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Participatory Mapping with High-resolution Satellite Imagery: A Mixed Method Assessment of Land Degradation and Rehabilitation in Northern Burkina Faso

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Cover Page Footnote

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RESEARCH ARTICLE

Participatory Mapping with High-resolution Satellite Imagery: A Mixed Method Assessment of Land Degradation and Rehabilitation in Northern Burkina Faso



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ABSTRACT

Sahelian West Africa is a region that has high population densities and that has frequent severe droughts and enormous pressure on natural resources. Because of these challenges, it is the place where the term desertification was originally coined. Recently, however, experts have identified large zones of greening where the amount of vegetation exceeds what one would expect based on rainfall alone. This pattern is well documented, but its mechanisms remain poorly understood. This research employs participatory mapping linked with high-resolution satellite imagery to better understand the human role behind regional vegetation trends. Through a case study of three communities in northern Burkina Faso, this paper presents a pilot methodology for explicitly mapping perceived areas of both land degradation and rehabilitation. Combining participatory mapping exercises with standard image classification techniques allows areas of land degradation and rehabilitation to be precisely located and their extents measured for individual communities and their surrounding terroirs. Results of the spatial analysis show that the relative proportion of greening and browning varies among communities. In the case of Sakou, nearly 60 percent of its terroir is degraded. While in another, Kouka, this is 48 percent. This method also elicits perspectives of Burkinabè agro-pastoralists on the local land-use practices driving these twin environmental processes. Altogether, this case study demonstrates the analytical power of integrating ethnography and high-resolution satellite imagery to provide a bottom-up perspective on social-ecological dynamics.

INTRODUCTION

The Sahel is a wide semi-arid band that stretches across Africa. It literally means shore in Arabic, and it forms the transition zone between the Sahara Desert to the north and wetter Sudanian savannas to the south. The Sahel was once synonymous with desertification, and the term was first coined in reference to

this region (Charney 1975). Severe droughts in the 1970s and mid-1980s affected the region severely and caused some of the worst famines of the 20th century (Franke and Chasin 1980). Experts theorized that population pressure and overgrazing drove the southern expansion of the Sahara, giving rise to the concept of desertification (Charney 1975) and bringing renewed international focus on the Sahel, its people,

and environments. Desert expansion purportedly proceeded at the alarming rate of 5 km per year (see Swift 1996).

A series of remote sensing studies in the mid-2000s sought to better characterize the rate and severity of Sahelian desertification. Using a time series of Normalized Difference Vegetation Index (NDVI) data derived from satellite images, several research teams detected just the opposite. Instead of finding an expanding desert, they detected large patches of increased vegetation across the Sahel (Herrmann et al. 2005; Olsson et al. 2005). This Greening of the Sahel (sometimes also referred to as the Re-Greening of the Sahel) is now well-established, but its mechanisms remain poorly understood (Mortimore 2009). Multiple recent analyses have confirmed these patterns, but there have been few investigations of what greening actually means for people on the ground (see Herrmann et al. 2014; Sendzimir et al. 2011).

This study investigates regional patterns of vegetation trends in local contexts with rural farmers and agro-pastoralists in Burkina Faso to better understand its social-ecological dynamics and possible “bottom-up” mechanisms. A bottom-up approach entails investigating global environmental processes and problems from the perspective of the people who are affected in terms of their landscapes and land-use practices. This is similar to the ethnoecology and situated knowledge discussed by Virginia Nazarea (1999) whereby ecologists, anthropologists, and indigenous swidden agriculturalists can gaze upon the exact same forest but interpret its dynamics completely differently. The fieldwork and methods presented here borrow from James Fairhead and Melissa Leach's (1996) seminal study of forest-savanna mosaics in Guinea, which combined local histories of vegetation change with a time-series of remote sensing imagery to question expert claims of rampant regional deforestation—a global environment threat. Like Fairhead and Leach,

this study assesses land degradation—also a global environmental issue—by using the perspectives of local resource users as a starting point for the analysis of empirical data—high-resolution satellite imagery. This bottom-up approach resonates with recent calls by anthropologists for less criticism of and more collaboration with scientists involved in climate change research (Fiske et al. 2014) and in global environmental change research within the broad context of the Anthropocene (Mathews 2020). This is particularly salient while anthropologists and physical scientists are increasingly integrating their ethnographic, meteorological, and other types of data to better understand long-term regional climate trends (Felzer et al. 2019).

To obtain this ground-based information, researchers used rapid participatory-research approaches combined with high-resolution satellite imagery (i.e., sub-meter and multispectral) to elicit local perceptions. Other Sahelian researchers have recently attempted to use participatory mapping methods to assess what vegetation trends detected in imagery actually mean for pastoralists in Senegal using photo-elicitation techniques (Herrmann et al. 2020). Doing so means not only collecting empirical data on local perceptions of environmental change, but also making local communities part of the data collection and mapping process (Kingsolver et al. 2017). By integrating participant perceptions with high-resolution imagery, the method presented here is able to render these perspectives on rehabilitation and degradation spatially-explicit, for which Stefanie Herrmann and her colleagues (2020) have advocated.

These participatory workshops were conducted with members of three villages in the Commune of Kongoussi in northern Burkina Faso on the southern fringe of the West African Sahel. For each village, there were separate workshops with older males, younger males, and women. Thus, nine workshops

took place in total among the three different localities. Researchers then obtained three separate satellite images of each village and their surrounding landscapes. The researchers used the workshop data to classify the images using a supervised maximum likelihood classifier (MLC) to identify areas of greening (i.e., rehabilitation), browning (i.e., degradation), and unclassified (i.e., neither rehabilitation or degradation; or simply null) for each village. This method is synoptic and provides for the precise spatial location of green and brown patches along with a measurement of their spatial extent. The fieldwork and analysis were designed as a pilot study with only three communities using standard image processing techniques. Thus, the results presented here are preliminary and intended to demonstrate the utility of these methods. Nonetheless, they indicate the spatial extent of rehabilitation or degradation varies among the three communities.

Because of the satellite imagery's high resolution, participants were able to identify specific land-use practices associated with both greening and browning. This elicits local perspectives on the bottom-up processes driving vegetation change. These provide insights on the observed patterns of land degradation and rehabilitation to explain why the extent of each varies across village lands. Altogether, this innovative use of high-resolution satellite imagery, participatory mapping, and image-processing techniques show that local patterns of greening and browning form patchy mosaics in these social-ecological landscapes. Integrating ethnography with imagery provides explanations for the processes driving these patterns, and that greening and browning are due to both natural and anthropogenic drivers.

