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Bottom-Up Perspectives on the Re-Greening of the Sahel: An Evaluation of the Spatial Relationship between Soil and Water Conservation (SWC) and Tree-Cover in Burkina Faso

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Abstract: The Re-Greening of the West African Sahel has attracted great interdisciplinary interest since it was originally detected in the mid-2000s. Studies have investigated vegetation patterns at regional scales using a time series of coarse resolution remote sensing analyses. Fewer have attempted to explain the processes behind these patterns at local scales. This research investigates bottom-up processes driving Sahelian greening in the northern Central Plateau of Burkina Faso—a region recognized as a greening hot spot. The objective was to understand the relationship between soil and water conservation (SWC) measures and the presence of trees through a comparative case study of three village terroirs, which have been the site of long-term human ecology fieldwork. Research specifically tests the hypothesis that there is a positive relationship between SWC and tree cover. Methods include remote sensing of high-resolution satellite imagery and aerial photos; GIS procedures; and chi-square statistical tests. Results indicate that, across all sites, there is a significant association between SWC and trees (chi-square = 20.144, $p \leq 0.01$). Decomposing this by site, however, points out that this is not uniform. Tree cover is strongly associated with SWC investments in only one village—the one with the most tree cover (chi-square = 39.098, $p \leq 0.01$). This pilot study concludes that SWC promotes tree cover but this is heavily modified by local contexts.

Keywords: land degradation; land rehabilitation; Sahel; high-resolution satellite imagery; GIS

1. Introduction

"Making the Great Green Wall a reality, we will create the largest living structure on the planet and we will have the opportunity to be part of a global movement to help 'grow a wonder of the world'" (Her Excellency Tumusiime Rhoda Peace, Commissioner, Department of Rural Economy and Agriculture of the African Union Commission [1])

"One notes the choice to abandon the initial idea of a vegetation band" (Ministre de l'Environnement et du Developpement Durable, Strategie et Plan d'Actions de l'Initiative Grande Muraille Verte au Burkina Faso [2]—translated from the French).

The quotes above exemplify divergent visions of the Great Green Wall for the Sahara and Sahel Initiative (GGW), which is a pan-African project to halt desertification across 20 countries. The first envisions an 8000–km long and 15–km wide reforestation band that stretches from Senegal to

Djibouti [3]. The second envisions a more realistic and practical mosaic of extensive improved land use practices within three regions of Burkina Faso. Both the proposed revegetation "band" and regional sustainable land management "mosaic" cover the northern Central Plateau of Burkina Faso. This is an area once historically associated with rampant and severe land degradation [4], which in more recent decades has been identified as a region of distinct "greening" [5]. Farming communities on the northern Central Plateau have engaged in massive soil and water conservation (SWC) projects since the mid-1990s, which are recognized as a spectacular example of environmental rehabilitation [6,7]. In fact, the National Action Plan for the Great Green Wall Initiative for Burkina Faso specifically aims to build on the success of existing SWC interventions and expand them to other parts of the country to promote greening [2]. This is part of the national effort to achieve Target 15.3 of the UN Sustainable Development Goals: By 2030, combat desertification, restore degraded land and soil, including land affected by desertification, drought and floods, and strive to achieve a land degradation-neutral world (https://www.un.org/sustainabledevelopment/biodiversity/). Most greening studies, however, have been dominated by large-scale analyses of relatively coarse satellite imagery, such as [5,8,9]. Likewise, assessments of SWC have been mostly large quantitative surveys of individual farmers within distinct villages [10–12]. Few scholars have attempted to spatially ground truth these positive Sahelian vegetation trends in local contexts identified as greening [13–15].

The West African Sahel was once synonymous with desertification and the term was first coined in this region [16]. Experts theorized that high population pressure, overgrazing, and deforestation drove the southern expansion of the Sahara, which purportedly proceeded at the alarming rate of 5 km per year [17,18]. This entrenched narrative permeated development thinking throughout the region, but there was little empirical evidence to support it. The availability of serial remotely sensed satellite imagery enabled this southern expansion to be tested for the entire Sahara-Sahel region across Africa. The first study to do so suggested that the Sahara both expands and contracts at least over the period from 1980 to 1990 [19]. Later, scholars assembled a multi-decadal time series of satellite imagery and rainfall data to better measure the long-term extent, rate and severity of desertification in the Sahel. Instead of finding a southern expansion, they detected large spatially coherent patches of increased vegetation across the region [5,8].

This "Re-greening of the Sahel," or sometimes "Greening of the Sahel," is a well-established regional vegetation pattern but the processes driving it remain under-examined [20,21]. There have been several recent calls to investigate Sahelian Greening from multiple disciplinary perspectives and spatio-temporal scales [9,22]. Scholars have also highlighted the importance of integrating remote sensing analyses with local knowledge [13–15]. This case study takes a "bottom-up" approach to evaluate the basic relationship between tree cover and local land-use practices in three village *terroirs* (Fr.—village use areas) of northern Burkina Faso. Specifically, it uses high-resolution satellite imagery (i.e., sub-meter WorldView-2 and GeoEye-1) to test the hypothesis that areas treated with soil and water conservation measures are positively associated with the presences of trees. This is done across three communities that are located in close proximity to one another but have different levels of SWC investment.

Northern Burkina Faso is semi-arid, drought-prone, and features very high population densities. For these reasons, it is considered extremely degraded and highly susceptible to desertification [4]. Government agencies partnered with international donors to promote SWC projects throughout the region in the late-1980s [23,24]. In these projects, communities constructed long lines of stone throughout their fields. Development organizations and village partners also rehabilitated degraded gullies and ravines with *digues filtrantes* (Fr. - level permeable dams).

Writing over a decade ago, Herrmann and her colleagues [25] specifically noted that northern Burkina Faso exhibited high normalized difference vegetation index (NDVI—a proxy for green biomass productivity) values "beyond what would be expected from the recovery of rainfall conditions alone and might be due to increased investment and improvements in soil and water conservation techniques, such as contour bunding, in response to the drought crisis experienced by farmers." There is strong visual evidence that SWC contributes to increased tree cover. In their time series analysis of aerial photographs from Ranawa in the Province of Zondoma, Reij et al. [6] show how tree density in areas treated with contour stone bunds increased dramatically between 1984 and 2002. The village of Ranawa represents a community with some of the most extensive *diguettes* (Fr.—bund; a colloquial term used to refer to contour stone bunds) in terms of area and had a long history of participation in SWC projects that date to the 1980s. The dramatic improvements in tree density may not be representative of other localities and the authors note, "A rapid analysis of satellite images and aerial photos of the Southern part of the Yatenga (what is now Zondoma Province) shows other villages with a similar evolution" [7].

