*Land* **2014**, *3*, 1075-1090; doi:10.3390/land3031075

OPEN ACCESS

*land*

**ISSN 2073-445X**

www.mdpi.com/journal/land/

*Article*

# The Re-Greening of the Sahel: Natural Cyclicity or Human-Induced Change?

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*Received: 20 February 2014; in revised form: 21 August 2014 / Accepted: 22 August 2014 / Published: 03 September 2014*

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**Abstract:** The Sahel has been the focus of scientific interest in environmental-human dynamics and interactions. The objective of the present study is to contribute to the recent debate on the re-greening of Sahel. The paper examines the dynamics of barren land in the Sahel of Burkina Faso through analysis of remotely-sensed and rainfall data from 1975–2011. Discussions with farmers and land management staff have helped to understand the anthropogenic efforts toward soil restoration to enable the subsistence farming agriculture. Results showed that area of barren land has been fluctuating during the study period with approximately 10-year cyclicity. Similarly, rainfall, both at national and local levels has followed the same trends. The trends of the area of barren land and rainfall variability suggest that when rainfall increases, the area of barren land decreases and barren land increases when rainfall decreases. This implies that rainfall is one of the main factors driving the change in area of barren land. In addition, humans have contributed positively and negatively to the change by restoring barren lands for agriculture using locally known techniques and by accelerating land degradation through intensive and inappropriate land use practices.

**Keywords:** Sahel; Burkina Faso; re-greening; land degradation; soil restoration

## 1. Introduction

Since the 1990s, the transition zone between the arid Sahara in the north and the sub-humid tropical savannas in the south (12°–20° N) has been the focus of sustained scientific interest in environmental dynamics [1]. There is on-going debate on whether there is a re-greening process in the West African Sahel and whether it can be attributed to natural processes (*i.e.*, annual and/or inter-annual variation of rainfall) or human activities (*i.e.*, change in land use practices) [2]. Brovkin *et al.* [3] developed a conceptual model to analyze the atmosphere-vegetation interactions in the Sahel/Sahara zone and found that a green equilibrium period occurred in the Sahel during the early to mid-Holocene (9000–6000 years ago). Similar investigations were made by Claussen and Gayler [4] using an asynchronously coupled atmosphere-biome model and revealed that during the Holocene, most of the Western Sahara appeared to be densely vegetated by xerophytic woods. These studies were challenged by Claussen *et al.* [5] who concluded that the desertification of the Sahel/Sahara from the mid-Holocene was a naturally driven phenomenon, described as climate-system dynamics and, land use may have played a negligibly small role in the mid-Holocene Saharan desertification.

Recently, following the devastating drought and famine that occurred in the Sahel in the 1970s and 1980s, during which farmers and herders lost substantial quantities of crops and domestic animals [6,7], researchers have investigated the trend of the environmental change, in particular, vegetation cover in the Sahel. There is a consensus that the Sahel, in some areas, is gaining in vegetation cover as compared to the 1980s, but there are speculations about the drivers of the changes. Anyamba and Tucker [8], Hickler *et al.* [9], Dardel [10] and Fensholt *et al.* [11] measured the Sahelian Normalized Difference Vegetation Index (NDVI) from 1981 to 2003 using the NOAA-AVHRR and/or MODIS (images and found that there was an increase in vegetation cover, and vegetation growth was associated with rainfall increase. Huber *et al.* [12] examined the relationships between the NOAA-AVHRR derived soil moisture, rainfall and vegetation cover of the Sahel from 1982 to 2007. This study showed that the three parameters were strongly correlated, particularly in the north of Burkina Faso.

Results from above cited studies suggest that rainfall improvement is the driving force of the recent greening trend of the vegetation in the Sahel. However, Herrmann *et al.* [13], Herrmann and Tappan [14], Olsson *et al.* [15] and Seaquist *et al.* [16] argued that although rainfall has obviously increased during the last three decades, the state of greenness as observed from remotely sensed data (mostly NOAA-AVHRR) could not have been reached without additional human factors. Likely man-induced change could be attributed to land use through agricultural practices [15,17]. Hiernaux *et al.* [18] attributed the greening trend to the shifting of certain tree species toward a more arid-tolerant flora. For Ahmedou *et al.* [19], Botoni and Reij [20], Kaboré and Reij [21], Reij *et al.* [22], Reij *et al.* [23] and Sendzimir *et al.* [24], the re-greening trend of the vegetation in the Sahel is mainly driven by human activities. For Brandt *et al.* [25,26], the vegetation trends in the Sahel area are mainly caused by varying tree- and land-cover, which are controlled by human impact, soil and drought resilience. The latter authors used findings from the soil and water conservation interventions, focus group discussion and field observations to come to the conclusion that Sahelian farmers, both in Burkina Faso and Niger, have ingeniously modified their agroforestry, water and soil management practices to attain more crops and permanent vegetation such as trees and "living fences" on agricultural land.

Although all mentioned studies have sound scientific evidence, they still lack site-specific evaluation at the landscape level. The use of NOAA-AVHRR data with 1 km resolution does not guarantee accurate results at a landscape scale. As Herrmann *et al.* [13] evidenced, it is unclear whether the greening trend is a return to pre-drought conditions or a transition to a new equilibrium state. This paper hypothesized that the use of an inverted approach to estimate area change of barren land rather than vegetated land at a fine scale resolution can provide more robust insights into actual re-vegetation signals due to changes in rainfall and land use practices. This paper aims to contribute to the on-going debate on the re-greening of the Sahel by examining barren land dynamics from 1975 to 2011 and their interaction with rainfall variability. The study used Landsat data with a spatial resolution of 30 m, rainfall data from local meteorological stations and several field visits/informal meetings with local soil and water conservation leaders in the north of Burkina Faso.