REMOTE SENSING AND ENVIRONMENTAL ANTHROPOLOGY

Environmental ethnographies on conservation (West 2006), deforestation (Tsing 2005), and land conflicts

(Escobar 2008) rely primarily on narratives that describe how global capitalism drives environmental degradation. These studies provide rich and detailed accounts of how the interests of external institutions and local actors intersect in a particular place, but we know little about the extent, rate, or severity at which these processes occur. As Orr et al. (2015) point out, cultural anthropologists rarely have long-term datasets that permit analyses of such biophysical environmental change over time. If available at all, these data tend to be very locally place-based and discontinuous. Remotely-sensed satellite imagery can fill in these gaps by providing repeat data over long time periods over large areas (Moran 2010). In fact, time-series analyses using many different forms of imagery and aerial photos have profound implications for understanding both the spatial and temporal dimensions of environmental change across subfields in anthropology (Anemone and Conroy 2018).

Integrating ethnography with remote sensing (RS) can yield insights on the social processes driving environmental change (Guyer et al. 2007). Doing so has allowed anthropologists to examine entrenched narratives on environmental degradation such as deforestation (Fairhead and Leach 1996), rangeland destruction (West and Vásquez-León 2008), and coral reef bleaching (Stoffle et al. 1994). In most cases, ethnographic fieldwork and remote sensing analyses are performed separately but in parallel by interdisciplinary teams, which results in distinct interpretations of causality (Harnish 2014). When ethnography and remote sensing are integrated from the beginning and throughout the research process, the methods complement one another and can lead to novel insights neither alone could have discerned (Jiang 2003).

To date, however, ecological anthropologists have relied primarily on satellite products with relatively coarse spatial resolution. Of these, Landsat imagery is the most popular and is available at no cost. Begin-

ning in 1982, Landsat 4 Thematic Mapper (TM) has featured a pixel resolution of 30 m by 30 m, which has allowed experts to assess the human role in Amazonian deforestation (Brondizio and Moran 2012) and land degradation in Mongolia (Jiang 2003), to compare deforestation patterns between West African contexts (Nyerges and Green 2000), and to examine many other environments around the world. The spatial resolution of Landsat imagery, however, limits the investigation of many anthropogenic processes that are practiced at small, or very localized spatial scales, such as tree-planting or field fallowing. These are too fine to detect with 30 m pixels—especially in rural marginal agricultural landscapes (Turner 2003).

Higher resolution imagery such as SPOT (2.5 m to 10 m) can discriminate among individual fields, clumps of trees, and settlements, which can make stronger causal relationships between human land-use and vegetation to be drawn (Guyer et al. 2007). In their celebrated work *Misreading the African Landscape*, James Fairhead and Melissa Leach (1996) definitively demonstrated the relationship between forest growth and human settlement using SPOT imagery. Islands of forest were readily apparent in a savanna matrix with villages at their center. With very high-resolution (i.e., sub-meter) satellite imagery, one can not only see the forest from the trees, but also discern the individual trees within a forest.

Cultural anthropologists have begun taking advantage of the enhanced analytical power of high-resolution imagery to map isolated indigenous communities in Amazonia (Kesler and Walker 2015), predict rural household wealth in Kenya (Watmough et al. 2019), and assesses urban forest change in Baltimore (Ogden et al. 2019). As discussed below, these fine-grained data allow researchers and project participants to better observe patterns and understand processes because anthropogenic features and vegetation are clearly visible.

SAHELIAN GREENING AND REMOTE SENSING

At a much coarser spatial resolution and greater extent, satellite images from Advanced Very High Resolution Radiometer (AVHRR) and Moderate Resolution Imaging Spectroradiometer (MODIS) (at 1 km – 8 km spatial resolution) indicate increasing greenness over large areas of the Sahel since the mid-1980s (Herrmann et al. 2005; Olsson et al. 2005). The Normalized Difference Vegetation Index (NDVI) is the most common indicator of greenness used in these analyses:

$$\text{NDVI} = \frac{\text{NIR} - \text{R}}{\text{NIR} + \text{R}}$$

where NIR = near infrared and R = red reflectance. Normalized Difference Vegetation Index ranges from -1.0 to 1.0 and is positively correlated to the amount of standing foliar biomass. Using coarse resolution (i.e., 8 km X 8 km pixel) data to measure Normalized Difference Vegetation Index, Herrmann et al. (2005:399) detected large spatially coherent areas that exhibit enhanced "greening" in many distinct regions of Sahelian West Africa. One of these regions lies in northern Burkina Faso where fieldwork for this project took place. This same greening hotspot in northern Burkina Faso has persisted in more recent remote sensing studies using similar data and methods (see Dardel et al. 2014:359; Stith et al. 2016:77; Ibrahim et al. 2015:5479).

The availability of very high-resolution sub-meter satellite imagery has exploded over the last decade. Collectively, these data now form a continuous global surface to observe the environment. With increased availability and advances in processing, imagery has also decreased in cost and anyone with access to the Internet can easily view these data with Google Earth for free. Analytical capabilities in Google Earth are, however, limited, but individual satellite images can be

relatively low cost. Users can purchase and download subsets of image data that spatially conform to their area of interest. The minimum area is generally 5 km X 5 km (25 km²), which costs approximately 350 United States dollars.

Most of the higher spatial resolution datasets contain both multispectral (MS) data with approximately 2 m X 2 m pixel resolution in four bands of the electromagnetic spectrum: red (R); green (G); blue (B) and near-infrared (NIR), as well as a 0.5 m resolution panchromatic (PAN) dataset in a single broader spectral band that spans the green, red, and near infrared wavelength regions (i.e., grayscale). Using image-processing software, these bands can be combined to create color maps, visualized, and automatically separate features of the landscape into distinct classes.

Most recent assessments of land-use/land-cover (LULC) change, desertification, or land degradation in Africa's drylands use moderate-resolution Landsat or Moderate Resolution Imaging Spectroradiometer satellite imagery. The term "land-use" refers to the general human-altered purpose for which land is used (e.g., agriculture, orchard). The term "land-cover" refers to the general unaltered or undisturbed state of land (i.e., forest, wetland, etc.). Landsat imagery has a long and continuous temporal record that extends from 1972 to the present. It consists of four bands at 30 m X 30 m pixel resolution. Moderate Resolution Imaging Spectroradiometer imagery is available from 1999 to the present and consists of 36 spectral bands, the finest of which are at 250 m X 250 m resolution. The spatial resolutions provided by Landsat and Moderate Resolution Imaging Spectroradiometer enable the classification of broad land-use/land-cover classes such as forest, grassland, bare soil, and agriculture, but are too coarse for identifying small-scale patterns in settlements, agriculture, and Soil and Water Conservation (SWC) interventions (e.g., semi-permeable rock dams) or individual trees that are relevant for the

study of highly localized land-use practices associated with subsistence agriculture. In contrast, individual dams, trees, and other small-scale features are readily observable in sub-meter GeoEye and WorldView imagery (West et al. 2017). Our study uses such high-resolution imagery to elicit local perspectives on greening and browning and measure the extent of each.

