African land degradation in a world of global atmospheric change

Paul L.G. Vlek*, Quang Bao Le, Lulseged Tamene

Center for Development Research (ZEF), University of Bonn
Walter – Flex – Str. 3, D-53113 Bonn, Germany
***** Corresponding e-mail: p.vlek@uni-bonn.de

Abstract: Changes in atmospheric chemistry appear to mask land degradation in sub-Saharan Africa (SSA). We analysed the vegetation observed from space as well as climate data from 1982 – 2002. A significant improvement in biomass was seen on 27.6% of SSA and a decline on about 2.5%. Global changes in atmospheric chemistry are likely responsible for increases in vegetation productivity and this masks anthropogenic land degradation processes such as land conversion, over grazing and soil degradation. A re-analysis of the vegetation productivity dynamics, taking into account atmospheric fertilization, suggests that 7 times more than the area of actual productivity decline is affected by land degradation processes that are masked by atmospheric fertilization. With this rate of surreptitious loss of vital land attributes and with the current rate of population growth (3%), the SSA subcontinent may soon lack the land resources necessary for economic development.
Key words: land degradation, net primary productivity (NPP), NDVI, atmospheric fertilization, sub-Saharan Africa

1. Introduction

Land is central to development in sub-Saharan Africa (SSA) as the livelihoods of about 60% of the population are dependent on agriculture [1]. With population pressures increasing and the low investments in land conservation, the future health of the land is in question [2]. Degradation of this terrestrial ecosystem [3] sets in when the ecosystem services, notably the primary production services, are persistently reduced or lost [4-6]. Assessing land degradation based on this definition in its spatial and temporal extent continues to pose a challenge. Climate change or other natural events may lead to land degradation, but the phenomenon is mainly due to the interaction of the land with its users. Separating human-induced land degradation from that caused by natural processes adds complexity to the assessment but is important for developing mitigation strategies.

A better understanding of the extent and nature of human-induced land degradation remains imperative, but quantitative data on land degradation as defined above for SSA is scarce [7]. Early land degradation assessments have focused on the soil aspect of land degradation [4] (e.g. the Global Assessment of Soil Degradation – GLASOD- project [8]). These studies used an expert-based approach that offered a snapshot of the situation in the late 1980ies but failed to capture the dynamics of the process. The study is now rather outdated. More recently a number of land degradation assessments using remote sensing technologies have been published. These studies tried to infer land degradation from the long-term relationship between vegetative productivity and weather dynamics. Most of these dealt with the dynamics of desertification processes in arid and semi-arid areas [9-12], but most recently an analysis was done of all of SSA [7].

2. Remote-sensing based land degradation assessment

A wide variety of remote sensing products are now available, some of them dating back more than 20 years, providing a long enough track record to capture the dynamic aspects of the land degradation process in terms of primary productivity. Combined with global data on climate, topography, soil, land use and human demographics, the remote sensing data allows for further analysis of the underlying causes and processes [7]. This study makes use of remote sensing databases that are sufficiently long-term and with frequent enough data sampling to provide longitudinal datasets to identify areas where land degradation is occurring and remedial measures are needed or where land is relatively stable or even improving.

Land degradation expresses itself as reduced biological activity [3,4,6] reflected in above ground net primary production (NPP). The most common remote-sensing derived indicator associated with vegetation productivity is the Normalized Difference Vegetation Index (NDVI), best described as a relative measure of vegetation vigour and photosynthetic activity. NDVI is strongly correlated with NPP and is often used to estimate NPP at large spatial scales and as a tool for monitoring temporal changes in vegetation [13,14]. We performed a spatial regression analysis between mean annual NPP and NDVI (1982 – 2000) across different biomes of SSA and found a strong linear relationship between the two parameters ($R^2 = 0.816$, $p < 0.001$). This study firstly utilized monthly composite NDVI data (1982-2003) to assess the spatial and temporal patterns of land productivity. The long-term persistent decline in NPP (as indicated by NDVI) reflects land degradation. Subsequently, in a step-wise approach we correlated the long-term decline in NPP to rainfall, land cover and land use and population density to identify areas of human-induced land degradation in SSA and assess their true extent.