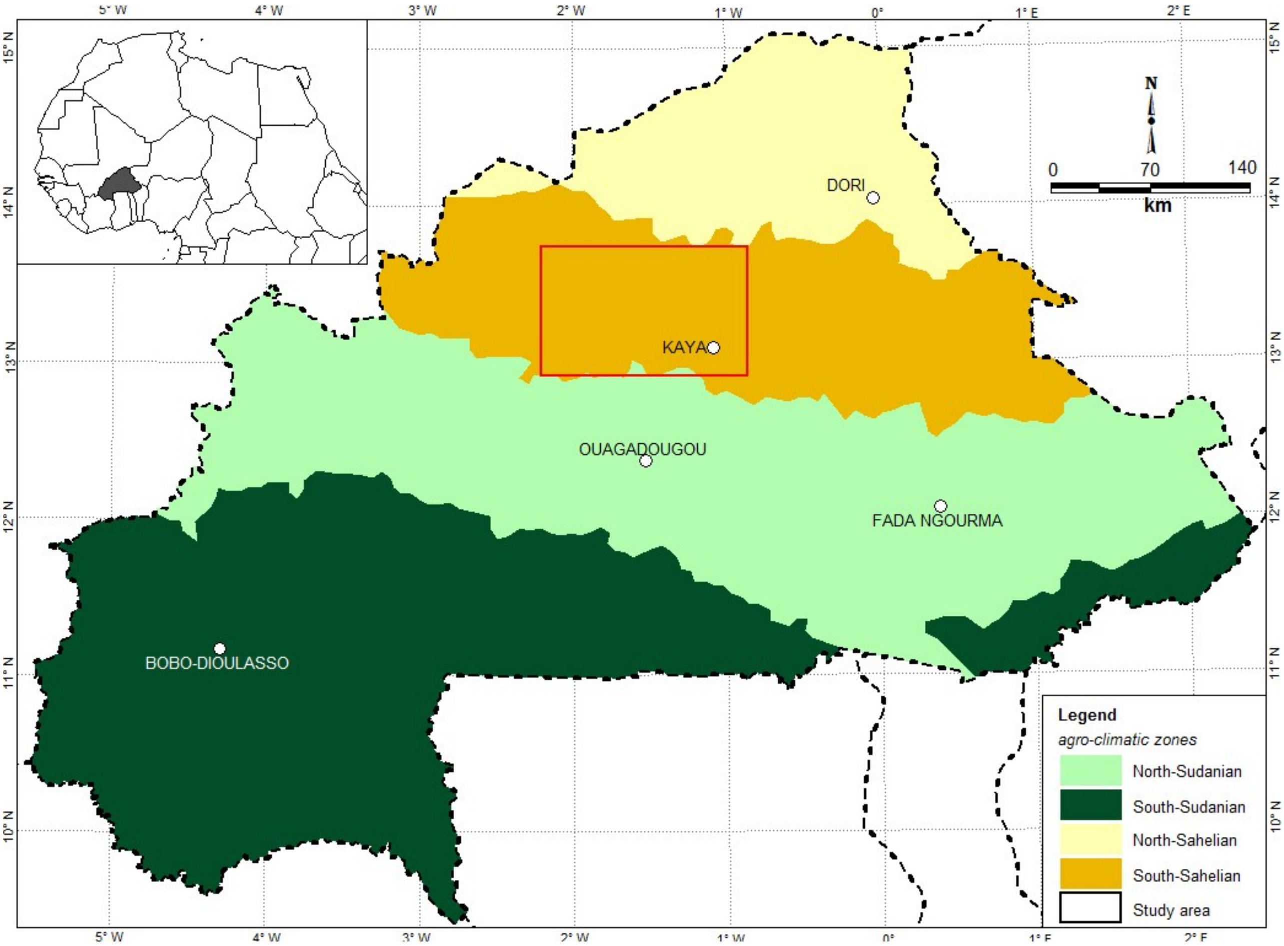
## 2. Materials and Methods

### *2.1. Study Area*

The study was carried out in the south-Sahelian phyto-geographical zone (12°54′ N to 13°45′ N and 2°13′ W to 0°50′ W) in the north of Burkina Faso, West Africa (Figure 1). The study zone covers an area of 13,574 $km^2$ in size and is characterized by a low relief with average altitude of 400 m a.s.l. The climate is the Sahelian type characterized by a long dry season (October to May) and a short rainy season (June to September) with an annual rainfall ranging from 400 to 600 $mm \cdot yr^{-1}$. Soils in the north of Burkina Faso are mostly less developed, marked by a high raw mineral content, low soil organic matter and spatially covered by crusts. Land use is dominated by agricultural practices and grazing. In addition, there is a predominance of sandy micro-dunes which are wind-trapped sediment at tree trunks or rocks, tilled by the local population [27–30]. The vegetation follows the edaphic characteristics and is dominated by a mixture of grassland, shrubs and thorny trees [31,32].

With a population of about 875,000 inhabitants in 2010 [33], the study area is among the most densely populated areas (60–200 inhabitants/$km^2$) in Burkina Faso [34]. The population is comprised of Mossi and Fulani ethnic groups who practice integrated subsistence agriculture and livestock farming. The dominant farming system is the traditional cultivation of cereals such as millet, sorghum and cow-pea. Over the last decades, there has been an intense seasonal and permanent out-migration of the population due to the environmental degradation [35,36].

