NOURA MALAN ISSA, WORLD FOOD PROGRAMME

TECHNICAL REPORT

Assessing the Impact of Agroecological Interventions in Niger through Remotely Sensed Changes in Vegetation

CONTENTS

EXECUTIVE SUMMARY

Water scarcity and soil degradation are significant challenges for land productivity in West Africa's Sahel region. The U.S. Agency for International Development (USAID) and other development organizations have made major investments in the Sahel to improve resilience through land rehabilitation activities in recent years. To help restore degraded lands, the World Food Programme (WFP) has aided construction of "half-moons," systems of semi-circular water retention ponds, as a strategy for improving agricultural productivity. This study investigates the effectiveness of half-moon interventions at 18 WFP sites in southern Niger using vegetative greenness indicators from Landsat 7 satellite observations. The pre- and post-intervention analysis shows that the vegetation greenness after half-moon construction was nearly 50% higher than in pre-intervention years. In the control analysis, the vegetation at the intervened area was more than 25% greener than the nearby control area. Together, the results indicate that the half-moon interventions are effective in land rehabilitation as evident through improved vegetation conditions in southern Niger.

INTRODUCTION

Water scarcity is a major challenge in the West African Sahel. Reliable water resources are vital to communities' crop production, livestock maintenance, and daily household activities. From a food security perspective, water availability, area of arable land, and market conditions all play a critical role in the type and quantity of crops being planted. Smallholder farmers therefore have a fundamental interest in optimizing their access to and efficient use of water, land, and markets. Market conditions are typically shaped by forces beyond the control of individual farmers or farming communities. However, measures can be taken at the farm level to manage and mitigate the impacts of land degradation and limited water availability. Such resilience measures can contribute towards improved household-level food security in a sustainable manner. Several innovative measures towards land regeneration have been applied over the past few decades (Bayala et al., 2020; Rinaudo, 2007; Weston et al., 2015). Typical restoration methods include enhancing vegetation cover and using other techniques that contribute to improved soil, water, and land management (Meroni et al., 2017). Half-moons, zaï, stone bunds, etc. are common techniques to prevent further land degradation while retaining the rainfall-driven soil moisture for longer durations (Danso-Abbeam et al., 2019; Nyamekye et al., 2021; Roose et al., 1999; Wouterse, 2017).

Half-moons (Figure 1) have been used in West Africa for several decades to restore degraded lands (Oakland Institute, 2015). The process involves excavating small (~1m radius) semicircular ponds and using the displaced soil to create a retaining wall on the downhill edge (Partey et al., 2018). The ponds retain rainwater and allow it to gradually seep into the ground, improving soil health in the proximity (Bayen et al., 2020). The half-moons are critical during the rainy season because the structures can ensure continuous moisture to the crops during subsequent dry periods (Nyamekye et al., 2018). Moreover, by limiting surface runoff, the half-moons conserve water, reduce erosion that help retain soil nutrients (Danso-Abbeam et al., 2019; Halbrendt et al., 2014). Vegetation grown in surrounding areas include subsistence crops and pastoral land.

Figure 1: Half-moons are a common land restoration practice in West Africa to conserve water. NOURA MALAN ISSA, WFP

Several non-governmental organizations and public international organizations including the World Food Programme (WFP) serve as critical links between donors and local agrarian communities. Farmers, along with such organizations, have been involved in projects to improve soil fertility, control runoff, and restore degraded natural ecosystems through soil and water conservation (SWC) projects in the region (Oakland Institute, 2015). Farmers whose lands have been restored have shown substantial benefit in terms of production (Sawadogo, 2011). WFP alone has conducted such restoration interventions at several hundred locations throughout Niger and neighboring countries.

For the past several decades, the U.S. Agency for International Development (USAID) has made major investments in the Sahel to improve resilience through land rehabilitation activities that improve water conservation and enhance agricultural and fodder production in previously desertified or degraded lands. These activities were carried out at large scales throughout Niger (namely in the Tahoua, Maradi, Zinder, and Tillaberi regions) as part of the USAID Bureau of Humanitarian Assistance's food security initiatives. Increased soil moisture and the related increase in tree survival has been reported at several sites (Bayen et al., 2020; Feed The Future, 2016), but getting a complete picture of impacts at a wider scale is challenging due to limited access to some of the remote locations, security concerns, financial aspects of survey and data, etc. Furthermore, ground surveys do not provide a complete historical view. As such, adequately measuring the efficacy of the half-moon method is difficult.

One alternative to ground surveys is the use of satellite remote sensing (Andres et al., 2018; Heiskanen et al., 2017; Jung et al., 2021; Kerle et al., 2019; Meroni et al., 2017; Nyamekye et al., 2021). Remote sensing can complement other methods by considering data at a landscape scale, supporting historical analysis, and producing meaningful quantitative metrics. In particular, with the availability of long historical records, remote sensing can provide valuable insight into vegetation conditions before and after interventions.

MOTIVATION

Replicating a successful pilot in Tigray, Ethiopia, SERVIR and USAID's Bureau for Humanitarian Assistance aim to measure the impact of water management interventions on production and resilience to drought. The interventions documented by WFP have provided context for this analysis. This document outlines the methodology to encourage replication of this assessment elsewhere. The hypothesis is that the prolonged soil moisture from the half-moons will increase vegetation as identified in satellite measurements of greenness. Better understanding the impact of agricultural interventions may help improve cost efficiency of community planning in low-resource environments.