The larger comprehensive evaluation project of which Ranawa was one site investigated the social, ecological, and hydrological impacts of soil and water conservation projects among twelve villages across several provinces in the northern Central Plateau [24]. The fieldwork took place in 2002 and involved farmer surveys, spatial analysis, transects, and village oral histories among other methods. The research design compared these impacts between nine communities with substantial SWC investments and three control communities with little or no SWC. Only two of the three control sites, however, were located in close proximity to one with SWC in order to minimize local geographic, cultural, and environmental differences. Transects for each village mapped land-use/land-cover change (LULCC), the presence of SWC, and trees for reach locality [26]. Across all twelve sites, SWC-treated areas featured a slightly higher mean density (126 trees/ha) than untreated areas (103 trees/ha) [24]. Moreover, 75 percent of all surveyed woody plants were found in managed areas, while the other 25 percent were located in non-managed areas [24].

Only the aggregate results of this intensive study have appeared in publications and it is difficult to discern inter-site variation. Two of the SWC villages, Ranawa and Rissiam, had especially long histories of soil and water conservation [24], which may have led to overestimation of the effect of SWC on tree cover. The pilot study presented here investigates three village terroirs with varying levels of SWC in relatively close proximity to one another. Instead of transects and field surveys of vegetation, researchers sampled grid cells in high-resolution satellite imagery in an attempt to remove bias in spatial autocorrelation. Finally, the methodology includes a statistical chi-square analysis of the relationship between SWC and tree cover. This work adds additional empirical, quantitative, and statistical insights to the role of soil and water conservation efforts on regional greening in the northern Central Plateau as documented by other researchers nearly twenty years ago.

Studies of Sahelian greening are dominated by highly sophisticated and complex regional analyses that yield robust spatio-temporal statistical models, including [5,9,22,27–30]. This pilot study emphasized a more modest and place-based approach to answering a fundamental question in regard to greening: are areas treated with SWC more likely to feature trees than those that are untreated? Answering this provides insights on how SWC could be implemented in other regions of Burkina Faso to promote the GGW mosaic.

2. Study Context

2.1. Regional Description

Burkina Faso is a landlocked country located in the Sahel of West Africa. It is a 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) northern Sahel. The study area in the northern Central Plateau region is located in the transition zone between the Sahel and Sudano-Sahel (Figure 1). The three villages studied lie in Bam Province within the Commune of Kongoussi. The first author has conducted long-term and intensive ethnographic fieldwork in each village since 2002.

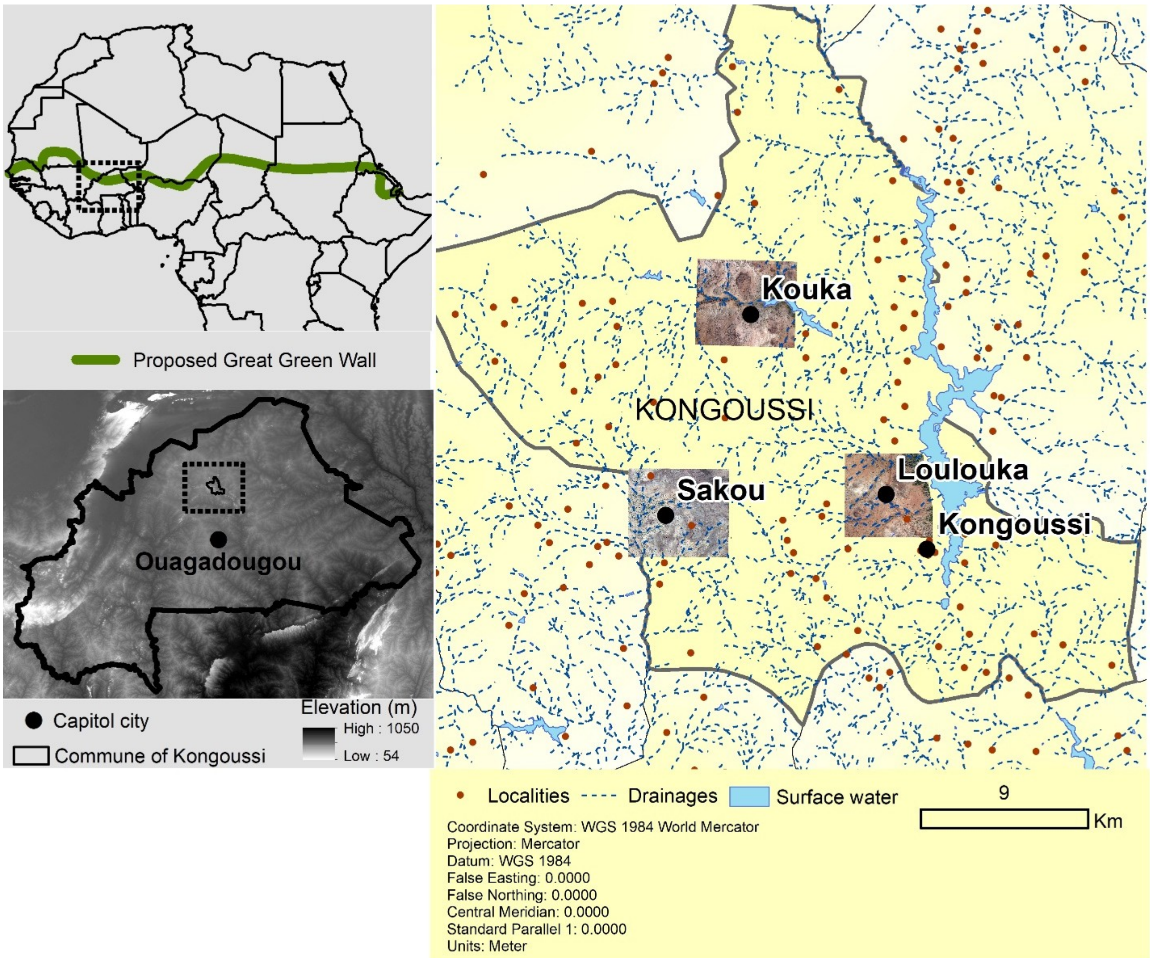

Figure 1. Map indicating proposed GGW (**upper left**); Map of Burkina Faso (**lower left**); Map of the Commune of Kongoussi and study terroirs (**right**)—dotted boxes designate inset maps.

The regional vegetation consists primarily of woody savanna and steppe and is dominated by thorny acacia (*Faidherbia albida* and *Acacia senegalensis*), *karité* (Fr.—shea nut, *Vitellaria paradoxa*), *néré* (Fr.—locust bean, *Parkia biglobosa*), and scattered baobab (*Adansonia digitata*) trees. Average annual rainfall measures between 600 and 800 mm. Geologically, the region consists of pre-Cambrian granite and birrimian schists, which form hills and plateaus capped by ferruginous crusts [31]. These form *bas fonds* (Fr.—seasonally flooded lowlands) that drain into the Nakambé (White Volta) River.

Livelihoods are mixed and diverse but rain-fed subsistence agriculture is the primary economic activity, which takes place in the valleys and surrounding slopes. Transhumant pastoralism is also practiced along with some fishing and pockets of 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 [4,32]. More recently, however, Mossi have intensified their agriculture by investing in a range of soil and water conservation techniques [7,33]. Mossi have progressively integrated animal husbandry into their farming and consider themselves full-fledged agro-pastoralists [34].