**Figure 1.** Study area (adapted from Ouedraogo [34]).




*2.2. Detection of Barren Land*

It was assumed that the greening pattern is associated with a decrease in the area of barren land in the Sahel zone. Barren land is defined as the partially crusted hard soil with little or no vegetation cover and almost impermeable and at risk to be swept away by harsh winds [37]. Barren lands were extended during the drought periods of the 1980s. During rainy seasons, the barren lands are covered by ephemeral grasses but, after the last rains, the grass dries up and is swept away by the first wind [38]. Barren lands are widely open areas and are easily detectable from satellite images taken during dry seasons.

Landsat imageries over 36 years spanning from 1975 to 2011 were used to detect the extent of the barren land in the study area during dry seasons (November to April) (Table 1). Images were downloaded from the USGS server. Additional geometrical corrections were made to ensure that all images have the same background reference and are in agreement with the administrative contour polygons of the study area. The MSS data has a resolution of 60 m while the TM data has a resolution of 30 m. For the sake of comparison, the spatial resolution of the image has been harmonized. The MSS image was first resized to 30 m. The classified raster both MSS and TM were smoothed using the Majority/Minority Analysis (Kernel 3 × 3). This has helped to make the MSS raster comparable with the TM. Prior to classification, all bands of the images excluding band 6 of the TM data were used to perform the Tasseled Cap Orthogonal Transformation into three new dimensional spaces corresponding to soil brightness, green vegetation and soil moisture indices [39]. A colour composite was built from the resulting three bands which in turn were used to perform a cover classification using the Isodata unsupervised classifier. Visual comparison between Isodata classes and false colour composites revealed the cover class corresponding to barren land. This process was coupled with intensive ground checks as well as examination of historical aerial pictures and fine resolution Google Earth images.

**Table 1.** References and dates of acquisition of the Landsat data used for this study.

| Scene Reference | Satellite | Date of Acquisition | Resolution |
|---|---|---|---|
| p210r51_2m19751125 | Landsat MSS | 25 November 1975 | 68 m × 83 m |
| p195r51_5t861118 | Landsat MSS | 18 November 1986 | 68 m × 83 m |
| L4195051_05119910108 | Landsat TM | 8 January 1991 | 30 m |
| L71195051_05120001218 | Landsat TM | 18 December 2000 | 30 m |
| L5195051_05120061109 | Landsat TM | 9 November 2006 | 30 m |
| L5195051_05120110208 | Landsat TM | 8 February 2011 | |

The accuracy assessment was done using random points taken both from field and from classified raster. A binary table (yes or no) was constructed in which all checked points were reported with their corresponding ground check: "yes" if it fell on barren land and "no" when it fell on a different cover type. The number of "yes" was calculated and divided into the total number of checked points to give the accuracy level.

### *2.3. Rainfall Data*

Two types of datasets were used to assess the rainfall trend. The first consists of rainfall data of all meteorological stations of Burkina Faso to calculate and map the mean annual rainfall for the decades 1971–1980, 1981–1990, 1991–2000 and 2001–2010. The second dataset used rainfall data of the study area (station of Kaya) to construct the local inter-annual means rainfall variability and trends.

### *2.4. Field Observations and Discussion with Land Managers*

Technicians and directors of decentralized governmental offices as well as non-government organizations in charge of the soil and water management (SWM) projects and farmers were invited to participate in informal meetings during which the mostly used management techniques were identified and visited during December 2012 and January 2013.

## 3. Results

### *3.1. Changes in Barren Land Area*

The overall accuracy for the classification of the barren lands maps as assessed during the ground check is 83.4%.

The results of the image classification are shown in Figures 2 and 3. At the onset of the study period in 1975, the barren lands represented 10% of the surface area of the study site. It was scattered into small patches with less intensity in the middle and the south-west. In 1986, the area of the barren land had more than doubled with sustained intensity in the north and north-east. In 1991, it dropped by one-third of its size in 1986 and reached its 1975 level in 2000. The barren land increased again in 2006 and in 2011, it reached the size it was in 1975. In general, in 2006 and 2011, the barren lands appeared importantly along the rivers and were almost equally distributed throughout the study area.

