21st century time-series analysis of reforestation in northern Burkina Faso using BFAST Lite

August Slomp[1], 1016791
[1]MSc Geo-Information Science, Wageningen University & Research – august.slomp@wur.nl

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ABSTRACT:

Due to climate change, the Sahara is expanding at an accelerated rate throughout the past centuries. If not stopped, desertification aggravates to hunger, energy shortages and conflict in already troubled Sahelian regions. To counter this desertification, projects like the Great Green Wall of Africa are underway, in which a border of trees is to be planted along the Sahel. One of the facilitators of the tree planting projects is Ecosia, a non-profit organization. Since 2014, among several others, Ecosia has planted trees in three Burkinabe communities: Lilengo, Béléhédé and Aribinda. Using R programming software and its Breaks For Additive Season and Trend (BFAST) package, this study utilized the BFAST Lite method for break and trend detection in Normalized Difference Vegetation Index (NDVI) between 2001 and 2022 to assess the effects of the projects in these communities. Results show that significant breaks in NDVI data were detected in around the time Ecosia started planting trees in 2014. NDVI trends in Lilengo and Béléhédé are successfully increasing, especially so since the detected breaks. However, in Aribinda found NDVI trends are negative and further focus on reforestation in this area is recommended.

1. INTRODUCTION

1.1 Background

Studies have shown that the Sahara has been expanding at a concerning speed due to human-caused accelerated climate change (Thomas & Nigam, 2018). According to the Intergovernmental Panel on Climate Change (IPCC), this desertification can lead to profound effects including severe water, food and energy shortages (IPCC, 2019). The Sahel and its regions, located right between the sandy Sahara and the green African tropics, are deemed to be at risk. In addition, the sub-Saharan African population is projected to increase rapidly the coming century and as a consequence, political and socioeconomic stability are feared to decline (May & Guengant, 2014), especially so in the Sahel where tensions in e.g. Mali, Ethiopia and northern Nigeria are already worrying. Currently, projects like the Great Green Wall are underway to combat the Saharan expansion by planting and growing a border of trees across Africa (Great Green Wall, n.d.). One of the countries that is subject to these tree planting projects is Burkina Faso, located in western Africa. According to Ecosia, a search engine that donates 80% of its profits to reforestation, more than 15 million trees have been planted and 14 thousand hectares have been restored in the Sahelian regions in Mali and Burkina Faso, including Burkina Faso's northern Sahel Reserve region ('Réserve sylvo-pastorale et partielle de faune du Sahel') (Ecosia, n.d.). The scope of this study is specifically on three of the communities Ecosia in 2014 helped planting trees in: the villages of Lilengo, Béléhédé and Aribinda, all located in Burkina Faso's Sahel region (Gonzalez Torres, What do communities think of Ecosia's tree-planting program?, 2015) (Gonzalez Torres, These are your first trees in Burkina Faso, 2015).

1.2 Other research

Several research has been done on desertification and (re)forestation in Burkina Faso and other Sahelian regions. Sterk et al. in effect observed an average increase of Soil Organic Carbon (SOC) in Burkina Faso (6.7 to 8.5 g/kg) in the last two decades of the 20th century and attributed it to Sahelian re-greening (Sterk & Stoorvogel, 2020). Zhongming et al. also acknowledged the positive parts of landscape restoration history in Burkina Faso, but warned that the country is still facing growing pressures and "restoration initiatives have only partly succeeded due to various constraints" (Zhongming, Linong, Xiaona, Wangqiang, & Wei, 2021). Yang et al. found mixed results: the Sahel has been re-greening, but deforestation and lacking pace of reforestation has still lead to desertification and decreasing natural vegetation in Burkina Faso among others (Yang, Gao, Lei, Meng, & Zhou, 2022). This paper finds that results differ as there is spatial variation in desertification rates, as well that there is a lacking amount of case studies on restricted study areas like Lilengo, Béléhédé and Aribinda.