USE OF SATELLITE DATA

Satellite datasets have tremendous potential to quantify the impacts of half-moon interventions. One of the unique advantages of satellite observations is the ability to see the landscape before intervention. With a repeat cycle of 16 days, the historical record of Landsat data extends back to the 1980s and provides an important window into the way the landscape has evolved. Several vegetation indexes have been developed to quantify vegetation health, including Normalized Difference Vegetation Index (NDVI: (Brown et al., 2006; Tucker, 1979)), Enhanced Vegetation Index (EVI: (Huete et al., 2002)), and Soil Adjusted Vegetation Index (SAVI: (Qi et al., 1994)), among others. Measuring vegetation greenness can be valuable in assessing the efficacy of soil moisture interventions. Although vegetation changes are slow (spanning over several days), 16-day revisits of

Landsat should be able to capture the natural vegetative growth cycle. However, frequent cloud cover poses a challenge to use of these indexes, particularly for data collected before 2010 when relatively few satellite overpasses were available. The spectral bands used in the computation of these indexes are in the visible and near-infrared bands and cannot penetrate clouds. Therefore, persistent cloudy conditions can cause significant data gaps.

ANALYSIS IN NIGER

The WFP is working on more than 300 sites for SWC interventions in southern Niger and has specific geographic outlines of half-moons at 18 sites (Figure 2). This analysis focuses on four districts in southern Niger – Maradi, Zinder, Tahoua, and Tillaberi. Each site has several concentrated geographic areas (termed as intervention polygons in this text) that were either developed as pastoral or agricultural half-moons (as illustrated in Figure 2 by red and blue sub-polygons at Dan Goudaou site). The 18 sites include a total of 101 distinct geographic areas and cover approximately 4400 ha of area developed between 2013-2020. We have excluded the half-moons developed in 2020 from this analysis due to insufficient sample size post-intervention for any statistical inferences. Interventions were not uniformly distributed during the analysis period. The study included a larger number of half-moons constructed in 2015 (24 polygons) and 2018 (26 polygons) compared to the half-moons constructed in 2016 (4 polygons) and 2017 (6 polygons).

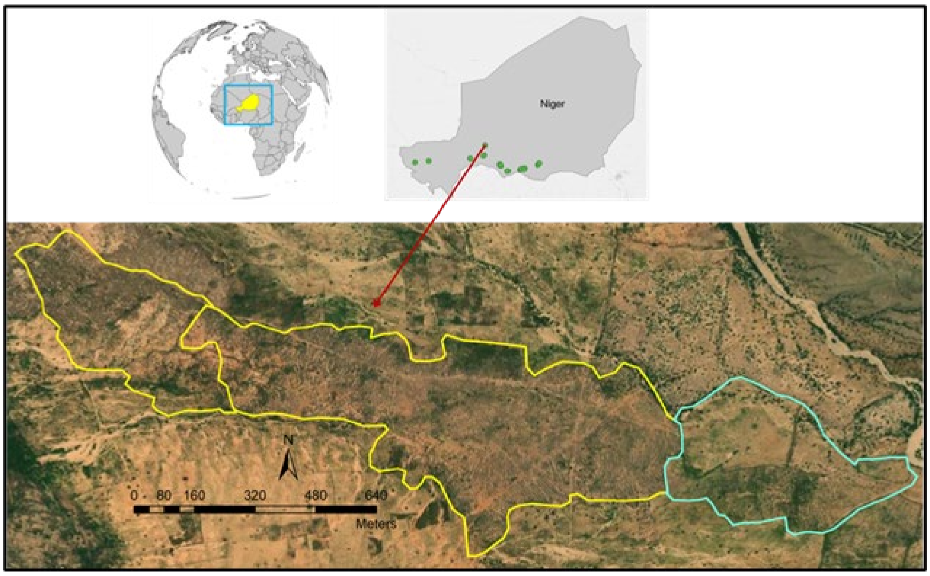

Figure 2: WFP intervention sites in southern Niger include interventions intended for agricultural (blue) and pastoral uses (yellow).

Southern Niger experienced variable rainfall during the study period. Figure 3 shows departures from long-term annual rainfall in the Maradi region, which represents about a third of the 101 half-moon interventions. Rainfall has been above average since 2018, while 2015-17 rainfall was slightly below the long-term (40 years) average.

We used NDVI data derived from Landsat 7 (2010-present) for this analysis. Rainfall data for contextual assessment was available from Climate Hazards Infrared Precipitation with Station Data [CHIRPS: Funk et al., (2015)]. CHIRPS is a station-corrected satellite rainfall product. Because the half-moons are intended to improve soil conditions in the surrounding area, peak NDVI values in these polygons can be expected to be significantly higher post-intervention under similar rainfall conditions. Together, there were 101 polygons with an average area of approximately 42 ha, equivalent to about 450 Landsat pixels each. NDVI values were analyzed at monthly and annual scales. The annual peak (95th) percentile data was analyzed to assess the variability in NDVI values over the study period. Because this study was designed retrospectively, we could not randomly assign control sites. It is possible that agro-ecological characteristics of control sites could vary, thereby influencing results. To address this challenge, we have considered the preceding years of the sites that were developed at a later stage (after 2017) as control for the treatment sites in the same region that were developed between 2013-2015.

