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Published in:
Remote Sensing

DOI:
10.3390/rs5031465

Publication date:
2013

Document Version
Publisher's PDF, also known as Version of record

Citation for published version (APA):
Kelder, Y., Nielsen, T. T., & Fensholt, R. (2013). The rolle of methodology and spatiotemporal scale in understanding environmental chance in peri-urban Ouagadougou, Burkina Faso. *Remote Sensing*, *5*, 1465-1483. https://doi.org/10.3390/rs5031465

Remote Sens. **2013**, *5*, 1465-1483; doi:10.3390/rs5031465

OPEN ACCESS

Remote Sensing

ISSN 2072-4292

www.mdpi.com/journal/remotesensing

Article

The Role of Methodology and Spatiotemporal Scale in Understanding Environmental Change in Peri-Urban Ouagadougou, Burkina Faso

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Received: 18 January 2013; in revised form: 24 February 2013 / Accepted: 15 March 2013 / Published: 19 March 2013

Abstract: In recent decades, investigations of NPP (net primary production) or proxies here of (normalized difference vegetation index, NDVI) and land degradation in Sahelian West Africa have yielded inconsistent and sometimes contradicting results. Large-scale, long-term investigations using remote sensing have shown greening and an increase in NPP in locations and periods where specific, small scale field studies have documented environmental degradation. Our purpose is to cast some light on the reasons for this phenomenon. This investigation focuses on the south of Ouagadougou, Burkina Faso, a city undergoing rapid growth and urban sprawl. We combine long-term MODIS (moderate resolution imaging spectroradiometer) image analysis of NDVI between 2002 and 2009, and by using high resolution satellite images for the same area and a field study, we compare trends of NDVI to trends of change in different categories of land cover for a selected number of MODIS pixels. Our results indicate a strong, positive association between changes in tree cover vegetation and trends of NDVI and moderate association between man-made constructions and trends of NDVI. The observed changes are discussed in relation to the unique processes of urban sprawl characterizing Ouagadougou and relative to their spatiotemporal scale.

Keywords: remote sensing; NDVI; land cover change; Ouagadougou; Sahel

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1. Introduction

The past decade has seen a number of studies investigating long-term trends in vegetation productivity for various parts of the world using satellite remote sensing data [1–19]. Common among these studies are the methods applied and the data types upon which the analysis has been built. All of these studies take their point of departure in hyper temporal satellite image datasets characterized by a coarse to medium range spatial resolution. Furthermore, these satellite images all offer the option of calculating the vegetation index, NDVI. Several studies have established an empirical, as well as theoretical, relationship between NDVI and the vegetation productivity of a given area, and it has been shown that the temporal integral of NDVI throughout the growing season (iNDVI) in semi-arid parts of the world correlates to the net primary production (NPP) [19–27]. This relationship has also been utilized in several of the above-mentioned studies of long-term trends in vegetation productivity, where NDVI is calculated for large areas for many years of data as a proxy for vegetation productivity. Currently, the longest period of validated continuous NDVI data availability is the AVHRR (advanced very high resolution radiometer) GIMMS (global inventory monitoring and modeling study) data set, which covers the entire globe from 1981 to near-present [28]. While this data set is in itself not distributed as daily images, it is nevertheless based upon daily global area coverage (GAC) images from the NOAA AVHRR, offering coarse resolution data since July 1981.

Also, critics have raised concern over the very coarse scale of the long-term GIMMS AVHRR-based analyses and pointed to the fact that an area of 64 km^2 is covered by a single pixel in the original GIMMS analyses. Especially in a landscape known for its very high degree of heterogeneity as the West African savannah, the very coarse spatial resolution of the GIMMS data must be acknowledged as a serious obstacle if the aim of the analysis is to understand also the underlying processes of the results. However, with the launch of the Terra and Aqua satellites (2000 and 2002), both carrying the MODIS sensor, data at a much finer spatial resolution (250 m) and at a similar temporal resolution has been made available. Analyses have shown that the large scale general increase in vegetation productivity can be reproduced also at this spatial scale [29], and other studies have established that the trends observed in the MODIS data are compatible to the results produced on the longer time series of the GIMMS data [30–33]. Yet, it must be acknowledged that very little information concerning the actual changes on the ground is available that can, at the same time, be used to qualify the results obtained from analyses of coarse or medium resolution satellite data.