1.3 BFAST Lite

This study makes use of RStudio open source & programming software (RStudio, n.d.) and its Breaks For Additive Season and Trend (BFAST) package (Verbesselt, Zeileis, & Herold, 2012). The BFAST package comes with BFAST Lite, which is "a lightweight break detection method for time series analysis" (Masiliunas, Tsendbazar, Herold, & Verbesselt, 2021). Breaks are determined as abrupt changes in a time-series, in which there is a significant difference in values between two time periods. BFAST Lite is a capable method, but has been underused in the extent of reforestation and desertification rates in Burkina Faso. Therefore, this study chose to use BFAST Lite to analyse vegetation content breaks and trends (and indirectly desertification) in the Ecosia facilitated tree planting sites of Lilengo, Béléhédé and Aribinda over the last twenty years.

2. RESEARCH QUESTION

- Using BFAST Lite, what trends and breaks in vegetation content can be detected in the Burkinabe communities of Lilengo, Béléhédé and Aribinda, in the period between January 2001 and January 2022?
    - Did the Ecosia facilitated tree planning projects successfully combat desertification?

3. MATERIALS AND METHODS

3.1 Study Area

This study concentrates on the Burkinabe communities of Lilengo, Béléhédé and Aribinda located in the Sahel region (figure 1 & figure 2). For each village (figures 3, 4 & 5), a 4 by 4 kilometres (16 square kilometre) area is taken. Time-series are created for vegetation content approximately 500 meter north, south, west and east of the villages' centres.

Figure 1: Location of Burkina Faso in Africa (left) and Sahel region in Burkina Faso (right).

Figure 3: Aerial view of Béléhédé.

Figure 4: Aerial view of Aribinda.

Figure 5: Aerial view of Lilengo.

Figure 2: Tree planting projects of Ecosia in Mali and Burkina Faso. Locations of Béléhédé (west), Aribinda (centre), and Lilengo (east) in red.

3.2 Data

Data used for this study involves Normalized Difference Vegetation Index (NDVI) datasets. NDVI is a measure for density of green vegetation on a surface (Weier & Herring, 2000). It is calculated by subtracting the Near Infrared Reflectance (NIR) with the red reflectance, and subsequently dividing this by the NIR plus the red reflectance:

$$NDVI = \frac{(NIR - Red)}{(NIR + Red)}$$

For this study, NDVI datasets were obtained from the MOD13Q1 product. MOD13Q1 is a product from the MODIS satellite instrument, which provides vegetation indices (NDVI as well as the Enhanced Vegetation Index (EVI)) on a 250 meter spatial resolution for every 16 days since February 2000 (USGS, n.d.). For this study, all images between January 1, 2001, and January 1, 2022, were used for analysis. As such, MOD13Q1 is used to download Lilengo, Béléhédé and Aribinda NDVI raster stacks (SpatRaster class).