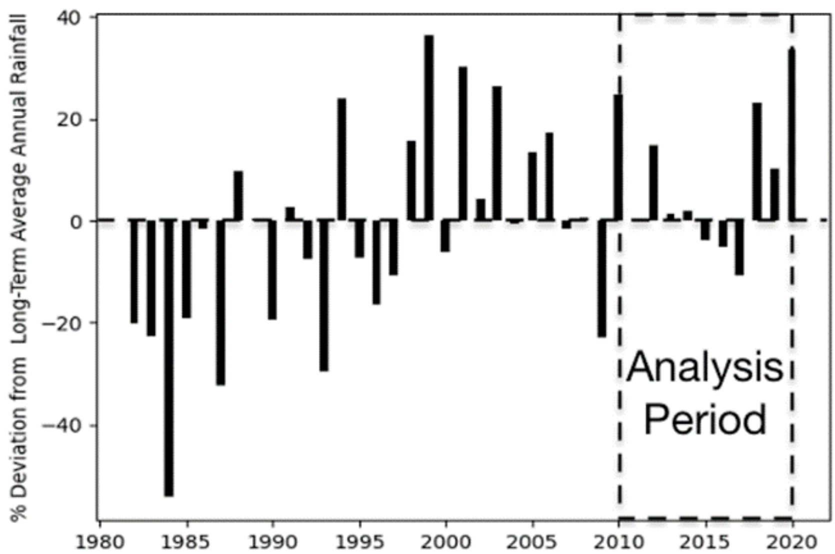

Figure 3: Percent rainfall anomaly for Maradi over the last ~40 years (1982-2020). Other districts in southern Niger have similar trends. While this analysis focuses on vegetation growth from 2010-present in relation to rainfall data, the longer-term data provides a perspective on the historical rainfall and corresponding vegetation conditions.

We conducted two sets of analyses to estimate the efficacy of interventions. First, we conducted a temporal analysis which shows the NDVI values before and after interventions. In the second set we used experiment and control analysis using adjacent sites to perform before-after control-impact assessments.

PRE- AND POST-INTERVENTION ANALYSIS

The max NDVI value during the peak growing season (Aug-Oct) for each of the sites showed a significant improvement after intervention (Figure 4). On average, the peak NDVI value increased by 49.7% (from 0.217 to 0.325) across all sites after the interventions (Table 1). NDVI values at four sites increased by over 60%, with a maximum increase of 81.1% (0.185 to 0.335) measured at Kafat. We observed the smallest NDVI increase of 29.7% (from 0.202 to 0.262) for Boussarague. The difference in the NDVI is statistically significant ($p<0.001$).

The rainfall during months preceding the peak growing season is expected to have a significant impact on vegetation conditions. Therefore, we compared NDVI values to the total rainfall in June and July, the two months preceding the start of peak growing season. Table 1 compares annual peak NDVI values to the total June-July rainfall at each site. The table shows that the average June-July rainfall post-intervention is higher (12.3%) for all of the sites, which can be attributed to above-average precipitation in recent years (2018-2020). Although rainfall is one of the primary drivers of vegetative growth, the table clearly indicates that the change in peak NDVI values is not linearly related to the differences in total rainfall before and after the intervention. Even though the rainfall only increased by 12%, the NDVI jumped by nearly 50% at these sites after the intervention.

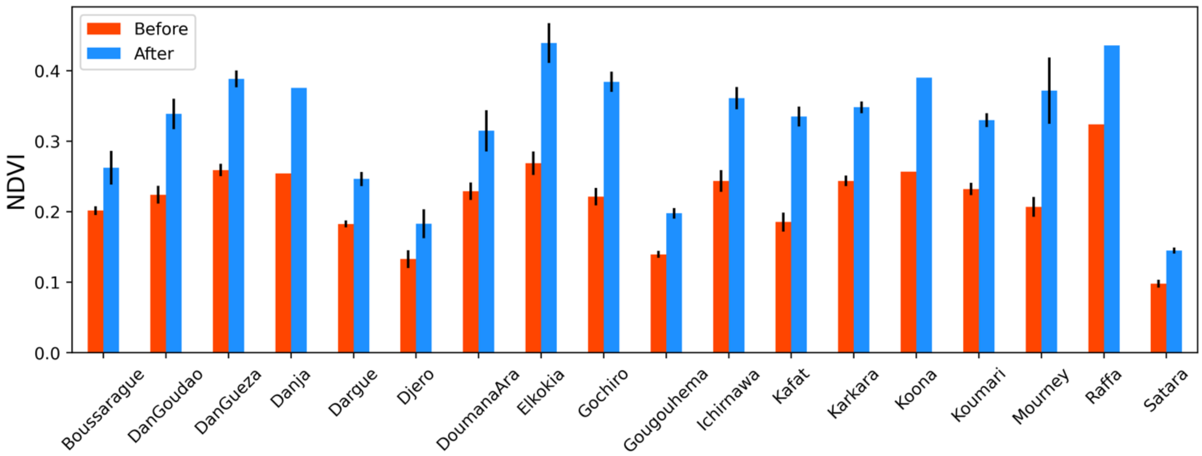

Figure 4: Mean peak NDVI across all sub-polygons for all sites intervened before (red) and after (blue) intervention. The error bars represent the standard error in mean NDVI values from different sub-polygons within a site.

TABLE 1. SUMMARY OF MEAN ANNUAL PEAK NDVI VALUES (AUG-OCT) BEFORE AND AFTER INTERVENTION AT EACH OF THE SITES WITH THE MEAN JUNE-JULY RAINFALL FROM 2010-2020.						
Site Name	**Landsat 7 Before**	**Landsat 7 After**	**Rainfall (mm) Before**	**Rainfall (mm) After**	**NDVI Difference**	**Rainfall Difference**
Boussarague	0.202	0.262	347	383	29.7%	10.3%
DanGoudao	0.224	0.339	348	392	51.3%	12.6%
DanGueza	0.259	0.388	310	331	49.8%	06.7%
Danja	0.254	0.375	407	410	47.6%	00.7%
Dargue	0.183	0.246	330	380	34.4%	15.1%
Djero	0.133	0.183	372	424	37.6%	14.0%
DoumanaAra	0.229	0.315	354	417	37.6%	17.8%
Elkokia	0.269	0.439	395	386	63.2%	02.2%
Gochiro	0.221	0.384	356	424	73.8%	18.9%
Gougouhema	0.140	0.198	274	312	41.4%	14.0%
Ichirnawa	0.244	0.361	388	428	48.0%	10.3%
Kafat	0.185	0.335	266	325	81.1%	22.4%
Karkara	0.244	0.348	336	352	42.6%	04.9%
Koona	0.257	0.39	359	422	51.8%	17.5%
Koumari	0.232	0.33	275	311	42.2%	13.3%
Mourney	0.207	0.372	360	409	79.7%	13.6%
Raffa	0.324	0.436	360	419	34.6%	16.4%
Satara	0.098	0.145	279	311	48.0%	11.2%
Mean	**0.217**	**0.325**	**340**	**380**	**49.7%**	**12.3%**