STUDY AREA

Burkina Faso is a landlocked country located in the Sahel of West Africa. It is a semi-arid dryland where rainfall is seasonal. The rainy season begins in approximately June-July and persists until September-October. There is a strong precipitation gradient between the wetter south (approximately 1200 mm of annual precipitation) and drier north (approximately 400 mm). Because of this precipitation pattern, the country is divided into three bio-geographic zones: 1) the southern Sudan; 2) the Sudano-Sahel; and 3) the northern Sahel (Somé and Sivakumar 1994). Our study zone in the northern Central Plateau region is located in the transition zone between the northern Sudan and Sudano-Sahel. The Commune of Kongoussi lies in an area identified as greening (West et al. 2017). Communes are the lowest level of administration in Burkina Faso and are roughly equivalent to counties in the United States

Livelihoods are mixed and diverse, but rain-fed subsistence agriculture is the primary economic activity and takes place in the valleys and surrounding slopes. Transhumant pastoralism is also practiced along with some fishing and extensive dry-season gardening. Mossi are the main ethnic group and are historically known for practicing extensive agriculture where fields were abandoned and left fallow once soils became exhausted (Marchal 1983; Batterbury 1998). More recently, however, Mossi rural producers have intensified their agriculture by investing in a range of

soil and water conservation practices (Reij et al. 2005; West et al. 2016; West 2013). Mossi smallholders—i.e., household-based subsistence farmers—have gradually integrated animal husbandry into their farming and consider themselves full-fledged agro-pastoralists (West 2015). Nonetheless, each village is distinct and together they reflect variation in the mix of livelihoods and land-use practices. Fieldwork took place in three Mossi communities: Sakou (approximately 1,750 inhabitants), Loulouka (approximately 1,500 inhabitants), and Kouka (approximately 900 inhabitants). As seen in Figure 1, Sakou and Kouka lie in a large contiguous cluster of greening pixels while Loulouka lies in a cluster of neutral pixels.

Sakou lies approximately 10 km from Kongoussi along a major dirt road. Fields here tend to be large and spread out over a large area. Smallholders in Sakou are also agro-pastoralists but tend to herd their animals during the day and corral them at night. Agriculture is mostly intensive but loosely integrated with animal husbandry. Loulouka is a peri-urban village, which lies 2 km from the urban population of Kongoussi. The population density of Loulouka is high, and residents have access to dry-season gardens along the shores of a nearby lake—Lac du Bam. Agricultural land is limited because of the lake and nearby town. Thus, households tend to practice very intensive agriculture on small parcels and stall-feed their

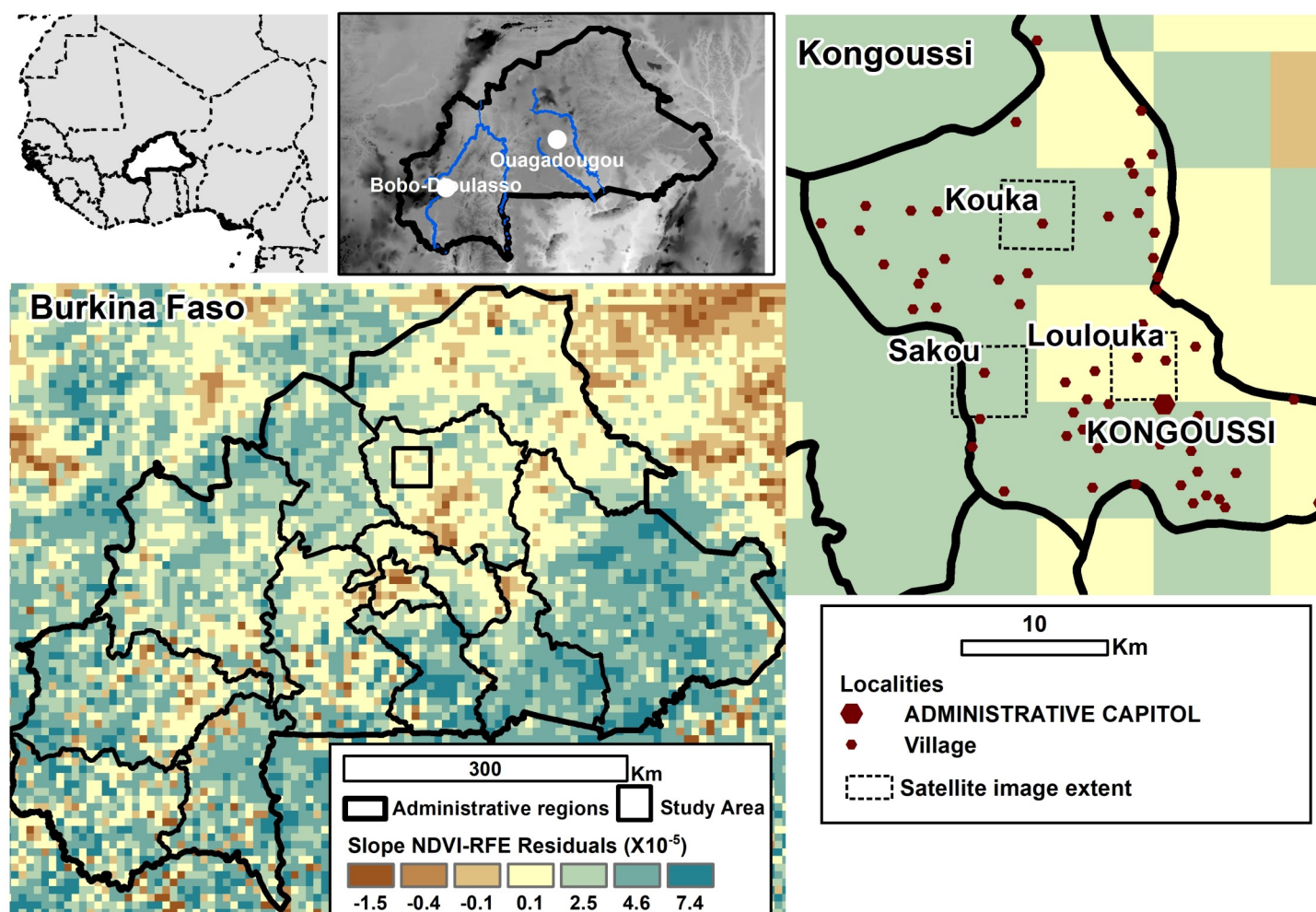


FIGURE 1. Study Region and Maps of Slope of Normalized Difference Vegetation Index-Rainfall Estimate Residuals for Burkina Faso and Kongoussi Commune (study sites are indicated by boxes and labeled).

animals. Manure from these animals is made into compost and added to fields every year. Thus, farming and animal husbandry are tightly integrated in Loulouka in comparison to Sakou. Last, Kouka is much more remote and isolated than either Sakou or Loulouka. It lies approximately 15 km from Kongoussi along narrow trails next to a low-lying **bas fond** (flood zone) that becomes inundated during the rainy season. This means that soils are relatively rich, and farmers here rely less on external inputs such as the manure used in Kouka. Because of its isolation, however, some agro-pastoralists have very large cattle herds compared to Sakou and Loulouka. This study investigates the views of Mossi agro-pastoralists across age and gender categories on land degradation and greening.

