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Evaluating the response of conventional and water harvesting farms to environmental variables using remote sensing

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ABSTRACT

The majority of people in Sub-Saharan Africa (SSA) live in rural communities and practice subsistence farming. Variations in climate and other environmental factors affect the stability of local food production. This instability makes the adoption of efficient farming techniques critical in helping farmers achieve food, income, and livelihood security. Agricultural water conservation techniques called water harvesting are being implemented to increase crop yields in SSA. These techniques have been shown to increase water productivity, nutrients, and organic matter in the soil. This paper uses high-resolution imagery to identify and differentiate between farms using conventional and water-harvesting farm methods. An ordinary least-squares regression model was used to correlate seasonal maximum normalized difference vegetation index (NDVI) values with environmental factors for the different farming methods. The results suggest that water harvesting farm techniques have higher crop yields and are less dependent on precipitation than conventional farming methods. The methodology presented in this paper can be used to map use of water harvesting over large areas and monitor associated differences in productivity.

1. Introduction

Agriculture in Sub-Sharan Africa (SSA) is vulnerable to the impacts of climate variability and soil degradation (Challinor et al., 2007; Smaling et al., 1997). Demand for higher crop yields will continue to increase in SSA where the population average growth is at 2.7% per year compared to the world average yearly growth of 1.1% (Canning et al., 2015). Monitoring agricultural productivity, including gaps between actual and potential yield, can help policy makers implement better ways to increase crop yields in rainfed agriculture. Precipitation rates and low soil fertility are the principal constraints preventing higher crop yields in smallholder farms in SSA (Chikowo et al., 2015; Smaling et al., 1997). As a result of environmental conditions on rainfed farms; farmers increasingly rely on marginal lands where crop production is low (Binswanger and Pingali, 1988; Wildemeersch et al., 2015). Approximately 65% of the agricultural lands in SSA have been degraded, threatening food security and the quality of the environment (Muchena et al., 2005).

Climate is a key driver in food production in SSA (Grace et al., 2012; Gregory et al., 2005; Verdin et al., 2005; and many others). Variation in climate leading to droughts, flooding, and soils leeched of nutrients can affect the stability of local crop production. Variability in precipitation has caused agricultural land to be vulnerable to poor crop production as annual precipitation can vary as much as 30% from year to year (Philipp and Christophe, 2006; Sultan et al., 2013). The intra-seasonal rainfall distribution in SSA is becoming more unstable, with increasing numbers of longer, very heavy rainy days, as well as flooding and longer dry spells causing a reduction in crop yield outputs. (Salack et al., 2015). Temperatures can also pose a threat to crop production. Lobell et al. (2011) found that for each day when temperatures were above 30 °C, crop yields were reduced by 1% under optimal rainfed conditions and by 1.7% under drought conditions. Farmers continue to find new ways to adapt to climate vulnerability by using drought and heat resistant seeds in SSA. Variability in temperatures, especially during early plant development can impede growth reducing yields (Christensen and Christensen, 2007).

Vulnerability in crop yields is not only a function of climate but of other environmental factors such as soil properties (Challinor et al., 2007; Ramankutty et al., 2002). The semi-arid/arid climate and windy conditions in SSA result in topsoil erosion and nutrient loss inhibiting the growth of plants (Smaling et al., 1997). Erosion reduces water infiltration where crops are grown and decreases water productivity. Wind and water erosion transport silt and clay from fields, leaving fields lacking in nutrients (Murage et al., 2000). Soils stripped of nutrients and organic matter reduce water productivity and increases the yield gap (Sidibé, 2005; Murage et al., 2000). Adaptation of farming

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techniques to climate variability and soil degradation is critical to helping farmers achieve food, income and livelihood security (Hassan and Nhemachena, 2008).