Figure 5a compares peak NDVI and total rainfall before and after the intervention. The results show that there was some relationship (albeit a weak one) between NDVI and rainfall before the intervention (R2 = 0.24). Interestingly, the relationship between the two variables reduced by 36% (R2 = 0.15) after the intervention. This confirms the assumption that there are other factors affecting vegetation growth in the region and that these external factors seem to play an even greater role post-intervention. Despite above normal rainfall at the end of the study period (2018-2020, figure 3) that may have contributed to the increased NDVI, the scatter plot (figure 5b) between the percent difference in total rainfall and NDVI peak also show that there is no linear relationship between these two variables in the study area. The analysis indicates that the effect of increased rainfall on observed greenness after the interventions is negligible. Therefore, the apparent improvement in vegetation condition is likely in response to the land rehabilitation activities.

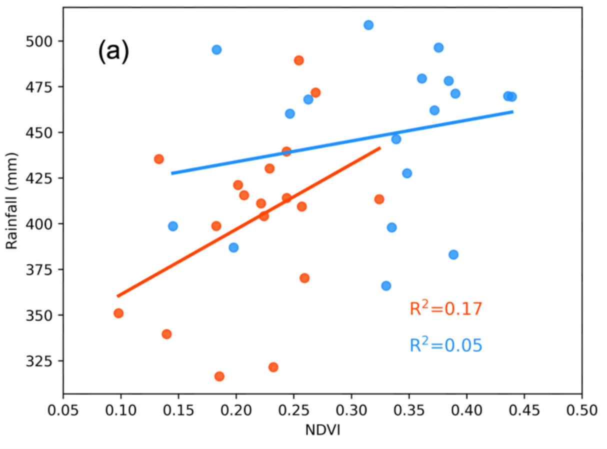

Figure 5: (5a) Scatter plot demonstrating the relationship between mean peak NDVI and June-July rainfall before (red) and after (blue) interventions; (5b) scatter plot illustrating the percent difference in peak NDVI and June-July rainfall before and after interventions.

Looking more closely, the NDVI values for each month give insights into the natural vegetative growth cycle before and after the intervention. For instance, monthly NDVI values across Kafat and Danja are shown in Figure 6. The shaded portion represents the standard deviation of the mean NDVI values across multiple sub-polygons (4 in case of Kafat). The WFP built half-moons in two of the sites in 2018 and developed the other two sites in 2019. Figures show that from January to July, NDVI values before and after interventions were similar. However, for months during and after the rainy season, the mean monthly NDVI values begin to deviate. The post-intervention NDVI values (blue lines in Figure 6) are substantially higher than pre-intervention (red lines in Figure 6) from August through December. The increase is consistent across all sub-polygons as evident by the standard deviations. The Danja site has only one polygon (42 ha, approx.) that was developed in 2015. Danja allows us to analyze and compare a few years of data both before and after interventions. Moreover, the post-intervention period contains at least 3 years of below average rainfall with 2017 as one of the most significant rainfall deficit years (deficit of more than 100 mm from the long-term average), thus providing a good mix of rainfall distributions to assess the impact of intervention using NDVI. Similarly, the mean monthly NDVI values were close in the relatively dry months, though post-intervention values were consistently slightly higher. The difference became even more pronounced during wet months, with the mean peak rising from 0.27 to 0.33.

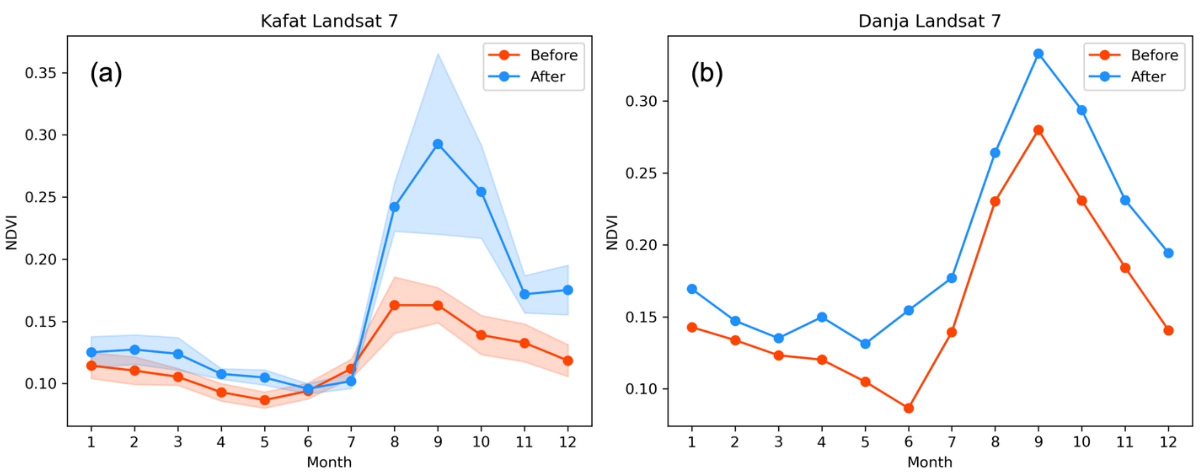

Figure 6: Average monthly NDVI values for two sites (Kafat and Danja) before and after the intervention. The shaded areas on the left represent one standard deviation computed from multiple polygons at each site.