To analyse long-term trends in green biomass changes over the SSA subcontinent, we processed a time-series NDVI product spanning from 1982 to 2003 from the Global Inventory Modelling and Mapping Studies (GIMMS), published by the Global Land Cover Facility (GLCF) [15]. The NPP trend for every pixel (8×8 km^2) was measured by a linear slope of NDVI over time. A pixel's NPP trend (improving or declining vegetation productivity) was considered meaningful if the NDVI slope coefficient was statistically significant ($p < 0.1$) and the NDVI net change was at least 15% of the initial status (1982) over the 22 years.

Above-ground NPP has been shown to increase with increasing annual precipitation [16], and indeed the relationship between rainfall and NDVI is often used to differentiate between human-induced and climate-induced land degradation where any NDVI trends not explained by rainfall dynamics are ascribed to human actions [10]. To distinguish human-induced biomass trends from climate-driven vegetation dynamics, we excluded those pixels that exhibited a strong biomass response to inter-annual rainfall variation. We extracted annual rainfall data for the period 1982 - 2002 from the Climatic Research Unit (CRU) dataset [17]. For every pixel, we calculated the Pearson's correlation coefficient between annual NDVI and rainfall over the period 1981 - 2002 and used the coefficient to determine areas of different NPP-rainfall relationships. The vegetation dynamics of a pixel was considered rainfall dependent if the correlation between NDVI and rainfall was statistically significant and its absolute value was more than 0.5. NPP changes for pixels in accordance with rainfall (positive correlation) were considered due to climate change or variation. Pixels with NPP not affected by rainfall (no or negative correlation) were interpreted as areas where green biomass (NDVI) changes had to be explained by other drivers, and was possibly human-induced.

The sensitivity of NPP to human interference or rainfall variation is substantially different across biomes [16]. To account for this effect, we stratified SSA into four precipitation zones: *Arid* (MAP < 500 mm.year^{-1}), *Semi-arid* (500 mm.year^{-1} ≤ MAP ≤ 800 mm.year^{-1}), *Sub-humid* (800 mm.year^{-1} ≤ MAP ≤ 1300 mm.year^{-1}) and *Humid* (MAP > 1300 mm.year^{-1}) using mean annual precipitation (MAP) for the period 1981 – 2002.

Table 1. Areas that experienced a significant change[(a)] in NDVI between 1982 and 2003 in excess of 15, 20 and 25% of the NDVI value in 1982[(b)]

Note: the total land surface of SSA is 21.4 million km^2

Declining biomass	*Area (1000 km^2)*	*% of SSA*	*Improving biomass*	*Area (1000 km^2)*	*% of SSA*
dNDVI < - 15%	542.3	2.5	*dNDVI* > 15%	4,382.1	20.5
dNDVI < - 20%	212.4	1.0	*dNDVI* > 20%	2,787.7	13.0
dNDVI < - 25%	80.0	0.4	*dNDVI* > 25%	1,781.6	8.3

[(a)] The NDVI slope (*A*) is significant at $p < 0.1$

[(b)] The magnitude of the relative change in NDVI over 22 years (*dNDVI*) in which NDVI in 1982 is the baseline: $dNDVI = A \times 21 \times 100 / NDVI_{1982}$ where *A* is the linear slope of inter-annual NDVI for the period 1982-2003.

The NPP trend analysis shows that some of the most significant changes in NPP were found for areas of low primary productivity. These areas lie in the dryer parts of SSA where NPP are very small to begin with. Small changes in absolute NPP values constitute large changes in relative terms in these dry biomes. To take a closer look at these regions, we expressed overall change in NPP for the 22-year period as a percentage of what it was at the onset (1982). The areas that experienced a significant NPP change ($p < 0.1$), exceeding 15, 20 or 25% of the baseline value in 1982 are summarized in Table 1. The areas of significant NPP decline are only a fraction of the area improving in NPP. Before offering an analysis of the decline in NPP, an interpretation of the widespread improvement is offered.

3. Improvements in NPP and atmospheric fertilization

The areal extent of declining, improving or stable NPP within each rainfall zone was calculated. The geographic distribution of the areas with long-term biomass improvement is shown in Fig. 1. A large proportion of the improving areas are found in the arid zone such as the Sahel and Horn of Africa regions as well as parts of Botswana, designated in blue. These are areas that are responsive to improved inter-annual rainfall and are largely confined to zones with less than 500 mm annual precipitation. This phenomenon has recently been reported in the literature as the "greening of the Sahel" [18-22] and reflects the gradual recovery from the early eighties' drought.