In addition to environmental factors, farming techniques used in SSA also affect crop yield. Conventional farming methods for rainfed farms in SSA usually consist of farmers plowing or hoeing fields without the aid of irrigation strategies. These conventional farming methods within SSA in some years have failed to provide enough nourishment due to low crop yields (Amede et al., 2011; Critchley and Gowing, 2012). Water harvesting techniques are methods of farming that provide the catchment of water for the use of agricultural purposes and are being implemented in SSA to increase crop yields. Water harvesting systems help increase water productivity and may be defined as "methods of collecting and concentrating various forms of runoff (rooftop, runoff, overland flow, stream flow etc.) from various sources (precipitation, dew, etc.) and for various purposes" (Reij et al., 1988). Water productivity in agriculture signifies an efficiency of water for growing crops and is measured as mass per unit of water transpired at any scale (Molden et al., 2003). Water harvesting techniques such as macro-catchments help keep soils from eroding by slowing the rate of the flow of water. These techniques help keep nutrients and organic matter in the soil and increase the water productivity of farms. Water harvesting techniques can be practiced within, around, and outside the area used for farming (Reij et al., 2009), and have been shown to have greater crop yield production than conventional farming techniques (Barbier et al., 2009; Sidibé, 2005; Tabor, 1995).

Water harvesting techniques commonly used in SSA include zai pits, stone strips, fallow bands, and catchment ponds. (Sidibé, 2005). Zai pits are shallow holes that capture water runoff and hold organic matter where crops are grown within. Stone or earthen strips are arranged perpendicular to the slope of the land in order to slow down water runoff and spread water across the farmlands for better moisture retention. Fallow bands include ridging, mulching with post-harvest crop residue and windbreaks to reduce soil erosion and increase water retention. Catchment ponds are barren water storage areas, which collect runoff water, to irrigate crops. The tactical placement of a farm can also be considered a water harvesting technique. Locating a farm near a wadi and using macro-catchments to divert water to farmlands is a common form of water harvesting in Burkina Faso (Barbier et al., 2009; Van Duivenbooden et al., 2000).

The first major water harvesting projects in Burkina Faso were implemented by governmental entities and NGOs between 1962 and 1965, called GERES (Groupment European de Restauration des Sols). GERES, in north-central Burkina Faso, treated 120,000 ha using stone and earthen bunds to catch water and reduce erosion (Marchal, 1979; Reij et al., 2009). The project was ineffective because it did not include the farmers' involvement and they did not maintain the earthen bunds (Marchal, 1979). In the mid-1980s, the Sahelian "Green Revolution" began within some regions of Burkina Faso. Local, national, and international organizations helped increase knowledge and funding for low-cost improved practices of farming (Harrison, 1987; Reij et al., 2009). Water harvesting practices included macro-catchments in watersheds and zai pits. The results of these projects have helped subsistence farmers become more resilient and less sensitive to climate variability. By the 1990's the technique of building stone earthen bunds had become more effective in increasing yields in comparison to conventional farming methods (Atampugre, 1993; Batterbury, 1998).

Multiple on-farm studies have compared the influence of crop yields of conventional farming techniques to water harvesting farms. A study by Tabor (1995) in Niger found that average conventional farming yields of millet to be 417 kg ha^{-1}. In contrast, average millet yields using catchments ponds and the addition of fertilizer were 3100 kg ha^{-1}. Niger's average yield unit-labor was 0.65 kg while the catchment ponds yield unit-labor averaged 0.83 kg (Tabor, 1995). Other field studies in SSA and Burkina Faso have demonstrated reduced yield gaps using water harvesting techniques including zai pits (Amede et al., 2011, Sidibé, 2005), stone strips (Barbier et al., 2009), furrow bands (Ikazaki et al., 2011), and catchment ponds (Sawadogo, 2011).

Remote sensing provides information on the health of crops, crop yield estimations, and crop identification. Monitoring crop production through remote sensing is becoming more important in long-term planning of food security initiatives due to droughts and rain variability (Marshall et al., 2011). Higher spatial resolution sensors, greater temporal availability and new sensor bands are increasing the ability to measure the vegetation index (VI) values of crops. VI's are radiometric measures that are usually a variation of band ratios or linear combinations used to serve as an indicator of the relative growth of green vegetation (Huete et al., 1994; Wickland, 1989).