DATA AND METHODS I: PARTICIPATORY MAPPING EXERCISES

Consistent with participatory and rapid appraisal approaches (Chambers 1994), this fieldwork integrated remote sensing and qualitative methods to ground-truth greening and browning. It builds on similar methods by Herrmann et al. (2014) in Senegal with pastoralists in which the researchers used coarse resolution (8 km X 8 km) satellite imagery. The PI, two graduate students from the University of North Carolina at Chapel Hill, and two local field assistants from a **Burkinabè** (meaning: of Burkina Faso) local non-governmental organization conducted fieldwork over two weeks in July 2017.

The local non-governmental organization helped the researchers recruit participants from the three different villages. These are three communities in which the first author, a human ecologist, has worked since 2002 and with which the non-governmental organization has strong collaborative relationships. The mapping took place in the offices of the non-governmental organization in Kongoussi. Institutional Review Board

permission for fieldwork was obtained through the University of North Carolina at Chapel Hill (UNC-CH IRB #17-3350).

For each village, the participatory mapping exercises were stratified by age and gender. Mossi society is strongly patriarchal, marriage is patrilocal, and there is a strong political hierarchy organized along patrilineages (Izard 1985; Izard-Héritier and Izard 1959). For these reasons, women tend to have subordinate roles and young men are expected to defer to older male members. Thus, there were three distinct groups for mapping exercises in each village composed of: 1) older men (men > 50), 2) younger men (men < 50), and 3) women (all ages).

Because of the academic schedule, fieldwork took place during the rainy season. Participants were very occupied with agricultural tasks and each session was limited to approximately 1.5 hours to minimize disruptions. Each group consisted of six participants and there were nine individual mapping exercises with 54 individuals (3 groups/village X 3 villages = 9 exercises; 9 exercises X 6 persons/exercise = 54 persons).

In each group, the participants were shown a high-resolution (2 m X 2 m) color satellite image (i.e., village map) of their village and its approximate **terroir** (village land-use area). The French term *terroir* loosely corresponds to the bounded use area for a given village over which member lineages control access to land, collectively manage natural resources, and engage in communal soil and water conservation activities (Marchal 1983; Batterbury 1996; Bassett et al. 2007). The image measured 5 km X 5 km (25 km²) in area and was printed on a sheet of cloth that measured 91.44 cm X 91.44 cm. The overall scale was approximately 1:10,000. The scale and pixel resolution was sufficient for participants to easily identify individual trees, soil and water conservation measures, structures, roads, and other relevant features of the

landscape. Printing on cloth—rather than paper—enabled the satellite image to be easily transported on airplanes and motorcycles to the non-governmental organization offices in Kongoussi.

The participatory mapping sessions used a topic outline to ensure each was conducted consistently and to ensure data integrity and comparability. Initially, participants were asked to orient themselves to the image and identify key features such as roads, schools, and mosques or churches. Once oriented, the PI, students, and a local facilitator asked participants to place two distinct sets of green and yellow buttons on areas they consider either rehabilitating (i.e., greening) or degrading (i.e., browning). Yellow buttons were selected for this exercise because brown buttons did not photograph well since they were not easily distinguishable from brown features in the printed satellite image. Each group then placed ten greening (green) and ten browning (yellow) buttons on the image.

Consistent with the United Nations Millennium Ecosystem Assessment on Desertification (2005), participants were asked to identify as browning/degraded those areas where they perceive a persistent reduction in biological and economic productivity in terms of the “things that ecosystems provide that matter to people” (MA 2005:5). The team provided brief and general examples such as: 1) places where there were fewer trees, 2) places where crops often failed, 3) places where animals could no longer browse or graze, and 4) others. In terms of greening/rehabilitated, the protocol solicited perceptions where the processes opposite to degradation were occurring—participants were asked to identify areas where there were now more trees, crops produced more grain, animals had better pasture, etc.

We encouraged participants to actively discuss the placement of these buttons to reach consensus. It generally took groups approximately five or ten

minutes to collectively discuss the satellite image, reflect on the meanings of greening and browning, and begin placing buttons. Following their placement, participants explained their decisions and described what these regions of greening and browning correspond to using indigenous land-use/land-cover categories such as **zipellé** (bare soil), **baogo** (seasonally flooded agricultural lowlands—*bas fond* in French), **bolé** (agricultural bottomland) and others (see Batterbury 1997:102).

Next, participants additionally described the processes they felt drive greening and browning. Last, researchers asked about the impacts of revegetation and land degradation on local livelihoods. Similar research on greening in West Africa suggests increased vegetation is due to the spread of exotic or invasive tree and shrub species that decrease biodiversity, which may not be beneficial for local farmers or herders (Herrmann and Tappan 2013). This study builds on these insights to more broadly ask about the implications of both greening and browning across social groups.

The position of the greening and browning buttons on the village satellite image for each group session was photographed using a digital camera. This resulted in a series of nine total photos across all groups and communities. In addition, one graduate student took hand-written notes during the participatory mapping exercises in order to document farmer responses. This same student transcribed the notes into digital files and then coded them into broad themes. These themes included areas of browning, causes of browning, impacts of browning, and parallel themes for greening. The participatory mapping exercises required significant translation among English, French and the local languages **Mooré** (Mossi language). The researchers opted for written note taking because they felt it was less distracting and obtrusive in these informal contexts.

DATA AND METHODS II: IMAGE CLASSIFICATION

Using Spatial Analysis within ESRI's ArcGIS 10.4 for Desktop, the high-resolution satellite images were classified into two classes based on the positions of the buttons placed on the maps: 1) greening—i.e., areas in which green buttons were placed, and 2) browning—i.e., areas in which brown buttons were placed. Because the classification used a threshold (discussed below), some pixels were also left unclassified—i.e., areas that could not be assigned to either greening or browning. This was done using the multispectral image, which has a coarser spatial resolution (approximately 2 m X 2 m) than does the panchromatic image, but which has a higher spectral resolution of four bands (red, green, blue, and near-infrared) as opposed to just one. Although the classifier used two classes as input, this method produced three classes of pixels: greening, browning and unclassified.

The image processing used a supervised classification method. Each photographed map with buttons produced a set of 20 button placements (ten green and ten brown). This produced 60 button placements (three groups per village) for each village map. The positions of buttons, however, frequently overlapped across each group for any given village. Thus, there were effectively only 40 independent buttons across all groups for each village. Hence, 30 of these green and brown buttons were used as *training data* for classifying each image while the other ten buttons were used as *testing data* for validating the classified image. These training and testing buttons were randomly selected using ArcMap 10.4. The area of each individual button was treated as training sample data for each class. Visually comparing the position of buttons from each village map photograph and their relative location in the corresponding satellite image allowed for the creation of 10-15 greening training areas and 10-15 browning training areas for each of the three images.