All intervention sites showed similar trends where NDVI values after intervention were consistently higher than the NDVI values before intervention. This higher difference in NDVI value is also observed for a couple of months after the rainy season, indicating prolonged greenness. Overall, for dry months the NDVI differences before and after interventions were in the range of 0.015-0.03, which more than doubled (0.044-0.063) during the months when NDVI peaked. Figure 7a shows the monthly mean NDVI from all sites before and after intervention and the differences (Figure 7b). The figure clearly indicates a consistent improvement in vegetative greenness across all sites.

When analyzed together, Table 1 and Figures 6-7 show that the half-moon interventions at all sites result in a statistically significant increase of greenness. NDVI values increased by 49.7% compared to the pre-intervention conditions, even after accounting for differences in rainfall during the time periods.

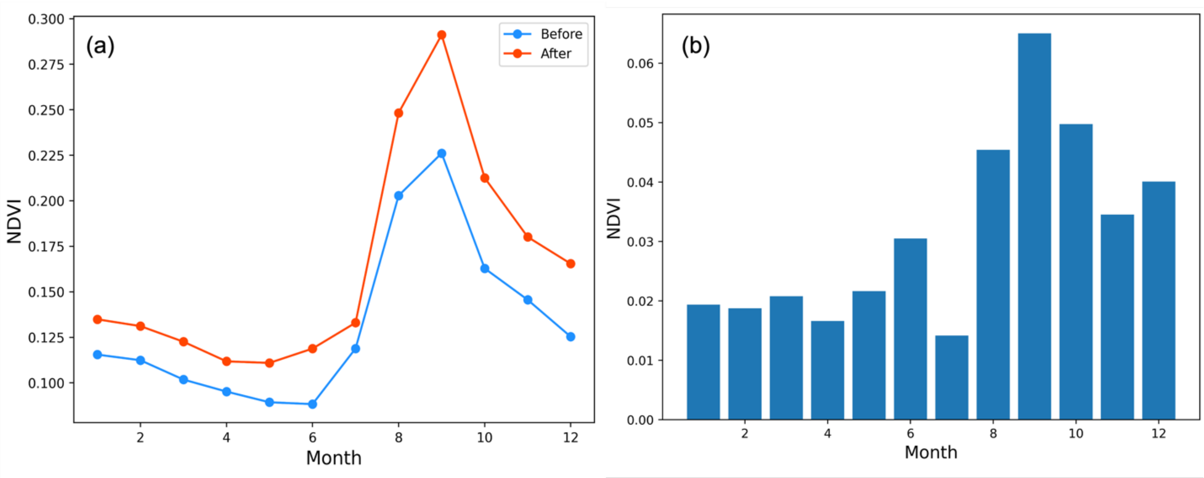

Figure 7: Overall, mean monthly NDVI response across all sites and all years before and after the intervention (a) and the difference in mean NDVI values before and after for each month (b).

CONTROL ANALYSIS

During the planning and implementation of these interventions, no control site was specifically identified. Therefore, for this analysis, we have taken an indirect approach where a pair of polygons from the same site that were developed a few years apart were used as experiment (or intervened) and control site. This approach ensured that the later-intervened area was suitable for the intervention, hence was worthy of inclusion in this comparison.

We applied three criteria for selecting the control and intervention pairs by ensuring:

A.) that the polygons were nearby (as part of the same larger site)
B.) that the sites are from the same livelihood zones (agriculture or pastoral)
C.) that the polygons have interventions at least 3 years apart.

The first criterion ensures that both sites have similar weather patterns and cropping/grazing practices. The second criterion ensures the similarity in vegetation types and patterns. The final criterion ensures that the evaluation can focus on years when the intervention sites are expected to exhibit increased vegetation, demonstrating a clear difference in NDVI values between the intervention and control sites. Effectively, the site that was developed earlier becomes the intervention site or experimental site whereas a site with a later intervention date can be used as a control site until its own intervention. Using this approach, a total of 7 pairs (Table 2) across multiple sites were found.

The duration of the control experiment ranged from 3-6 years depending upon site. Although such an approach can be used as a proxy for a real control site, certain limitations must be kept in mind while interpreting the results. For example, there could be a disparity in the areas of the experimental and control sites (Table 2). To account for this, the minimum area selected in either control or intervention is 13 hectares, which has nearly 150 Landsat pixels. This ensures that we have substantial pixel counts for estimating NDVI. We divided NDVI data into two time periods:

1. Baseline period - Years 2010 to the intervention year on experimental sites, pre-intervention baseline years.

2. Experiment period - From intervention on experimental site to the intervention on control site.

Note: We excluded the time period after the intervention at the control site because the data available for the post-intervention at both sites was too short to make inferences.

For example, the polygon with site ID 1 in Dan Goudau was developed in 2013 whereas site ID 0 was developed in 2018. Therefore, polygon ID 1 becomes experimental polygon whereas polygon ID 0 can be used as control till 2018. The years 2010-2013 is termed as the baseline period, 2014-2018 as experiment period, and 2019-2020 as the post-experiment years excluded from this analysis. Figure 8 shows the NDVI time series for two locations, Dargue and Karkara, for the intervention and control sites. Intervention polygons at both locations had NDVI values similar to or less than the corresponding control sites during the baseline period. During the experiment period, NDVI values at the intervention sites increased significantly, resulting in larger differences with the control sites. After the end of the experiment period, the NDVI values for the control sites begin to match with the NDVI values from the intervention sites due to increased vegetation, thus reducing the differences of NDVI values between the paired sites. The analysis again shows that the intervention had a significant positive impact on vegetative greenness in the region.