We used high spatial resolution remote sensing to map farms using water harvesting or conventional agricultural techniques in Burkina Faso. Coarser resolution Landsat remote sensing data were used to monitor normalized difference vegetation index (NDVI) values, a proxy for crop yields, over time. A multiple ordinary least squares (OLS) regression model was used to examine relationships between environmental factors and maximum NDVI values of water harvesting and conventional farms. In addition to demonstrating a novel methodology for comparing productivity on farms using water harvesting and conventional techniques, we also addressed the following research questions: 1) Is there a significant difference in the maximum NDVI values between conventional farms and water harvesting farms? 2) What are the differences in environmental factors that impact the development of vegetation (as reflected in maximum NDVI) for conventional and water harvesting farms, and how can these differences be explained?

2. Data

2.1. Study area

Burkina Faso lies within the Sahel region of Africa on the fringe of the Sahara Desert (Fig. 1). The terrain is mostly flat with dissected plains and plateaus. The elevation of the country ranges from 200 to 750 m. Approximately 70% of Burkinabe live in rural areas (WB, 2015). Over 90% of the workforce is employed in agriculture and is dominated by small-scaled farms of less than 5 ha (FAO, 2014). The main crops grown in the study areas for this paper are millet and sorghum. The majority of farmers rely on rain and not irrigation to grow crops.

There are four climatic regions from north to south within Burkina Faso: Sahel, Sub-Sahel, North-Sudan, and South-Sudan. Average rainfall varies from 250 mm in the north and increases to 1200 mm in the south-west (Lodoun et al., 2013). Burkina Faso lies in the intertropical convergence zone (ITCZ) which moves north and south of the equator; this zone creates convectional lifting resulting in increased precipitation (Fontaine et al., 2011). Most of the rain comes during the monsoon season from May to September in Burkina Faso, and crops are grown during the monsoon season. The country has a high seasonal variation in rainfall and degraded soils that often lead to uncertain food harvests (Mertz et al., 2012). Agricultural output is sporadic, droughts occur frequently, soils are poor and agricultural fields are prone to erosion (Rojas et al., 2011).

2.2. Imagery and NDVI data

QuickBird (QB) imagery was used to map farm types in the northern Burkina Faso study areas (Fig. 1). Each QB panchromatic (grayscale) image is approximately $16 \times 16\,km^2$. The panchromatic QB images have a spatial resolution of 0.6 m and were acquired on 14 November 2013. Google Earth imagery was used to confirm farm type and agricultural use for each sample in this study. Two satellite imagery companies provide Google Earth with the high-resolution imagery to be used in this study. First, Digital Globe provides imagery from two satellites, QuickBird and WorldView-2. In addition to panchromatic data, Quickbird has a multispectral spatial resolution of 2.2 m. WorldView-2

