Human Ecology

Ground Truthing Sahelian Greening: Ethnographic and Spatial Evidence from Burkina Faso

--Manuscript Draft--

Manuscript Number:	HUEC-D-16-00061R1
Full Title:	Ground Truthing Sahelian Greening: Ethnographic and Spatial Evidence from Burkina Faso
Article Type:	Research Report
Keywords:	Sahel; land degradation; adaptation; soil and water conservation (SWC)
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Manuscript Region of Origin:	UNITED STATES
Funding Information:	National Science Foundation (BCS-1261800) — Dr. Colin Thor West
	UNC Carolina Population Center — Dr. Colin Thor West
	UNC Center for Global Health and Infectious Diseases — Dr. Colin Thor West
	Wenner-Gren Foundation (Wadsworth International Fellowship) — Ms. Elisabeth Kago Nébié

Abstract:

Historically, the Sahel of West Africa has been considered synonymous with desertification. In recent decades, however, satellite images reveal patterns of enhanced vegetation termed the "greening of the Sahel." This greening is well-documented but its mechanisms remain poorly understood. The Sahel is also a region emerging from a thirty-year period of reduced rainfall in which several severe droughts occurred. As a response to droughts and land degradation, farmers have rehabilitated thousands of hectares of degraded soils by constructing low barriers of rock through widespread soil and water conservation (SWC) development projects. Remote sensing analyses suggest that these extensive soil conservation projects may explain greening in northern Burkina Faso. This study combines ethnographic fieldwork with the analysis of Geographic Information System (GIS) and remote sensing (RS) data to test whether SWC investments contribute to greening. Ethnographic data reveals a tension between the perceptions of rural producers who feel that their SWC efforts contribute to greening and those of state officials who contend that SWC has only local impacts and that the regional landscape continues to degrade. Our analysis of GIS and RS data suggest that both perspectives are valid but contingent on the particular spatial and temporal scale used for analysis.

Figure 1. Annual Rainfall Anomalies (in S.D.) for 12o to 15oN, -3o to -5oE based on the 1981-2010 mean (~700 mm). Source: Climate Explorer at: climexp.knmi.nl

Click here to download Line Figure Figure1_Rainfall_desiccation.tif

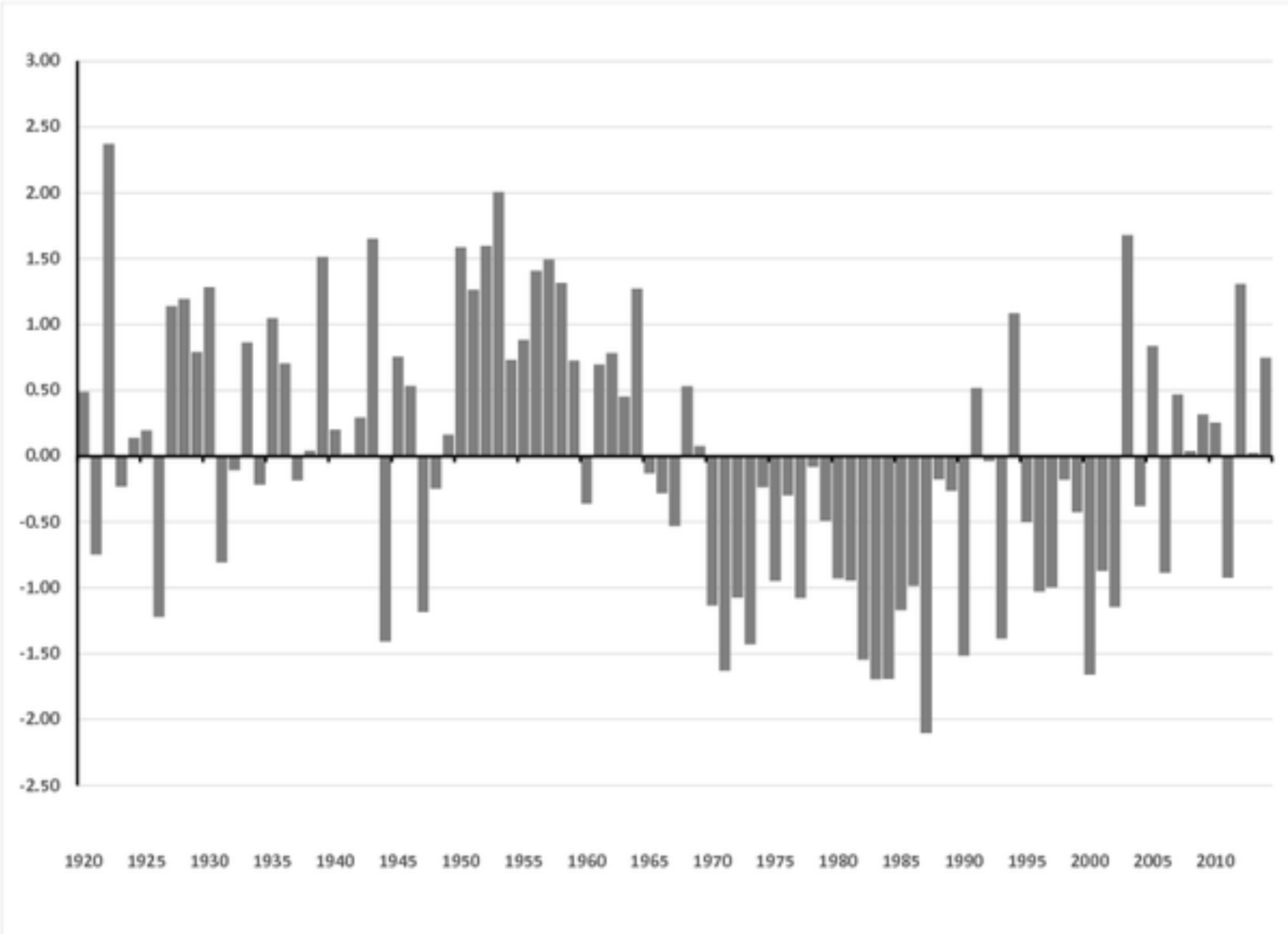

Figure 2. Study Region

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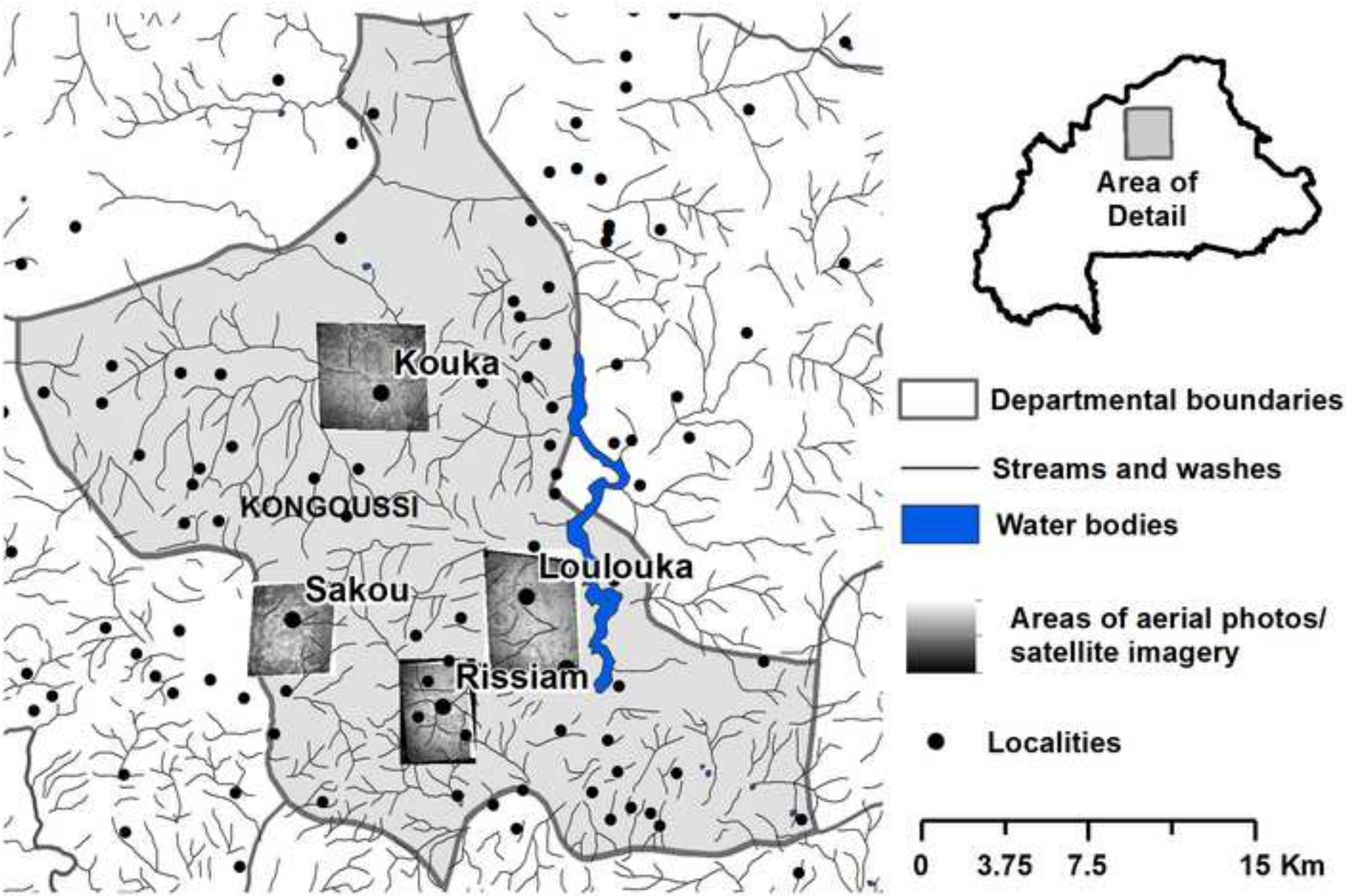