Much attention has been offered to the results from West Africa, as these have been both unexpected, as well as somewhat contradictory to many previous ground-based studies. On an overall level, all of the studies in West Africa based on long-term analysis of satellite images have found a general increase in vegetation productivity across West Africa in the past two to three decades [10,11,16,34]. These results have spurred a debate that seems to direct itself in two separate directions. On one hand, the results and methods have been discussed, and many shortcomings of the methods and data have been identified [15,32,33]. These relate to the notorious problems of NDVI in arid and semi-arid areas concerning soil background influence [35], atmospheric correction [36] and image compositing [37], and also, the correlation between NPP and iNDVI has been found to be place- and season-specific [19,22,38]. However, none of these reservations have been able to dislodge the basic finding of the analyses: that the trends in vegetation productivity may actually have been increasing across the Sahel in the past decades.

Another range of discussions have been the mounting evidence from case studies, which almost unanimously seem to reproduce past findings and identify a wide range of local land degradation, resource depletion and desertification [39]. As noted by Rasmussen *et al*. [40], the contradiction between the two sets of results may very well be the result of scientific traditions and internal logic in the scientific community, as well as in donor agencies, often financing much research into land degradation and desertification. This, however, does not address the underlying issue, which seems to be that two different approaches, traditions and methods apparently produce contradictory results. Nielsen and Rasmussen [41] further compares results found using long-term trends in satellite data with a number of case studies examining land degradation in detail. It was found that in almost all cases (spanning a wide range of natural and semi-natural Sahelian ecosystems) where land degradation and desertification was found in the field, a positive trend in vegetation productivity could be established in long-term trends in the satellite data.

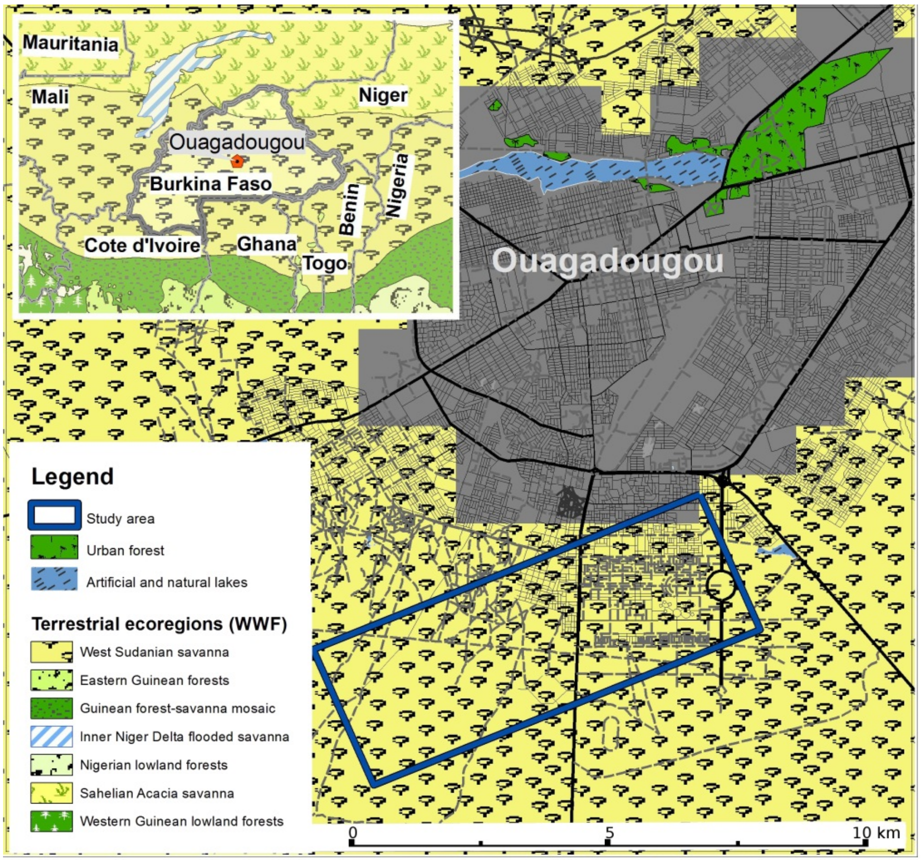
Research and monitoring of urban environments is an increasing field of interest within the remote sensing community, and little is known about the influence from urban sprawl on such changes and trends in vegetation productivity. The current emphasis in the field of urban remote sensing is two-fold. The first subject of focus is the developments in our capacity to understand, monitor and map the spatio-temporal dynamics of biophysical properties and processes in urban landscapes [42–44]. The second theme is the influences that recent developments within remote sensing and image processing and the combination of various remotely sensed data and *in situ* data have on monitoring urban environments [45–51]. The current paper falls within the scope of the latter.