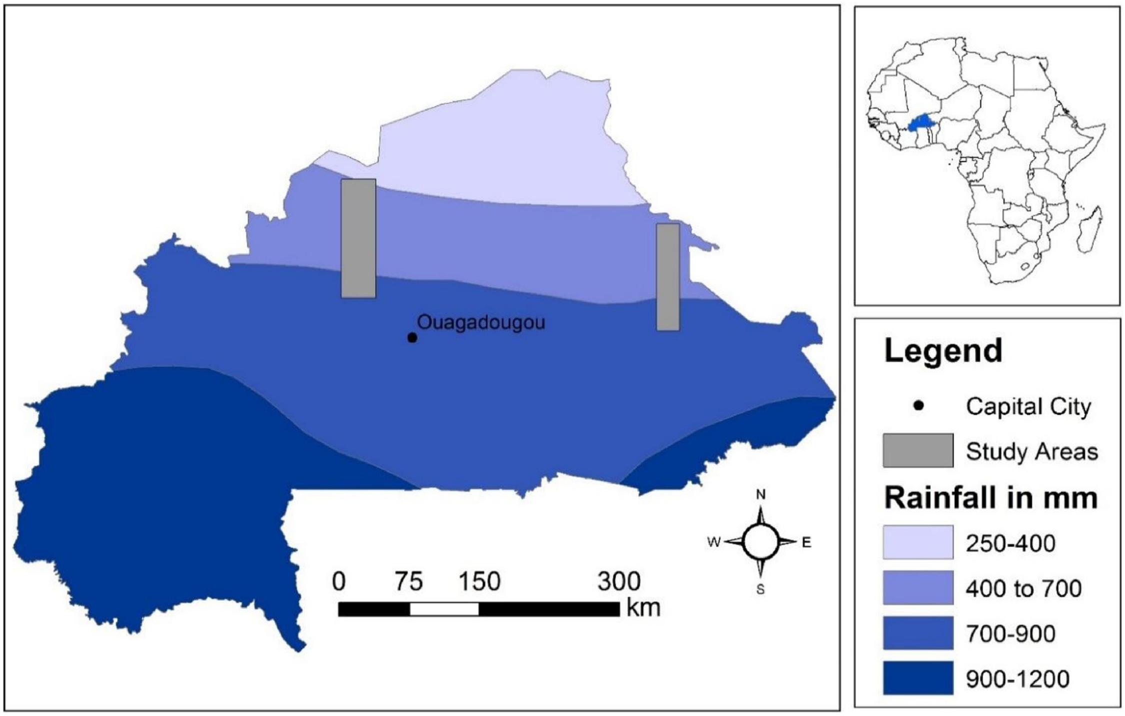

Fig. 1. The study area covers various study sites within Burkina Faso. Approximate ranges of precipitation were averaged from 1950 to 2000 (www.worldclim.org).

has a panchromatic resolution of 0.46 m and a mutlispectral resolution of 1.85 m (DigitalGlobe, 2013). Second, CNES/Astrium provides imagery from two satellites, Pléiades 1A and Pléiades 1B. The images produced from the two satellites have a 0.50 m panchromatic with a 2 m multispectral resolution (Pléiades, 2015). Both satellite companies pan sharpen their multispectral images using higher resolution panchromatic data to provide sub-meter colored images (DigitalGlobe, 2013; Pléiades, 2015).

Landsat 8 Operational Land Imager (OLI) imagery was acquired from May–November of 2013 to find the maximum NDVI values for each farm. NDVI is the most common VI used for crop monitoring by many government and non-government organizations (NGOs) (e.g., Goswami et al., 2015; Machwitz et al., 2015), and provides a measure for "greenness" that has been shown to be related to primary productivity and leaf area of plants (Townshend and Justice, 1986). NDVI correlates well with leaf area index (LAI) and the evapotranspiration values of farms (Biradar et al., 2008).

OLI imagery has a spatial resolution of 30 m and a temporal resolution of 16 days. Images with cloud cover over farms were discarded. Farm locations were selected where Landsat 8 OLI imagery paths overlapped allowing for an average temporal resolution of eight days. Bidirectional reflectance distribution function (BRDF) affects the NDVI in overlapping scenes, however, the 15° field of view of OLI is small relative to many sensors and should result in only minor differences in NDVI between the forward and backscattering directions. The OLI imagery was acquired as a level-1 tier product having a high quality of precision (< 12 m root mean square error) and radiometric quality that was cross-calibrated among different Landsat sensors.

3. Methodology

3.1. Remote sensing analysis

Water harvesting and conventional farms were digitized within each study area from Quickbird (QB) images. Farms with distinct attributes of conventional and water harvesting farm qualities were selected. Google Earth historical imagery was used to verify agricultural use through the growing season. Water harvesting farms were identified by having one or more of the following attributes: zai pits, furrow bands, contour stone-bunds and catchment ponds. Conventional farms were identified by having no water catchment techniques visible in or around the farming area (Fig. 2). Five hundred conventional and five hundred water harvesting farms were analyzed for this study. Digitized farm polygons were converted to centroid points for extraction of other variables. Farm types could have been misclassified with no on-ground observations, however, the use of high-resolution imagery (< 1 m)