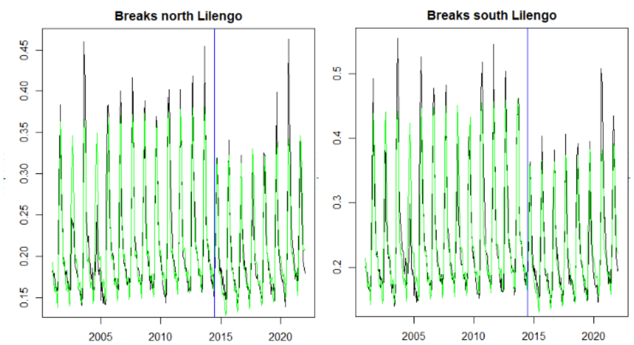
3.3 Methods

The R package MODISTools is used to download MODIS imagery (https://cran.rproject.org/web/packages/MODISTools/index.html), whereas the BFAST package is used for time-series analysis (https://cran.rproject.org/web/packages/bfast/index.html). Coordinates (latitude, longitude) inputted for Lilengo, Béléhédé and Aribinda are respectively (14.494986, -0.108897), (14.084705, -1.291897) and (14.226179, -0.862255), which were determined, using Google Maps, to be of the towns' centres. The '250m_16_days_NDVI' band is used to acquire the NDVI data for all pixels, after which the '250m_16_days_pixel_reliability' band is used to filter out the pixels with unreliable data (due to e.g., cloud coverage). After downloading the resulting NDVI raster stacks for each location, a pixel 500 meter north, south, west and east of the village's centre is assigned (respective pixel numbers: 112, 180, 144 and 166). These pixels represent 250 by 250 meter areas of non-urban land that are subject to reforestation and desertification next to the town. From the values for each pixel between January 1, 2001, and January 1, 2022, NDVI time-series are made. These time-series are used in the BFAST Lite function, which subsequently detects breaks and analyses trends. For this, linear regression is used in which the trend and 'harmon' (seasonality) are inputted as independent variables. The Bayesian Information Criterion (BIC) is used to assess the optimal number of breaks. BIC practically punishes models for overfitting (Stoica & Selen, 2004), after which the model with the lowest BIC score is used for the analysis. For each location, also time of break and magnitude rasters are made by assessing the time of break for each pixel and its magnitude of change during the 2001-2022 time-period in NDVI content.

4. RESULTS

4.1 Lilengo

In all four parts (north, south, west and east) of Lilengo a break is detected in 2014 (figures 6 & 7). Before the break, the NDVI content was on average higher than after: the overall trend (between $-5.9e^{-6}$ and $-1.5e^{-5}$) indicates a small decrease of NDVI in this 20-year period in all four locations. However, before the break for all locations the NDVI had an increasing trend (between $6.7e^{-5}$ and $9.7e^{-5}$) and after the break an even higher trend can be observed (between $1.5e^{-4}$ and $2.0e^{-4}$).



Figures 6 and 7: Time-series of pixels north, south, west and east of Lilengo. Green lines are fitted lines by BFAST Lite, the blue line is the detected break. X-axis: year (AD), Y-axis: NDVI.

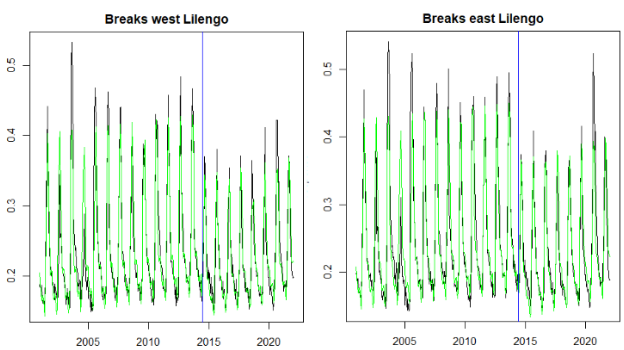


Figure 7

Most breaks for all pixels in the Lilengo area are found in 2014, except for some of the outer parts of the area (figure 8). The magnitude of change is relatively small for the area, with most of the pixels not changing by more than about 0.060 times in 2022 compared to its state in 2001.

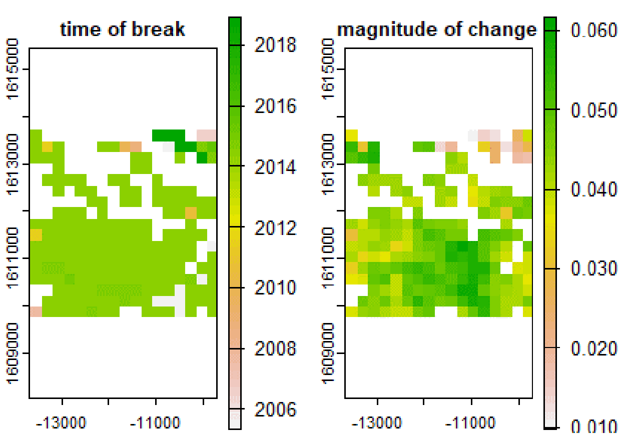
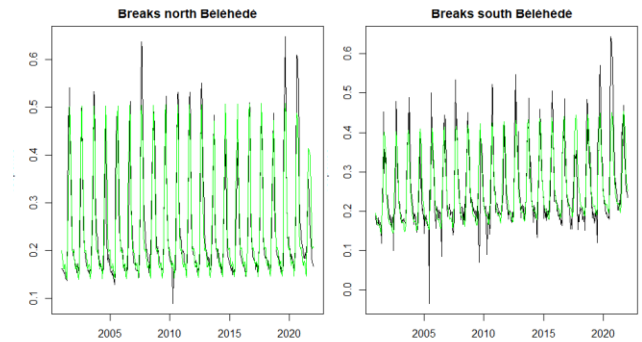