Figure 3. Comparison of May, 1992 Aerial Photograph and January, 2013 WorldView-1 Sattelite Image for Rissiam,

Click here to download Colour Figure Rissiam_1992_2013.tif

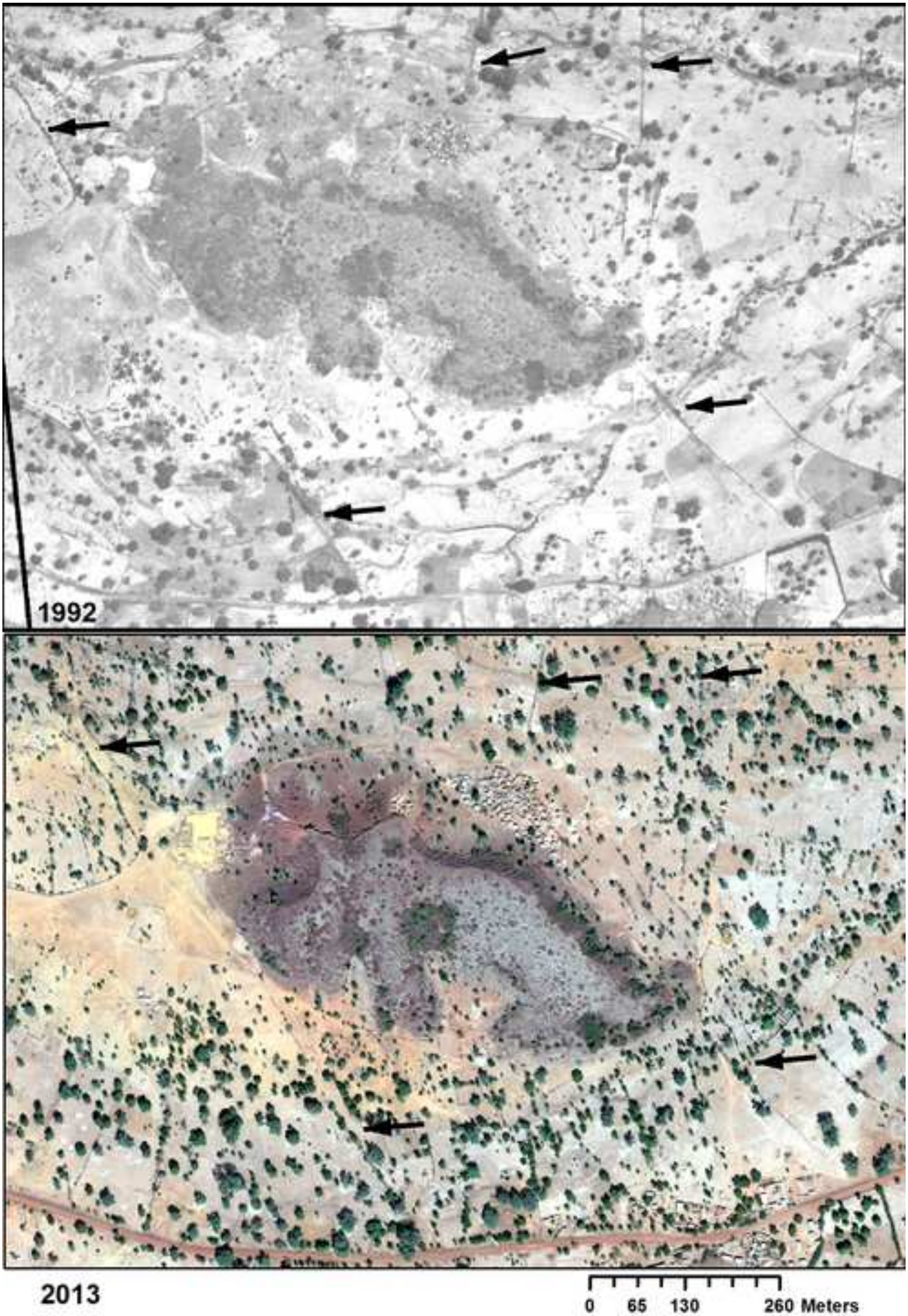

Figure 4. Kongoussi Land-Use and Land-Cover Change (LULCC) between 1975 and 2000 (top panels) and between 1992 and 2002

Click here to download Colour Figure BDOT_EROS_humanecology.tif

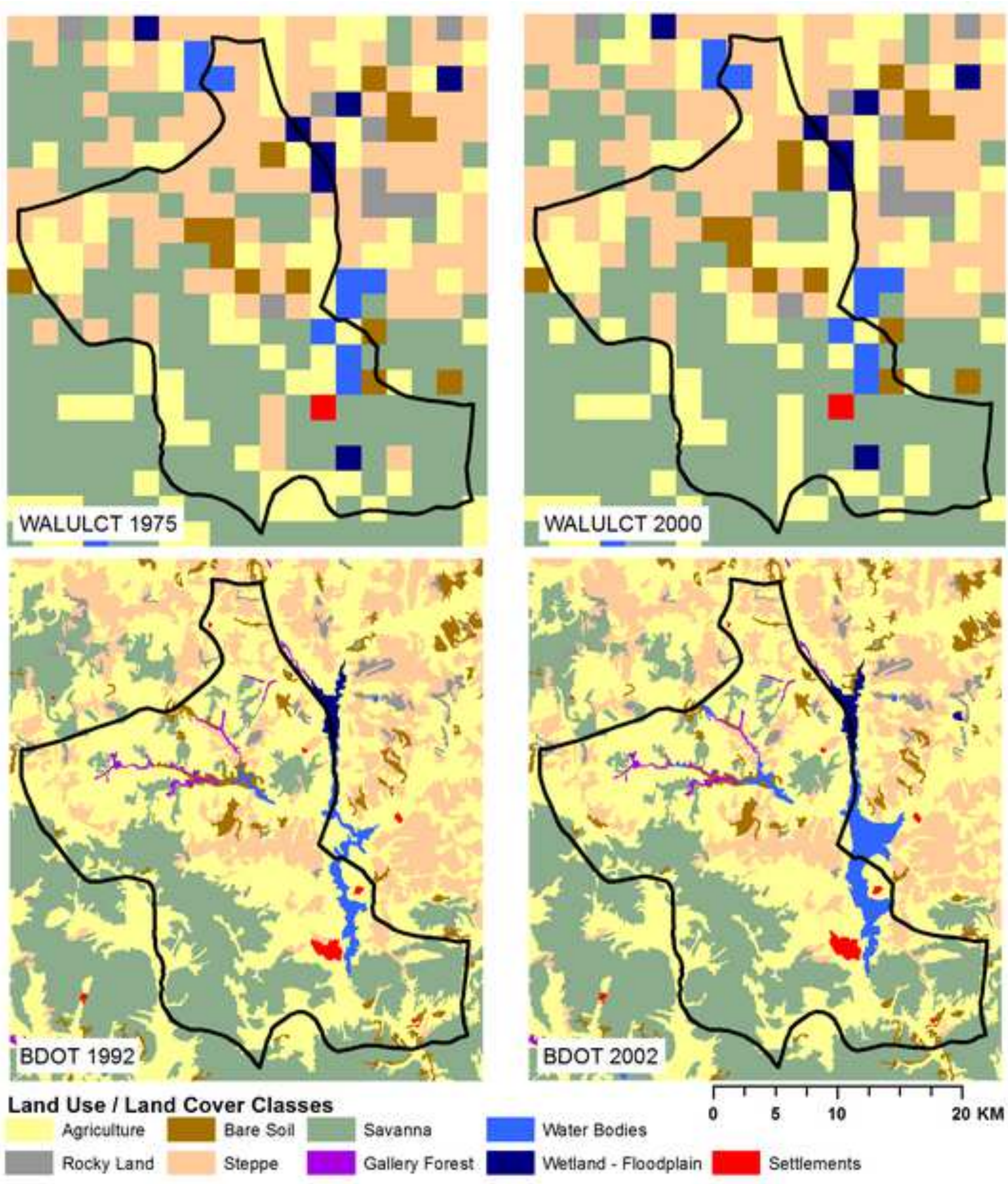

Figure 5. Percent of total area for each LULC class for Kongoussi, 1992 and 2002 Click here to download Line Figure Kaya_BDOT_m.tif