2.2. Soil and Water Conservation

Bam Province and the Commune of Kongoussi (hereafter simply Kongoussi) have a long history of SWC and form one of the epicenters of the development of these techniques and their diffusion [7,32]. The topography of Kongoussi consists of numerous volcanic chains of hills and plateaus. This geology produces wide valley floors where farming takes place that are surrounded by steep slopes. This makes erosion a severe problem and the entire commune is prone to gulley formation, expansion, and entrenchment. Early anti-erosion projects began in the 1960s and 1970s but largely failed due to poor community engagement. The French Volunteer Service (*Association Française des Volontaires du Progrès*—AFVP) introduced the first level permeable dam in Rissiam 7 km from the provincial capital Kongoussi in 1982 and built 148 dams by 1987 [35]. The much larger German-funded *Projet d'Amenagement des Terroirs et de Conservation des Ressources dans le Plateau Central* (PATECORE—Land Resources Conservation and Management Project of the Central Plateau) had its headquarters in Kongoussi and promoted SWC in hundreds of villages between 1988 and 2006. In collaboration with local farmers, PATECORE improved level permeable dam techniques and communities rapidly adopted them. They are prominent features of the rural landscape throughout Kongoussi and the Province of Bam.

2.2.1. Semi-permeable Dams

Soil and water conservation takes on many different forms on the northern Central Plateau. Level permeable dams are large rock barriers constructed perpendicular to gullies and parallel to one another (Figure 2). Depending on the size and depth of ravines, they typically measure 0.5 m tall, up to three meters wide, and up to 800 m long [35]. They prevent gullies from growing and allow them eventually to fill in with sediment. After several years, these degraded areas become completely rehabilitated and farmers have been able to return and reestablish fields. To be most effective, however, dam construction should commence at the head of a valley, move downslope, and be spaced no more than 200 m apart depending on the slope [35].

Figure 2. Level permeable dam, Commune of Kongoussi, July 2017—Photo by Colin Thor West.

In Kongoussi, PATECORE initially assisted communities with level permeable dams in collaboration with Village Land Resource Management Committees. These require significant technical assistance and enormous amounts of rock. PATECORE and agricultural extension agents provided trucks and engineering expertise while the local village committees provided volunteer labor. Over two or three dry seasons, some villages were able to treat the entire drainage system within their terroir with these dams. Level permeable dams contribute to greening by rehabilitating abandoned agricultural land cut by gullies and trapping native seeds. As fields are brought back into production and trapped tree seeds germinate and grow; afterwards, vegetation increases and tree cover expands.

2.2.2. Contour Stone Bunds

Contour stone bunds are low lines of rock commonly referred to as "*diguettes*" by local Mossi farmers. These measure approximately 20–30 cm high, 30–40 cm wide, and can be up to hundreds of meters long [35] (Figure 3). They are constructed parallel to one another, run along the contour, and are usually constructed in existing degraded fields to prevent erosion and rehabilitate them. Once communities had stabilized local soils with level permeable dams, PATECORE assisted them with diguettes. Like dams, contour stone bunds require technical assistance and logistical support. Again working with *grouppements* (Fr. - village volunteer work groups), PATECORE provided trucks and training while the grouppement provided labor. Villages collected rock from nearby hills and loaded them into large lorries (dump trucks), which delivered them to individual fields. Grouppement members then aligned these stone barriers along the contour. In Mossi customary land tenure systems, fields are held in usufruct and "owned" by the patrilineages that first cleared them [36]. A patrilineage consists of all male members who trace descent through the male line back to a distant male ancestor. Households gain access to agricultural land through their respective lineage or by borrowing. Households donated labor to help other patrilineages construct diguettes so that over time, those previously helped would eventually assist them. By this process of mutual assistance, many communities eventually treated nearly all agricultural land within their entire terroir.

Figure 3. Contour stone bund ("diguette"), Commune of Kongoussi, July 2017—Photo by Colin Thor West.

2.2.3. Zaï

Zaï are an indigenous planting technique developed by Mossi farmers in neighboring Yatenga Province. They consist of shallow pits with low berms on the downslope side (Figure 4). Each hole measures approximately 20–30 cm in diameter and 10–15 cm deep. Farmers specifically rehabilitate degraded bare soils, locally referred to as *zipellé* in Mooré (the Mossi language), using zaï. Holes are dug during the dry season in these crusted lateritic soils. The shallow pits allow rainfall to pool, percolate, and persist in the soil during dry spells. The berm prevents runoff. Development organizations helped improve this technique and trained local farmers to incorporate small amounts of compost [37]. With time, this organic matter improves soil structure and decreases the need for fertilizer. Some Mossi also plant native tree seedlings such as baobab in these pits because it improves survivability [38]. The use of zaï has proliferated throughout northern Burkina Faso and the Sahel because they are effective, demand only household labor to construct, and can be modified for local conditions. Zaï promote greening because they bring degraded zipellé lands into agricultural production and can increase the density of planted trees.

Figure 4. Field treated with zaï, Commune of Kongoussi, July 2017—Photo by Colin Thor West.

2.2.4. Other SWC

There are other forms of SWC that include *demi-lunes* (Fr. - half-moons), *paillage* (Fr. - mulching), farmer-managed natural regeneration (FMNR), and agroforestry [6,38–40]. With the exception of half-moons, farmers practice all of these but contour stone bunds, level permeable dams and zaï are most common in Kongoussi. Most villages feature a combination of several SWC measures in different parts of their terroir. Dams are located in gullies, contour stone bunds line the slopes, and zaï are often interspersed among the other two and in zipellé areas. Because soils become stabilized, more fertile and promote the spontaneous regeneration of native trees, shrubs, and grasses, the entire village landscape can become an agroforestry parkland [41]. As Reij et al. [6] note, communities with a long history of SWC can have between 72 and 94 percent of all agricultural land treated but those with a shorter history may have only nine to 43 percent treated. In some cases, the SWC interventions of several village terroirs extend throughout an entire catchment area [12].

2.3. Study Sites

2.3.1. Sakou

Sakou lies in a narrow valley surrounded by rocky plateaus and hills. Farmers cultivate in the valley floor where soils are more fertile and water retention is high. At the same time, however, these low-lying areas are very prone to erosion and gulley formation due to the surrounding steep terrain. Sakou has a population of approximately 1500 Mossi who practice mostly subsistence rain-fed agriculture and animal raising. Sakou is located near the epicenter of Rissiam where level permeable dams were first developed and spread throughout the region [7,35]. It is also connected to the provincial capital Kongoussi by dirt roads that are relatively well maintained and passable by vehicle during the rainy season. These conditions have made SWC construction both necessary and relatively easy in Sakou. Likewise, residents have long practiced farmer-managed natural regeneration (FMNR) in areas treated with SWC and Sakou's terroir is now a quintessential agroforestry parkland.