Figure 8: Time of detected break for each pixel in the Lilengo area (left) and respective magnitude of change during the 2001-2022 time-period (right). X-axis: longitude, Y-axis: latitude.

4.2 Béléhédé

Only for the western part of Béléhédé did BFAST Lite detect a break (figures 9 & 10). The break was detected in 2014, as was the case for the previous Lilengo parts. It furthermore follows the same pattern: relatively higher NDVI content pre-break, but stronger increase post-break (with a trend of $8.1e^{-5}$ pre-break compared to $4.9e^{-4}$ post-break). In contrast to Lilengo however, the overall trend is also positive, especially for the southern part, which has the highest increase ($1.3e^{-4}$) in NDVI from 2001 to 2022.



Figures 9 and 10: Time-series of pixels north, south, west and east of Béléhédé.

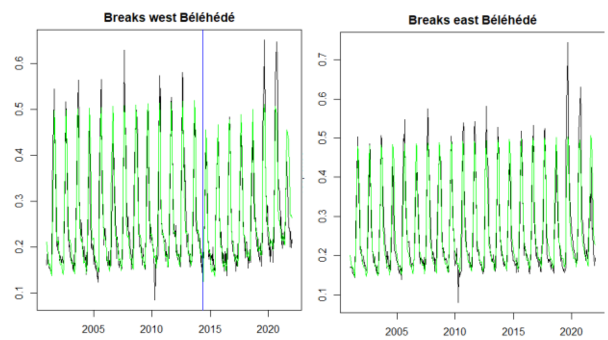


Figure 10

For most of the pixels in the 16 square kilometre Béléhédé area BFAST determined the time of break to be around the year 2018 (figure 11), on average four years later compared to its Lilengo counterpart. For the centre part, which is near the town centre and where the pixels for the time-series analysis were taken from, the time of break found however was also around 2014 (as was detected in the West Béléhédé time-series). The scale of magnitude of change is the same as for the Lilengo area, with relatively small values of up to about 0.080. As can be noticed in the time-series, mostly the southern parts have the strongest magnitude of change between 2001 and 2022.

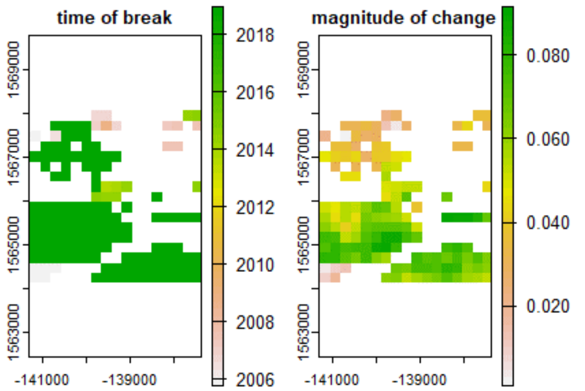
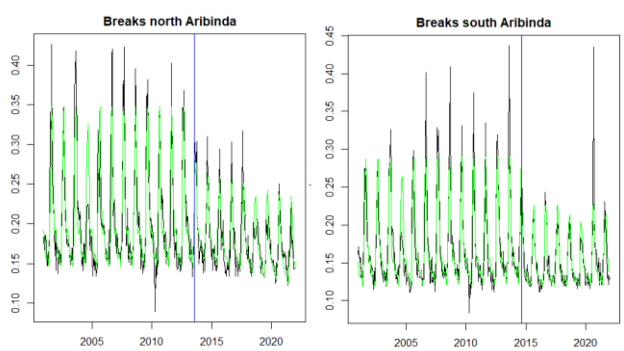