**Figure 2.** Pictorial representation of the evolution of the Barren Land in the study area from 1975 to 2011.

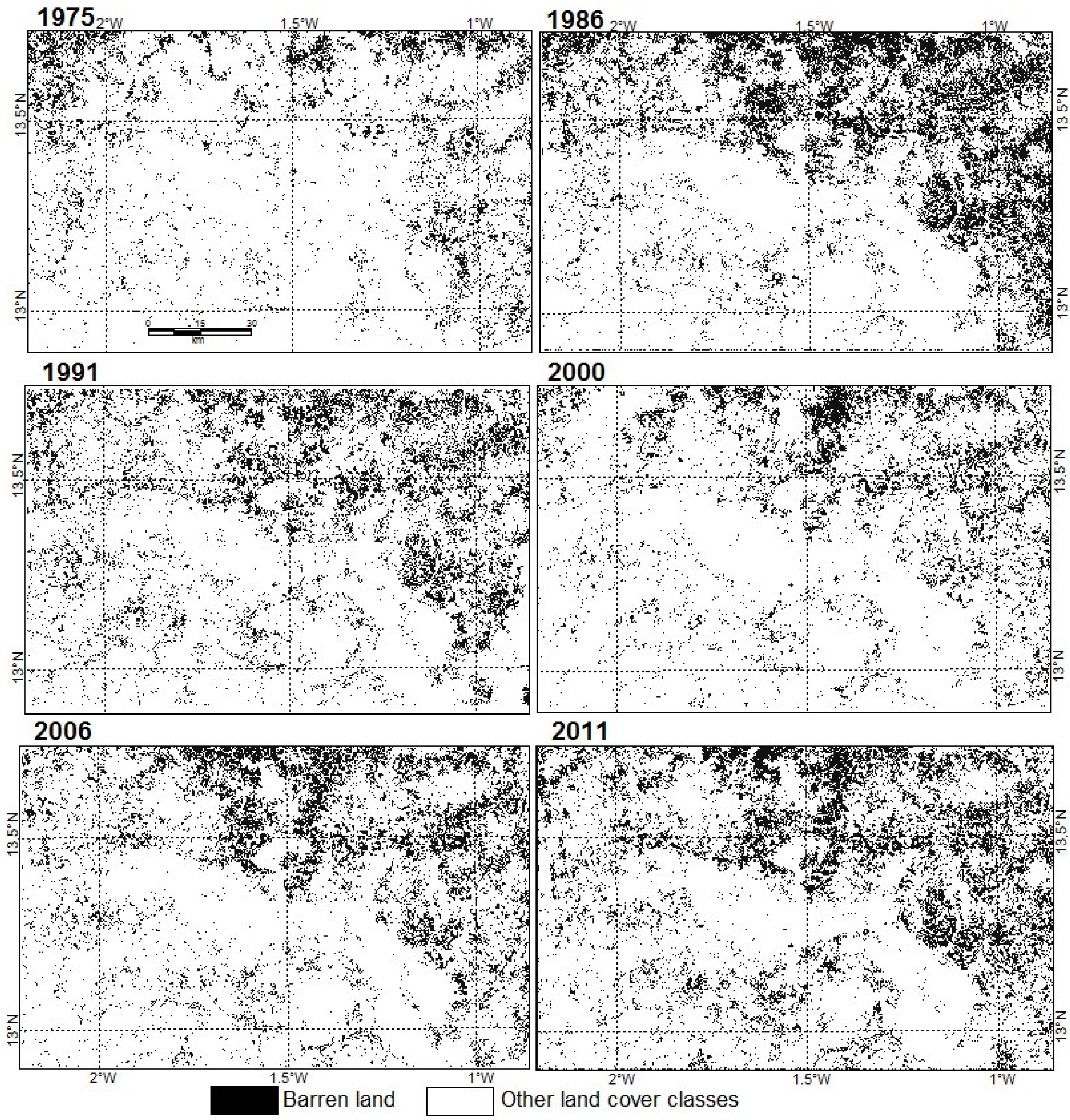
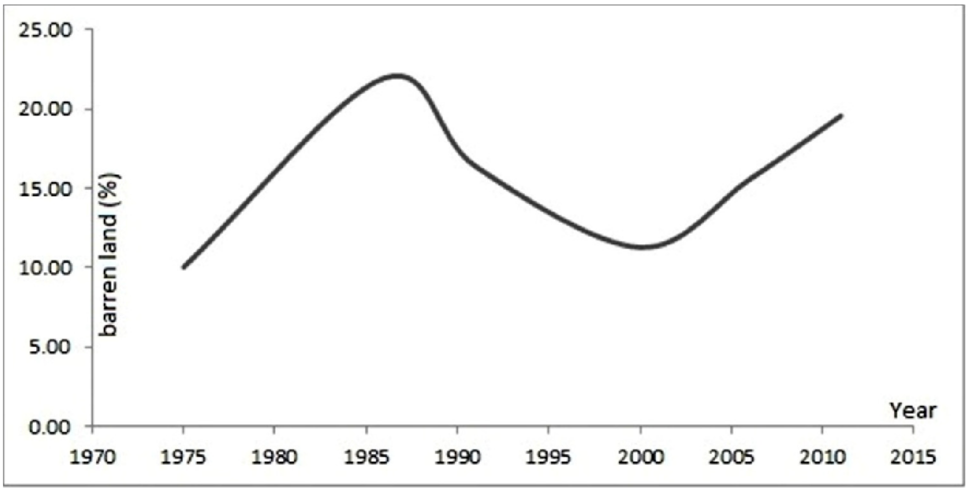


**Figure 3.** The dynamics of the barren land during the study period (percentage of barren land *versus* years).




### *3.2. Rainfall Variability*

Rainfall of Burkina Faso has almost a decadal oscillating shape (Figure 4). During the decade 1971–1980, annual rainfall varied from 500 mm to more than 1100 mm from the north to the south-west of the country. During this decade, the study site was located within the isohyets 500 mm and 700 mm. In the decade 1981–1990, new isohyets (≤300 mm) appeared in the extreme north of the country; the isohyets higher or equal to 900 mm disappeared in the south-west and the in-country isohyets shifted downward. The study site was at that period located within the isohyets 300 mm and 500 mm.