Using heads-up digitizing (i.e., drawing using the mouse cursor on the computer screen), we created 30 sets of training data for each satellite image. Next, these training areas were grown throughout the image to classify pixels using a maximum likelihood algorithm. The maximum likelihood classifier (MLC) makes use of the spatial patterns of pixels and their reflectance in the red, green, blue, and near-infrared bands to classify pixels. Based on their proximity (i.e., clusters of pixels with similar spectral signatures) and the reflectance of these clusters in red, green, blue, and near-infrared wavelength regions, digital image processing classified each pixel as either green or brown and mapped them for each satellite image.

In this case, the maximum likelihood classifier used pixel values from the button areas used as training data to classify the rest of the image pixels into either of two predetermined classes: green or brown. The MLC assumes a normal distribution of values in the red, green, blue, and near-infrared bands for each class and calculates the probability that a given *unknown* pixel can be assigned to either the green or brown pixel class. As an example, green vegetation produces high reflectance values in the near-infrared band but low values in the red band. Bare soil, on the other hand, reflects very little light in the near-infrared band but a lot in the red band because most of the soil is lateritic (i.e., volcanic and composed of oxidized iron) and therefore red. Thus, the maximum likelihood classifier can strongly discriminate between green and brown pixels in the near-infrared and red bands because the mean values for each class and their distributions are distinct. Essentially, the bell-shaped curves for green pixels and brown pixels would appear separate with little overlap in the near-infrared and red bands.

Without a threshold, however, the classifier will assign all pixels to one class or the other. Thus, we selected a 75 percent threshold for the maximum likelihood

classifier so that some pixels would be unclassified. This is because participants did not place buttons in some parts of the satellite image and felt these places had neither rehabilitation nor degradation occurring. The maximum likelihood classifier therefore used this 75 percent spectral threshold to assign each pixel to either class. Any pixels that did not fall within 75 percent of the distribution for either the green or brown class across all four bands were left unclassified. This meant 25 percent of all pixels for each image obtained null values because they could not be assigned to either class—i.e., were unclassified or null.

The classified regions of greening and browning were then visually compared to the positions of the ten green or brown test buttons for each of the three villages. Each test button could be either: 1) correctly classified (i.e., a green test button lying within an area classified as green), or 2) incorrectly classified (i.e., a green test button lying with an area classified as brown. Whether a test button was correctly or incorrectly classified was determined for all green and brown test buttons and these conditions were entered into a table using Excel. This produced a two-by-two crosstab of correctly and incorrectly classified green and brown buttons for all three villages. Because there were a total of only 15 green or brown test buttons, there were not enough observations to yield any meaningful Chi-square test statistic. Last, the percentage of green and brown pixels were calculated for each village using Excel to estimate the total area of greening/rehabilitated and browning/degraded land for each village and its terroir.

RESULTS

Overall, participants in all villages and groups actively engaged in the mapping process. Men in their groups and women in their groups typically discussed criteria for browning and greening among themselves and asked for clarification. Then they nominated one

member to place green and then brown buttons. They subsequently re-positioned buttons to achieve consensus among all participants. Within each village, the placement of green and brown buttons was remarkably similar across groups (Figure 2).

For the most part, green buttons were placed in areas dominated by crops with substantial tree cover. These



FIGURE 2. Button Placements by Village and Group: Sakou (top), Kouka (middle) and Loulouka (bottom); Elder men (left), Younger Men (middle) and Women.

are agroforestry parklands where crops are grown under a discontinuous and scattered canopy of native trees (Bayala et al. 2014). These were also commonly fields treated with soil and water conservation techniques such as semi-permeable dams and/or **diguettes** (contour stone bunds) (Figure 3A). In Kouka, participants additionally associated low-lying gallery forests as greening (Figure 3B). Last, residents of Kouka and Loulouka identified irrigated dry season garden areas as examples of greening (Figure 3C). Sites of greening/rehabilitation were mostly dispersed and located throughout the terroir of each village. In contrast, non-agricultural areas were strongly asso-

ciated with browning and land degradation. These were commonly large bare patches devoid of vegetation, which are referred to as zipellé in Mooré (Figure 4A). Participants also identified elevated rocky outcroppings as degraded (Figure 4B). In a few cases, farmers placed yellow (i.e., browning) buttons in agricultural fields that lacked trees or shrubs and showed little vegetation. They explained that these are fields that are constantly cultivated, never allowed to rest and are becoming zipellé (Figure 4C). Like greening

areas, sites of browning/land degradation were mostly dispersed throughout the terroir of each village.

Participants emphasized that areas of greening or rehabilitation are mostly places they actively manage. In the case of agroforestry parklands, these are fields that village organizations have extensively treated with soil and water conservation techniques. They explained that diguettes and dams trap organic matter and make their fields more fertile. These interventions are wide-

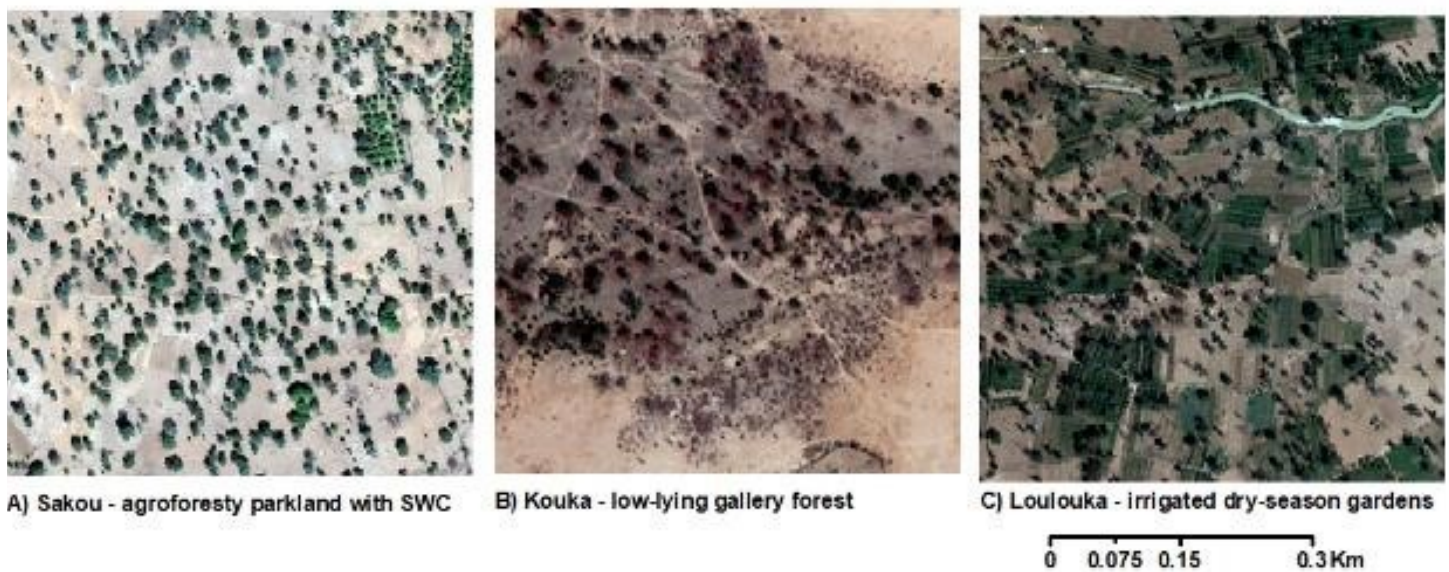


FIGURE 3. Land-use Types Associated with Greening.