In this study, we examine in detail the city of Ouagadougou, its sprawl in the past decade, its layout and composition and relate the changes we find to trends in vegetation productivity as obtained by analyses of long-term trends of MODIS data. The pulses of peri-urban development offer an especially attractive opportunity to study the impact of land cover changes (LCC) on signals in coarse and medium resolution satellite images, as neighborhoods can be tracked and identified on an individual basis, and the changes from peri-urban agriculture to mud-brick houses and, then, to fully developed neighborhoods clearly are related to the observed trends in NDVI from the MODIS data. Hence, we aim to undertake a detailed case study to investigate if it is possible to link changes in long-term trends in vegetation productivity to physical changes in a peri-urban setting in West Africa. We do not claim that the findings of this endeavor will result in a generalized model to explain changes on a wide scale across the continent. Rather, we will argue with Flyvbjerg [52] that if a satisfactory explanation for peri-urban Ouagadougou can be established, it should be possible also to establish a similar understanding in other places. *Vice versa*, if we fail to explain a relationship between changes in long-term trends in vegetation based on detailed observations of changes in the physical environment in the study area, then establishing such a relationship in other places may prove equally difficult.

2. Study Area

The research area is located at the West-Sudanean-Savannah ecoregion, which runs as a wide east-to-west belt south of the semi-arid Sahelian-Savannah and north of the moist Guinean-Savannah [53], as can be seen in Figure 1. The current study focuses on a rectangular area (659150E, 1360412N, Universal Transverse Mercator (UTM) zone 28) of 3.00 over 8.34 km, located at the south-western outskirts of Ouagadougou at an altitude of 300 m above sea level. Mean annual precipitation in Ouagadougou is 740 mm [54].

Figure 1. Ouagadougou and the research area. The city of Ouagadougou is located in the center of the Sudanean-Savannah ecoregion. The research area, shown as a blue rectangle, contains planned and unplanned urban patches, as well as mixed patches of agriculture and savannah forest. Source for terrestrial ecoregions: [53].



Due to many years of anthropogenic influence, much of the Sudan-Savannah has turned into an agro-pastoral ecosystem [55,56]. In recent years, a process of urban sprawl led to replacement of the agro-pastoral ecosystem, at the surroundings of the city, with the urban ecosystem of the outskirts of Ouagadougou. This urban expansion is mainly the result of three factors: natural growth of the urban population, rural to urban migration and a wave of Burkinabe immigrants returning from *Côte* d'Ivoire, due to the political instability there at the beginning of the 2000s [57–60].

The growth of the city is in many respects compatible to the growth in other large West African cities [58,61]: areas in the outskirts of city are encroached upon and developed with mud-brick houses. After a while, the area will be parceled by the authorities, and as such, a new area will be part of the city [62].

Urban patches closer to the city center show planned distribution of both vegetation and man-made constructions. The large majority of these constructions are permanent brick-houses and temporary mud-brick houses [58,59,62]. In most cases, flora thriving in the savannah and agro-pastoral landscapes prior to the urban development was removed, and new vegetation was planted, usually confined to private gardens and yards [58]. This means that trees and bushes in these areas are usually young and small, growing around houses and gardens.

In areas further from the city center, on the other hand, the spatial distribution of both vegetation and man-made construction is more sporadic. Here, the unauthorized mud-brick houses are not organized into blocks, and not all trees were removed in the expansion process [58]. In these areas and in the areas of savannah-bush and agro-pastoral characteristics, much of the vegetation maintained its natural clumping pattern (field study 2011).

