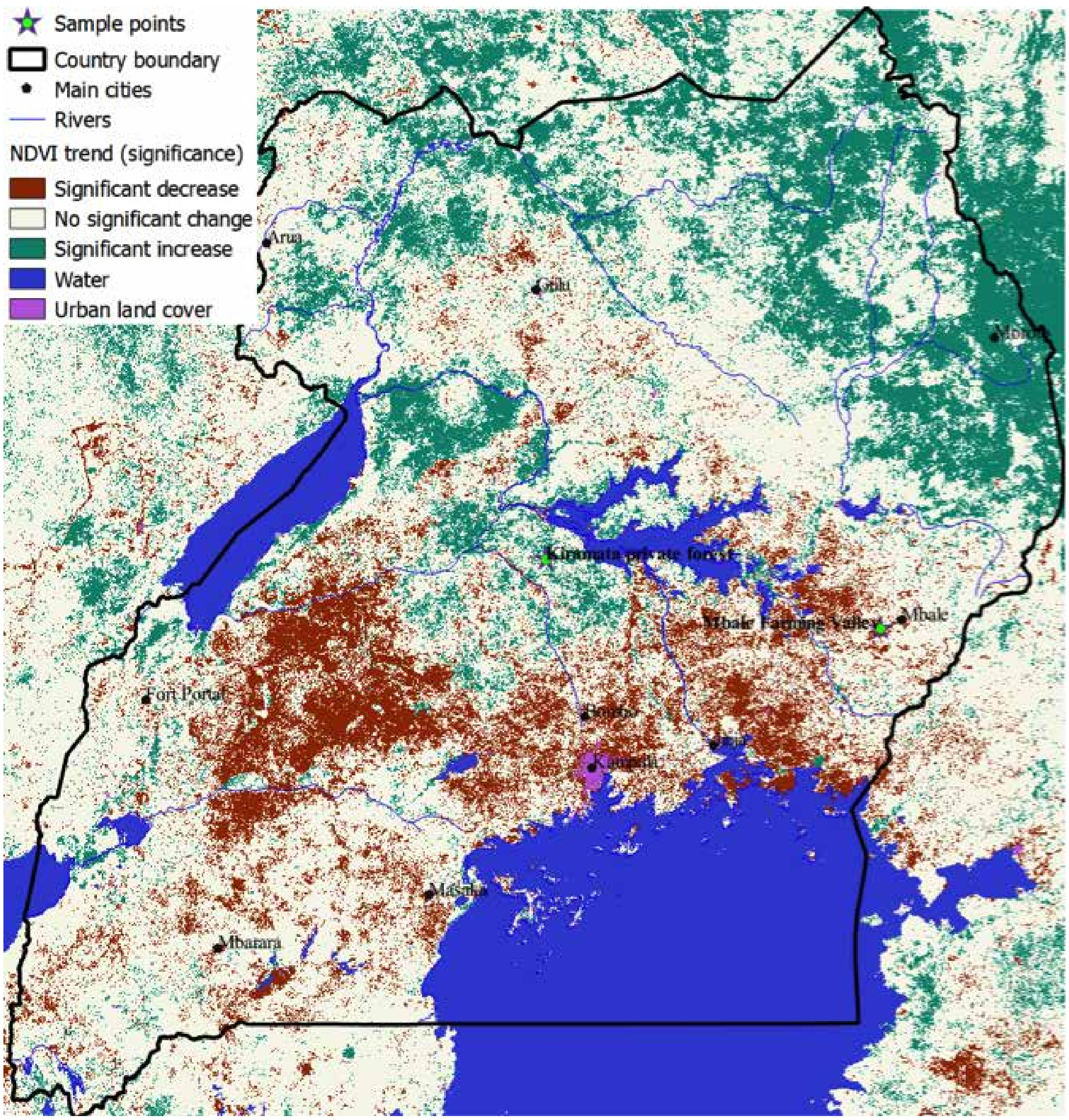
CONTINUED

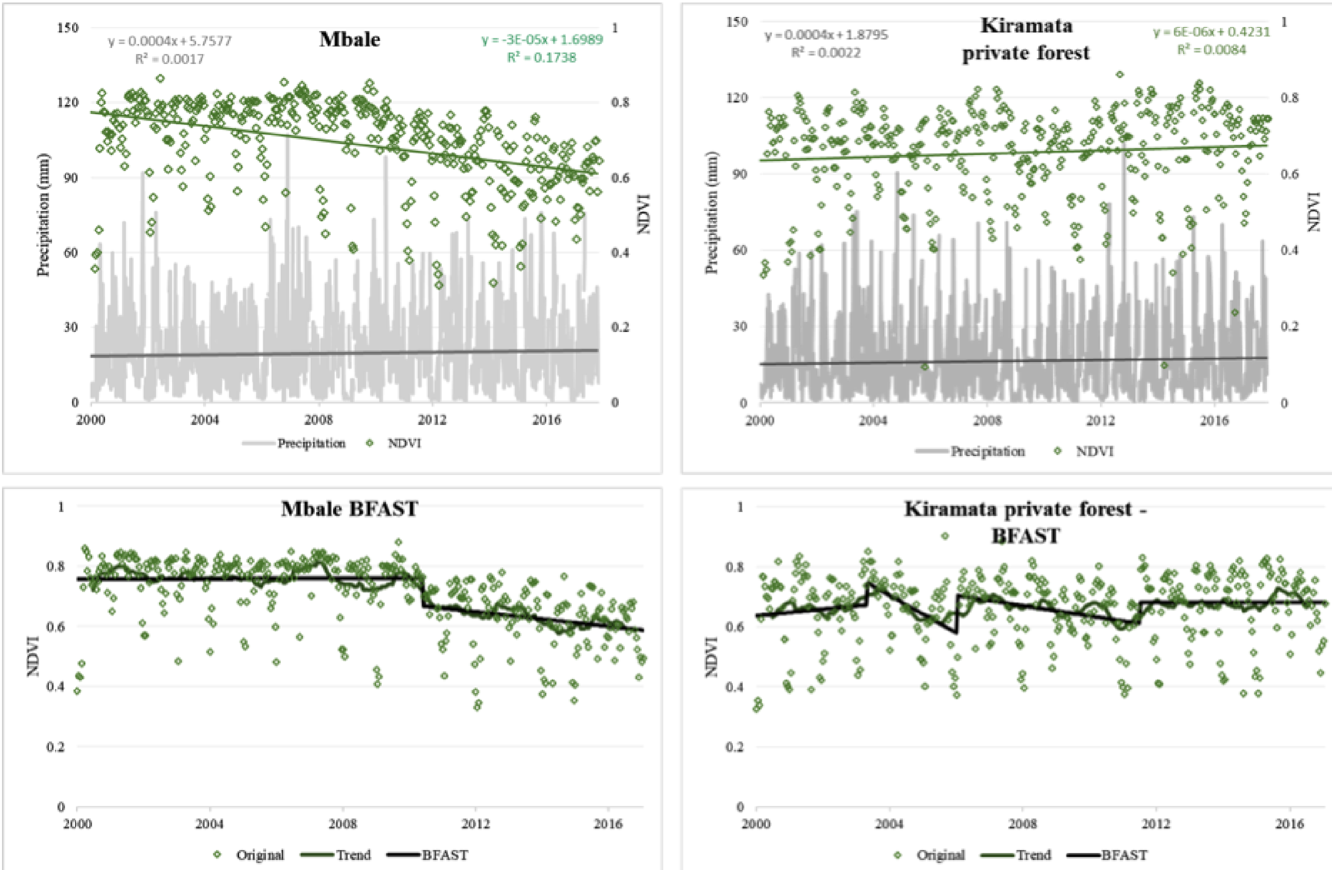
LOCATION	GROUND DATA
LOCATION 5 **13.31352, -14.88760**	**Guimara Forest in Pata:** The Guimara Forest undergoes similar dynamics as the Gouloumbou Forest. It is an area conserved by the local community living around it. Nonetheless, it is surrounded by human settlements and economic activities, including cultivated lands. While the conditions are favorable for the growth of the forests it supports, pressures on its resources contribute to shaping vegetation dynamics here. Increased NDVI trends indicate periods of vegetation recovery while declines point to degenerations associated with human activities.
LOCATION 6 **13.305107, -14.97546**	**Taifa, in Pata:** This area constitutes remnants of forestland, now used for agriculture. This particular point is situated in an area currently under fallow. Fallows in this region can be long, sometimes extending for more than a decade. The positive NDVI trend observed is explained by the regeneration of Combretaceae spp. on the fallow land.
LOCATION 7 **13.419382, -14.89675**	**Morogoro:** A valley dominated by smallholder farmers cultivating both subsistence food crops (such as maize, beans, and vegetables), as well as market crops (chiefly tomatoes). Farms are small, and the cultivation of market garden crops demand the use of inputs such as pesticides and fertilizers. Most household food crops are cultivated without external inputs. Local communities report experiencing yield declines over the years, and associated these with declining soil fertility.
LOCATION 8 **13.19596, -15.47758**	**Tankon:** This is an example of a forest location where no conservation efforts are in force. Observation on the ground revealed recent selective cutting of large trees with the use of modern equipment, such as chainsaws. The absence of large trees in the wider area also indicate the persistence of deforestation as a factors of vegetation dynamics in this location. The effects of bushfires on vegetation is also evident on burn scars and ground litter. These diverse human activities contribute to abrupt breaks in the NDVI trends. The dynamics of the NDVI trend showing periods of massive decline and recovery are evidence to the lack of planning in the management of the forest.