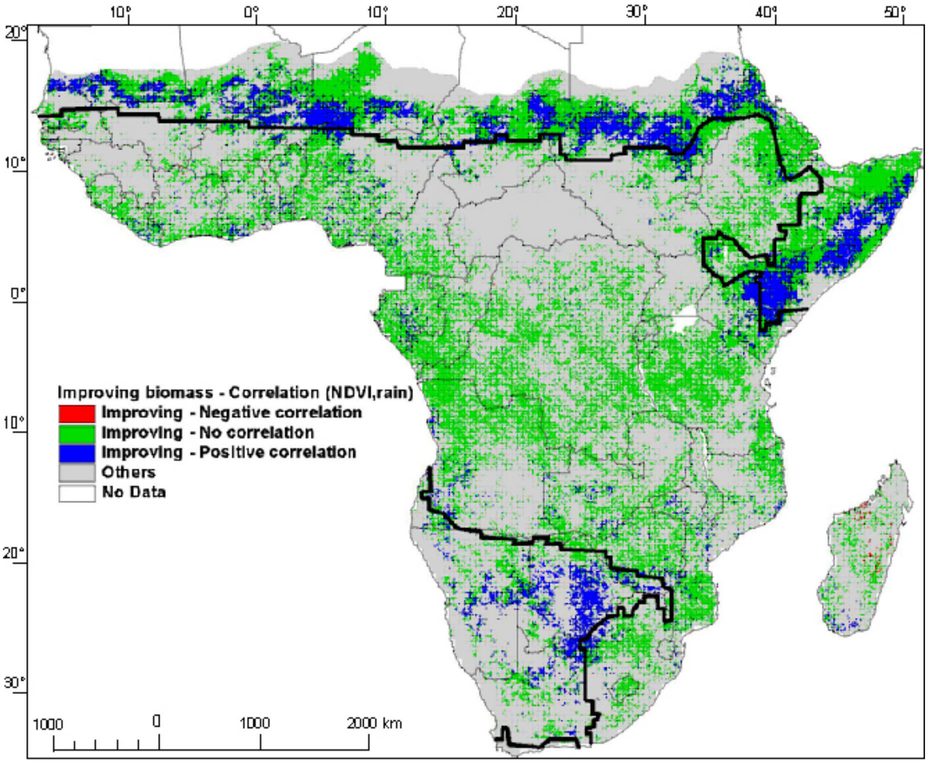

Fig. 1. Geographic extent of areas with improving NPP and different vegetation-rainfall relationships for the period 1982 – 2002. The bold black lines are the 500 mm.year^{-1} isohyets averaged for the same period.

The improvement in NDVI in the remaining areas (mostly green) in Fig. 1 cannot be attributed to rainfall trends as no such correlation could be established for this region. The greening of these areas, representing 20.5% of the SSA land mass, may plausibly be related to the change in atmospheric composition, both in terms of CO_2 [23-33] and NO_x [24-26], [33,36,37]. An overall positive response of vegetation productivity to rising levels of atmospheric CO_2 due to a stimulation of photosynthesis has been established elsewhere [23,29,30,33]. Elevated atmospheric CO_2 has also been shown to improve active-tissue quality in plants, yielding smaller C/N ratios [27]. An additional explanation may be the increasing NO_x load of the atmosphere over SSA causing an increase in reactive nitrogen (N) deposition [34-37]. Recent experiments indicate that an increase in N deposition enhances carbon sequestration [37-39]. Ecosystem-level observations across Western Europe and North America demonstrated a high positive correlation (R^2 = 0.97) between average carbon sequestration and wet N deposition [40]. A recent study showed that most terrestrial ecosystems are N limited with an average response of NPP to supplied N of 29% and the strongest N control of NPP is found in tropical forests [37]. Atmospheric fertilization at a rate of 0.63 ± 0.31 Mg ha^{-1} yr^{-1} over the past 4 decades was recently also reported for closed-canopy tropical forest sites in Africa [41]. Thus, the observed improvement in NPP in SSA is likely due to atmospheric fertilization.