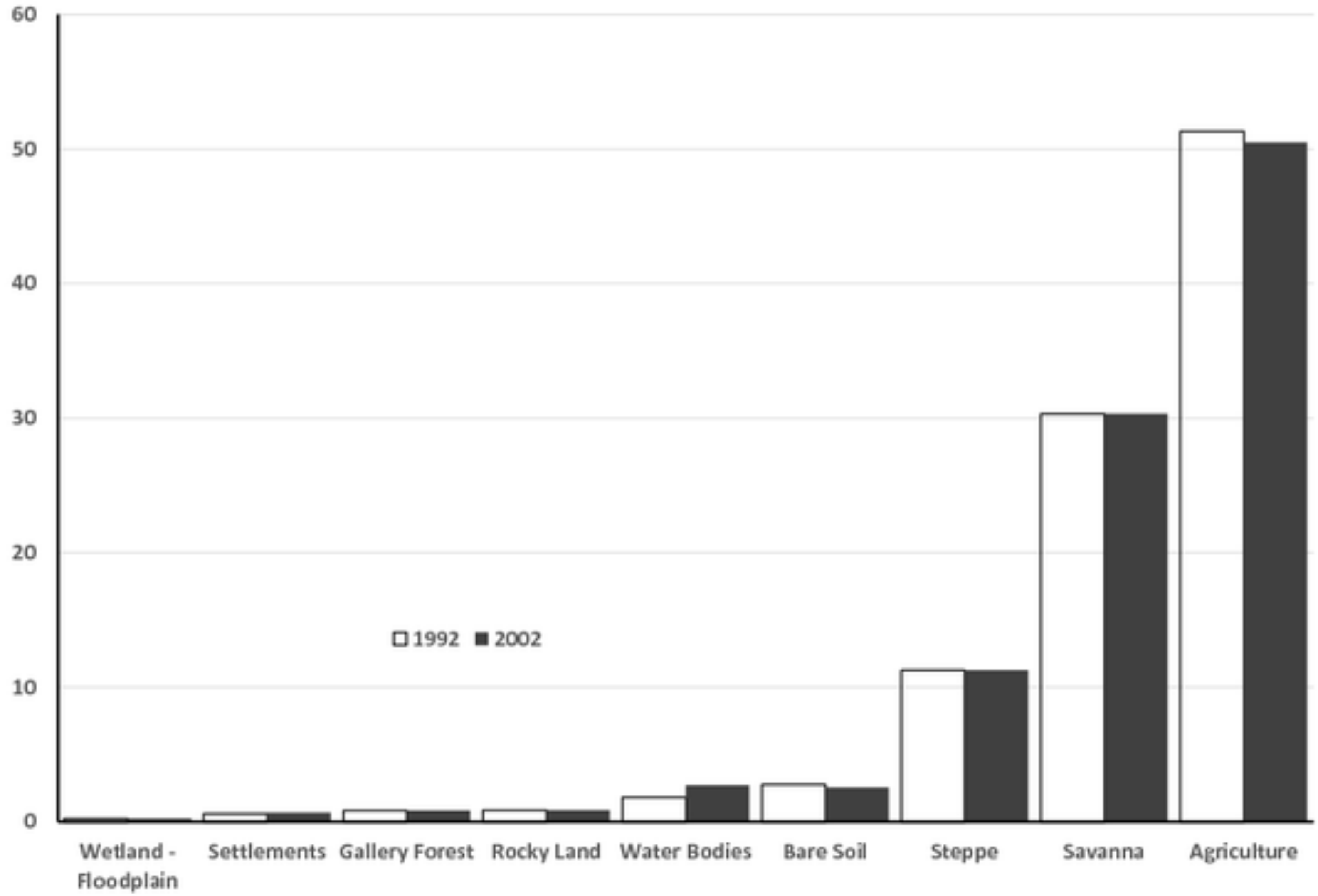

Figure 6. Percent of total area for each LULC class for Kongoussi, 1975 and 2000

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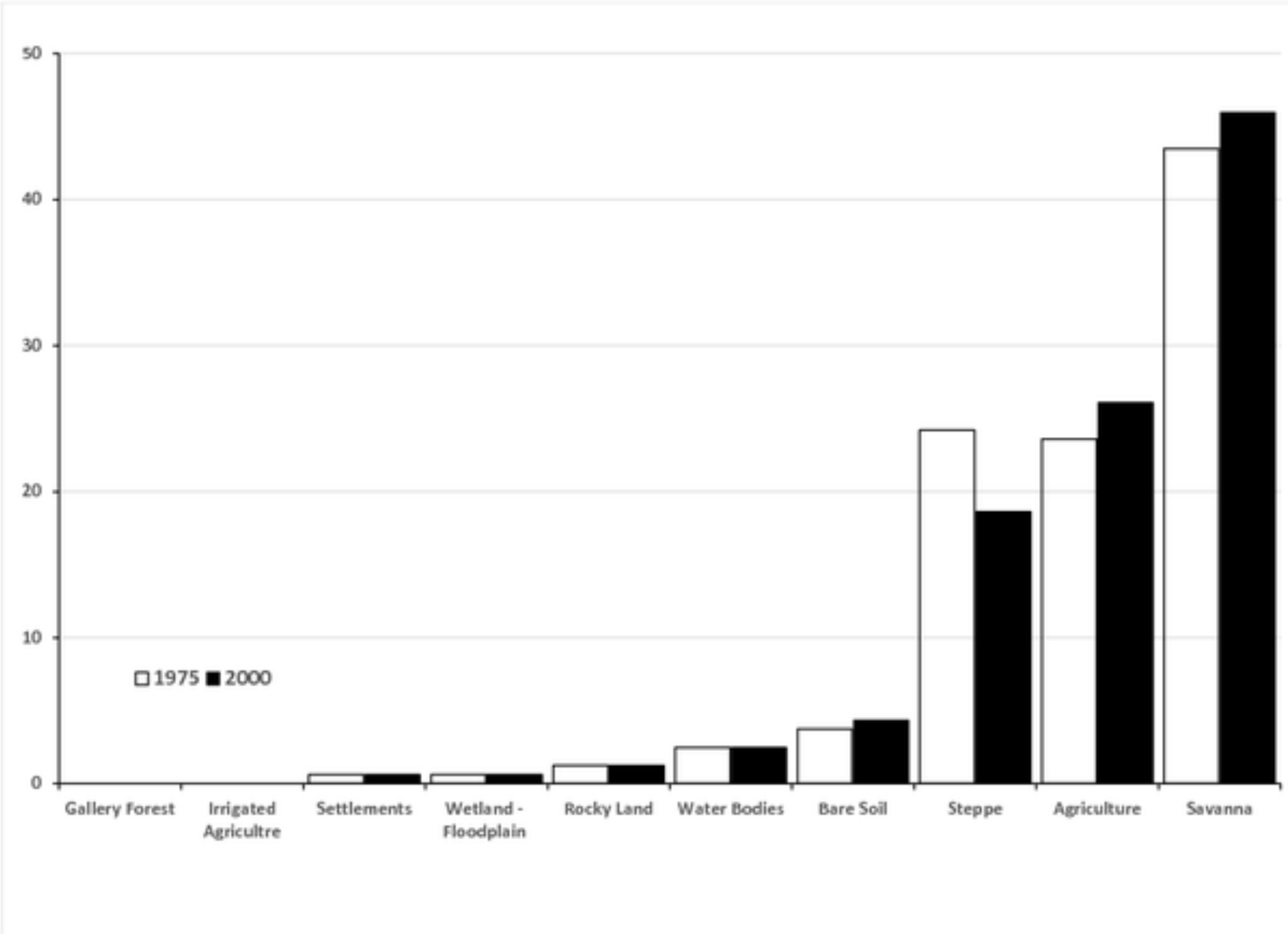

Figure 7. Predicted v. observed NDVI (top panel); Residuals and slope of residuals (bottom panel) for Kongoussi, 1995 to 2009