**Figure 4.** The mean annual rainfall of Burkina Faso for the decades 1971–1980, 1981–1990, 1991–2000 and 2000–2010.

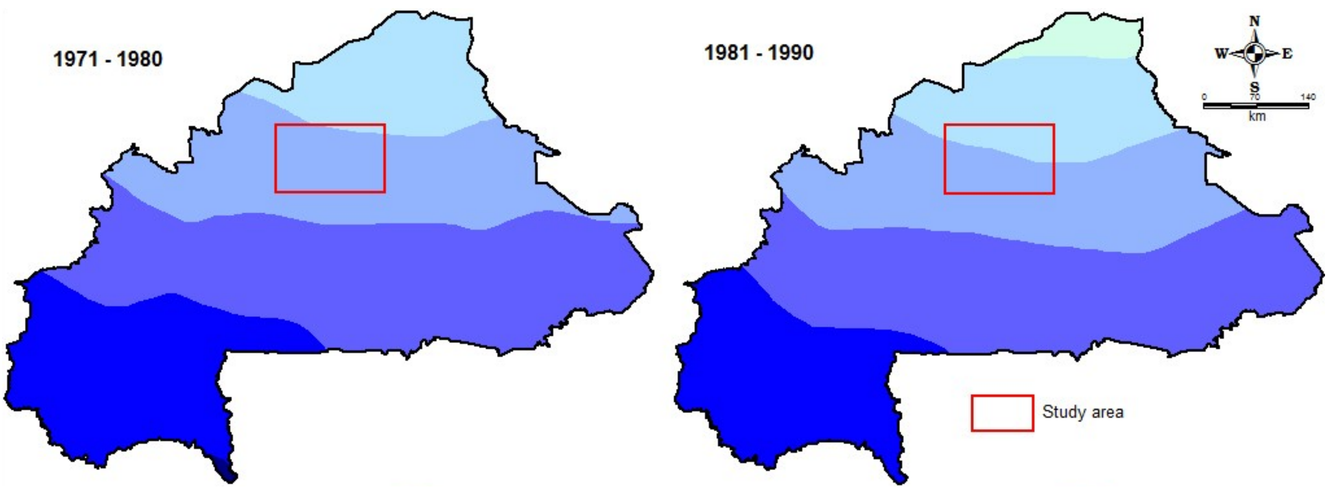
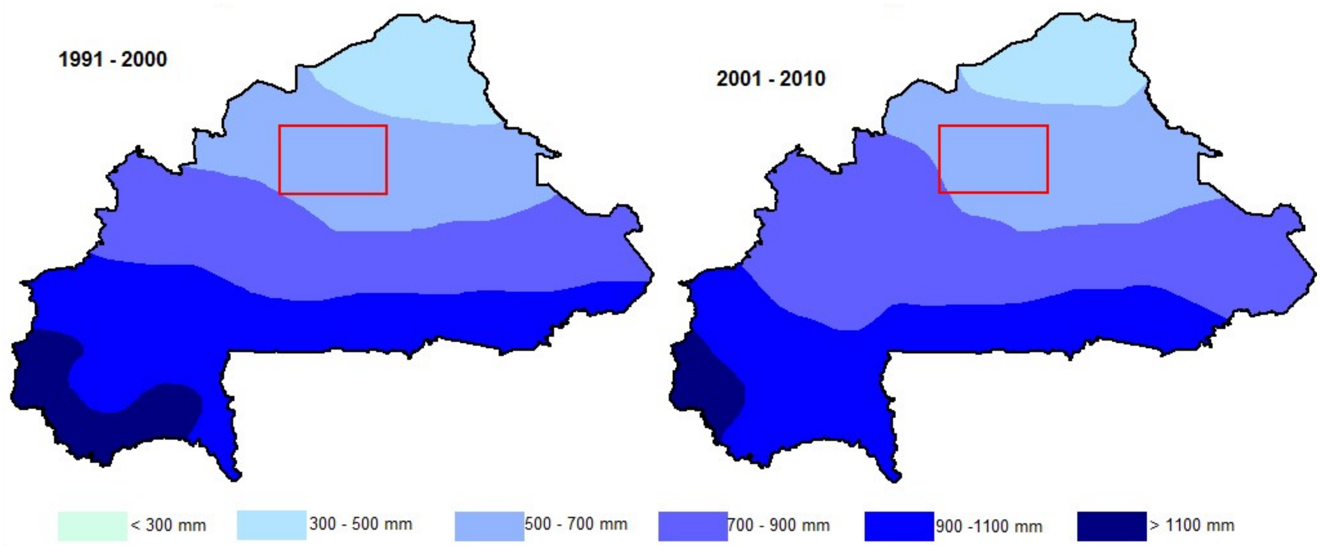