4. Actual NPP decline

The actual area with sustained decline in NPP of at least 15% over the observation period of 22 years amounts to 0.5 million km^2 (Table 1). If the threshold of 15% is dropped, the area of decline increases to as much as 2.1 million km^2 [7]. Of this area, 92% is not affected by inter-annual shifts in rainfall and is likely to reflect the human impact on vegetation. In addition, some 6% of the 0.5 million km^2 shows a negative correlation with rainfall and a declining NPP. These areas are of particular concern. The remaining 2% are areas with decreasing NPP but with a significant positive vegetation-rainfall correlation where any human-induced degradation processes may not be discernable. Similarly, in regions that are greening due to improved rainfall, some land attributes such as the soils may be degrading without this being reflected in NPP. As it stands, the step-wise analysis suggests that some 2.5% of the SSA land surface (0.5 million km^2) is experiencing a human-induced decline in NPP affecting at least 10.2 million people (Fig. 3a). A more detailed analysis of such findings, in which the areas in decline are related to land quality, land use and human pressure on the land provides further insights that will help guide policy makers in mitigation and conservation matters [7].

5. The benefits of atmospheric fertilization

We estimated the spatial extent of declining NPP for the hypothetical case that the atmospheric composition had remained stable. The actual change in vegetation productivity ($dNDVI_{act}/dt$ = slope coefficient-A) can be considered the net balance between the partial changes caused by human activities ($dNDVI_{human}/dt$) and those caused by natural processes ($dNDVI_{natural}/dt$) as shown below:

$$dNDVI_{act}/dt = dNDVI_{human}/dt + dNDVI_{natural}/dt$$

Positive values for $dNDVI_{natural}/dt$ can be due to environmental change such as improved rainfall or atmospheric fertilization and positive values for $\boldsymbol{dNDVI_{human}/dt}$ can be related to aforestation, exclusion zones or soil remediation. Having excluded the areas with rainfall–related increases in NDVI, we sought to quantify the effect of atmospheric fertilization on the dynamics of vegetation productivity over time. To eliminate the compensatory effect of atmospheric fertilization we calculated the component of declining NPP trends that have been masked by this fertilization effect for each rainfall zone. To avoid confoundment with human activity or shifts in weather, only 57983 pixels in pristine regions with no human disturbance and lacking significant NDVI-rainfall correlation were considered (Fig. 2). The rate of NPP improvement for these areas as expressed in the average NDVI-slope ($dNDVI_{act}/dt$ = A) was ascribed to atmospheric fertilization. The baseline slope values of biomass accrual in those pristine lands for each climate zone were subsequently used as a new baseline to re-calculate the trend of NDVI over the 22-years period.