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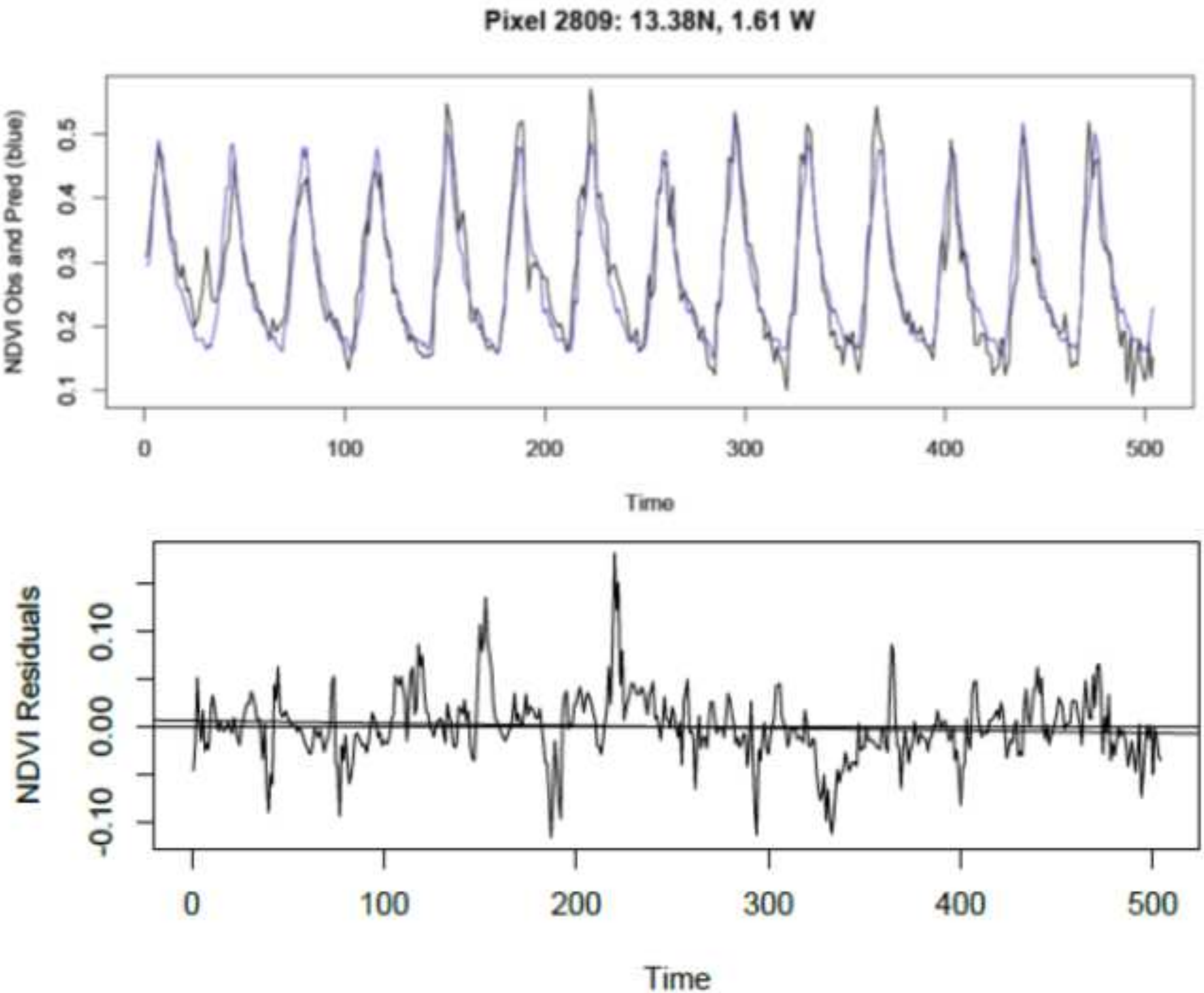

Figure 8. Results of NDVI-RFE analysis for the Department of Kongoussi from 1995-2009 (left) and 1983-2009 (right). Brown indicates negative slopes (degrading) and

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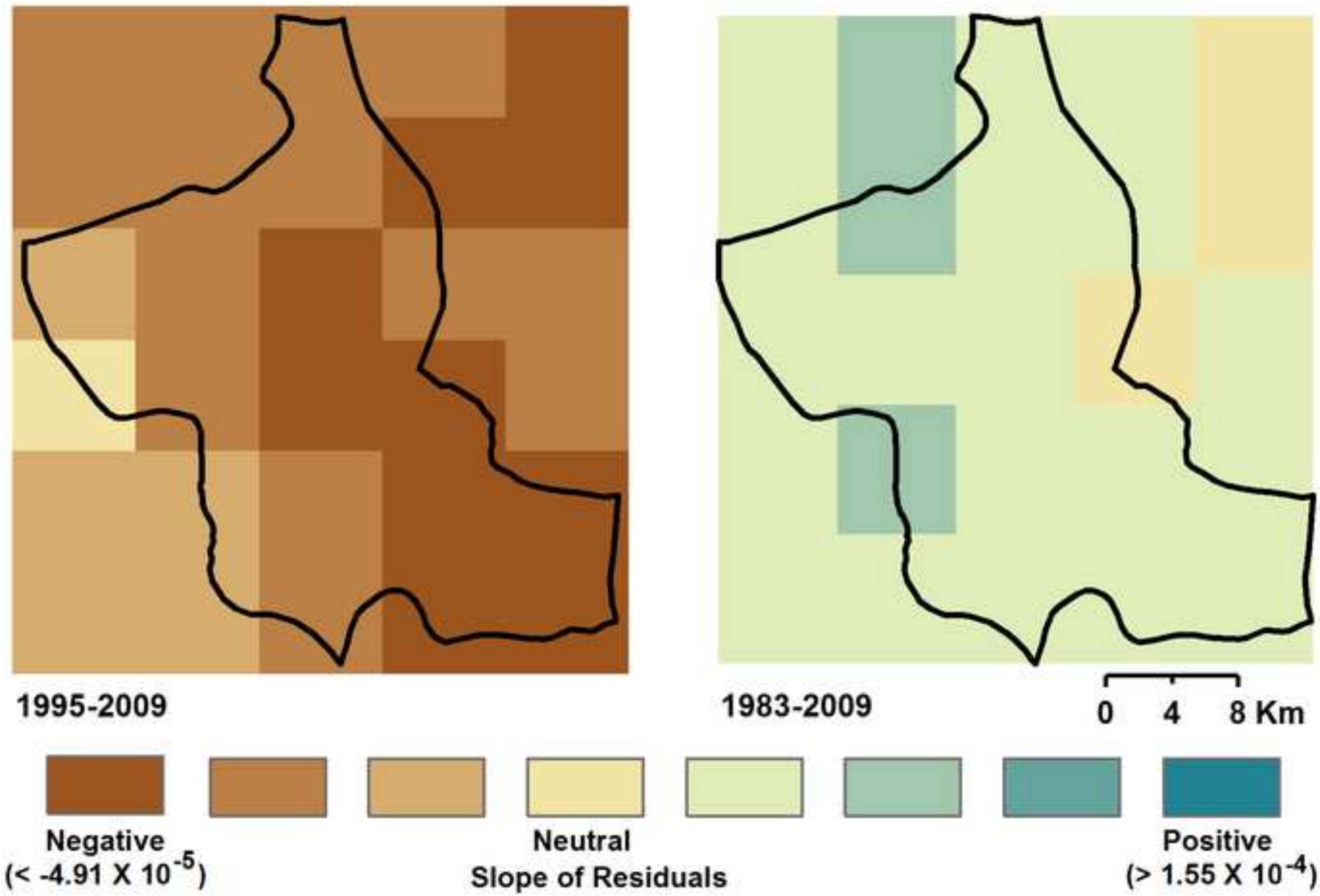

Ground-truthing Sahelian Greening: Ethnographic and Spatial Evidence from Burkina Faso

Historically, the Sahel of West Africa has been considered synonymous with desertification. In recent decades, however, satellite images reveal patterns of enhanced vegetation termed the "greening of the Sahel." This greening is well-documented but its mechanisms remain poorly understood. The Sahel is also a region emerging from a thirty-year period of reduced rainfall in which several severe droughts occurred. As a response to droughts and land degradation, farmers have rehabilitated thousands of hectares of degraded soils by constructing low barriers of rock through widespread soil and water conservation (SWC) development projects. Remote sensing analyses suggest that these extensive soil conservation projects may explain greening in northern Burkina Faso. This study combines ethnographic fieldwork with the analysis of Geographic Information System (GIS) and remote sensing (RS) data to test whether SWC investments contribute to greening. Ethnographic data reveals a tension between the perceptions of rural producers who feel that their SWC efforts contribute to greening and those of state officials who contend that SWC has only local impacts and that the regional landscape continues to degrade. Our analysis of GIS and RS data suggest that both perspectives are valid but contingent on particular spatial and temporal scale used for analysis.

Ground-truthing Sahelian Greening: Ethnographic and Spatial Evidence from Burkina Faso

Introduction

Among the drylands of the world, the African Sahel is often considered a region undergoing severe deforestation, desertification, desiccation and degradation (MA 2005)[1]. In fact, the term 'desertification' was coined in the Sahel by scientists who believed the Sahara Desert was creeping southward due to the destructive land use practices of African pastoralists and farmers (Herrmann and Hutchinson 2005). It is also a region where people have responded to degradation and taken measures to conserve soils, reforest areas, and rehabilitate degraded lands (Mortimore and Adams 2001; Raynaut 2001). The West African Sahel underwent an extended thirty-year period of decreased rainfall referred to as Sahelian desiccation (Hulme 2001). This trend is evident in Figure 1 for northern Burkina Faso. Two periods of intense droughts and attending famines occurred in 1968-73 and 1983-85, which enhanced degradation and stressed social-ecological systems. Reynolds et al. (2007) note that from the 1960s through the 1990s, the Sahel epitomized the negative "dryland syndrome" associated with social, economic, political, and ecological decline and crisis in the world's dry regions. Exceptions to this syndrome existed but were rare, small-scale, and isolated anomalies. Interdisciplinary experts are now calling for these exceptions to form the template for a new Drylands Development Paradigm (DDP) (Reynolds*, et al.* 2007). The goal is to scale-up from these success stories and reverse degradation throughout the world's drylands.