2.3.2. Kouka

Kouka lies approximately 20 km from Kongoussi along narrow unimproved trails that are impassable by motorized vehicles in the rainy season. It is very remote, low lying, and located next to a bas fond area with a *barrage* (Fr.—dam/reservoir) that floods during the rainy season but retains rainwater during the dry season. Low volcanic hills surround Kouka and its soils are relatively rich and fertile due to the bas fond and local topography. For these reasons, soil erosion and land degradation are not nearly as severe as in other nearby villages. The population of Kouka is about 900 and is mostly Mossi. Silmi-moose, a mixed ethnic group composed of Mossi and Fulbè pastoralists, make up approximately one-quarter of Kouka's population and they manage very large cattle herds. The barrage and bas fond provide ample water and pasture for these animals whose manure naturally enriches farmer fields as they graze throughout Kouka. These advantageous conditions partially explain why Kouka has much less SWC than Sakou because residents exert less pressure on natural resources compared to Sakou and Loulouka.

2.3.3. Loulouka

Loulouka is a peri-urban village located next to the lake *Lac du Bam*. Agricultural land is constrained by this water body and the urban center of Kongoussi. This makes population pressure particularly intense in Loulouka where parcels are small and residents engage in both dry season gardening and wage work. The village lies along a major improved dirt highway, which provides access to other towns. Loulouka is relatively flat with a few low hills that make it less prone to erosion, although two large gullies cut through the southern half of the community. These have been treated with level permeable dams but the community generally considers land degradation to be less of a concern because their livelihoods are highly diversified and depend less on rain-fed agriculture. Farming households cannot grow enough millet, sorghum, and maize on their small plots located within Loulouka's terroir and are forced to farm satellite fields found several kilometers from their homes. Loulouka does not feature the same sort of agroforestry parkland as Sakou or Kouka, and demand for wood is extremely high due to the nearby urban population. These conditions explain why Loulouka has comparable levels of SWC to Kouka, but much less than Sakou.

3. Materials and Methods

3.1. Datasets

High-resolution satellite imagery and GIS analytical procedures were used to examine the relationship between SWC and the presence of trees. The first author has conducted ethnographic research in northern Burkina Faso since 2002 and documented how local farmers perceive that their improved land-use practices contribute to environmental rehabilitation [42,43]. His research took place in the three villages discussed here (see Figure 1). These villages were selected because they represent a gradient of population density and, hence, the demographic pressure on natural resources. Population density is highest in Loulouka (131 persons/km^2), medium in Sakou (46 persons/km^2), and low in Kouka (11 persons/km^2) [44]. High-resolution imagery is expensive (approximately $US 6.00 to $US 15.00 per km^2), while digitizing dams and trees is time-consuming. Thus, funding and time constraints also limited the scope to these three village terroirs. At the same time, they have been the sites of intensive intermittent human ecology study for over eighteen years. Figure 5 provides a flow chart summarizing the GIS procedures.

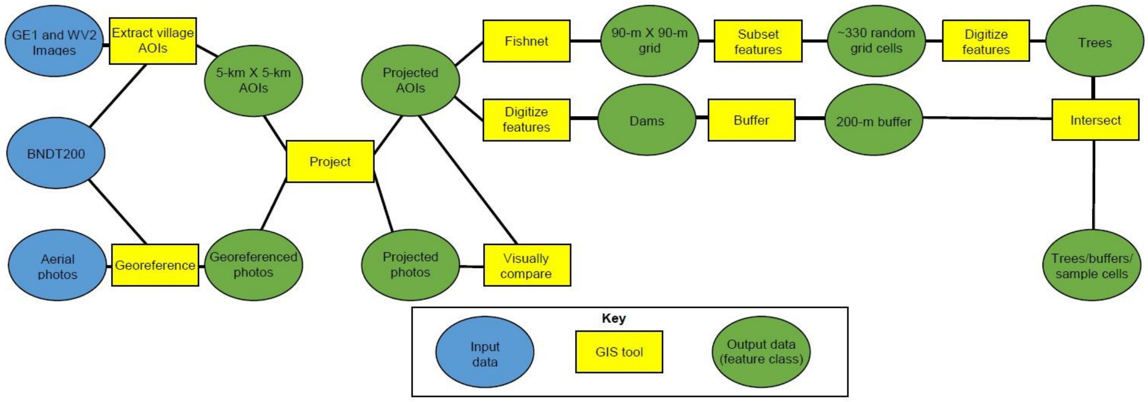

Figure 5. Flowchart of GIS Procedures.

3.1.1. Satellite Imagery

Satellite images consist of the most currently available at the time this study commenced (2015). High-resolution (i.e., sub-meter) imagery is ideal because many features (such as dams, diguettes, and individual trees) are readily visible due to the fact they exceed the size of individual pixels. This study used Geo Eye-1 (GE1) and World View-2 (WV2) products that consist of both 4-band multispectral (MS) and panchromatic (PAN) images (Table 1). Each scene corresponded to the dry season when SWC, trees, and other features are most apparent and cloud-cover is minimal. A 5-km X 5-km area of interest (AOI) was extracted from the larger scene for each locality. This AOI was centered on the coordinates of each village defined as points in the Institut Géographique du Burkina (IGB—Burkinabè Geographic Institute) Base de Donnés Nationales Topographique—1:200,000 (BNDT200—National Topographic Database) GIS dataset [45] (Figure 6).

Table 1. Data used.

Locality	Product	Scene ID	Acquisition Date	Bands - MS	Max Pixel Resolution (m^2)
Sakou	WorldView–2	103001001D92A600	01–05–2013	R, G, B, NIR	0.53977 (PAN); 1.97 (MS)
Kouka	Geo Eye–1	1050410010266D00	03–10–2014	R, G, B, NIR	0.52997 (PAN); 1.97 (MS)
Loulouka	Geo Eye–1	1050410010266D00	03–10–2014	R, G, B, NIR	0.52997 (PAN); 1.97 (MS)
All	BNDT	–	2014	–	None - vector
All	IGB aerial photos	–	12-15-1992	Panchromatic	~0.25 (PAN)

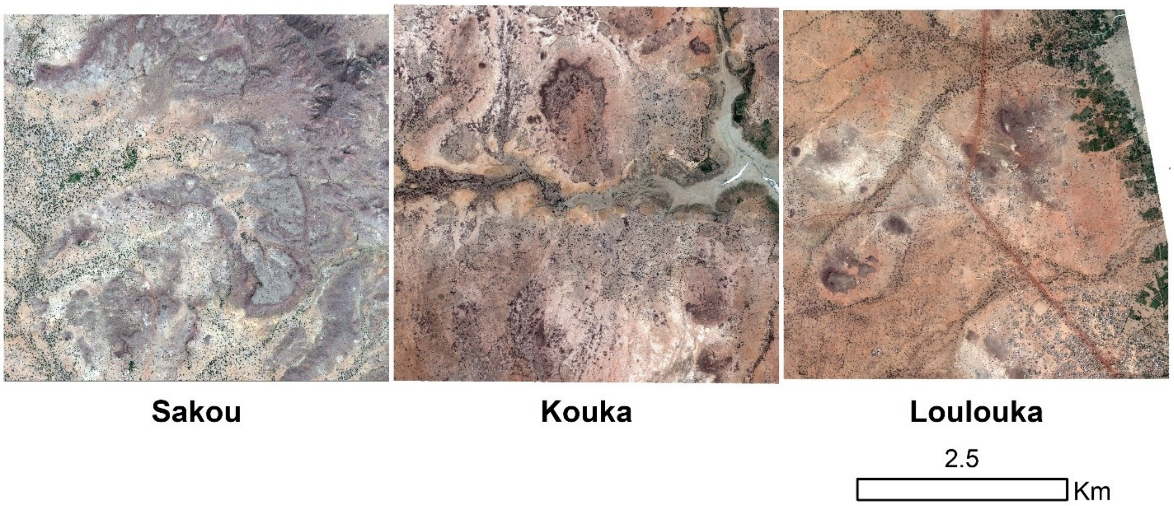

Figure 6. Study localities and multispectral satellite images (3, 2, 1—true color).