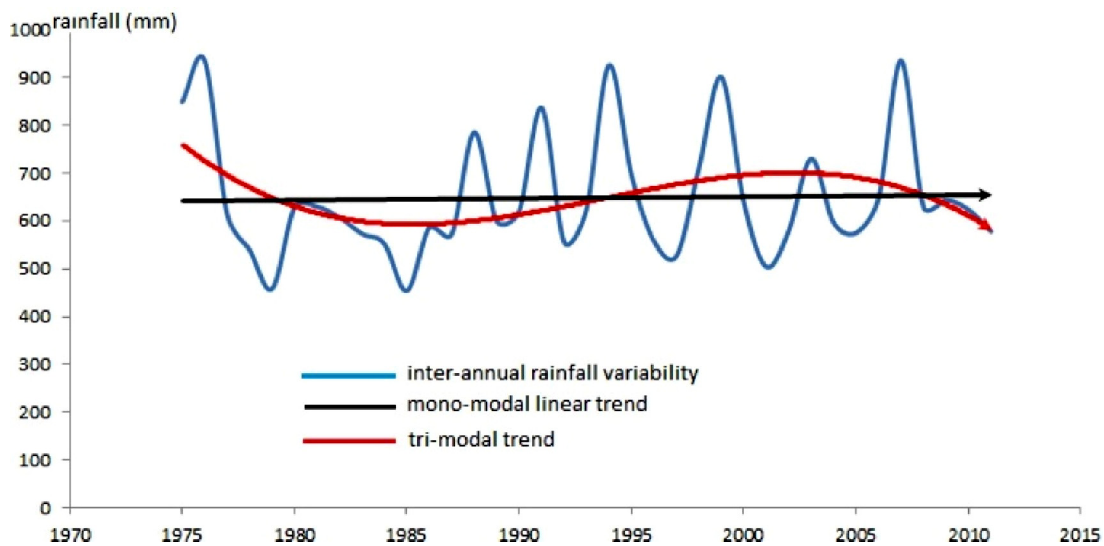
**Figure 4.** *Cont.*




The decades 1991–2000 and 2001–2010 witnessed the return to the 1970s rainfall stage. The dry isohyets (≤300 mm) disappeared in the north, the 1100 mm and above isohyets showed up in the south-west and the in-country isohyets moved upward. The study site was embraced between the isohyets 500 mm and 700 mm.

The inter-annual change of the mean annual rainfall of the study site during the period 1975–2011 is shown in Figure 5. The average annual rainfall was about 900 mm at the onset of the study period but it decreased by half in the 1980s during which it remained almost stable till the 1990s. From the 1990s–2000s, the average rainfall fluctuated between 500 mm and 700 mm. From the 2000s–2010s, it dropped slightly to 600 mm. Two trend lines are observed in the figure. The first is a mono-modal linear trend which shows a steady shape tending to slightly rise up (y = 0.3258x). The second is a tri-modal trend with a complex shape showing a decrease of rainfall from 1975 to 1985, an increase from 1985 to 2000 and a second decrease in amount of rainfall from 2000 to 2011.

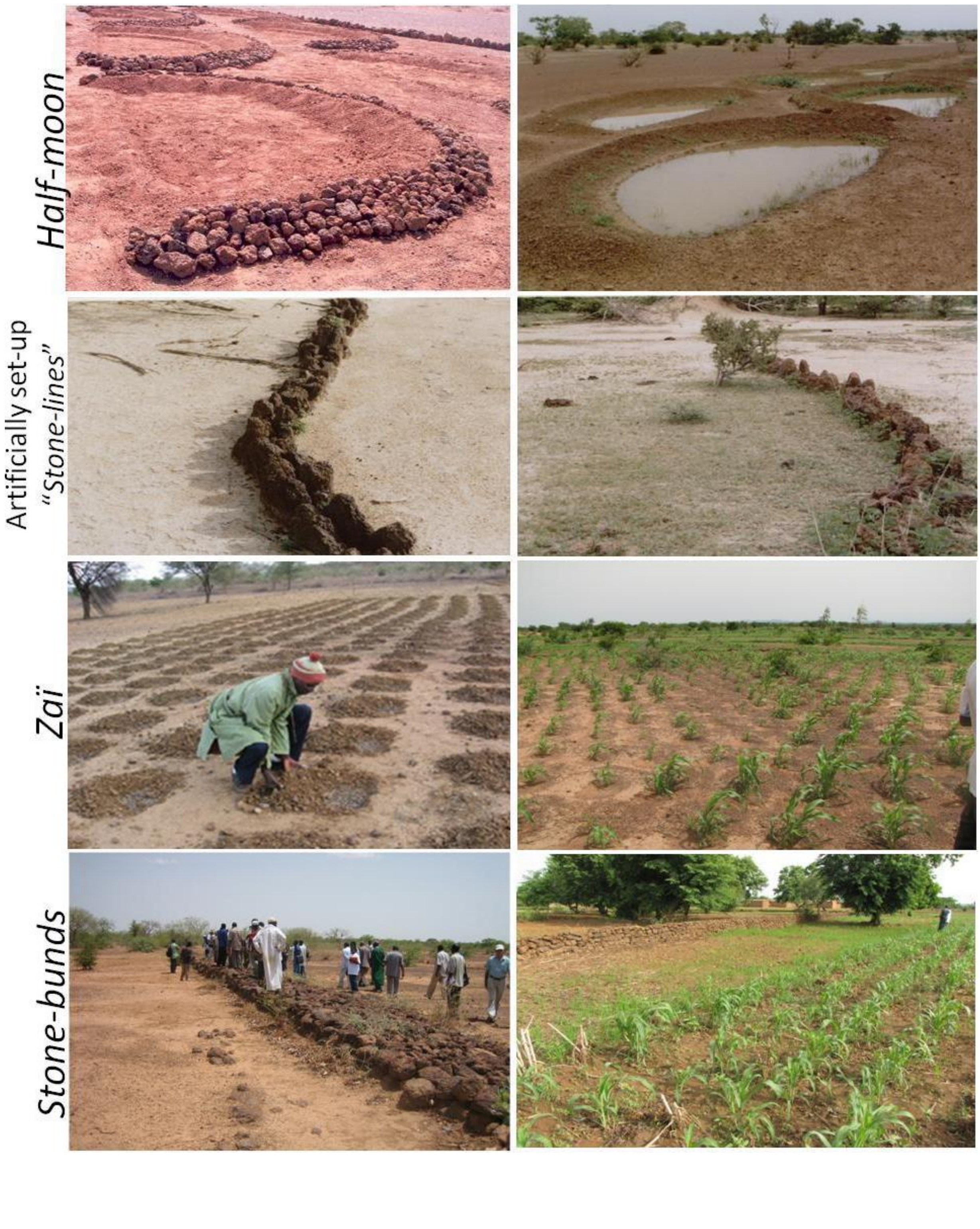
**Figure 5.** The mean annual rainfall of the study site during the study period and the red trend-line curve (rainfall in mm *versus* years).