[1] Desertification is defined by the UN Convention to Combat Desertification (UNCCD) as "land degradation in arid, semiarid and dry subhumid areas resulting from various factors, including climatic variations and human activities." Land degradation is further defined "as the reduction of loss of the biological or economic productivity of drylands." Thus, the two terms are nearly synonymous but this paper uses the term "degradation."

[insert **Figure 1. Annual rainfall anomalies . . .** here]

Recent analyses suggest that this reversal is beginning to occur in certain parts of the West African Sahel. Climatologists have detected a rainfall recovery and cautiously conclude that regional desiccation has ended (Nicholson 2005). Furthermore, scientists have detected an overall increase in vegetative cover, or "greenness," using satellite imagery (Olsson*, et al.* 2005). Herrmann *et al.* (2005) investigated these positive trends comprehensively across the entire Sahel using rainfall and vegetation data from 1982 to 2003. The greening of the Sahel is well-established but its mechanisms remain poorly understood. The study presented here combines ethnography with spatial analysis to assess the role of large-scale soil and water conservation (SWC) projects in driving vegetation trends at local and landscape scales.

To date, there have been few studies that ground truth the greening process - especially from the perspective of Sahelians themselves. Notable exceptions include Herrmann *et al.*'s (2014) fieldwork among pastoralists in Senegal; Sendzimir *et al.*'s (2011) study of agro-pastoralists in southern Niger; and Sop and Oldeland's (2013) analysis of woody vegetation trends in northern Burkina Faso. In his 2003 article, Matthew D. Turner identified the urgent need for remote sensing and social scientists to integrate their methodologies to better understand complex human-environment interactions in the Sahel. Combining ethnography with geographic information science (GIS) and remote sensing (RS) allows researchers to extend insights based on local analyses with small sample sizes to draw stronger inferences about landscape dynamics and directions of change than either method alone (Guyer and Lambin 1993). Likewise, it permits the rigorous testing of local and global narratives on environmental change (Fairhead and Leach 1996; Nyerges and Green 2000). Lastly, utilizing ethnography and remote sensing in parallel can facilitate the discovery of underlying mechanisms behind landscape dynamics that are not apparent when these methods are used independently (Jiang 2003).

As discussed below, we have incorporated the perceptions of local actors in northern Burkina Faso with the spatial analysis of GIS and RS data to test the degree to which Sahelian greening in our study area is anthropogenic. The ethnographic accounts, however, diverge; rural producers state that their land-use practices have rehabilitated the environment while local officials claim that these practices have only local effects and the overall landscape continues to degrade. We start by briefly describing the context of Mossi SWC projects and Sahelian greening. Then, we present the ethnographic methods and results. Middle sections describe the GIS and RS datasets, the analytical methods, and the results of the spatial analysis. Local narratives focus on land-use and land-cover change (LULCC) and the tension revolves around temporal and spatial scales. Thus, we compare LULCC at the fine geographic scale of individual villages over a 20-year timespan using aerial photos and high-resolution satellite imagery. This is followed by landscape analyses of LULCC at the coarser spatial scale of a department at ten- and 25-year timescales. Last, we use normalized difference vegetation index (NDVI) and gridded rainfall data to assess landscape vegetation trends at 20- and 30-year timescales.

Overall, we find that both perceptions are indeed valid depending on the spatial and temporal dimensions of analysis. Thus, the analysis of high resolution aerial photos and satellite imagery at the local scale of individual villages supports farmer claims that SWC efforts contribute to greening. These views are also corroborated in long-term analyses (i.e., 1983 to

2009) of coarser vegetation trends that take extreme droughts into account. On the other hand, the analysis of coarser resolution LULCC data supports the views of government agents that the benefits of SWC are primarily localized. Their completing claim that the larger landscape continues to degrade is corroborated in the short-term and recent analysis (i.e., 1995 to 2009) of the same coarse vegetation data. Our case study demonstrates the utility of integrating ethnography with remote sensing and how local narratives can be used as a starting point and guide for spatial analysis.

The Social-ecological Context of Mossi Soil and Water Conservation (SWC)

The northern Central Plateau region of Burkina Faso is dominated by rain-fed subsistence farming, pastoralism and agro-pastoralism. The Mossi are the predominant ethnic group although there are sizable numbers of Fulani pastoralists and pockets of other ethnicities. Mossi farming systems were intensively studied by French geographers of the *terroir* school who pioneered their influential approach on the northern Central Plateau. Works by Kohler (1971), Marchal (1983), and others provided detailed accounts of the dynamic nature of Mossi agricultural techniques and how they adapted to changing climatic, environmental, and socioeconomic circumstances. Marchal (1985) warned of an impending crisis and possible collapse of Mossi farming systems following the 1983-1985 drought. He specifically noted rampant vegetation removal, the extension of gullies, and the massive expansion of bare soils. These soils are locally referred to as *zipellé* in the *Mooré* language. Zipellé are exhausted soils which have been over-grazed or farmed continually with no fallowing. These works and their warnings helped draw attention to the region and initiated development projects in soil conservation.

In the early-1980s a French development volunteer helped community members in the village of Rissiam construct an experimental level permeable rock dam across a large gulley (Reij*, et al.* 2005). These dams are made of local rock and constructed perpendicular to gullies. With time, the gullies fill in and farmland can be reclaimed. Level permeable rock dams proved very successful and villages throughout the region adopted them. Today, they are prominent features of the landscape found wherever gullies occur. Not only do level permeable dams slow erosion, they also assist the spontaneous regeneration of native grasses, shrubs and trees as their seeds become trapped behind the dam (Reij*, et al.* 2005).

By far the most important and widespread of SWC techniques are the ubiquitous contour stone bunds, or "*diguettes*" in French. These are low rock barriers constructed along the contours of agricultural fields. Diguettes slow sheet runoff and, like level permeable rock dams, prevent soil erosion and trap organic matter. They require a great deal less technical sophistication, however, than dams. A typical village may have approximately 50 level permeable rock dams in limited gulley-prone areas. At the same time, it may have hundreds of diguettes that cover nearly the entire agricultural zone within 5 km of the village core. Native plant seeds also get trapped and spontaneously germinate and become established along individual diguettes (Reij*, et al.* 2005). This contributes to the gradual re-vegetation of local landscapes.

Collectively, these SWC investments have had spectacular results and rehabilitated well over 150,000 ha in the northern Central Plateau (Reij*, et al.* 2005; Reij and Thiombiano 2003). Yields have improved, soils have stabilized, and vegetation has increased. There are also indications that food security has improved (West*, et al.* 2014). In short, these SWC measures have been very successful adaptations to land degradation in the northern Central Plateau of Burkina Faso for individual households and communities. Less is known about their impact on larger landscapes.

Rapid Participatory Rural Appraisal Fieldwork

The first author has conducted ethnographic fieldwork in the study region since 2002. Household surveys, participant-observation, and interviews have documented the local benefits of SWC for livelihoods and ecological conditions in the Department of Kongoussi (West 2013; West 2009; West 2010). These results are based on intermittent fieldwork in three Mossi villages, which limits the degree to which they are representative of larger social-ecological processes. In 2012, participatory methods were used to elicit local views on Sahelian greening in Kongoussi.

Rapid participatory rural appraisal (RPRA) techniques are methods rooted in development anthropology that seek to quickly but systematically collect data in ways that actively involve participants in the research process (Chambers 1994; Finan 1988). Over a brief three-week period, the first author and a research assistant conducted the RPRA with the following: four international NGO and government experts in the capital city Ouagadougou; four local NGO, traditional and government officials in the provincial capital Kongoussi; and six local farmers with knowledge of historical environmental change in the region. Though a small sample, these informants were people with whom the first author had previously worked and the goal was to obtain general perspectives on greening from a diversity of stakeholders. Thus these experts were chosen so that their perceptions would represent a range of geographic scales from national, to departmental, and local.

In all cases, participants were shown visual materials and then were asked to reflect on their personal impressions. A topical outline was used to guide the conversation and ensure relevant themes were discussed. Most of the interviews were conducted in French but a translator, the research assistant, translated between *Mooré*, the local language of Mossi people, and French. These narratives were recorded using a notebook and transcribed in the field. The visual materials consisted of the following:

- A chart displaying annual rainfall amounts from 1946 to 2010 based on records for the meteorological station in Kongoussi
- A black-and-white aerial photo from 1992 for each village at the scale of approximately 1:5,000
- A high-resolution hard copy of Google Earth high resolution satellite images from 2010 that match village aerial photos.

Each image was briefly explained to the participant and they were allowed a few minutes to gather their thoughts. They were then asked to explain how the visual aid related to greening and their personal experiences. Participants typically pointed to features on the graphs or photos as they discussed their perceptions of environmental change.

In discussing the rainfall graph, all participants commented on the apparent droughts from 1968 to 1975 and between 1983 and 1984 (see Fig. 1). According to older farmers, desiccation and its attendant droughts had a marked impact on the landscape. The severe and prolonged droughts of the 1970s and 1980s caused trees to die and gullies to extend and widen. Throughout the region, farmers describe how trees fell into ravines as they expanded. These gullies cut into fields and Mossi rural producers could do little to stop the erosion process. They pointed out that the contemporary landscape had to be understood in terms of these past events.