7.6 UGANDA

In Uganda, three main areas of negative vegetation trends are easily discernible. These include the western zone around Mubende, north to Hoima, and south to Mbarara. Another zone of negative trends is found around Kampala and the main cities in this southern region, and extend north to Kakoge. The last major zone is east of Mbale, and into the western lands bordering Lake Kyoga. One of the most notable vegetation trends in Uganda is the greening in the northeast, a tendency which extends into the northwest of Kenya.

Land fragmentation, overexploitation, and poor practices of soil and water management are blamed for the declining agri-environmental conditions in the country. The government has undertaken several efforts at identifying areas affected by land degradation. Some of the results of these initiatives were reported back in 2001 [95]. Many of the locations identified as facing serious land degradation then are associated with significant declines of vegetation trends over fifteen years later. These include Kabale and Kisoro in the south west regions of the country where about 85%-90% of land was reported to be affected, and Mbale, Rakai and Kotido where about 75% - 80% was degraded [95].



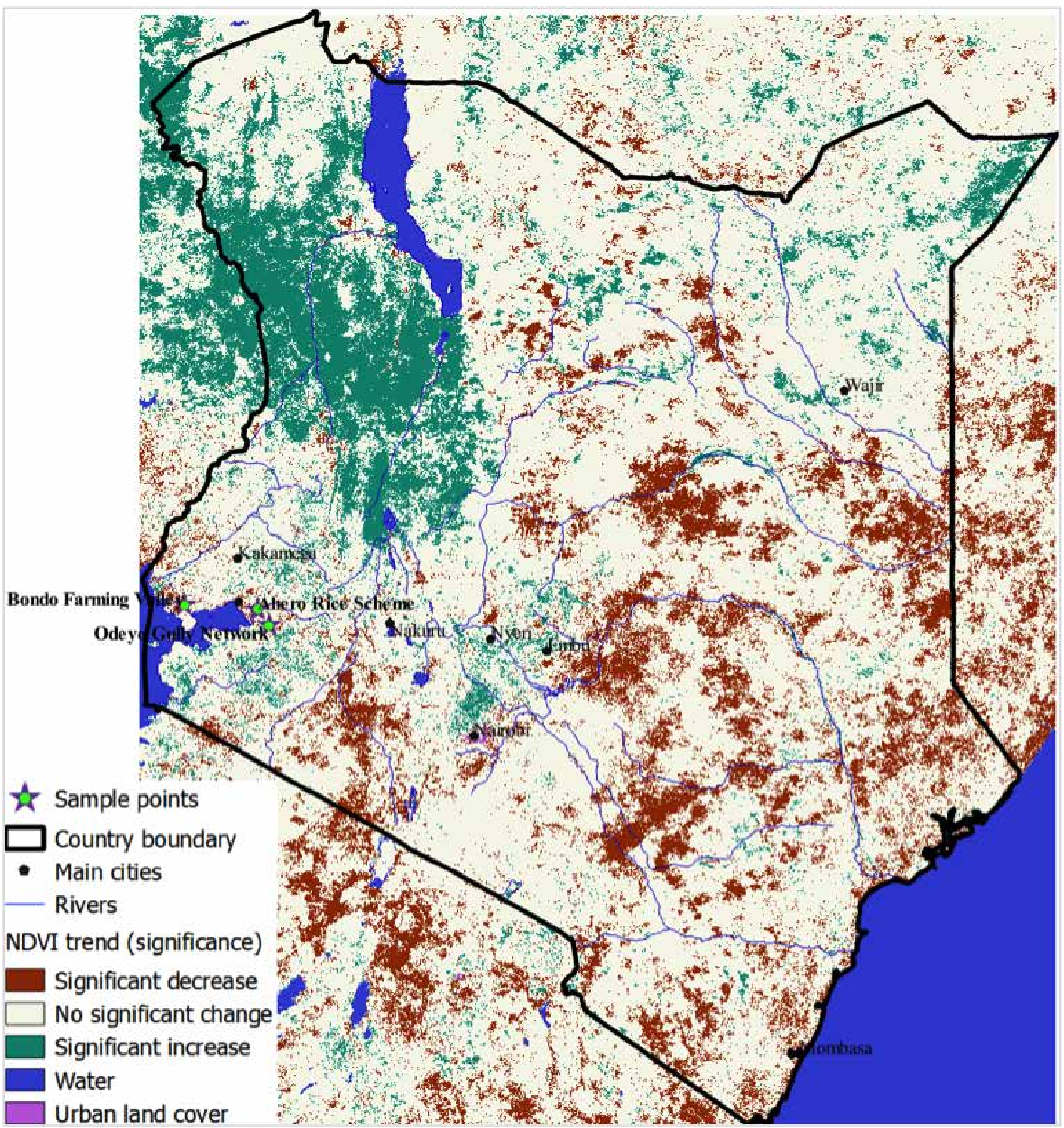


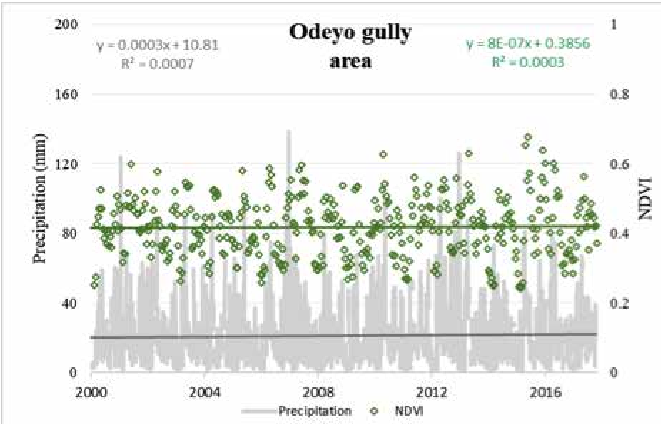
LAT, LON	REASON FROM OBSERVATION AND INTERVIEWS
LOCATION 1 1.038782 34.056619	**Mbale Farming Valley:** A concentration of smallholder farming initiatives. Most of the crops cultivated are annuals and there are periods of the year when the soil is bare (uncultivated), hence vulnerable to erosion. Contributing factors to land degradation and declining performance of vegetation in the region include steep slopes, limited use of soil amendments, deforestation, and poor farming techniques. 2011 marks a break from the relatively steady non changing trend of NDVI activity for the sampled area, and may indicate changes in yield-influencing anthropogenic factors of agricultural production.
LOCATION 2 1.393982 32.334205	**Kiramata private forest:** An enclosed private forest. Despite being enclosed and private, the breaks in the NDVI trends seem to suggest that the forest is subject to non-climatic forces that contribute to vegetation dynamics. For example, the rapid decline of NDVI in 2003-2005 suggest cutting.