3.1.2. Archival Aerial Photographs

Panchromatic aerial photographs acquired through the IGB archives complement the satellite imagery. These photos date to a December 1992 survey mission of the northern Central Plateau region, which were used by PATECORE to conduct focus groups in Bam Province [35]. Each individual photo was georeferenced to the BNDT GIS data using common points such as washes, roads, trails, and other spatial features. They are used to visually show SWC features and changes in tree cover.

3.2. Methods

3.2.1. Digitizing SWC and Buffers

Village locations and satellite images were projected to the same projection (Adindan_ UTM_ZONE_30N) and each image was displayed in true color (R = Band 3; G = Band 2; and B = Band 1) using ESRI's ArcGIS Desktop 10.5. Research assistants digitized level permeable dams comprehensively for each village terroir using the higher resolution panchromatic image. Next, a 200-m buffer around each dam was constructed to approximate the total area treated in SWC. This corresponds to the maximum distance between dams discussed above and creates a contiguous network of treated areas along an entire gully system (Figure 7). Dams and diguettes are co-located in village landscapes, but the latter cannot be easily differentiated from surrounding soils in the imagery. Likewise, zaï are too small to be visually identified in high-resolution imagery but areas treated lie in close proximity to level permeable dams. Thus, this 200–m circular buffer around digitized dams approximates the total area treated in SWC for each village terroir. This is consistent with field observations throughout Kongoussi.

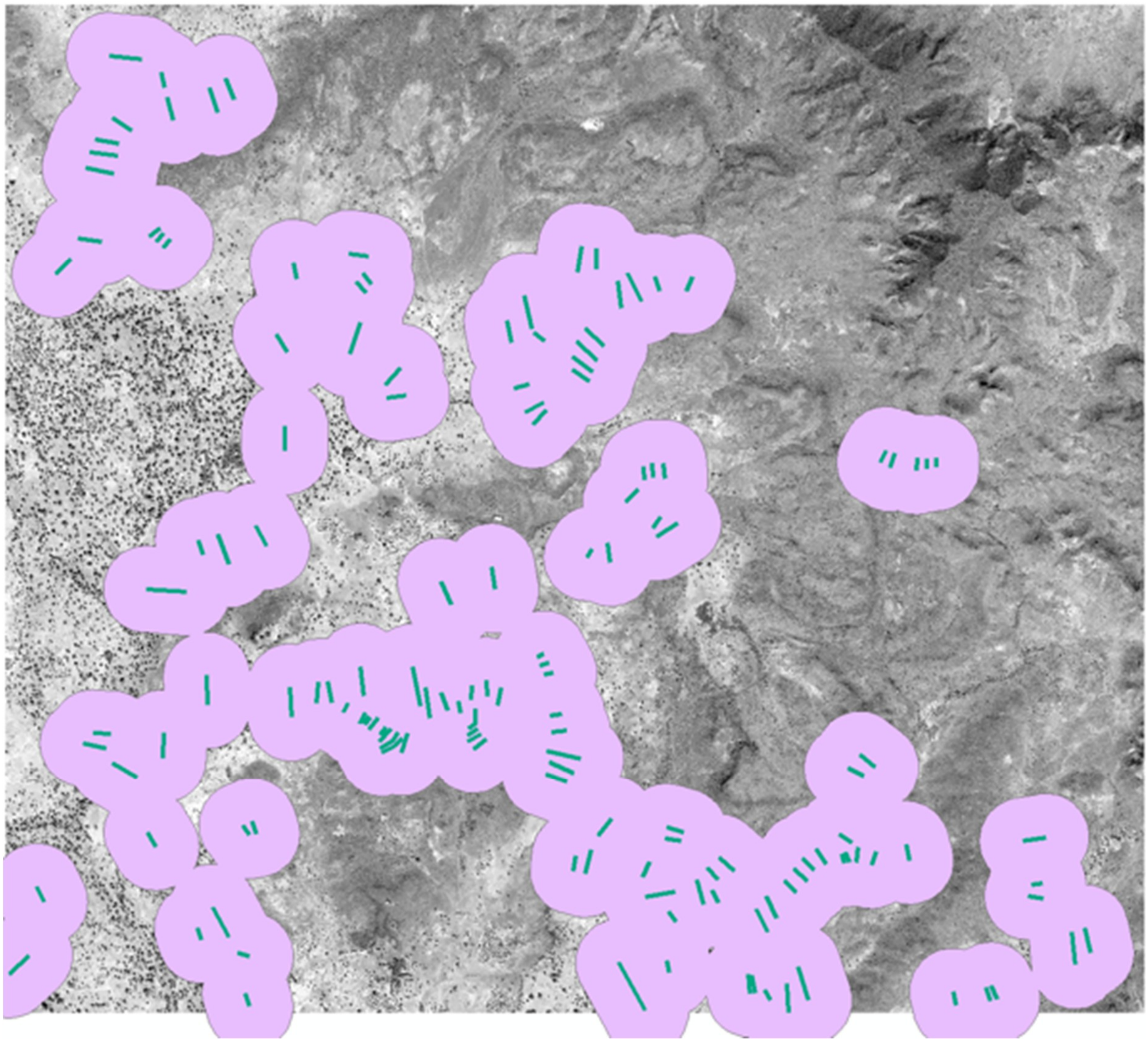

Figure 7. Digitized semi-permeable dams and 200-m buffers—Sakou.

3.2.2. Digitizing Trees

Three grids of 900 90-m X 90-m cells—one for each village terroir—were created using the Fishnet tool in ArcMap 10.5. GIS procedures, we then randomly selected approximately 330 sample cells within each grid (Figure 8). This sample represents 37 percent of the total area for each village terroir. All tree canopies measuring 10-m or greater in diameter were then digitized within all sample grid cells. This was done using the higher resolution panchromatic images to more precisely and accurately create these features. Likewise, this was done at the large scale of 1:500 so that the actual tree canopy could be differentiated from its shadow and more precisely digitized. This 10-m threshold was selected due to resource constraints and because it represents mature trees that were likely either established soon after SWC construction occurred or were likely protected by SWC investments (see [26]).

3.2.3. Spatial Analysis

To assess the relationship between SWC buffers and trees, the geometric intersect tool in ArcMap 10.5 was used to determine the presence/absence of trees for all sample grid cells (Figure 9). The intersect tool also produced a table for each village. Last, a chi-square test of independence assessed the statistical relationship between SWC and the presence of trees.