In comparing the 1992 aerial photos and 2010 imagery, farmers quickly identified key differences. They noted that the number of "lines" increased and pointed out these were permeable rock dams and diguettes. Participants also indicated areas where there were more trees and talked about local reforestation efforts. One elder farmer discussed his view that the number of trees had increased dramatically and invited the first author to visit a nearby reforestation project. During the walk, he pointed out that before, one could see all the way from his village to the lake (Lake Bam) because there were no trees. Now, he said, their village seems more like a forest and you can't see the lake anymore. A younger farmer in the village of Loulouka pointed out that their community has a lot of land pressure and there is no room for reforestation projects. Comparing the photo and imagery, he emphasized he could plainly see how trees grow along the diguettes and permeable rock dams. He explained that these barriers trap local tree, shrub, and grass seeds that later germinate and grow.

One representative of a development NGO in Kongoussi stated people remember how severe droughts in the 1970s and 1980s were. This person was an autochthone of Kongoussi who was born in the department and directed a grassroots organization that focused on environmental protection and sustainable development. He talked about how "everyone suffered" and people learned that they had to take matters into their own hands. He explained that this is why "diguettes and rock dams are found all over the place in Kongoussi. People have to use SWC measures or they won't eat." Their NGO and many others have partnered with the Government of Burkina and international donors to promote SWC throughout the northern Central Plateau. This work began in the late-1980s following the 1983-85 drought. Soil and Water Conservation activities peaked in the late-1990s and the major international NGO providing technical assistance, the German-funded PATECORE, closed operations in 2005. Diguette and permeable dam construction has continued on the northern Central Plateau, but is much more sporadic. This particular NGO based in Kongoussi continues to help villages rehabilitate degraded soils. Working with village groups, they target the most degraded zipellé areas first so that farmers can reclaim these degraded soils for agricultural fields.

As we left his office, we passed through a barren open space measuring several hectares in the middle of town. Though late-July and despite nearly a month of intermittent rain, hardly any grasses, trees, shrubs or even weeds grew in the barren soil. It was difficult to walk or pass by motorcycle because of the numerous shallow gullies and incipient ravines. The Director told us:

> "See this? This is true zipellé right here in the middle of Kongoussi. I remember this place. It was once packed with fields and the town was really a large village with scattered huts. People planted millet, sorghum and some maize right here in this very place. But you see it is surrounded by these low hills and people did not take good care of the land. That makes it prone to erosion and the thin layer of fertile soil has been washed away. Nothing holds the soil together anymore and nothing can grow. Rain takes any seeds or plants and washes them away. But with diguettes . . .

> with some dams and with some hard work . . . this could all be brought back into production. In just seven years, the whole area could become agricultural fields again."

Local government officials, agricultural extension agents, and government foresters also participated in the RPRA. These experts stated that diguettes, level permeable dams, and reforestation projects mostly improved individual farmer fields or the immediate village surroundings in which they are constructed. They contend that demographic pressure on the environment, however, is so great that land degradation continues and overwhelms SWC efforts. For these civil servants, SWC improvements are mostly localized and have little impact on the larger landscape, which continues to degrade. One middle-aged female forestry agent described how she was born and raised in the town of Kongoussi. As a young girl, she could gather firewood from the surrounding forests. Now, all the forests are replaced by fields and women have to walk for at least one or two kilometers to find wood. She emphasized that "the forests are gone." She pointed to places in the satellite image where there were many trees growing in a regular pattern. These are plantations, she explained, but all trees are neem (*Azadirachta indica*), eucalyptus, or prosopis (*Prosopis juliflora*). These are exotics and people plant them to sell for housing construction or as living fences. Thus, they do little to enhance biodiversity.

In summary, there are conflicting views on greening and its drivers. Local farmers contend that that greening is taking place and that it is due to their reforestation and SWC efforts. The graphs, aerial photos, and satellite images elicited strong reactions and these participants pointed to specific locations and details to support these claims. Moreover, they contextualized these improvements within a long historical timeframe that took into account the severe droughts. Thus, for them, greening is part of a long-term process of ecological recovery from these extreme events. Government experts, on the other hand, expressed doubt regarding any sort of widespread greening. Agricultural extension agents, forestry officials and others felt that the beneficial impacts of SWC projects were localized. The overall regional landscape continued to degrade. The following sections use these divergent accounts from the participatory fieldwork as a starting point and guide for the analysis of GIS and RS data.

Spatial Analysis

Administratively, the country of Burkina Faso is hierarchically divided into regions, provinces and departments. There are currently 351 communes (also called "departments") and they tend to be relatively homogeneous in terms of ethnic groups, natural resources, and livelihoods. They range in area from approximately 125 km^2 (12,500 ha) to 1,000 km^2 (100,000 ha). For these reasons, the Department of Kongoussi (654 km^2) is used as the unit of analysis, or "landscape," for the following remote sensing and GIS analysis (see Figure 2). Two spatial datasets on land-use and land-cover change (LULCC) in Burkina Faso were used to assess landscape effects of SWC and desiccation. Two additional remote sensing datasets were used to assess trends in plant biomass production, which serves as a coarse indicator of degradation or rehabilitation.

[insert **Figure 2. Study Region** here]

Datasets

Hardcopy aerial photographs of the study region were obtained from the National Geographic Institute (*Institut Géographique du Burkina* - IGB). These consist of black-and-white photos taken in May, 1992 at the scale of 1:20,000 for four villages in the study region (see Fig. 2). These photos were scanned at a resolution of 600 dpi and georeferenced to GIS control points. This resulted in an effective pixel resolution of 0.91-m^2. This resolution is sufficient to visually identify SWC investments such as diguettes, level permeable dams and trees. May precedes the rainy season and makes it possible to discriminate among different types of land-use and land-cover classes. There were a total of four aerial photographs that covered most of the territory for the villages of Loulouka, Sakou, Kouka and Rissiam. The total area of each photo was approximately 4.4-km x 4.4-km, or a total area of 19.36-km^2-per-photo/village.

In addition, the study used high-resolution WorldView-2 and GeoEye-1 multispectral satellite imagery. These data consist of 4-band multispectral (red, green, blue and near-infrared) 2.0m X 2.0 m images along with panchromatic 0.5m X 0.5m images for four villages in the study region. The WorldView-2 image acquisition date was January 5, 2013 and the GeoEye-1 image acquisition date was March 10, 2014. These dates were chosen because they approximate the anniversary date of the aerial photographs and precede the rainy season. Thus, vegetation phenology and senescence is similar in all the aerial photographs and satellite images. Both the WordView-2 and GeoEye-1 satellite imagery products allow SWC structures such as diguettes and level permeable dams to be easily identified. Again, there were four 5-km X 5-km (25-km^2) high-resolution satellite images -- i.e., one for each village.

The Land Use Database of Burkina Faso (*Base de Donnée d'Occupation des Terres* - BDOT) is a Geographic Information System (GIS) dataset that contains land-use and land-cover (LULC) types for the entire country (IGB, 2006). It contains a total of 43 hierarchically organized man-made, vegetation, agriculture, and water classes. These classes are mapped for 1992 and 2002. Thus, the BDOT indicates the distribution of different land use types for these two periods and can be combined to identify changes in LULC over the ten year period. It is a vector product mapped to an effective scale of 1:200,000 and LULC classes are based on minimum mapping units of 25 ha. These database properties are at an appropriate resolution for assessing LULCC at the scale of departments. We worked with a 1^{o} by 1^{o} (~ 110-km X 110-km) subset of the BDOT for our study area surrounding the Department of Kongoussi.

The West Africa Land Use and Land Cover Trends Project (WALULCT) developed a raster product of LULC classes for 1975 and 2000 (Tappan*, et al.* 2004). It consists of 18 classes that also include vegetation, agriculture, water, and others. The classes are analogous to those in the BDOT. Pixel resolution is 2-km, which is sufficient for analyses of change over time for individual departments.

The last spatial dataset consists of remotely-sensed Normalized Difference Vegetation Index (NDVI) and Rainfall Estimate (RFE) raster data. The NDVI product was developed by the Famine Early Warning System (FEWS) Network and derived from NOAA Advanced Very High Resolution Radiometer (AVHRR) Pathfinder missions (Tucker*, et al.* 2005). It consists of processed 10-day maximum NDVI at 8-km resolution. The RFE data is also a FEWS product that provides a 10-day estimate of cumulative rainfall at 8-km resolution (Novella and Thiaw 2013). Both the NDVI and RFE data are processed to the same temporal and spatial resolution in order to be compatible for vegetation and rainfall monitoring. Thus, they are spatially and temporally coherent.

NDVI is a ratio of the difference in reflectance from the Red (R) and Near-Infrared (NIR) spectral bands over the sum of the reflectance of the same two bands. This unit-less measurement is a proxy indicator for biomass production of green vegetation, or "greenness." Higher values indicate more green plant biomass productivity, or greater "greenness." Lower values indicate the opposite. Vegetation in the seasonally dry Sahel is almost entirely dependent on antecedent rainfall. Thus, NDVI and RFE data are used together in order to control for rain - i.e., to remove the effect of any long-term trends in precipitation in measured trends in greening (reclamation) and browning (degradation).