Figure 11: Time of detected break for each pixel in the Béléhédé area (left) and respective magnitude of change during the 2001-2022 time-period (right).

4.3 Aribinda

For all parts of the Aribinda area (north, south, west and east) breaks were detected in the time-series (figures 12 & 13). The break detected in the northern part was found in 2013, compared to 2014 in the southern part (and Lilengo and Béléhédé pixels). For the western and eastern part even two breaks were detected: in 2006 and also 2013. For all parts the general trend is negative (between $-5.8e^{-5}$ and $-5.5e^{-4}$), indicating lower overall NDVI content in 2022 compared to 2001. The northern part follows the same pattern as observed in the Lilengo time-series (higher NDVI pre-break), except that both pre- ($-4.8e^{-7}$) and post-break ($-1.9e^{-4}$) trends are negative, indicating that the NDVI is even decreasing faster after the break than before. For the southern part, higher NDVI is also found pre-break (with a trend of $1.20e^{-5}$) than post-break (with a near equal trend of $1.23e^{-4}$). For the eastern part, the NDVI content was increasing up until the second break (with a trend of $1.7e^{-5}$ pre-2006 and $1.1e^{-4}$ post-2006 and pre-2013) after which it also started to decrease ($-2.9e^{-4}$). In contrast to the eastern part, for the western part the trends before the breaks were also decreasing ($-1.8e^{-4}$ pre-break one (2006), $-5.2e^{-5}$ pre-break two (2013) and $-1.4e^{-4}$ post-break two).



Figures 12 and 13: Time-series of pixels north, south, west and east of Aribinda.

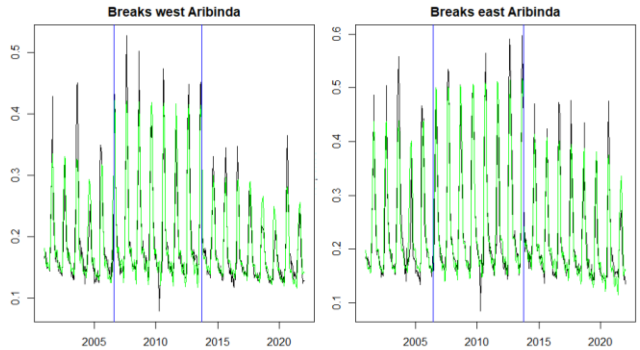


Figure 13

For all pixels in the Aribinda area, most breaks were found around 2006 (as was the case in the western and eastern pixels) (figure 14). In the north-eastern part most recent breaks were found in 2018. The overall magnitude of change is small, even lower than at the Lilengo and Béléhédé counterparts. The highest change is found in the west, with a magnitude of change of up to 0.060.

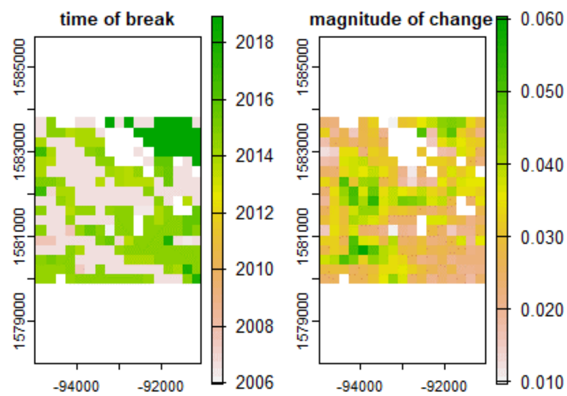


Figure 14: Time of detected break for each pixel in the Aribinda area (left) and respective magnitude of change during the 2001-2022 time-period (right).