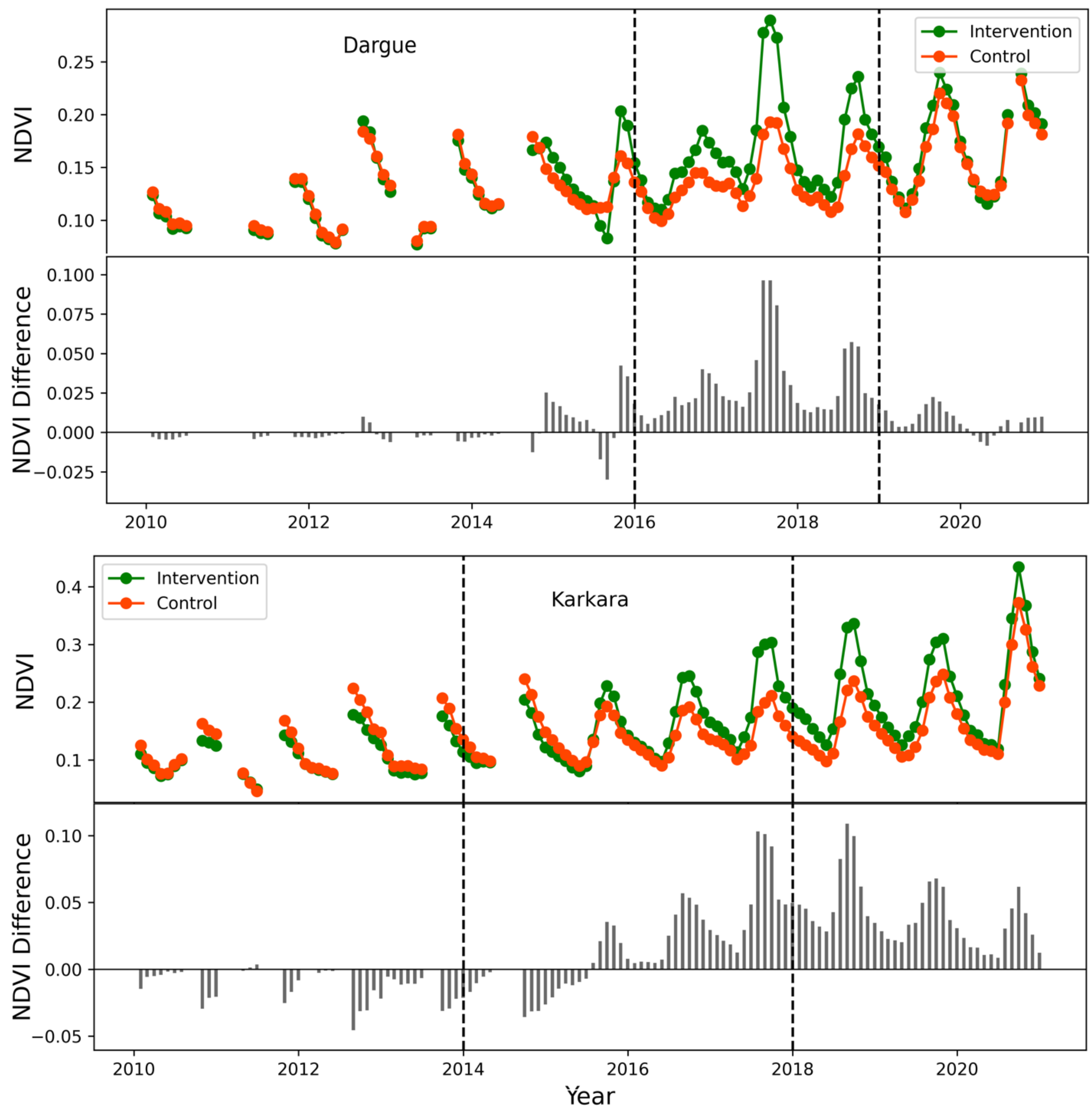

Figure 8: NDVI values as seen at the control and intervention sites from 2010-2020 for Dargue (top) and Karkara (bottom). The vertical lines show the beginning and end of the control experiment periods.

Analysis of the control areas shows that the difference in mean NDVI values at baseline for both experimental and control sites are similar. A test of difference failed to reject (p-value =0.4) the null-hypothesis that the means are statistically similar. During the experiment period, the average difference in mean NDVI across the sites was 0.028 (p-value <0.05), indicating a statistically significant difference between the control and experimental sites. Furthermore, we performed the before-after control-impact (BACI) (Smith, 2002; Underwood, 1992) analysis to quantify the impact of interventions during the experiment period. The analysis shows that there was a BACI contrast of -0.061 with nearly 56% relative contrast in NDVI value. The negative value of the BACI contrast (in the units of NDVI) indicates that greenness has increased in the experiment site with respect to the control relative during the baseline period. The relative contrast (a ratio of BACI contrast to mean baseline NDVI from experiment site) is a unitless normalized value used to express the impact of intervention expressed as a percentage.