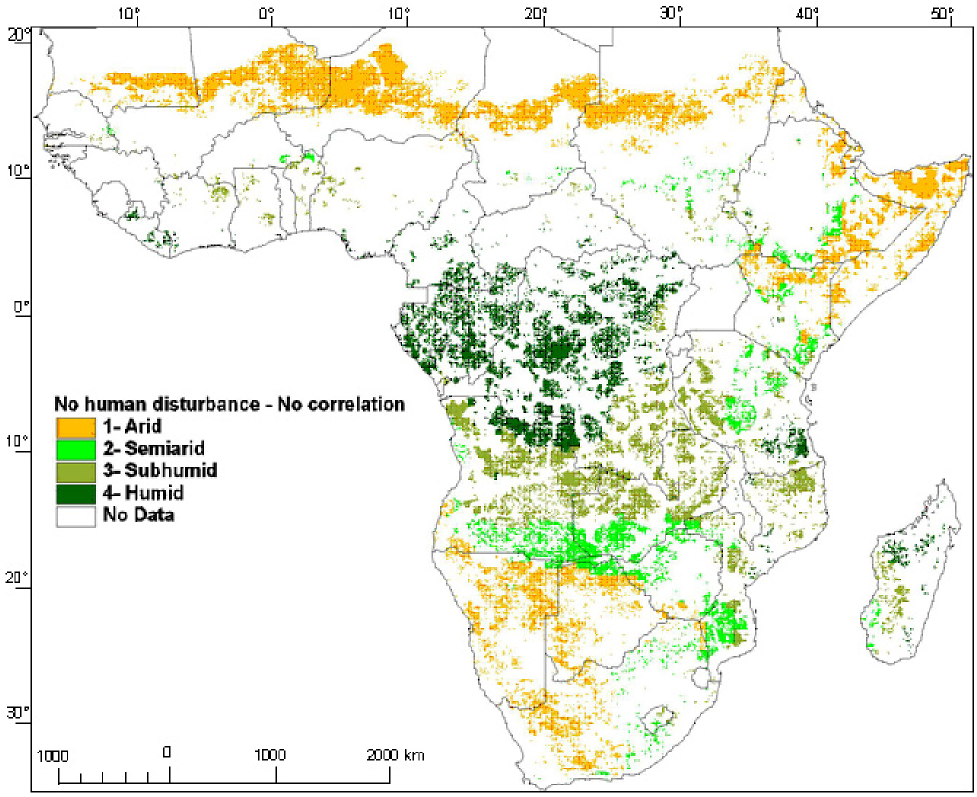

Fig. 2. Areas across different precipitation zones free of human disturbance, and with no significant correlation between annual NDVI and rainfall during the period 1982-2002. Improvement in productivity in these pixels, if any, is likely due to atmospheric fertilization.

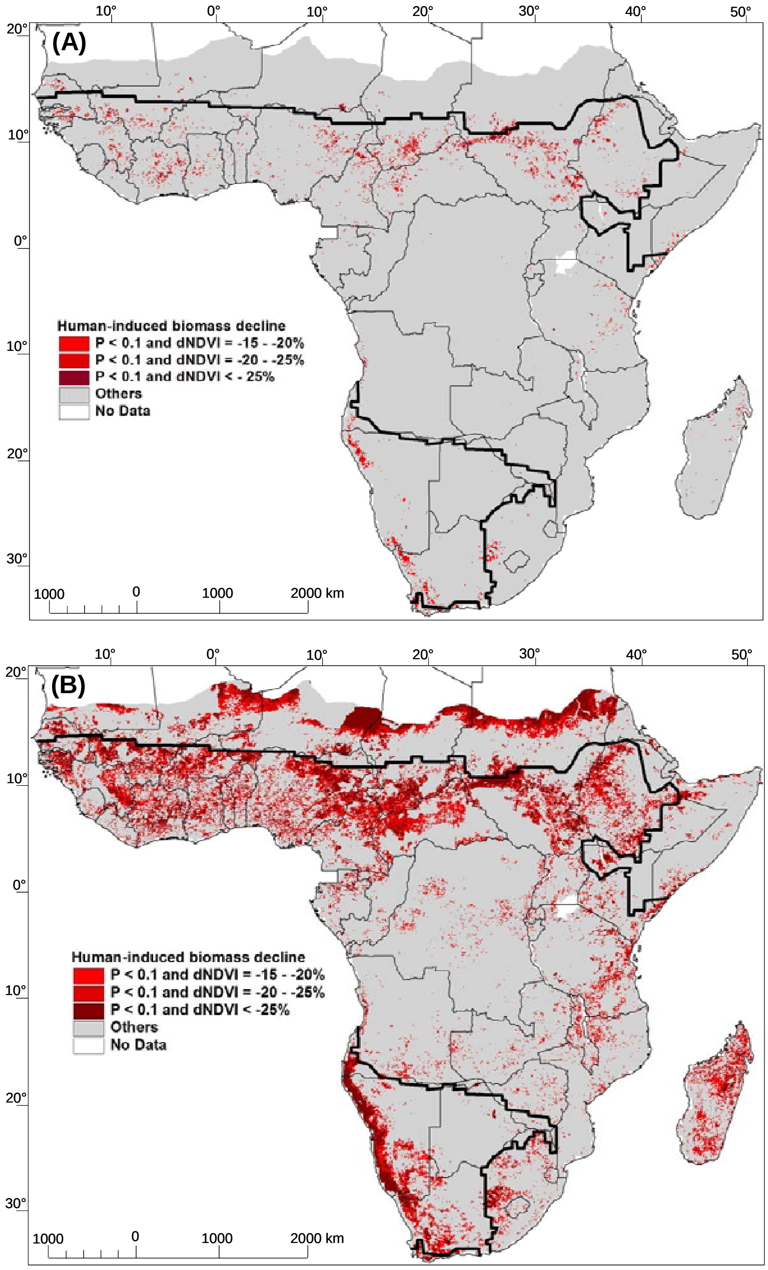

Fig. 3. (a) Geographic extent of actual human-induced degradation in green biomass from 1982 to 2002. (b) Geographic extent of human-induced NPP decline in the same period after correction for atmospheric fertilization. The bold black lines are the 500 mm.year^{-1} isohyets averaged for the same period.

