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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