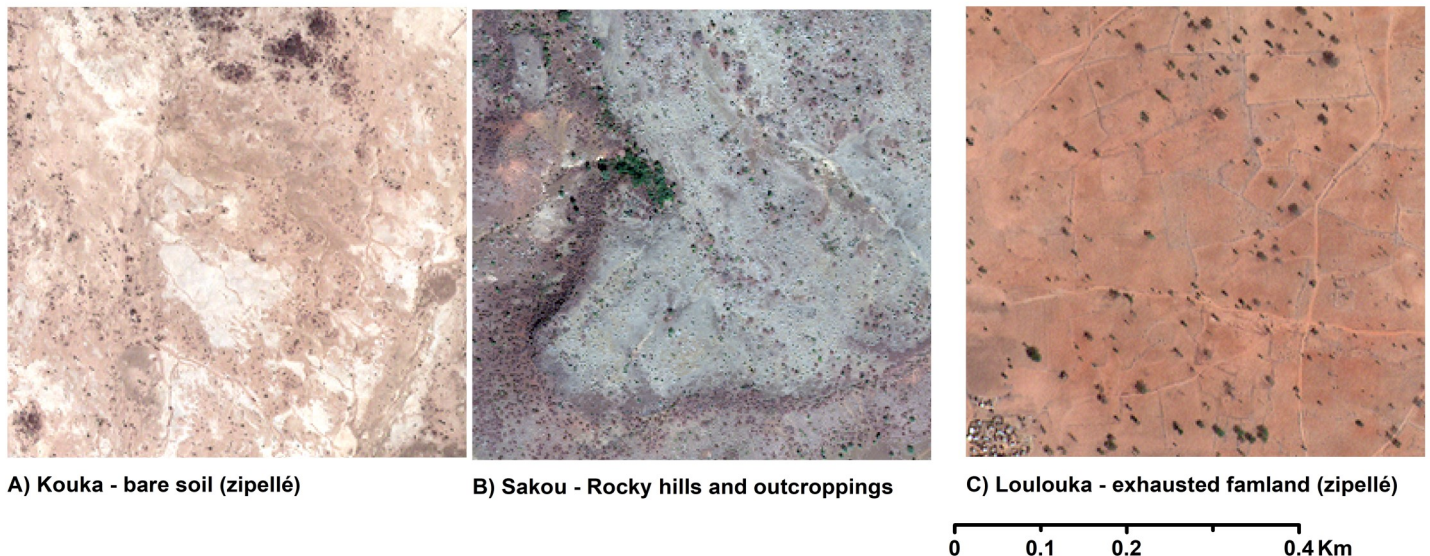


FIGURE 4. Land-use Types Associated with Browning.

spread—especially in Sakou—and likewise catch seeds from surrounding flora and enable these seeds to germinate and grow. Thus, they pointed out how trees, grasses and shrubs are often located along diguettes or dams because such plants have spontaneously revegetated in those areas of soil and water conservation.

Similarly, some areas of greening are dry season gardens, orchards, or reforestation projects (particularly in Kouka and Loulouka). Mango orchards in Sakou allow agropastoralists to gain additional income from selling fruit. They also feed leftover mangoes to their animals to supplement natural forage. Gardens allow residents to earn income during the dry season and to improve the nutritional status of their households.

Reforestation projects consist primarily of neem (*Azadirachta indica*) and eucalyptus tree plantations, which provide termite-resistant wood. Owners of these plantations sell trunks and branches of these trees for housing construction and tool handles. Figure 5 shows an area treated with soil and water conservation techniques in Sakou in 1992 and 2013. We see how tree cover has increased between the two periods along with soil and water conservation activities. There were only a few scattered sites of greening, such as gallery forests, that are natural in the sense

that they are not actively managed by people. Residents graze their animals in these areas because there are water, grasses, and leaves for them to feed on, and they are especially shady and cool. Overall, participants across all groups view greening as positive and beneficial. Rehabilitating areas provide men and women with higher crop yields, tree products, fresh vegetables, and, sometimes, additional sources of cash.

In contrast, participants mostly identified areas of browning or degradation as places that are **wéogo** (French – **brousse**; English – bush). These are sites where people rarely go and which they do not actively manage. They emphasized that these are mostly hillsides, plateaus, and low hills where residents go to collect firewood, hunt wild animals, or collect medicinal plants. They explained that a growing population puts increased pressure on these resources and they become prone to deforestation. Because these areas are steep and rocky, no one can replant trees, shrubs or grasses, which makes them even more susceptible to erosion.

Participants did cite some isolated zipellé patches as examples of degradation. In some cases, these are zipellé soils where nothing has ever grown and that they are naturally bare for edaphic reasons—they are completely crusted hardpans or lie along gullies. In others, they are soils that have been exhausted by continuous use and are never left fallow. Some farmers stated that zipellé are caused by people using too much fertilizer that eventually burns the soil. Not surprisingly, people associated areas of browning and degradation with negative and harmful ecosystem services. They added, however, that some of these areas—notably zipellé soils—could eventually be rehabilitated with active management and especially soil and water conservation.

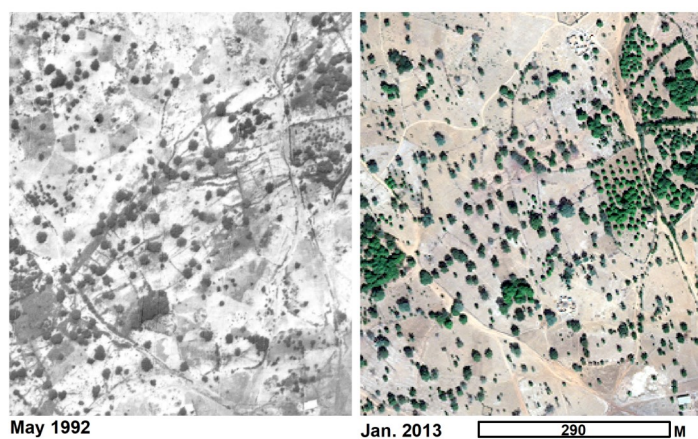


FIGURE 5. Aerial Photo of Area Treated with SWC in Sakou (1992 – left) and WorldView-2 satellite image (2013 – right) Indicating Increase in Tree Cover.