Methods

First, we sought to determine whether SWC investments could affect greening by comparing aerial photographs from 1992 and the 2013-14 high-resolution multispectral imagery. Using ESRI's ArcGIS 10.2.1, the 1992 aerial photographs were scanned and then georeferenced to the high-resolution imagery by selecting corresponding control points in both the photos and the images. After doing so, we visually compared changes in the prevalence of SWC investments and change in vegetation between 1992 and 2013-14. This process was performed for each of the four villages but only results for Rissiam are discussed below.

Using ESRI's ArcGIS 10.2.1, we integrated the BDOT, WALULCT and Burkina Faso departmental boundary files into a Geographic Information System (GIS) database. Using the department of Kongoussi as the boundary, the percent of each LULC class of the total area for Kongoussi was calculated using the BDOT data. The 43 original classes were aggregated into just the nine classes represented in the WALULCT dataset to enable direct comparison between the two datasets. Specifically, we measured the change in "bare soil", which is a general indicator of land degradation (Marchal 1985). This class corresponds to zipellé soils, which farmers are rehabilitating with SWC.

A similar comparison was performed with the WALULCT data for 1975 and 2002. This detected LULC change over a 25-year period. Using ArcMap 10.2.1 and Spatial Analyst, we calculated the percent of each land class of the total area of Kongoussi. The WALULCT dataset also contains a bare soil land-cover class and we measured change in this class between the two periods.

Combined, the two LULC datasets permit the assessment of long-term (i.e., 25-yr) and more recent and short-term (i.e., 10-yr) land-use and land-cover change. Moreover, the 1975-2000 WALULCT data allows us to assess change in LULC during the period of Sahelian desiccation. The 1992-2002 BDOT data allows us to assess change in LULC during the period in which SWC activities were initiated and adopted.

The LULC datasets can only detect change in classes while the NDVI and RFE data can detect general trends in biomass productivity - regardless of land-use or land-cover type. Using a method similar to Herrmann *et al.* (2005), we developed a linear regression model where the NDVI for each pixel for each 10-day period was regressed against the cumulative 30-day antecedent total RFE for the same pixel. Thus, we modeled the 10-day NDVI based on the cumulative 30-day (i.e., three 10-day periods). Next, our model calculated the residual - i.e., the difference between the modeled NDVI and observed NDVI for each pixel at each time-step. By regressing NDVI on RFE and then extracting the residuals, we controlled for the effect that variation in precipitation may have had on greening. In this way we attempted to isolate anthropogenic effects, controlling for natural variation in precipitation. We then calculated the slope of the residuals for each pixel across all time periods (15 years X 36 10-day periods per year = 540 periods). Positive slopes indicate rehabilitation because they detect enhanced greening - i.e., observed NDVI exceeds expected values after controlling for the effect of precipitation changes. Negative slopes indicate land degradation because observed NDVI is less than the expected value (Herrmann*, et al.* 2005). We did this for two time periods: 1995 to 2009 (15 yrs.) and 1983 to 2009 (27 yrs.) This allows us to infer the effect of SWC investments on short-term vegetation productivity (1995 to 2009) and their effect relative to the severe droughts of the early-1980s (1983 to 2009).

Results

Visually comparing the 1992 aerial photos and 2013 high-resolution satellite images, one can easily see that the number of permeable rock dams increased substantially in the village of Rissiam (Fig. 3). These structures appear as straight lines that lie perpendicular to the two gullies that trend right-to-left in the upper and lower (next to the road) portions of the images. Likewise, trees tend to be aligned with these structures, which indicates how SWC contributes to the spontaneous natural regeneration of vegetation. Last, the visual comparison indicates a significant increase in the number and density of trees between 1992 and 2013. This is especially apparent in the bottom portion along the road.

[Insert **Fig. 3 - Comparison of 1992 Aerial Photo and 2013 WorldView-1 Satellite** . . . here]

These two images detail only a portion of the entire area that corresponds to the *terroir*, or territory, of Rissiam. The overall network of permeable rock dams visible in Figure 3 extend approximately 5-km East-West along the road and approximately 1.5-km North-South in the valleys. An even more extensive network of diguettes throughout the Rissiam terroir is visible using the sub-meter panchromatic imagery. The total area treated in diguettes or permeable rock dams for Rissiam is estimated to be 29-km^2 (2,900 ha) based on visual inspection.

Results were similar for the other three villages with the exception of Kouka, which had significantly less permeable rock dam construction but equivalent amounts of diguettes. There are 58 villages in the Department of Kongoussi and the average distance between them is 2.1 km (see Fig. 2). Other surveys estimate that between 12 and 66% of all village agricultural fields have been treated with SWC (Reij and Thiombiano 2003). Given these results and those of previous studies, we find it plausible that that local-scale investments in SWC could contribute to larger-scale processes of greening by increasing the amount of vegetative cover in terms of trees, shrubs, and grasses due to the high density of villages.

The analyses presented next test whether SWC investments have affected the percentage of bare soil cover in Kongoussi between each time period. They also test whether SWC investments produce positive trends in NDVI - i.e., positive residual slopes, after controlling for long-term trends in precipitation.

BDOT Analysis

Differences in LULC between 1992 and 2002 in Kongoussi were slight and difficult to distinguish in the two BDOT LULC maps (Fig. 4 - bottom panel). Analysis of changes in each individual class (calculated as the percentage of total area within Kongoussi) between 1992 and 2002 indicate that the landscape shows remarkable stability over this time period (Fig. 5). The percentage of each LULC type remained nearly the same between the two periods. The relative amount of bare soil decreased very slightly from 2.8% to 2.5%.

[Insert **Figure 4. Kongoussi Land-Use and . . .** here]

[Insert **Figure 5. Percent of total area . . . for Kongoussi . . .** here]

WALULCT Analysis

As with the BDOT analysis, assessment of the WALULCT data over the longer period 1975-2000 indicates a high degree of stability in the distribution of LULC types for Kongoussi (Fig. 4 - top panel). There is a slight increase in bare soil from 3.7% to 4.3% (Fig. 6). Both agriculture and savanna showed a moderate increase as these two classes replaced steppe.

[Insert **Figure 5. LULC for Kongoussi . . .** here]

[Insert **Figure 6. Percent of total area . . . for Kongoussi . . .** here]

NDVI/RFE Analysis

The slope of the residuals for the pixel located near the center of the Kongoussi department is very shallow but negative (Figure 7).

[Insert **Figure 7. Predicted v. observed NDVI . . . Kongoussi, 1995 to 2009** here]

The NDVI-RFE analysis shows two distinctly different short- and long-term trends (Figure 8). Over the recent 15 years (Fig. 8 - left panel), the slope of the residuals is consistently negative, which suggests decreased vegetative productivity throughout Kongoussi. Over the longer term (Fig. 8 - right panel), however, slopes are positive and suggest increased productivity. These results indicate competing process of recent land degradation (i.e., from 1995 to 2009) but overall greening over the longer time period (i.e., from 1983 to 2009).

[Insert **Figure 8. Results of NDVI-RFE Analysis . . .** here]

Discussion

Using the Department of Kongoussi as the boundaries of a continuous landscape, we sought to understand the degree to which diguettes and level permeable rock dams were reducing zipellé and increasing overall biomass production. By assembling remote sensing and GIS data on LULC and vegetation, we were able to assess temporal trends at several temporal and spatial scales. This analysis was used to validate the participatory fieldwork, which revealed a tension between perspectives of individual Mossi rural producers and government officials. Farmers felt their SWC efforts had undeniably reversed desertification. Agricultural and forestry agents, however, stated that these projects had only local beneficial effects and that the regional landscape continues to degrade.

Our results support both points of view. At the local scale of villages, SWC investments have contributed to increased tree cover as evidenced in the comparison of aerial photographs and satellite imagery. The results of the LULCC, however, indicate that these improvements are highly localized. Between 1992 and 2002, the amount of bare soil, or zipellé, had been reduced but only by a modest amount. On longer time-scales, between 1975 and 2000, zipellé actually increased, but only very slightly. In both LULCC analyses, the percentage of most classes remained stable and constant. This suggests that SWC has had little landscape impact on land-use and land-cover -- there has not been a significant decline in bare soil. As an alternative, it is possible that zipellé soils have been treated with SWC and become revegetated. This increased vegetative cover is not, however, substantial enough to affect an area's overall spectral signature and affect its reclassification from "bare soil" to "agriculture" or "savanna."

The results of the NDVI/RFE analysis point out that whether the landscape is greening or degrading depends on the temporal scale of analysis. On a more recent and shorter time scale of 15 years, the slopes of the residuals are negative across all of Kongoussi. This implies that there is less vegetation than one would expect based on rainfall alone for the period 1995 to 2009. This suggests ongoing land degradation, which is consistent with the views of government agents. Extending the time period back to the early 1980s, when one of the great Sahelian droughts occurred, the slopes of the NDVI/RFE residuals become positive. This is consistent with the views of local farmers who have lived in Kongoussi their entire lives and experience the current landscape in terms of these disastrous events. It is possible that vegetation is still recovering from massive and extreme droughts.