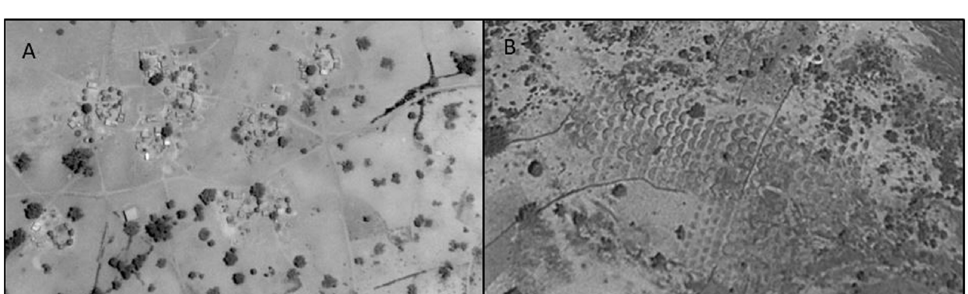

Fig. 2. QuickBird image subsets displaying farming methods practiced around villages in Burkina Faso. (A) Conventional farming methods; (B) water harvesting methods using contour lines and demi-lunes to capture water run-off.

allows the image analyst to identify water harvesting structures providing a high level of confidence that each farm type is classified correctly.

The Landsat 8 OLI imagery was acquired during May–November 2013. NDVI values derived from the OLI imagery were overlaid on each farm. NDVI values were collected within each farm that was clear of shrubs and trees. NDVI values were collected in the beginning of May as a control value between conventional and water harvesting farms. The maximum NDVI of farms corresponding with plant growth was collected based upon the highest NDVI value within the growing season.

3.2. Environmental variables

Additional variables, mostly derived from remote sensing, were used to model maximum NDVI values of farms practicing water harvesting and conventional agriculture. Each variable is described below.

Tree density - Trees provide multiple benefits for farmers and their fields (Reij et al., 2009). The trees reduce wind speed and evaporation (Reij et al., 2006). Many of the trees selected to grow on farmers' fields such as *Faidherbia albida* are nitrogen-fixing, enhancing soil fertility. The trees also provide fodder for livestock, which in turn fertilize the farm fields (Amede et al., 2001). Tree density was measured by the number of trees per farm plot divided by the area of the farm, as determined in QB imagery.

Village distance - The proximity of farmers to their farm can be significant in the production of crops in SSA. Studies by Amede et al. (2011) and Elias et al. (1998) have observed the closer the farm to the homestead, the higher the crop yields due to more attention being given to taking care of the farm plot. Farms close to homesteads are favored for application of household refuse, manure and enriched by nutrients in the form of feed and mulch (Amede et al., 2001). Village distance was measured as the distance of a farm to a cluster of structures used as a settlement.

Slope - Cultivation of farms on steep slopes may cause soil loss and water runoff (Sanchez, 1987). Gentle slopes can aid in capturing runoff water for crops to improve crop yield (Reij et al., 1988). Runoff water is often slowed by contour stone-bunds and the runoff water is concentrated into cultivated fields. Slope data retrieved from Shuttle Radar Topographic Mission (SRTM) datasets were acquired from the U.S. Geological Survey's (USGS), having a spatial resolution of 90 m to measure the slope of farms (USGS, 2016).

Soil type - Most soil types in Burkina Faso lack essential nutrients such as phosphorous and nitrogen constraining production of smallholder farms (Gemenet et al., 2015; Vanlauwe and Giller, 2006). There are a variety of soil types in Burkina Faso, the most common soils are Plinthosols and Lixisols (Jones et al., 2013). Soil variations occur over broad landscapes as well as within small field plots (Huete, 1988). Soil data was acquired from Joint Research Centre – European Soil Data Center (JRC-ESDAC, 2013), having a spatial resolution of 100 m.

Farm size - Studies have shown an inverse relationship between productivity (economic efficiency) and size of rural smallholder farms (Byiringiro and Reardon, 1996; Dorward, 1999). Byiringiro and Reardon (1996) and Dorward (1999) explain that smaller rural smallholder farms are better managed than larger farms and smaller farms have better soil conservation. Polygons were created for each farm plot using QB imagery.