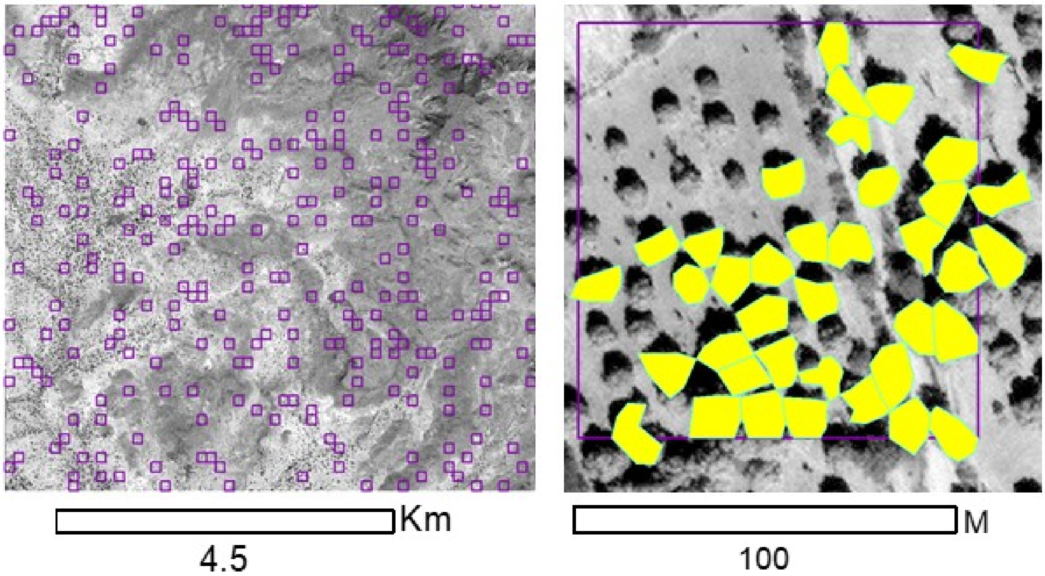

Figure 8. Example of sampling grid cells for Sakou (**left**) and example of digitized tree canopies within a sample grid cell for Sakou (**right**).

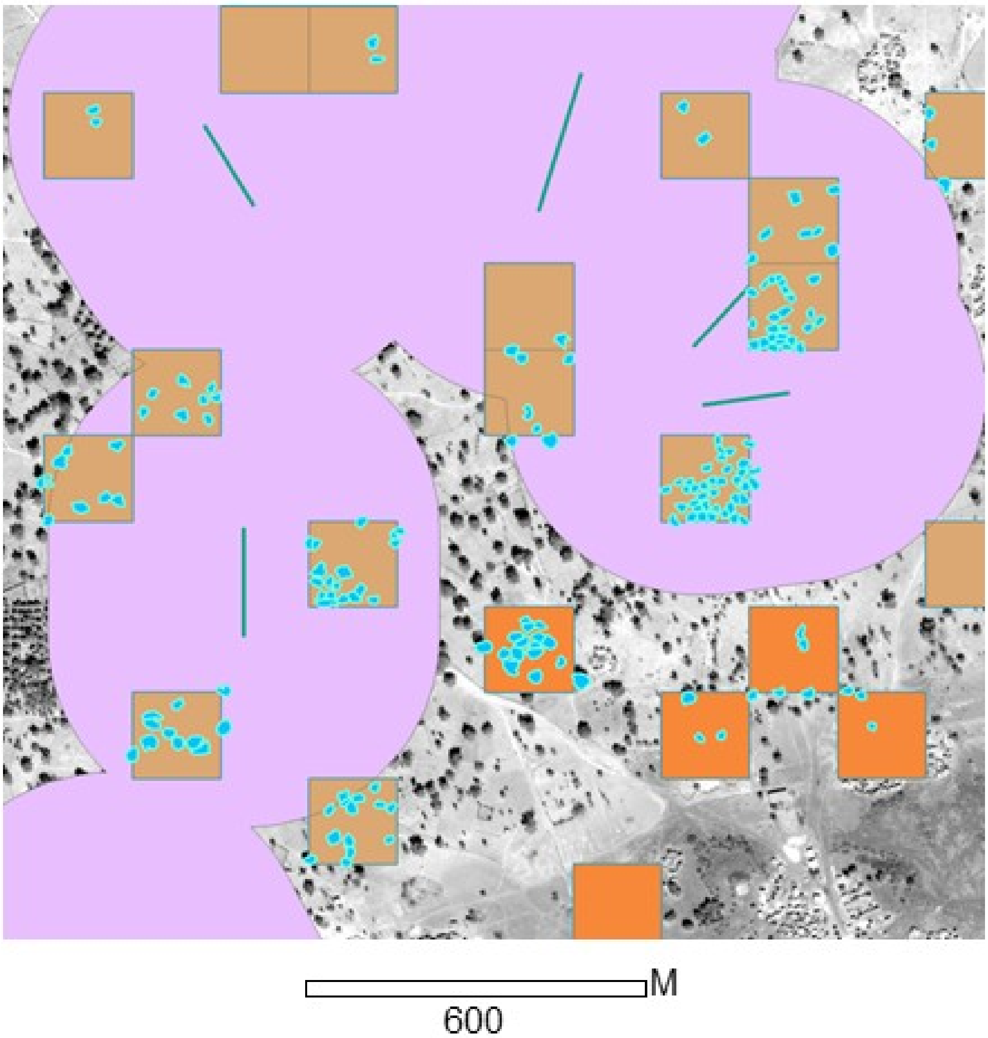

Figure 9. Example of sampling grids (orange squares), dams (blue lines), SWC buffers (purple polygons), and trees (blue polygons).

4. Results and Discussion

4.1. Results of Temporal Analysis

Comparing aerial photographs from 1992 with the high-resolution imagery from 2013 or 2014 visually shows that level permeable dams can promote the establishment and growth of trees (Figure 10). The paired images are from a treated gully in Sakou in which PATECORE assisted with the construction of these dams in 1998. The red arrows indicate dams and there are almost no trees present between or along them in the 1992 photo. In contrast, many trees are apparent both along and between the dams in the 2013 image but absent from the earlier photograph. To the south (i.e., below the dams) the area appears very bright and devoid of vegetation in the 1992 image, which is true in the 2013 image as well. By 2013, the region treated with SWC contained many more trees than the untreated area.