Table 1. Specification of the five land cover classes used in the study and their characteristics.

	Land Cover Class	Characteristics
Manmade constructions	Mud-brick houses in un-parceled areas	Unplanned, temporal and sometimes illegal mud-brick houses. These are usually built by people who immigrated to the city from nearby rural areas or by young people whose parents live in the urban center, as a measure of land capture. These are usually relatively small-sized construction, made out of local materials. Neighborhoods of this accommodation type would rarely have any type of infrastructure, and their inhabitants would usually be from a lower socioeconomic class. Some complement their income with small-scale agricultural activity.
	Sheds in parceled areas	These are small-sized construction, which are usually seen as the first stage of planned construction. This type of land cover feature appears in areas of the city where parcelation has already taken place, but construction of the permanent house has not started yet. These sheds are usually inhabited by the construction team or by a guard until construction of the family house on the parcel is completed. Sheds are usually built of bricks and serve as a garage once a house is constructed.
	Brick houses	Permanent, planned constructions in neighborhoods, which are usually connected to the municipal infrastructure. Inhabited by middle-to upper socioeconomic classes.
Vegetation	Large trees	Trees with a crown diameter over 12 m, keystone species in the semiarid Sudanean-Savannah ecotone.
	Small trees	Trees and bushes with crown diameter under 12 m

3. Data

3.1. Field Work

During the months of February–March 2011, a detailed field study was conducted in the study area. The field work included spatial survey and characterization of five random squares of 300 × 300 m, which are located within the study area. The purpose of the field work was to collect qualitative data to gain a detailed understanding of the occurrence of features (manmade constructions and perennial vegetation) in the peri-urban and urban landscapes of Ouagadougou. The field work allowed us to better identify individual features from the Quick Bird images for visual interpretation of land cover classes (Table 1; mud-brick houses in no-parceled areas, sheds in parceled areas, permanent houses, small trees and bushes, large trees).

The field based inventory of manmade constructions was done with the help of a local geographer. The detailed level of the inventory allowed for a deeper understanding of the socioeconomic and ecological context of the study area during the time of the research. The occurrence of features in the landscape were analyzed in relation to the socioeconomic status of the inhabitants in different areas of the city and in relation to the different stages of the urban sprawl.

3.2. Satellite Data

The Terra MODIS NDVI 250 product (MOD13Q1, collection 5) is based on the Terra MODIS level 2 (L2G) daily surface reflectance product (MOD09 series), which provides red and near-infrared surface reflectance corrected for the effect of atmospheric gases, thin cirrus clouds and aerosols. The MOD09 band 1–7 product is an estimate of the surface spectral reflectance, as would be measured at ground level if there were no atmospheric scattering or absorption [63].

Two spatially adjacent scenes covering the study area were acquired from the Quick Bird sensor. The scenes were captured in 2002 (27 October) and 2009 (29 September), respectively. The scenes were geometrically rectified from a set of *in situ* measured reference points collected during field work.

4. Methods

The analysis is split three steps. First, trends in vegetation productivity are estimated using well established methods [2,5,13,16]. Next, changes in land cover in peri-urban Ouagadougou are established. In order to characterize LCC, very high resolution images from the Quick Bird sensor were used in combination with detailed field observations. Finally, changes in vegetation productivity were compared to LCC.

4.1. Long-Term Trend Calculation

The long-term trend analysis performed here used a Theil-Sen median slope trend analysis, which is a linear trend calculation that is resistant to the impact of outliers. The Theil-Sen median slope is a robust trend statistical method [64–66] calculating the median of the slopes between all n(n-1)/2 pairwise combinations over time. This method is related to linear least square regression trend techniques; however, it is based on non-parametric statistics and is particularly effective for the estimation of trends in short and noisy series. Because it is based on the median, approximately 29% of the samples can be unrelated noise and have no impact on the statistic [66]. MODIS 16-day NDVI composites were summed into annual NDVI values (MODIS iNDVI) before calculating the trends. The value of the slope of the line fitted to the NDVI-time series data indicates the rate at which the change in greenness has taken place. Slope values represent the total increase/decrease in MODIS iNDVI over the period of 2002 to 2009.