TABLE 2. HECTARAGE AND MEAN NDVI VALUES OF EXPERIMENT AND CONTROL SITES

	Intervention ID	Intervention Year	Intervention Area	Control ID	Control Year	Control Area	Baseline NDVI (Ctrl)	Baseline NDVI (Intervened)	Expt NDVI (Ctrl)	Expt NDVI (Intervened)
Dan Goudau	1	2013	370	0	2018	110	0.118	0.121	0.122	0.154
*Dan Gueza**	*0*	*2015*	*310*	*6*	*2018*	*50*	*0.130*	*0.148*	*0.149*	*0.180*
Dargue	4	2016	90	3	2019	11	0.124	0.127	0.149	0.176
Djero	2	2013	17	1	2017	14	0.101	0.118	0.088	0.157
Gougouhema	1	2014	67	11	2019	30	0.100	0.094	0.113	0.121
Karkara	0	2014	59	9	2018	15	0.122	0.110	0.143	0.177
Satara	2	2013	13	4	2019	47	0.065	0.060	0.087	0.105
Mean							**0.109**	**0.111**	**0.122**	**0.153**

Overall, the NDVI analysis shows that the vegetation during the baseline period was comparable between the two sets of polygons. During the experiment period, the vegetation was more than 25% higher at intervention sites compared to control sites.

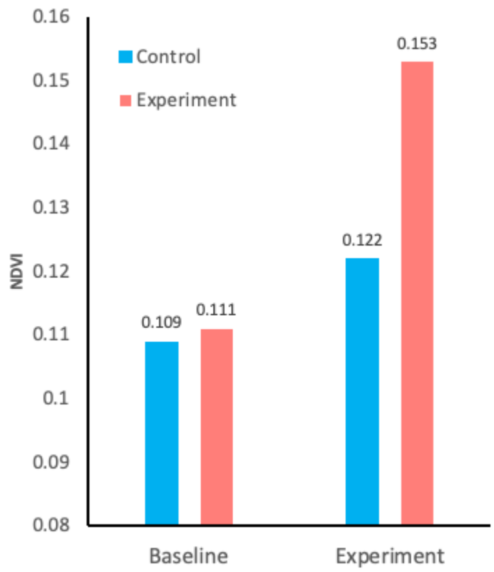

Figure 9: Difference in mean NDVI during the baseline and experiment period for control and intervened sites.

LIMITATIONS AND FUTURE DIRECTIONS

Satellite-driven vegetative greenness can be used to assess the impact of soil water conservations. However, certain limitations of such an approach must be taken into account while interpreting the results. The satellite measurements used in this analysis are based on visible and near-infrared bands that cannot penetrate clouds. Therefore, cloud cover could result in significant data gaps. We mitigated this challenge by using Landsat 7 data from 2010 only, ensuring data availability of more than 74% for the months when NDVI value peaked. Potential data gaps on top of 16-day temporal resolution of Landsat 7 sensors can lead to missing data on key phenological stages. Furthermore, the spatial resolution of 30 m may not be appropriate for some of the smaller (>1 ha) intervention sites. Use of harmonized multi-sensor analysis including more recent Landsat 8, Landsat 9, and Sentinel-2 has the potential to mitigate some of these limitations. Inclusion of Sentinel-1 synthetic aperture radar (SAR) data can penetrate through most thin clouds and thus alleviate data gap concerns.

Another gap in this analysis is testing the robustness of the interventions under drought conditions. For most of the sites, the rainfall during the post-intervention time frame was higher than the long-term mean. Therefore, we could not assess the efficacy of these interventions under drought conditions. Continuous monitoring of these sites for longer periods of time will give more insight into the effectiveness and sustainability of these interventions.

CONCLUSION

This analysis covers 18 sites in southern Niger in which the WFP assisted to develop half-moons between 2013-2020. Each site has several polygons of sizes ranging from less than one to nearly 400 ha. The satellite-based NDVI measurements were used to assess the impact of these interventions on vegetative conditions. Using Landsat 7 imagery, the analysis shows that the peak NDVI values increased nearly 50% after the interventions. Satellite data was able to detect significantly higher vegetation greenness as compared with the pre-intervention periods. This indicates improved grazing land for pastoralists and cropland for farmers. Analysis of vegetation at intervention sites and nearby control sites suggests that the interventions had a large significant impact on increased vegetation as measured by the NDVI values, whereas the control sites showed a modest increase in vegetation conditions. The increase in vegetation greenness at the intervention sites is more than 25% greater than at the control sites.

Overall, the analysis shows that the half-moons result in substantial improvement in the greenness of landscapes. Additional work is needed to link the increased greenness to crop productivity analysis.

REFERENCES

Andres, L., Boateng, K., Borja-Vega, C., Thomas, E., 2018. A Review of In-Situ and Remote Sensing Technologies to Monitor Water and Sanitation Interventions. Water 10, 756. https://doi.org/10.3390/w10060756

Bayala, J., Sanou, J., Bazié, H.R., Coe, R., Kalinganire, A., Sinclair, F.L., 2020. Regenerated trees in farmers' fields increase soil carbon across the Sahel. Agroforest Syst 94, 401–415. https://doi.org/10.1007/s10457-019-00403-6

Bayen, P., Lykke, A.M., Moussa, B.M., Bognounou, F., Thiombiano, A., 2020. Effects of Three Different Planting Techniques on Soil Water Content, Survival, and Growth of *Senegalia* Seedlings on Semi-Arid Degraded Lands in Burkina Faso. Tropical Conservation Science 13, 194008292097208. https://doi.org/10.1177/1940082920972081

Brown, M.E., Pinzon, J.E., Didan, K., Morisette, J.T., Tucker, C.J., 2006. Evaluation of the consistency of long-term NDVI time series derived from AVHRR, SPOT-vegetation, SeaWiFS, MODIS, and Landsat ETM+ sensors. IEEE Trans. Geosci. Remote Sensing 44, 1787–1793. https://doi.org/10.1109/TGRS.2005.860205

Danso-Abbeam, G., Dagunga, G., Ehiakpor, D.S., 2019. Adoption of Zai technology for soil fertility management: evidence from Upper East region, Ghana. Economic Structures 8, 32. https://doi.org/10.1186/s40008-019-0163-1

Feed The Future, 2016. Feed the Future Impact Evaluation Resilience in the Sahel- Enhanced (RISE) Project 2015 Baseline Report. USAID, Rockville, MD: Westat.