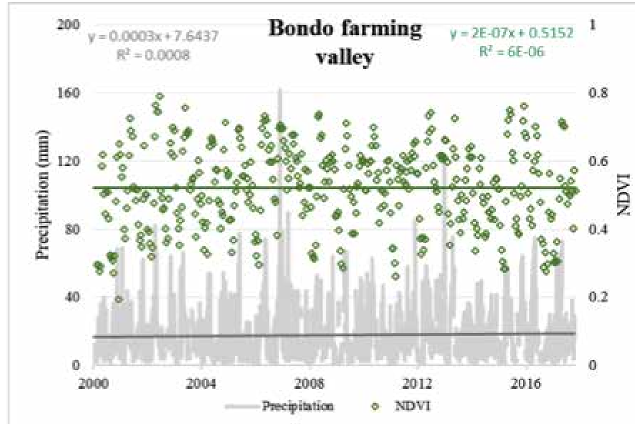
7.7 KENYA

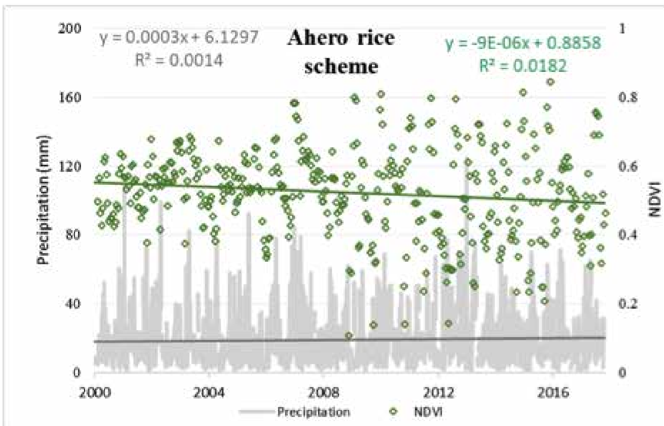
In Kenya, NDVI slopes indicating inter-annual vegetation change are positive for northwestern regions of the country – areas west of Lake Turkana. These cover areas around Lodwar and Kainuk, and into northeastern Uganda. Other zones of positive vegetation trends are in the northeast – from Wajir into the border with Somalia. There are several zones of negative vegetation trends in portions of the center and southeast of the country. These are located south of Wajir, and the east and south-east of Embu and Nairobi. Another zone of declining vegetation trends is south of Nankuru and into northern Tanzania.

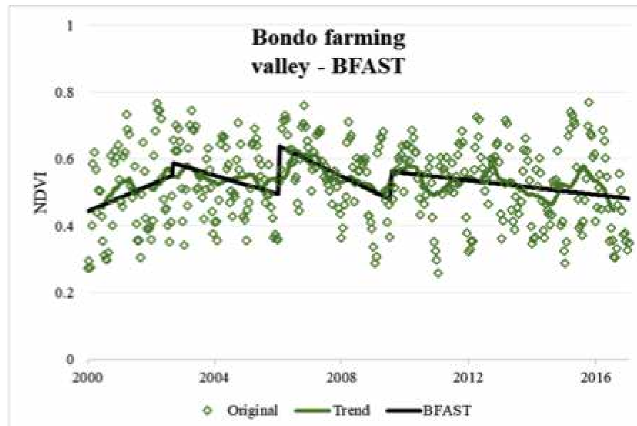
Many factors have been identified as drivers of declining vegetation trends in Kenya. These include the use of fire for land clearing in savanna zones and along forest margins, grazing pressures in rangelands, and declining productivity in farmlands owing to poor land management and limited use of soil nutrient amendments [96]. Deforestation for fuelwood and charcoal production as well as for timber is also a major factor affecting vegetation dynamics in the country. Besides these anthropogenic factors, biophysical factors including climatic factors (extreme weather events such as droughts and floods), topography, and soil conditions are also seen as culprits for environmental changes in the country [96].











LAT, LON	REASON FROM OBSERVATION AND INTERVIEWS
LOCATION 1 **-0.124569** **34.275956**	**Bondo Farming Valley:** A farming valley that has undergone substantial transformation owing to increased population growth, land fragmentation, and land use changes. During this process, changes in the types of crops cultivated, nutrient amendments used, and other aspect of agricultural practices are inevitable. These tend to be responses to decreases in the sizes of farm plots, changing market situations, etc.
LOCATION 2 **-0.161730** **34.915026**	**Ahero Rice Scheme:** The largescale rice cultivation in this location has been run by the Ahero Irrigation scheme, which became operational in 1969. At its height, the scheme had about 1650 farmers with a gross area of 1740 Ha and farm size of 1-4 acres. The production of three main rice varieties (Basmati 370, IR 2793, ITA 310 and BW 196) was the primary activity of the scheme. At its best, the programme used to obtain yields of about 3.5 – 4.5 tonnes per ha. Technical and management issues currently plague production.
LOCATION 3 **-0.305394** **35.017006**	**Odeyo Gully System:** This gully system is described as the biggest in east and southern Africa. At this location, it has dimensions of about 20 – 25 meters wide, by 5-6 meters depth. Nonetheless, it is has no effect on the 250-meter resolution NDVI time series, as most of the surrounding area is vegetated.

VIII. REFERENCES

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