4.2. Manual Classification of LCC

LCC was collected by visual interpretation of Quick Bird scenes from 2002 and 2009 and manual object classification of features in the landscape. This method was chosen in order to count for the variety of features of interest and for the extensive variation in their spatial distributions. Visual interpretation allowed us to compensate for the difficulty of identifying individual trees and bushes in clumps of vegetation by considering the size and shape of shadows. Manual object classification enabled accounting for variations in the spatial organization of otherwise similar features in the landscape (*i.e.*, unauthorized mud-brick houses in the unplanned neighborhoods and sheds in the planned areas) and for the size of tree crowns and buildings. Moreover, manual classification enabled distinguishing trees and bushes from the vegetative background below them [62]. The manual classification was combined with detailed field work.

4.3. Comparison of Data Sets

For each of the relevant 390 MODIS pixels, which fall inside the Quick Bird images generalized statistics of LCC, were collected. These were, respectively, changes in: the number of larger trees (crown diameter larger than 12 m), number of smaller trees and bushes, number of mud-brick houses in the pre-parceled zone and changes in mud-brick houses and brick houses in the parceled zone.

The 12 m crown size was chosen to differentiate between large trees and small trees and bushes, as trees with a crown diameter larger than 12 m are thought to represent keystone species in African savannahs [67]. The different types of man-made constructions above represent various stages in the urban sprawl of Ouagadougou. Unauthorized construction of mud-brick houses in the pre-parceled areas, temporary mud-brick houses and shacks in parceled areas are prior to the construction of permanent brick houses [62].

The absolute change in the land cover parameters was subsequently used in five single-variable Guttman weak monotonicity analyses, where each of the LCC parameters was independent variables and the Theil-Sen trend (see Section 4.1) the dependent variable.

We use Guttman's Weak monotonicity coefficient [68], μ_2, to test for a correlative relationship between the value of Theil-Sen median slope and the change in features in the landscape. The μ_2 coefficient uses ranking of the compared datasets to test for similarity in the direction of change. Its basic assumption is that a positive or negative change in the independent variable would cause positive or negative change in the dependent variable, respectively, yet it has no assumption as for the size of change. The range of values for the monotonicity coefficient is -1 to $+1$.

The use of a monotonicity coefficient that captures changes in variables that do not necessarily develop linearly is considered appropriate for the current analysis, since the NDVI variable analyzed is a non-linear index [69], and therefore, changes with other variables like tree cover cannot be expected to be linearly related. Fifteen pixels were chosen for a detailed analysis of the change in LCC relative to the trend in MODIS iNDVI. The purpose of this analysis is to examine whether in cases of extreme MODIS iNDVI trends or cases of extreme LCC, the respective correlated parameter can stay without change.

For this detailed analysis, we picked 15 pixels according to their Theil-Sen trend, five pixels with the highest negative Theil-Sen trend, five pixels with the highest positive trend and five pixels with the lowest MODIS iNDVI change (Table 2). The location of these pixels can be seen in Figure 2.