A goal of this study was to extrapolate from the patch data of green and brown buttons to classify the entire

landscape. Using the maximum likelihood supervised classification and training data discussed above, each village terroir was classified into two distinct classes: greening/rehabilitated or browning/degraded (Figure 6). Pixels with spectral values beyond the range of either class were left unclassified or null. Comparing the classified images to the validation data (i.e., the remaining test buttons), less than ten percent (three of the 30 test buttons) of all green or brown testing buttons *did not* visually correspond to their respective greening or browning classes across all classified images. Thus, the classification error was minimal and deemed acceptable for this case study.

The maps show there are different patterns of greening and browning among the three terroirs. Sakou exhibits a simple dichotomous pattern with just two spatially distinct regions of greening and browning. The other two terroirs exhibit more complex and patchy patterns where areas of greening and browning are interspersed. In the case of Kouka, however, the matrix appears to be mostly greening but interspersed with patches of browning. Loulouka is just the opposite—a matrix of browning interspersed with patches of greening.

Across all three villages, the percentages of both classes likewise varied (Figure 7). Because participants were given the same number of green and brown buttons to place, the proportion of greening and browning should be equal—50 percent each. Their particular placements could, however, alter these proportions. Degradation was most extensive in Sakou where the amount of degraded territory (58.1 percent) was over twice that of rehabilitating (27.4 percent). This proportion was similar for Loulouka. Kouka, however, had approximately equal amounts of greening and browning.

DISCUSSION

Combining ethnography with remote sensing provides several advantages. On the one hand, it allows for the analysis of patterns and processes at multiple spatial scales. The above section demonstrates how one can zoom into individual button placements and associate specific land-use or land-cover types with either greening or browning. On the other, it allows for these distinct points with their unique spectral characteristics (red, green, blue, and near-infrared signatures) to be extrapolated over larger areas for which

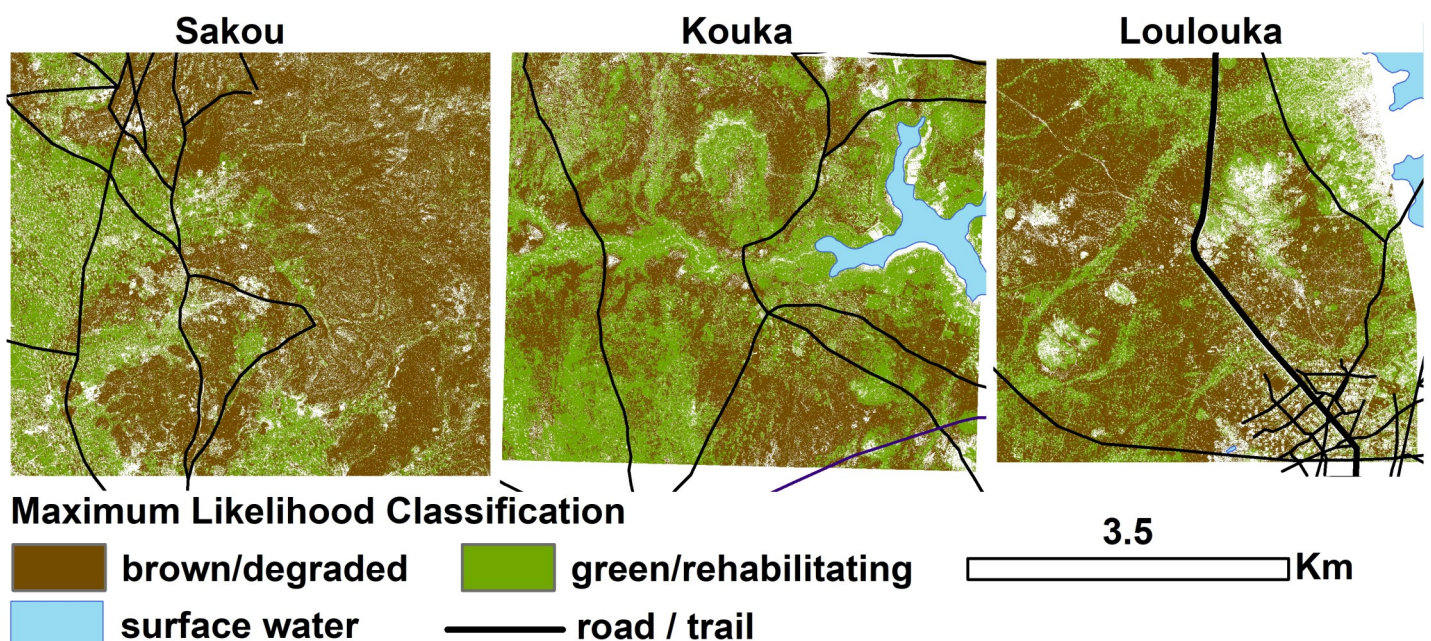


FIGURE 6. Regions of Greening and Browning for Each Village Terroir.