Funk, C., Peterson, P., Landsfeld, M., Pedreros, D., Verdin, J., Shukla, S., Husak, G., Rowland, J., Harrison, L., Hoell, A., Michaelsen, J., 2015. The climate hazards infrared precipitation with stations—a new environmental record for monitoring extremes. Scientific Data 2, 150066. https://doi.org/10.1038/sdata.2015.66

Halbrendt, J., Kimura, A.H., Gray, S.A., Radovich, T., Reed, B., Tamang, B.B., 2014. Implications of Conservation Agriculture for Men's and Women's Workloads Among Marginalized Farmers in the Central Middle Hills of Nepal. Mountain Research and Development 34, 214–222. https://doi.org/10.1659/MRD-JOURNAL-D-13-00083.1

Heiskanen, J., Liu, J., Valbuena, R., Aynekulu, E., Packalen, P., Pellikka, P., 2017. Remote sensing approach for spatial planning of land management interventions in West African savannas. Journal of Arid Environments 140, 29–41. https://doi.org/10.1016/j.jaridenv.2016.12.006

Huete, A., Didan, K., Miura, T., Rodriguez, E.P., Gao, X., Ferreira, L.G., 2002. Overview of the radiometric and biophysical performance of the MODIS vegetation indices. Remote Sensing of Environment 83, 195–213. https://doi.org/10.1016/S0034-4257(02)00096-2

Jung, J., Maeda, M., Chang, A., Bhandari, M., Ashapure, A., Landivar-Bowles, J., 2021. The potential of remote sensing and artificial intelligence as tools to improve the resilience of agriculture production systems. Current Opinion in Biotechnology 70, 15–22. https://doi.org/10.1016/j.copbio.2020.09.003

Kerle, N., Ghaffarian, S., Nawrotzki, R., Leppert, G., Lech, M., 2019. Evaluating Resilience-Centered Development Interventions with Remote Sensing. Remote Sensing 11, 2511. https://doi.org/10.3390/rs11212511

Meroni, M., Schucknecht, A., Fasbender, D., Rembold, F., Fava, F., Mauclaire, M., Goffner, D., Di Lucchio, L.M., Leonardi, U., 2017. Remote sensing monitoring of land restoration interventions in semi-arid environments with a before–after control-impact statistical design. International Journal of Applied Earth Observation and Geoinformation 59, 42–52. https://doi.org/10.1016/j.jag.2017.02.016

Nyamekye, C., Schönbrodt-Stitt, S., Amekudzi, L.K., Zoungrana, B.J. -B., Thiel, M., 2021. Usage of MODIS NDVI to evaluate the effect of soil and water conservation measures on vegetation in Burkina Faso. Land Degrad Dev 32, 7–19. https://doi.org/10.1002/ldr.3654

Nyamekye, C., Thiel, M., Schönbrodt-Stitt, S., Zoungrana, B., Amekudzi, L., 2018. Soil and Water Conservation in Burkina Faso, West Africa. Sustainability 10, 3182. https://doi.org/10.3390/su10093182

Oakland Institute, 2015. Soil and Water Conservation Techniques in Burkina Faso, Agroecology Case Studies. Oakland Institute and Alliance for Food Sovereignity in Africa.

Partey, S.T., Zougmoré, R.B., Ouédraogo, M., Campbell, B.M., 2018. Developing climate-smart agriculture to face climate variability in West Africa: Challenges and lessons learnt. Journal of Cleaner Production 187, 285–295. https://doi.org/10.1016/j.jclepro.2018.03.199

Qi, J., Chehbouni, A., Huete, A.R., Kerr, Y.H., Sorooshian, S., 1994. A modified soil adjusted vegetation index. Remote Sensing of Environment 48, 119–126. https://doi.org/10.1016/0034-4257(94)90134-1

Rinaudo, T., 2007. The development of farmer managed natural regeneration. Leisa Magzine 32–34.

Roose, E., Kabore, V., Guenat, C., 1999. Zai Practice: A West African Traditional Rehabilitation System for Semiarid Degraded Lands, a Case Study in Burkina Faso. Arid Soil Research and Rehabilitation 13, 343–355. https://doi.org/10.1080/089030699263230

Sawadogo, H., 2011. Using soil and water conservation techniques to rehabilitate degraded lands in northwestern Burkina Faso. International Journal of Agricultural Sustainability 9, 120–128. https://doi.org/10.3763/ijas.2010.0552

Smith,E.P. 2002. BACI design. Encycl. Environmetr. 1, 141–148, http://dx.doi.org/10.1002/9780470057339.vab001.pub2.

Tucker, C.J., 1979. Red and photographic infrared linear combinations for monitoring vegetation. Remote Sensing of Environment 8, 127–150. https://doi.org/10.1016/0034-4257(79)90013-0

Weston, P., Hong, R., Kaboré, C., Kull, C.A., 2015. Farmer-Managed Natural Regeneration Enhances Rural Livelihoods in Dryland West Africa. Environmental Management 55, 1402–1417. https://doi.org/10.1007/s00267-015-0469-1

Wouterse, F., 2017. Empowerment, climate change adaptation, and agricultural production: evidence from Niger. Climatic Change 145, 367–382. https://doi.org/10.1007/s10584-017-2096-8

Underwood, A.J., 1992. Beyod BACI: the detection of environmental impacs on poplations in the real, but variable, world. J. Exp. Mar. Biol. Ecol. 161,145–178, http://dx.doi.org/10.1016/0022-0981(92)90094-Q.