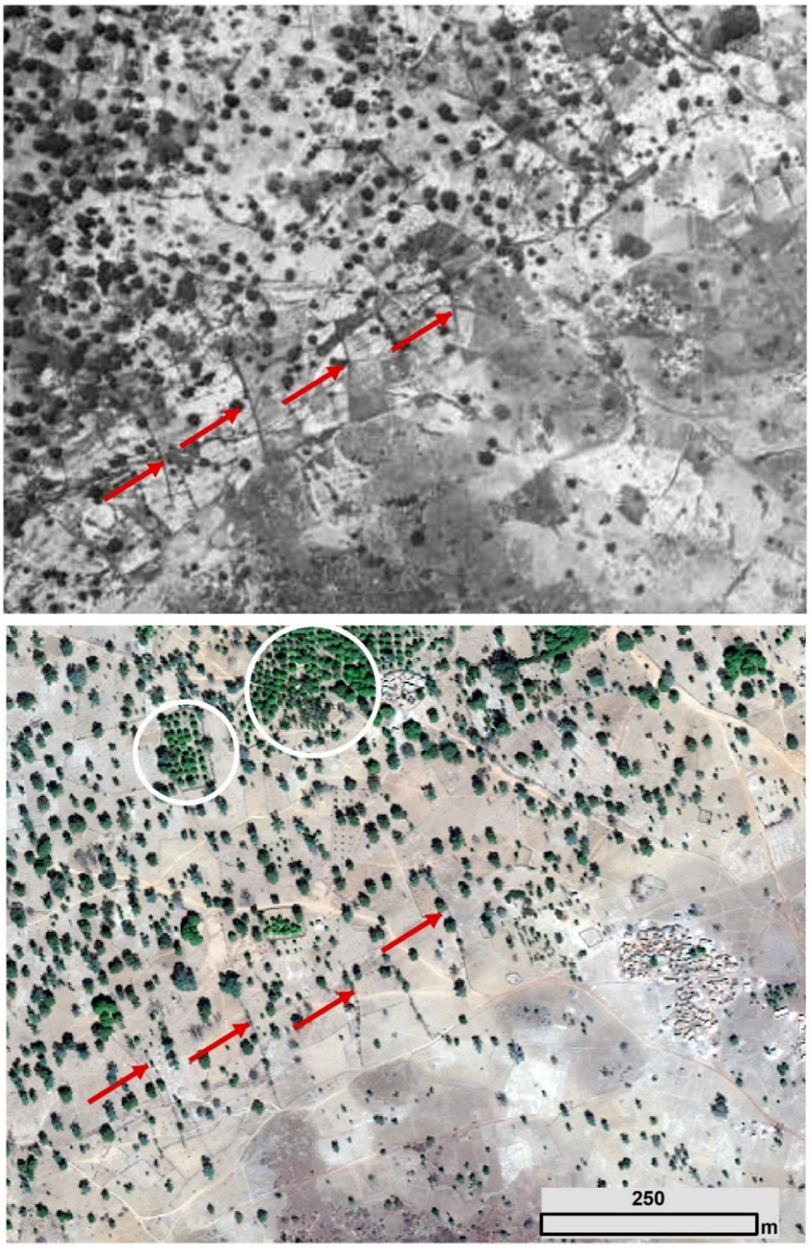

Figure 10. Aerial photo from 1992 (top) and 2013 WorldView-2 image (bottom) for Sakou. Arrows indicate dams.

The 2013 image also displays many clusters of trees arranged in rows and evenly spaced apart, which are absent in 1992. These are mango (*Mangifera indica*) and guava (*Psidium guajava*) orchards that returned migrants from Côte d'Ivoire established in the mid–1990s. Local residents explain that these returnees had seen fruit plantations in Côte d'Ivoire and wanted to invest in similar cash crops in their natal village. The rehabilitation of gullies made these expensive and long-term investments possible because erosion had decreased and soils had stabilized. Similarly, these became areas where rainfall pooled and penetrated deeper, which assisted the growth and development of these exotic fruit trees. Where other studies have documented an increase in general tree cover associated with SWC, this indicates [6,7,11] a particular type of expansion—tree orchards.

Visual comparison of 1992 aerial photos and current satellite imagery reveals similar evidence of greening in relation to SWC in many parts of Sakou, but certainly not all areas. Similarly, the effects of dams on tree cover are much more pronounced in Sakou than they are in either Kouka or Loulouka. Figure 11 shows sample areas treated with SWC in Kouka and Loulouka. Comparing 1992 photos with recent imagery indicates some increased tree density, but this is ambiguous. No SWC-treated areas of Kouka or Loulouka show the same definitive expansion of tree cover as Sakou. Compared to other similar studies [6,7,15,24], this demonstrates how SWC investments can have little or no effect on tree cover.

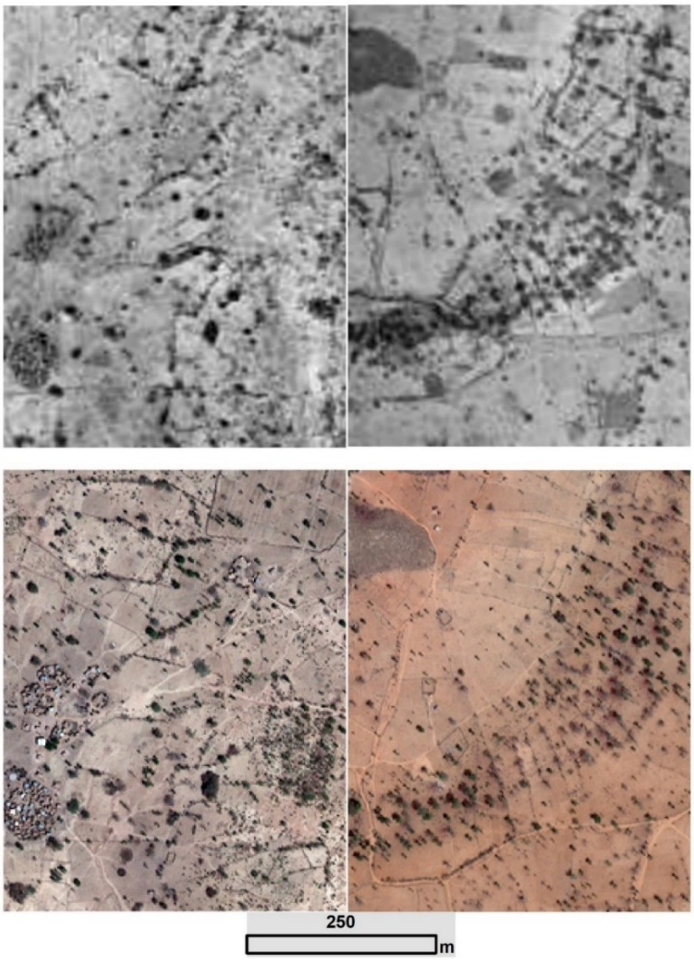

Figure 11. Comparison of 1992 aerial photos (**top**) with 2014 GeoEye satellite images for SWC-treated areas in Kouka (**left**) and Loulouka (**right**). Dams and contour stone bunds appear as faint straight lines in bottom panels.

4.2. Results of Chi-Square Analysis

Table 2 summarizes the results of dam and tree digitization for all three villages. The total area treated by SWC are nearly double those from earlier official figures furnished by development NGOs in 2004 [44]. Communities continued to construct diguettes and prepare zaï pits after 2004. It is distinctly possible that the areas treated increased two-fold over this ten-year period.

Table 2. Summary of dams, trees, and SWC by village.