### *3.3. Land Management Practices*

Informal meetings with local land management staff and farmers as well as field observations helped to identify soil management practices in vogue in the area (Figure 6). In total, four major soil and water conservation practices were identified and about 15 relevant projects helped to root the practices in the area. Farmers use at least one of the four practices in the farming system. However, in general, they combine two or three of the techniques for the sake of efficiency. They are: artificially setup "Stone-lines", "*Zai*", "*Half-moon*" and "*Stone-, Hearth- or Herb-bunds*".

**Figure 6.** Soil and water conservation techniques in the study area.



The term "*stone-lines*" used here refers to man-made apparatus built upon stone alignment following the contour lines of the landscape. The "*stone-lines*" are usually constructed on barren land, less degraded land and also on land with fragile soil. The objective is to reduce the runoff and improve water infiltration. The Zaï is a planting pit system used to rehabilitate barren lands in which rainfall could no longer infiltrate [21]. In general, a pit has 15–30 cm diameter and about 20 cm depth in which manure is applied during dry seasons. During the first rains, the crops are directly sown in the pits. The *half-moons* are also planting pit systems but they differ from the Zaï in size. The *half-moons* have 2–4 m diameter. *The half-moon* collects important quantities of water during the rains and therefore improves the soil permeability and humidity for cropping. The bunds (built from stones, hearth or herb) are edifices constructed perpendicularly to the direction of runoff with principal objective to reduce the speed of the surface runoff, collect sediments and improve soil fertility and humidity for subsistence farming.

## 4. Discussion

Results revealed that during the study period (1975–2011), the area of barren land showed alternating decreases and increases. The period before 1975 was reported as a wet period in the Sahel during which there was an equilibrium between the environment and the climate [8,13]. The type of vegetation was adapted to the climate and to the local farmers' needs in terms of food and fodder for the small scale farming and breeding systems [27,31]. During that period, only few barren lands, scattered into small patches were present in the study area. The severe droughts occurred in the 1980s until 1990s and disturbed the secular equilibrium in the Sahel. The barren lands increasingly appeared during that period as shown in Figure 3. This magnitude of increased barren land agrees with the weak rainfall pattern as shown in Figure 5. Furthermore, Anyamba and Tucker [8] who reported that in 1985, the area from Burkina Faso to Chad showed negative departures in NDVI, corroborate our finding. This is also in line with Herrmann *et al.* [13] who argued that the mid-1980s saw the peak of the Sahelian desiccation. The severe droughts in the 80s caused famines and hunger to Sahelian populations due to sustained decrease in food production and loss of domestic animals [34,40,41]. To face the devastating impacts of the drought, the populations had two main choices: either they adapted the situation by changing the land use practices (changing crop varieties, cropping in shallows, adopting new soil and water conservation techniques) or else, they migrate out of the area.

From the 1990s to 2000s, the rainfall increased as shown the rainfall isohyets maps (Figure 4) as well as the rainfall curve of the study area (Figure 5). This has had a positive impact on the environment with decreased barren lands in the study area as confirmed by Anyamba and Tucker [8] who found that the period 1994–2003 was marked by a trend towards wetter conditions with region-wide above normal NDVI conditions and maxima in 1994 and 1999. Our finding is also in keeping with previous regional-scale findings for the same period (e.g., [9,13,15,19,42]). Many factors may have contributed to the decreased area of barren land during this decade. The soil and water conservation interventions, widely introduced and largely adopted by farmers have helped to restore large barren lands [21,22,37,43–45] even though, the success of these interventions was a function of the spatio-temporal distribution of the rains [36]. It was revealed during discussions with project leaders and farmers in the field that the *Zaï* techniques, as well as the "*Stone-lines*", *Half-moons* and *Hearth-*, *Stone-* and *Herb-Bunds* were widely adopted by local farmers within the study area, as a result of mitigation strategies under increasing aridity. Interestingly, Rasmussen *et al.* [46] argued that the non-climatic factors may play a more crucial role than rainfall in land cover change in the Sahel. The out-migration, for instance of entire households as a meaning of earning cash income and reducing the risk [47], has also played an important role in the decreased barren land during the period, as it reduced the pressures on lands.

Contrarily to some regional-scale studies that forecasted a continuous trend of greenness and rain improvement up to the 2010s, our results show a slight decrease in rainfall and an important increase in the area of barren lands from the 2000s–2011. This could be explained by the difference in the scale of measurement: at the regional-scale with low resolution images (e.g., NOAA), there are details at the landscape level that cannot be perceived as pointed by Anyamba and Tucker [8] and Herrmann *et al.* [13]. While at the landscape scale (as it is in this paper), such details can be detected and Brandt *et al.*'s study [48] supports our findings. The barren lands have increased importantly in the 2010s and reached every corner of the study area with pronounced concentration along the rivers. However, the decrease in the amount of rainfall as shown in this specific area would not suggest such changes. This could be explained by the increased pressure on lowlands and shallows for the subsistence farming activities. In so doing, the soil layer along the rivers becomes fragile and erodible; therefore, it can no longer resist to transportation into the rivers during heavy rains. The rivers get filled by sediments and the water flow becomes diffuse and rises above the river banks. The soil layer in lowlands is continuously eroded and thereafter they are converted to barren lands [49]. At long run, this may negatively reflect on food production systems in the Sahel. As pointed by Reenberg *et al.* [50] while investigating land saturation in similar landscape in Niger, the assumption that rural people should be self-sufficient elsewhere in the Sahel, with regards to their food production may no longer hold true. Further studies on specific land use in the converted barren land is needed at landscape scale, to determine what are the highly fragile land use types as well as the most persistent areas of barren land.