The baseline slope values of biomass accrual were 0.0012, 0.0025, 0.0028 and 0.0036 for the arid, semi-arid, sub-humid and humid zones, respectively. We then re-calculated the time-series of NDVI decline against these new baselines and delineated the areas that would have experienced significant and sustained loss in NPP had the atmospheric chemistry not changed. The spatial extent is shown in Fig. 3b and covers around 27.6% of SSA instead of the 2.5% actually showing a human-induced decline in NPP. The actual extent of the degrading territory would diminish under both scenarios if the criteria for degradation were tightened; e.g. to require more than 15% decline over the 22-year period (Table 1). Either way, the chemical pollution of the atmosphere has obviously had a beneficial effect in sustaining NPP over wide areas of SSA that would otherwise have experienced a significant decline. The down-side of this phenomenon is that atmospheric fertilization is compensating for the degradation of land attributes that would otherwise have caused a decline in NPP such as soil degradation or deforestation that thus go undetected.

The distribution of the degrading areas among the different types of land covers are summarized in Table 2 for each scenario. The areas where degradation processes are masked by atmospheric fertilization cover around 1.4 million km^2 in the mosaic woodland/shrubland, 0.8 million km^2 in the grasslands, 0.9 million km^2 for agricultural areas and 0.4 million km^2 for dense forest. The population affected by underlying land degradation processes increased from 10.2 million people to 137.5 million when atmospheric fertilization was taken into account. With the surreptitious loss of vital land attributes at this rate and with the current rate of population growth (3%), the SSA subcontinent may soon lack the land resources necessary for economic development.

Table 2. Extent of land degradation in various rainfall zones of SSA estimated with and without accounting for atmospheric fertilization.
Note: numbers within the parentheses are the area percentages compared to the SSA's land surface.

Land use/cover	Areas of human-induced degradation (1000 km^2)		
	With atmospheric fertilization (WITH)	Without atmospheric fertilization (WITHOUT)	Degradation masked by atmospheric fertilization (i.e. WITHOUT - WITH)
Dense forest	23.2 (0.11)	445.4 (2.08)	422.2 (1.98)
Forest/savanna	9.8 (0.05)	276.5 (1.29)	266.7 (1.25)
Forest/crop	29.1 (1.14)	249.6 (1.17)	220.5 (1.03)
Woodland/shrubland	226.4 (1.06)	1,634.4 (7.65)	1,408.1(6.59)
Grassland	97.2 (0.45)	952.5 (4.46)	855.2 (4.00)
Agriculture	110.8 (0.52)	993.471 (4.65)	882.6 (4.13)
Others	43.5 (0.20)	1,346.1 (6.30)	1,302.7 (6.10)
Total	**540.0 (2.54)**	**5,898.0 (27.60)**	**5,358.0 (25.07)**

6. Future prospects

This assessment can only be seen as a first approximation, and the maps and assessments made here need verification in the field. The analysis, in essence, is as good as the underlying databases. However, as better data becomes available the analytical framework proposed here allows for easy substitution of this information and rapid generation of a new assessment. As it stands, the following conclusions can be drawn:

(1) In the absence of any instruments for monitoring the rate of land degradation on the ground in SSA, satellite-based systems offer the best hope for tracking the state of this vital natural resource on this vast continent. A systematic research effort should be made to verify the validity of the findings reported here and to refine the analytical tool and interpretation of the results.

(2) The current mapping exercise can be used to identify application domains, areas with common climatic, vegetation, physiographic and soil and land use characteristics that appear to be threatened by human-induced land degradation. Sustainable land management options can then be targeted for these regions that will maximize social benefits from the use of the land.

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