Locality	Total Trees	Total Dams	Total Trees Inside Buffers (within Sample Grid Cells)	Total Area Treated by SWC (ha)
Sakou	679	146	535	939
Kouka	198	50	55	487
Loulouka	330	51	66	545

The spatial model predicted a positive relationship between soil and water conservation investments and the presence of trees. Table 3 summarizes the relationships among sample grids, SWC buffers and trees. Overall, sample grids treated with SWC are more likely to feature trees than chance alone would predict. This is true for Sakou and Kouka but not Loulouka. Only results for Sakou and for all the villages together, however, are statistically significant.

Table 3. Cross-tabulation of villages, SWC, and the presence of trees.

				SWC Buffer		
Locality				Yes	No	Total
Sakou [a**]	Trees	Yes	obs.	77	32	109
			exp.	51	58	109
		No	obs.	65	130	195
			exp.	91	104	195
	Total			142	162	304
Kouka [b]	Trees	Yes	obs.	25	50	75
			exp.	20	55	75
		No	obs.	56	172	228
			exp.	61	167	228
	Total			81	222	303
Loulouka [c]	Trees	Yes	obs.	28	73	101
			exp.	32	69	101
		No	obs.	97	192	289
			exp.	93	196	289
	Total			125	265	390
All [d**]	Trees	Yes	obs.	130	155	712
			exp.	100	186	712
		No	obs.	218	494	285
			exp.	249	464	285
	Total			348	649	997

[a] Pearson chi-square = 39.098; [b] Pearson chi-square = 2.217; [c] Pearson chi-square = 1.173; [d] Pearson chi-square = 20.144; ** $p < 0.01$.

These statistical aggregate results show a positive relationship between SWC investments and the presence of trees. Similarly, the series of visual comparisons between aerial photos and satellite images demonstrates that level permeable dams and contour stone bunds can increase the density of tree cover. Yet, this is especially true for the terroir of Sakou, which has the most soil and water conservation. Conservation activities began slightly earlier in Sakou (1989) than the other two localities (1991), but dams and bunds are much more extensive. Figure 7 shows how treated areas in Sakou cover nearly the entire valley floor of its terroir and form a contiguous network. Kouka and Loulouka feature smaller patchy areas of SWC that are fragmented across the village terroirs. Moreover, Sakou features many large fruit tree orchards, which are physically located in areas treated by SWC. This analysis extends the insights of previous studies in Burkina Faso [6,7,11,21] to provide statistical evidence that SWC contributes to increased tree cover, but that this can be very location-specific.

4.3. Limitations and Future Directions

This research is framed as a pilot study to demonstrate a spatial and statistical methodology for assessing the relationship between SWC and tree cover in northern Burkina Faso. As such, it has several limitations. One, the spatial analysis is limited to only three localities in relatively close proximity to one another. This is due to resource limitations, but enhanced by the first author's long-term fieldwork in these communities. It is possible to extend the scope of the research to include a much larger sample over a larger area. Rather than using expensive commercial high-resolution satellite imagery, much of the feature digitization could be done with existing imagery in Google Earth Pro and incorporate the time slider tool of historical imagery. Nonetheless, digitizing dams and trees remains a manual process, which is very time consuming. There are possibilities to automate these processes using an array of image processing filters, spectral signatures, and object-oriented classification techniques. Last, this study is restricted to a relatively small area in a region of distinct greening within Burkina Faso. The analysis could be extended across a gradient of greening, neutral, and browning regions of the country to better assess the role of improved land-use practices in driving vegetation processes.

5. Conclusions

Just as the West African Sahel was once synonymous with land degradation and desertification, it is now celebrated as a region of environmental rehabilitation and recovery. Several studies have established a definitive pattern of enhanced vegetation using remotely sensed satellite imagery. Scholars have designated this pattern as the "greening of the Sahel" or "re-greening of the Sahel" and the northern Central Plateau of Burkina Faso figures prominently in these analyses. In fact, the innovative Mossi farmer Yacouba Sawadogo recently received a Right Livelihood Award in 2018, which is widely recognized as the "Alternative Nobel Prize" [46]. He is recognized as "the man who stopped the desert" for his work promoting zaï in Yatenga Province and converting 40 ha of barren land into forest. Similar local village-level efforts to rehabilitate degraded lands using soil and water conservation measures have been put forth as potential mechanisms behind regional greening in northern Burkina Faso [5,6]. In fact, scaling these efforts throughout the country could put it on track to attain UN SDG 15.3—Land Degradation Neutrality by 2030. The research presented here tests the relationship between SWC and tree cover among three village terroirs located in close proximity to one another in a greening hot spot.

This comparative case study uses GIS procedures, high-resolution satellite imagery, and aerial photos to assess the spatial relationship between areas treated with SWC and the presence of trees. Aggregate results from all three communities indicate that there are more trees in treated areas than chance alone would predict. Disaggregating these by village terroir, however, shows that positive relationship between SWC and trees is only statistically significant for Sakou, which has a slightly longer history of interventions and much more extensive SWC than the other two. Our in-depth knowledge of these communities complements that spatial analysis. Sakou is indeed a particular case of extensive landscape modification that has promoted not only revegetation but allowed its inhabitants to invest in orchards and diversify livelihoods. This finding will hopefully encourage other researchers to go beyond just the analysis of remotely-sensed satellite imagery and conduct fieldwork with communities. Doing so provides a more "bottom-up" perspective and land-use/land-cover change, which can explain the underlying anthropogenic processes driving vegetation patterns.

The comparative approach presented here aims to be a pilot study of how village land-use processes can influence regional greening patterns. In contrast to other similar studies, the methodology used has been relatively low-cost, simple, and straightforward. It was designed to be easily and efficiently replicated for other Sahelian contexts. Thus, a similar analysis could be scaled up to multiple sites and provide more robust insights on the relationship between SWC and greening. The northern Central Plateau region of Burkina Faso features several areas of both distinct greening and also browning—i.e., ongoing land degradation. These methods can be used to assess the bottom-up drivers of these divergent dynamics by sampling localities across a gradient of greening and browning.

The Commune of Kongoussi in northern Burkina Faso is a hot spot of both Sahelian greening and soil and water conservation. Hundreds, if not thousands, of rural producers like Yacouba Sawadogo have "stopped the desert" in this dryland that was once considered highly degraded. Hundreds of communities have participated in this rehabilitation process through a variety of SWC interventions over a very large area. Are these village-level investments driving a larger regional process of greening? Maybe. Does SWC contribute to an expansion of tree cover? Yes, but this is dependent on local contexts. Unlike previous scholars, the work presented here points out that the positive relationship between soil and water conservation measures and the expansion of tree cover is not consistent or uniform. Instead, it appears that this relationship depends on the amount, extent and configuration of SWC interventions. This analysis highlights that the dynamics of greening, soil and water conservation, and tree cover are best understood at the spatial scale of individual villages and their surrounding terroirs than at larger aggregated scales. SWC projects in other parts of Burkina Faso could reproduce greening and contribute to the country's great green mosaic, but this requires similar intensive village-by-village investments.

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