5. DISCUSSION

For the Lilengo, Béléhédé and Aribinda data MOD13Q1 was used, which uses a 250 meter spatial resolution. This (250 by 250 meter) is a relatively large area to detect sometimes small but significant changes in a sparsely vegetated area. Detected changes therefore might be underestimated or overestimated. Most significantly, the exact locations in which the trees were planted, as well as how many trees were planted in these areas could not be determined. As mentioned in 3. Materials and Methods, pixels for time-series analysis were chosen around 500 meters away from the city centre, but since the exact locations are unknown, these locations are possibly not affected or impacted by Ecosia's projects. In that case, results cannot reflect the effects to be analysed. The town centres are possibly also not precise enough, as small changes in latitude or longitude, inputted into R programming software, can offset its centre point by 10 or more significant metres. According to Ecosia, trees were planted in late 2014 (Gonzalez Torres, Lilengo 3 years later: how planting trees helped an entire town, 2015). Since most trees need a significant longer time to fully grow than eight years (2014 – 2022), the analysis of the full effects of these projects are yet limited by time. For future research, communication with the facilitator, in this case Ecosia, as well as the local communities is recommended in order to determine the exact locations as well as the number of trees planted per study areas. Furthermore, further cross-validation and exact field measurements can help assessing the quality of the data, methodology and results used and obtained in this study.

In concordance with Zhongming et al. and Yang et al. (Zhongming, Linong, Xiaona, Wangqiang, & Wei, 2021) (Yang, Gao, Lei, Meng, & Zhou, 2022), the results are mixed as in all three locations different results were obtained. In contrast to Sterk et al. (Sterk & Stoorvogel, 2020), most obtained trends in NDVI were negative and indicate an overall decreased vegetation content between 2001 and 2022, be it in a different time-period (Sterk et al. analysed SOC contents in the last two decades of the past century). However, most post-break (2014) trends in NDVI were positive and/or higher than pre-break trends, which corresponds with Ecosia, which observed a significant improvement vegetation growth in 2015 (Gonzalez Torres, Lilengo 3 years later: how planting trees helped an entire town, 2015).

6. CONCLUSION

The results show that the overall NDVI content has decreased in both Lilengo and Aribinda between 2001 and 2022. Only in Béléhédé the NDVI has increased in this entire period. However, these observations can be explained by a sudden drop of NDVI content in mostly 2014. These drops happened just before the planting projects started, and thus a reason could be that old vegetation was ploughed to make way for new trees. When looking at the trend in NDVI, the vegetation content is actually increasing and pre-2001 NDVI levels are likely to be reached coming decade. In total, especially so for Lilengo, most breaks were detected in 2014. This corresponds with Ecosia's claim that the tree planting projects started in late 2014. Trends in NDVI after 2014 also were mostly higher than trends pre-2014, indicating that the projects had positive effects in re-greening the areas and thus combating desertification. In Aribinda many breaks however were also detected in 2006 and 2013, which seem to be unrelated to the tree planting projects facilitated by Ecosia. The trends (pre- and post-break(s)) in Aribinda also mostly do not differ significantly overall from each other. For most parts in Aribinda the trend in NDVI after the break(s) are negative and/or decreasing even faster. This could indicate that the studied areas were not reforested (by e.g., Ecosia) or that current reforestation projects did not have strong enough effects. The overall magnitude of change and trends of all areas are too small to be considered significant and a longer time period is necessary to fully analyse the results, especially since reforestation only started since 2014. This study concludes that the areas of Lilengo and Béléhédé do seem to be safeguarded for desertification as the NDVI still seems to be reaching relatively high levels (up to 0.5) and current NDVI trends are, overall, positive and increasing. Around the community of Aribinda however negative trends in NDVI are still observed and further focus on tree planting projects in this area is advised.

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