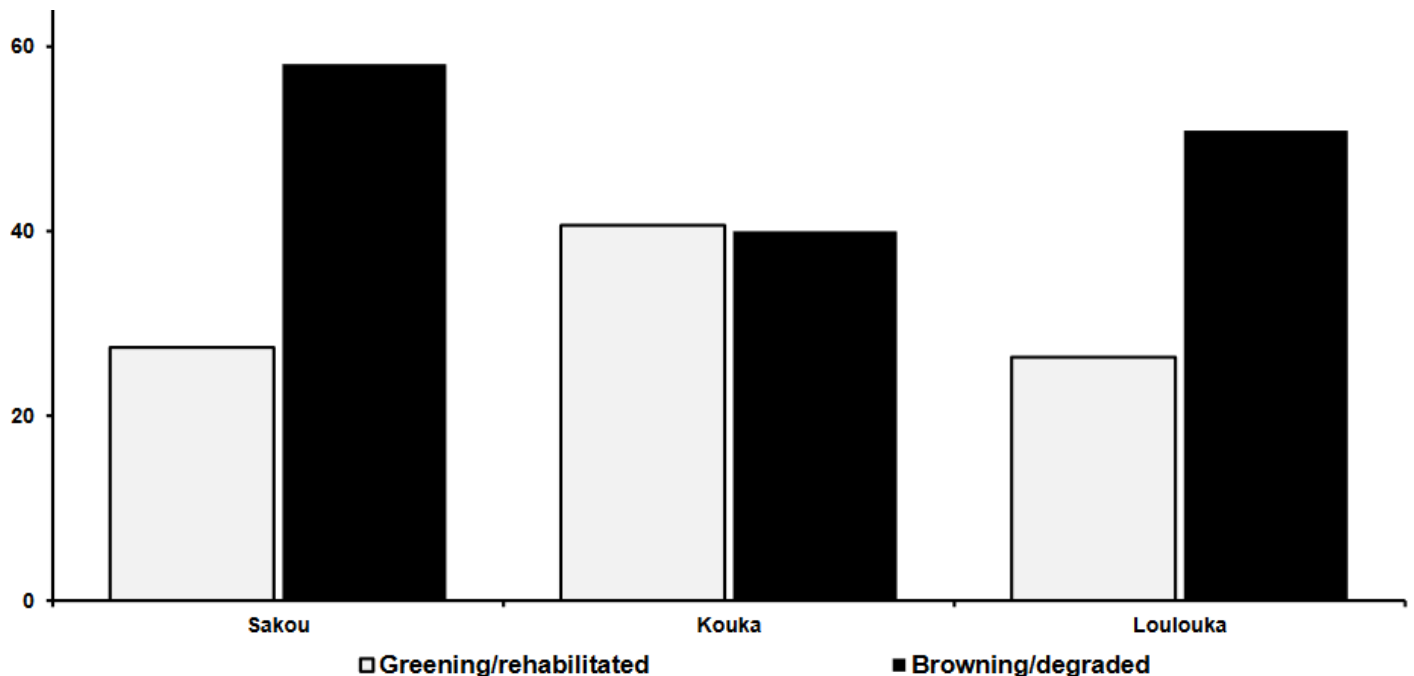


FIGURE 7. Percentage of Greening and Browning for Each Village Terroir.

we lack observations. A goal of this study was to calculate and map the percentage of greening or browning for each village terroir. This was accomplished by using the buttons as input data to train the maximum likelihood classifier. These techniques allow researchers to calculate the percentage of greening and browning community-by-community.

Results show that only one community has equal amounts of greening and browning (Kouka). In the other two, browning exceeds greening by a factor of two. Sakou had the highest amount of land degradation—nearly 60 percent. Similarly, areas of greening and browning are spatially contiguous and form two distinct regions in Sakou. Kouka and Loulouka exhibited more complex and patchy patterns of greening and browning. These patterns are likely due to each village's local geography and population. Both Sakou and Loulouka are more degraded compared to Kouka. They also have high population densities and their agricultural areas are constrained by valleys, urban areas, or lakes. Kouka, on the other hand, has a low population density and is remote, which may explain why

it is greener because it faces less demographic pressure on its local natural resources.

Integrating ethnography with satellite imagery also facilitates the understanding of ecological processes. Participants explained why they considered some areas rehabilitated and others degraded. For the most part, greening is anthropogenic and associated with areas people actively manage through soil and water conservation, reforestation, or dry season gardening. Residents perceive greening as positive and emphasized its benefits: improved soil fertility, spontaneous revegetation, and the ability to earn cash through vegetables and fruits. Browning, on the contrary, takes place mostly in areas considered bush and not actively managed. Degradation is entirely negative, reduces ecosystem services and results in deforestation and exhausted soils. The participatory mapping also revealed that Mossi rural producers believe that the processes of greening and browning are highly dynamic; degraded zipellé soils can be rehabilitated through social and water conservation just as productive soils can be degraded by overuse and excessive fertilizer.

There are several limitations to this case study. First, only a single high-resolution satellite image was used instead of using a time series of imagery from the same location for each village terroir. Budgetary constraints prevented the acquisition of multiple images, which would have allowed researchers to better describe change over time. Participatory mapping exercises were conducted with only three communities, which limits the degree to which insights can be generalized. Each of the three satellite images was only 5 km X 5 km while the Normalized Difference Vegetation Index-Rainfall Estimate (NDVI-RFE) residual pixels were slightly larger at 8 km X 8 km (see Figure 1). Moreover, the classified satellite images were not spatially aligned with individual Normalized Difference Vegetation Index-Rainfall Estimate residual pixels. This makes it difficult to directly compare fine-scale local patterns of greening and browning within each terroir with coarser regional patterns of greening and browning. Last, the classification technique was very simple. Researchers used a limited number of training data observations (30 for each satellite image) and classified images into just two very broad classes using default maximum likelihood classification settings in ArcMap 10.4. In part, this is an artifact of the participatory fieldwork—it only asked groups about greening and browning. More training data, a more sophisticated classification algorithm, and asking participants to describe multiple land-use/land-cover classes would certainly produce different maps. Nonetheless, this methodology is presented as a pilot study given constraints in time and resources. Additional resources would allow the researchers and their local partner organization to obtain more recent satellite imagery and evaluate whether greening or browning is increasing or decreasing.

CONCLUSION

Results inform ongoing debates on land degradation and greening in the Sahel. Specifically, this study de-

scribes a participatory methodology to elicit local perspectives and then use these narratives to guide the spatial analysis. Doing so allows researchers to explain mechanisms behind greening and browning—namely village-scale land-use practices—from the bottom-up. It also permits the mapping of environmental rehabilitation and land degradation for each individual village terroir. Last, these data were used to calculate the extent of greening and browning for each of the three communities.

The participatory mapping exercises produced rich descriptions of the processes driving both greening and browning. Separate groups of older men, younger men, and women collaboratively identified specific areas of rehabilitation and land degradation using buttons and high-resolution satellite images. The positions of green and brown buttons for each group within each village were very similar. These placements were georeferenced using Geographical Information System software to accomplish two research objectives. First, they were used to identify land-use/land-cover types that correspond to greening and browning. This takes advantage of the high-resolution (2-m pixel size) of the satellite imagery which allowed researchers to discriminate among agroforestry parklands, bare soil (*zipellé*), and other very specific land-use/land-cover types described by participants. Second, these button placements were used as training data for classifying regions of greening or browning.

Patterns of greening and browning differed among the villages as well as the extent of each class. These are explained mostly by the local geography and demography of each locality. Sakou exhibits a dichotomous pattern of greening and browning. It also features the most browning (~60 percent). It lies within a steep valley surrounded by hills and plateaus, which constrains agricultural land. It also has the highest population and, hence, population density. Kouka exhibits a patchier pattern of greening and browning

and the amount of rehabilitated land exceeds the amount of degraded. Kouka has the lowest population and lies in a broad plain. Thus, the amount of rehabilitated and degraded land is strongly linked to demographic pressure.

This was a pilot study designed to demonstrate how local narratives of environmental change can be elicited using high-resolution satellite images. Moreover, a goal was also to describe a methodology for using the insights of participants to both map and measure the extent of greening of browning within a village terroir. The participatory mapping exercise and spatial analysis were highly compatible and likewise complementary. As Jiang (2003) concluded, together they provide compelling understandings of complex human-environment interactions that neither alone could.

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