Seasonal mean and maximum land surface temperature - Land Surface Temperature (LST) is the temperature of the interface between the Earth's surface and its atmosphere (Stisen et al., 2007). Crop yields are sensitive to the temperature throughout the growing season. Higher mean temperatures reduce crop yield for subsistence small holder farmers (Kurukulasuriya et al., 2006; Lobell et al., 2011). NASA produces a MODIS (Moderate Resolution Imaging Spectrometer) LST raster data that was used for finding seasonal mean and maximum surface temperatures. This dataset has a 1 km spatial resolution and an eight-day temporal resolution. The mean and maximum data sets were acquired during the growing season (May–November).

Precipitation total and anomaly - The majority of rain in Burkina Faso comes during the monsoon season, but there are strong fluctuations of precipitation amounts within short distances (Ibrahim et al., 2014). Precipitation data were obtained from May-November 2013 using Climate Hazards Group InfraRed Precipitation with Situ-data (CHIRPS) daily raster images. The raster datasets are accumulated rainfall, which has been aggregated from daily estimates using satellite infrared raster images in congruence with rain data collected from the nearest rain stations (Funk et al., 2014). The CHIRPS raster data have a spatial resolution of 0.05° or roughly 5.5 km. Precipitation anomaly refers to the departure of 2013 precipitation from long-term average for a given area.

Land use - The land cover type around farmland can affect its microclimate (e.g. wind speed, evapotranspiration and soil type) (Belsky, 1994; Cleugh, 1998; Senjobi and Ogunkunle, 2011). The surrounding land use types of farms influence soil composition. Dense vegetation in and around farms can increase soil nutrients and productivity (Senjobi and Ogunkunle, 2011; Jonsson et al., 1999). Trees around farmland can act as a windbreak reducing soil erosion (Cleugh, 1998). The land-use classification was attained from GlobeLand30-2010 (GLC30). GLC30 produces a multispectral 30 m spatial resolution image with 10 land-use classes.

Region - Burkina Faso varies in many aspects throughout the country including precipitation (Lodoun et al., 2013), temperature (Rasmussen, 1992), farming practices (Reij et al., 1988), soil types (Smaling et al., 1997), *etc*. Province was considered as a variable that might impact crop yields.

3.3. Modeling

The paired *t*-test is a statistical technique used to compare two sample means where the samples are matched-pairs. Two paired *t*-tests were calculated to compare NDVI values for water harvesting and conventional farms. The first paired *t*-test was conducted at the beginning of the season as a control for NDVI values between farming techniques. The second paired *t*-test compared the seasonal maximum NDVI values of the two farming methods. Conventional and water harvesting farms within a proximity of 5 km of each other were paired for both tests. Matching farms in proximity to each other reduced confounding factors such as environmental variables that vary spatially throughout Burkina Faso.

Environmental factors such as precipitation, temperature, and soil composition can affect yields (Smaling et al., 1997; Sultan et al., 2013; Waongo et al., 2015), but different farming methods may have differing sensitivities to environmental factors. For example, it is expected that water harvesting farms may be less sensitive to rainfall and temperatures due to their ability retain more water in the soil (Amede et al., 2011; Reij et al., 1988).

OLS regression modeling can be used to determine the relationship between a dependent variable and multiple independent variables (Burt et al., 2009). A multiple OLS regression model was used to assess how multiple independent variables are related to maximum NDVI values of the two farm types. The equation for a model examining the relationship of several independent variables to one dependent response variable is (Aldrich and Nelson, 1984):

$$NDVI_{max} = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \ldots \beta_n X_n + \varepsilon \quad (1)$$

where X represents environmental variables and β indicates model coefficients. Each β parameter indicates the average change in $NDVI_{max}$ that is associated with a unit change in X while simultaneously controlling for other explanatory variables in the model. ε represents an error term which is minimized by the model. Model fitting can be determined by comparing the observed and predicted values of maximum NDVI.

Table 1
Descriptive statistics of Farming methods used in this study.