Results showed that area of barren land and rainfall variability have opposite trends: when rainfall increases, the area of barren land decreases and when the rainfall decreases, the area of barren land increases. This confirms the findings of previous studies arguing that rainfall is the main driving force of the re-greening in the Sahel [13,16] although some secondary factors could be associated [15]. Without any land management system to secure and enhance vegetation cover over the fragile and erosive soils, the rainfall could become a devastating factor in the Sahel since the area receives heavy and sporadic rains with turbulent flow, because there is no obstacle on the ground able to slow down the rapid water flow. The practices of small reservoirs and soil and water conservation techniques to enhance vegetation and crops are critical in this respect, to preserve the soil resources for human wellbeing. The trend of the degradation, in association with rainfall variability during the study period reveals an apparent cyclicity behind the fluctuation, occurring each 10 years roughly, with which, human can interact to slow down or speed-up the process depending on the degree of resilience of the ecosystems. Similar cyclic droughts were found by Nicholson [51] for the periods 1820s and 1830s in Sahelian Africa. Relatively good rainfall conditions returned during the 1920s and 1930s, and in the 1940s, there was again a widespread drought in the Sahel [51,52]. For Charney [1], droughts in the Sahel are recurrent with a mean period of about 30 years. The land management techniques, largely adopted by the populations in the study area, with the essential aim to improve soil quality for food production, have positively contributed to the conversion of barren land into croplands. The planting-pit systems (*Zaï* and the *half-moon* at the biggest scale) have played important roles in the conversion techniques [45]. They concentrate the water and nutrients in the pits and more importantly, the manure applied during the dry seasons attract termites that in turn play a crucial role in digging channels in the soil and digesting the organic matter, therefore, making nutrients more easily available to the crops in the pits [21,37]. Similarly, the "*stone-lines*", *herb-bunds*, *hearth-bunds* and *stone-bunds* as observed in the field, have also contributed to restoring and conserving soil quality at the largest scale. This was supported by Reij *et al.* [37] and Traoré and Toé [53]. Unfortunately, the extent of the barren land restored for agriculture by means of these techniques has not been estimated in the field, but considering the level of adoption we witnessed in the study area, coupled with the significant number of assisting institutions, it can be assumed that tens of thousands of hectares have been added to the 300,000 ha previously estimated by Reij *et al.* [37]. It is important to note that the techniques in use in the study area, although they are efficient in soil restoration and conservation for agriculture, they are not oriented toward permanent vegetation cover, such as the natural savannah grasslands or tree recovery. Therefore, restored soils remain under the threats from runoff and winds. In Niger, large-scale adoption of farmer-managed natural regeneration techniques, using valuable tree species such as *Faidherbia albida*, whose roots lay underneath the land thus, improving soil richness, has absolutely improved tree cover on millions of hectares [20,37]. The vegetative period occurs during dry seasons, providing livestock with palatable leaves and pods. During the rainy season, the plant drops its leaves and allows cropping under the canopy. Such techniques might be encouraged in the Sahel in Burkina Faso too. Such an initiative could also be promoted in the north of Burkina Faso.

## 5. Conclusions

The findings of this study disclose the cyclic fluctuation of the area of barren land and rainfall variability during a 36-year period in the Sahel of Burkina Faso. Increased rainfall does explain a decrease in area of barren land and, a decrease in rainfall predicts an increase in the area of barren land. Anthropogenic factors such as land use practices may have contributed to the change in the area of barren land. The barren land assessment approach does not support the continuous re-greening argument as suggested by regional scale studies. The re-greening trend might be a cyclic phenomenon following rainfall variability and the ecosystems resilience at local levels.

Although it is evident that the observed dynamics of barren land is the result of combined natural and human factors, most of these factors need to be understood better. Therefore, there is a need to perform a complex regression analysis using biophysical and socio-economic variables to understand the driving force of the changes. Also, some hydrological modeling techniques could be tested to understand the role of the soil and water conservation techniques on restoration of barren land. Furthermore, predicted trends of the Sahel ecosystems could be tested using appropriate models to guide policy-makers for efficient management. Finally, agricultural water management techniques that combine appropriate tree species plantation should be encouraged for sustainable soil conservation.

**Acknowledgments**

This work has been financially supported by the German Research Foundation (DFG) through the Academy of Science for Developing World (TWAS). We are grateful to DFG/TWAS for supporting the three-month cooperation visit programme at the University of Frankfurt (April–June 2012). The field visits were conjointly financed by the Challenge Programme for Water and Food (CPWF, V1) and the EU research project WHaTeR: Water Harvesting Technologies Revisited: Potentials for Innovations, Improvements and Upscaling in Sub-Saharan Africa. The generous contributions of the National Meteorological Office (DNM) of Burkina Faso in Ouagadougou to rainfall data archives are gratefully acknowledged.

**Author Contributions**

Issa Ouedraogo was involved in all stages of the research: data gathering and interpretation, field visits, barren land classification, ground truthing GIS and statistical analysis and performing the informal meetings. Jürgen Runge and Joachim Eisenberg were involved in data gathering, design of the informal meeting and the isohyets migration mapping. Jennie Barron, Séraphine Sawadogo/Kaboré were involved in the field visits, ground truthing and performing the informal meetings. All authors were involved in the design of the research and writing of the manuscript.

**Conflicts of Interest**

The authors declare no conflict of interest.

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