There are important caveats and limitations to our fieldwork and spatial analysis that we would like to briefly summarize and acknowledge. Our participatory approach was non-random and we could not control for important social variables. We spoke mostly with older male Mossi rural producers and it is possible younger men or especially women could have different interpretations of landscape change. Kongoussi is a renowned hot-spot of development activity in Burkina Faso and there is the possibility farmers or NGO staff want to emphasize their successes in hopes of attracting additional development assistance. Similarly, extension agents and forestry officials may downplay the benefits of SWC projects to promote their positions of authority and maintain government control over natural resources.

There are also some practical explanations for these divergent views. All of the rural producers and NGO staff with whom we spoke are native residents of Kongoussi and have lived in the department nearly their entire life. They interact intensively and intimately with their local village territories over long periods of time. Droughts of the 1970s and 1980s were major disturbances and they see their community's contemporary landscape as product of those disastrous events. As Burkinabé civil servants, however, agricultural extension and forestry agents intervene in multiple villages throughout Kongoussi. They typically begin their professional service later in their adult life and are deliberately placed in departments far from their natal villages. Government agencies also frequently relocate their rural agents every five years so that they do not become enmeshed in local politics. Thus, government agents have a larger geographical perspective on landscape dynamics than local farmers but for a shorter amount of time - just the most recent five years in which they have been posted. These practical aspects of residence and zones of interaction may explain divergent perceptions of environmental change.

In terms of the spatial analysis, we recognize the spatial mismatch between SWC interventions and NDVI/RFE pixels. A single 8-km by 8-km NDVI/RFE that indicates greening may contain four to eight communities. Some of these villages might have extensive soil and water conservation investments while their neighbors have few or none. Likewise, browning pixels might also contain a mix of villages with low or high SWC investment. Based on our analysis presented here, we cannot rule out other explanations for greening and browning. Carbon fertilization, unique geological features, invasive plant species, topography, or much more complex groundwater-surface interactions could also contribute to the coarse patterns of greening and browning we have detected. Moreover, the fact there have been no recent droughts of the same severity, duration and extent as the great Sahelian may mean all greening is simply a recovery from these extreme events. This study simply demonstrates that SWC investments may contribute to overall greening but more systematic fieldwork and analyses are necessary test this more definitively.

Conclusion

The West African Sahel is a challenging environment where population pressure, droughts, and inappropriate land-use practices place enormous stress on social-ecological systems. For these reasons, in fact, it is a region considered synonymous with "desertification" (Charney 1975). It is also a highly dynamic system where both land degradation and rehabilitation co-occur -- but in different places and at different points in time. This study has integrated ethnography with spatial analysis to better understand these dynamics. Specifically, we have used empirical data to evaluate two competing points of view held by local experts. One, held by rural producers, states that SWC efforts have dramatically improved the environment. The other, held by government officials, states that these impacts are highly localized and that the larger landscape continues to degrade.

The positive impacts of SWC on households and individual communities are well-known and well-documented. Scholars of global change, however, have begun asking broader questions regarding the implications of such adaptations for the resilience of social-ecological systems beyond the actors and institutions involved (Nelson*, et al.* 2007). This study considers such implications at the scale of both individual villages and entire landscapes at short (i.e., 10-yr.) and long (i.e., 30-yr) timescales. Soil and water conservation projects in Mossi communities have undeniably helped smallholders adapt to desiccation. Farmers recognize the benefits of investing in diguettes and level permeable rock dams. The results of the spatial analysis, however, point out that bare soil persists and that the relative proportions of land-use and land-cover types has remained remarkably unchanged over 25- and 10-year periods. Thus, SWC efforts have reduced zipellé, or bare soil, at local scales but not those of an entire department. While LULC has remained stable and constant, there has been change in biomass productivity. Over the most recent 15 years, NDVI/RFE residuals are negative and indicate land degradation. Over the longer period of record, 1983 to 2009, NDVI/RFE residuals are positive and suggest SWC has contributed to a recovery in vegetation after severe droughts.

We intentionally use terms such as "suggest" and "indicate" because we recognize the limitations of our data and analysis. The LULC data used here are secondary data developed for the entirety of Burkina Faso (BDOT) or the West African Sahel (WALULCT). Deriving our own LULC classification from raw imagery specifically for the study region could provide different results. Nonetheless, both independent datasets exhibit significant stability and validate one another. The NDVI/RFE data are at a very coarse spatial scale (8-km^2) and a rigorous sensitivity analysis of our regression model was beyond the scope of our study. Using higher resolution MODIS imagery could improve our results but the time period would be shorter. Our main goal has been to integrate ethnography with the spatial data and use Sahelian perceptions as a starting point and guide for the analysis of imagery and GIS data. At very local scales and long time periods, farmer views that their SWC efforts contribute to revegetation are valid. At larger scales and shorter time periods, official views that land degradation persists are likewise substantiated by our analysis.

In conclusion, we suggest that SWC interventions on the Northern Central Plateau of Burkina Faso provide a template for the new paradigms of dryland development advocated by Reynolds et al. (2007). It appears distinctly possible that the diguettes and level permeable dams Mossi rural producers have constructed locally but throughout a large area are collectively contributing to greening in this part of the Sahel. Thus, in the case of northern Burkina Faso, Sahelian greening is likely anthropogenic. Given that the Mossi farmers and agro-pastoralists who constructed them are encouraged by the results and continue to be enthusiastic, SWC efforts should be reinvigorated in the region. They should also be initiated in other African drylands to prevent the severe forms of land degradation that precipitated SWC projects on the northern Central Plateau in the first place. Just as past unsustainable human-environment interactions in the Sahel gave rise to the term "desertification" in the past, they also show the potential for reversing it in the present.

Funding

This project was funded by a grant from the National Science Foundation (BCS-12618000). Support from the Wenner-Gren Foundation for Anthropological Research, the Carolina Population Center (CPC), and the Center for Global Health and Infectious Disease (CDHI) also helped fund this research.

Conflict of Interest

The authors declare they have no conflict of interest.

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Dear Dr. Bates:

Please accept our revised manuscript titled, "Ground Truthing Sahelian Greening: Ethnographic and Spatial Evidence" (HUEC-D-16-00061)submitted to *Human Ecology.* We appreciate the reviewer comments and have incorporated them into our revised manuscript. This letter describes our revisions.

Reviewer 1 suggested that our paper is not "ethnographic" in the sense that it does not entail prolonged and immersive fieldwork. The first author is trained as a sociocultural anthropologist and has a PhD in the discipline. The meaning of ethnography is constantly debated in anthropology and this work is indeed ethnographic because it involves empirical fieldwork in remote locations that consists of interviews and participant observation. The first author has worked intermittently in the northern Central Plateau of Burkina Faso for 14 years and some sessions have been for extended periods of time. This article is informed by this larger body of fieldwork, which we acknowledge by citing previous publications (West 2013; West *et al.* 2009; etc. on p. 6) and is thus, definitively ethnographic. We acknowledge, however, that the specific fieldwork data we draw on here is from rapid participatory rural appraisal and have retitled the section, "Rapid Participatory Rural Appraisal Fieldwork" on p. 6. More substantially, we have emphasized that these limited ethnographic narratives provide the starting point for the spatial analysis and guide it (Introduction - p. 4; methodology - p. 11; and Conclusion - p. 23). Reviewer 1's insight helped us re-think the link between our fieldwork and analysis, which helped us articulate it more clearly as a problem statement and conclusion.

Likewise, we also recognize Reviewer 1's concern that SWC cannot be the sole driver of greening in northern Burkina Faso. Thus, we more carefully describe the limitations of our fieldwork methods (p. 6) and analysis (i.e., we do not take other factors into account - pp. 21 - 22). The revised paper also lists the other possible explanations for greening such as carbon fertilization, groundwater interactions, and the lack of droughts (Discussion - pp. 21 - 22). We additionally provide more context regarding the position and possible motivations for the farmers, NGO staff, and government agents with whom we spoke (Discussion - p. 21). It is possible that participant perceptions are affected by their need for additional donor support or government prerogatives as well as practical matters such as the length of time they have resided in the study area. All of Reviewer 1's minor comments were also incorporated.

Reviewer 2 also suggested we discuss the limitations of our data and analysis in greater depth, which we did in the Discussion section. We specifically note the non-random nature by which we selected participants (p. 20); the fact we did not control for "green" and "brown" pixels for conducting the RPRA (p. 21); and the possibility that simply the absence of severe droughts makes the region greener (p. 22). We also describe the next steps we would like to take to build on this preliminary work by using higher resolution MODIS data and conducting a more rigorous sensitivity analysis with the NDVI/RFE data (p. 23). In line with Reviewer 2's suggestion, we have added more direct quotes and narratives (pp. 9 -10) that illustrate how farmers and NGOs feel SWC improves the environment. We are not able to provide more contextual ethnographic data on Mossi livelihoods and persistence, however, because this has been the subject of numerous other articles by the authors and would be redundant.

Last, we have included a Burkinabé collaborator from the IGB as a fourth author because the agency provided data and this scientist provided helpful insights.

Thank you very much.
Your most humble and obd't servant,

Colin Thor West