Farming Method	Max NDVI Average	Standard Deviation	% of Sample Size
Conventional	0.314	0.073	50%
Catchment Ponds	0.332	0.073	2.5%
Fallow Bands	0.342	0.067	10%
Mix	0.334	0.84	10.5%
Stone Strips	0.334	0.069	25%
Zai Pits	0.377	0.066	2%

4. Results

A description of conventional farms and the various types of water harvesting techniques are displayed in Table 1. The sample includes 500 conventional farms and 500 water harvesting farms. All water harvesting techniques have a higher maximum NDVI average than conventional farms. The most prevalent water harvesting techniques found in this study were the use of stone strips. It was common for multiple water harvesting techniques to be combined together to increase soil and water retention. The numerical averages of environmental factors for conventional and water harvesting farms are displayed in Table 2. Conventional and water harvesting farms had similar averages of maximum LST, mean LST, elevation, slope, tree density, and household distance. Water harvesting farms received slightly less precipitation and were slightly smaller than conventional farms. Water harvesting farms had a larger difference in NDVI values from May to when the NDVI values were the highest during the growing season than conventional farms.

The control matched paired *t*-test conducted at the beginning of the season showed no significant difference between NDVI values for the two farming methods. Water harvesting farms displayed a significantly higher ($p \leq 0.005$) maximum NDVI for the 2013 growing season. The maximum NDVI average for water harvesting farms was 0.023 higher than conventional farms. While this difference is relatively small in comparison to the seasonal range in NDVI, these results are in accordance of other on-the-ground productivity tests between water and conventional farming methods (Adamtey et al., 2010; Amede et al., 2011).

The variables that were most significant for explaining maximum NDVI values for conventional farms included precipitation anomaly, village distance, precipitation total, region, landcover, farm size, and soil (Table 3). Precipitation was highly correlated to maximum NDVI in conventional farms. Maximum NDVI values were highly negatively correlated ($p \leq 0.001$) with precipitation anomaly for conventional farms. Precipitation total had a strong positive correlation, with an increase in precipitation correlated to an increase in maximum NDVI. Village distance was another highly correlated variable, with farms further from a village having an overall lower maximum NDVI value.

Table 2
Numerical environmental averages for conventional and water harvesting farms.

Averages	Conventional Farms	Water Harvesting Farms
Precipitation Total (mm)	543.2	539.8
Precipitation Anomaly (mm)	33.7	31.7
Mean LST (C°)	24.6	24.5
Max LST (C°)	29.8	29.9
Elevation (m)	285.2	288.7
Slope (%)	0.04	0.13
Area (ha)	0.61	0.54
Trees per Hectare	0.16	0.16
Household Distance (m)	615	617
May NDVI	0.129	0.134
Max NDVI	0.314	0.337
NDVI Difference	0.185	0.203

Table 3
Variables found significant for modeling maximum NDVI values for conventional and water harvesting farms. The sign of the beta coefficient indicating a positive or negative correlation is in parentheses following each variable.

Significance	$p < 0.001$	$0.001 < p < 0.01$	$0.01 < p < 0.05$
Conventional Farming	Precipitation Anomaly (−) Village Distance (−)	Precipitation Total (+) Yagha Province (+) Shrubland Cover (−) Farm Size (+)	Soil − Vetric Cambisols (+)
Water Harvesting Farming		Seasonal Maximum LST (−) Soil − Petric Plinthosols (+)	Farm Size (+) Slope (+) Shrubland Cover (−)

Other factors which correlated well with maximum NDVI values for conventional farming methods include shrubland landcover, Yagha Province, and vetric cambisol soils.

A different set of explanatory variables was correlated with maximum NDVI of water harvesting farms (Table 3). Precipitation variables were not significantly correlated with maximum NDVI. Seasonal maximum LST was highly negatively correlated with maximum NDVI values of water harvesting farms, indicating that high temperatures may result in reducing yields. Other factors that were significantly positively correlated were Petric Plinthosols, farm size, slope and shrubland cover.

5. Discussion

Precipitation anomaly and precipitation totals may be major drivers for crop production in conventional farms, with both variables being significantly correlated to maximum NDVI. Water harvesting farms are identified as being less dependent on precipitation. Water harvesting techniques such as contour stone bunds and zai-pits result in the catchment of water from larger areas and increased water storage for crops. Variability in seasonal climate in SSA, such as small droughts during the monsoon season, should have less of an effect on water harvesting farms due to their ability to hold water in the soil around the crops.

Maximum LST was found to be correlated with reduced maximum NDVI for water harvesting farms. The average high temperatures in Northern Burkina Faso are above 30 °C, which has been shown to reduce crop growth (Lobell et al., 2011). Temperature extremes are known to negatively impact the development and growth of crops causing a reduction in biomass (Hatfield and Prueger, 2015). Although seeds grown in this area are more durable to drought and heat, there are many possibilities such as extreme temperatures in early development that could still cause a reduction in biomass later in the growing season. Seasonal mean LST had no significant correlation with water harvesting or conventional farming methods.

For conventional farms, distance to a village was negatively correlated with maximum NDVI. This agrees with rural SSA studies on farm distance to villages from Amede et al. (2001) and Elias et al. (1998). Farms closer to villages tend to be managed better than farms further away from a village or home. Elias et al. (1998) found that soil degradation increased as distance to villages increased. Due to soil erosion and lack of inputs of important nutrients. Contrary to Byiringiro and Reardon (1996) and Dorward (1999), larger water harvesting farm size would seem to be correlated with higher yields as indicated by maximum NDVI, although water harvesting farms were still on average smaller than conventional farms.

Low crop yields resulting from poor soils have been a major issue in SSA. Soils leeched of nutrients due to wind, flooding and overuse can reduce crop yields. Conventional farm maximum NDVI values were positively correlated to Vetric Cambisols. These soils have a clay-rich subsurface horizon and are developed in medium and fine-textured materials derived mostly from alluvial, colluvial and aeolian deposit and are good quality soils for agricultural purposes. Water harvesting farm maximum NDVI values were positively correlated with Petric Plinthosols soil. They have a strongly cemented or indurated layer starting within 100 cm of the soil surface with an accumulation of iron that hardens irreversibly when exposed to air and sunlight. This soil type is considered naturally poor for agricultural use and overall needs fertilizer and nutrient inputs to be effective in growing crops. Water harvesting provides a sustainable method to close the yield gap by increasing soil fertility and water retention.

Remote sensing provides the ability to examine important environmental factors that affect crop yield at a moderate to high spatial resolution. The use of remote sensing data allowed the ability to monitor hundreds of small farms in this study. High-resolution remote sensing data can be an effective way to identify different farming methods and allows the ability to monitor environmental factors throughout the growing season(s) in remote places such as is found in SSA. The use of multiple remote sensing products used in this study were supportive in the analysis of how environmental factors can affect farms in remote areas of the world. However, not all factors affecting crop yields can be measured by remotely sensed data. Unknown factors include how well an area is weeded or cleared of pests can play an important factor in the success of crop yields.

Choosing to implement water harvesting techniques can improve farmland by reducing soil and wind erosion and help increase water retention in the soil. More work needs to be done throughout SSA and other parts of the world to examine the potential of different farming methods for increasing crop yields. Understanding how environmental factors influence farming methods will give us a better understanding of constraints in crop yield gaps and find the most effective ways to farm where little resources are available.

6. Conclusion

This study examined correlations between environmental variables and maximum NDVI for water harvesting and conventional farms. The use of high resolution imagery was effective in identifying the different methods of water harvesting used in this study. Selecting farm locations where Landsat 8 OLI imagery paths overlapped allowing for higher temporal resolution was effective in getting higher accuracies in maximum NDVI values. The sampling techniques used in this paper were effective in analyzing 12 environmental factors using remote sensors that have shown to be associated to crop yields in SSA. The environmental variables had a different impact on crop yields depending on the farming method used in this study. Based on our results, water harvesting farms are likely to be less dependent on precipitation than conventional farming methods but may still be dependent on temperature. Water harvesting farm methods have contributed to overall improvements of increasing the yield potential, helping secure livelihoods to rural farming families in Burkina Faso. Implementing the best farming techniques can help farming communities by reducing poverty by greater crop yields and reduce vulnerability to climate variability in situations such as drought and flooding.

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