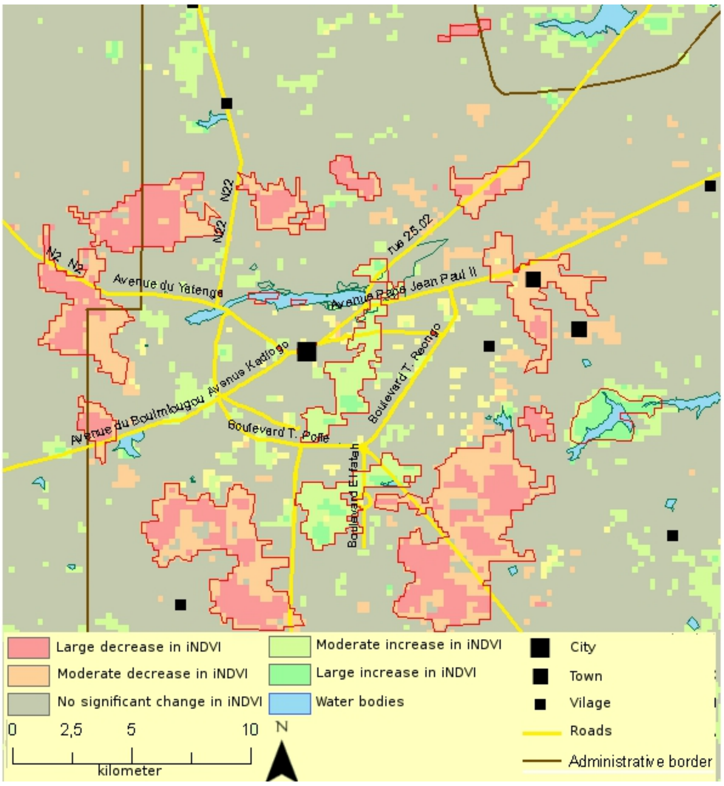
5. Results

The shift from a rural, agro-pastoral ecosystem into an urban ecosystem is described by various authors [58,59,62], suggesting that differences in vegetative land cover can be related to infrastructure, the socio-economic status of the inhabitant and the time since establishment of the new urban vegetation [58,59].

Table 2. Pixels that were selected for detailed analysis of land cover changes (LCC). Grey rows illustrate pixels with an insignificant Theil-Sen slope ($p < 0.05$, n = 390). Bold numbers represent pixels, which are studied in detail below. The row numbers correspond to the numbers in Figure 3, showing the location of the pixels in the study area. iNDVI, temporal integral of normalized difference vegetation index.

Change in iNDVI (2002–2009)		Theil-Sen Slope	Z-Score	Absolute Change in:				
				Mud-Brick Houses in Un-Parceled Areas	Sheds in Parceled Areas	Brick Houses	Large Trees	Small Trees
1.	Negative trend	**−0.126**	**−2.846**	**0**	**27**	**28**	**0**	**−25**
2.		−0.111	−1.856	0	18	33	−11	−152
3.		−0.110	−2.103	5	10	20	−13	−43
4.		−0.108	−2.598	0	30	27	−10	−61
5.		−0.106	−2.351	0	9	4	−7	−45
6.	No change	−0.001	0.000	−8	−4	0	−3	−23
7.		−0.001	0.000	0	0	4	0	20
8.		**0.000**	**0.000**	**0**	**0**	**0**	**0**	**0**
9.		0.000	0.000	−18	−11	17	2	35
10.		0.000	0.000	0	−10	10	−1	69
11.	Positive trend	0.061	2.846	0	0	5	2	−57
12.		0.062	2.846	0	0	6	7	24
13.		0.062	2.351	0	0	0	0	−1
14.		0.067	2.846	0	0	0	2	141
15.		**0.069**	**3.093**	**0**	**6**	**7**	**1**	**3**

Figure 2. The decrease in MODIS iNDVI can be seen as a wide belt of reddish patches around the center of the city.



Such changes can be clearly seen when comparing images of the study area from 2002 and 2009 (on the left of Figure 3). Here, fields, plantations and patches of savannah bush were replaced by various planned and unplanned patches of the urban ecosystem. This shift is also evident in trends in MODIS iNDVI for the same spatio-temporal frame, as illustrated in Figure 2, where trends in MODIS iNDVI for Ouagadougou and the surrounding environment are illustrated. This figure is based on MODIS iNDVI trends from 2002–2009. The figure coloration illustrates positive trends in MODIS iNDVI in greenish, while negative trends are illustrated in reddish colors. A wide red belt of decreasing MODIS iNDVI trends is clearly identifiable around the urban center. These red areas correspond to areas that have undergone a shift from agro-pastoral into the urban ecosystem, as part of an urban sprawl process. This is further illustrated in Figure 3 showing a zoomed view of the southern part of Figure 2 (see Figure 4 for a high resolution illustration of urban sprawl processes in the study area).

Out of the 390 MODIS pixels contained inside the study area, 211 pixels show a significant Theil-Sen trend. Out of these, 68 MODIS pixels show a positive trend ($p < 0.05$, $n = 390$) and 143 pixels show a negative trend ($p < 0.05$, $n = 390$).

Figure 3. iNDVI trend of MODIS 250m pixels in the study area (2002–2009). Numbered pixels are the pixels with extreme negative (1–5) and positive (11–15) Theil-Sen values and the pixels with lowest change in iNDVI (6–10). Numbers correspond to raw numbers in Table 2. Pixels with grey foreground are pixels with non-significant trends at the 95% confidence interval.

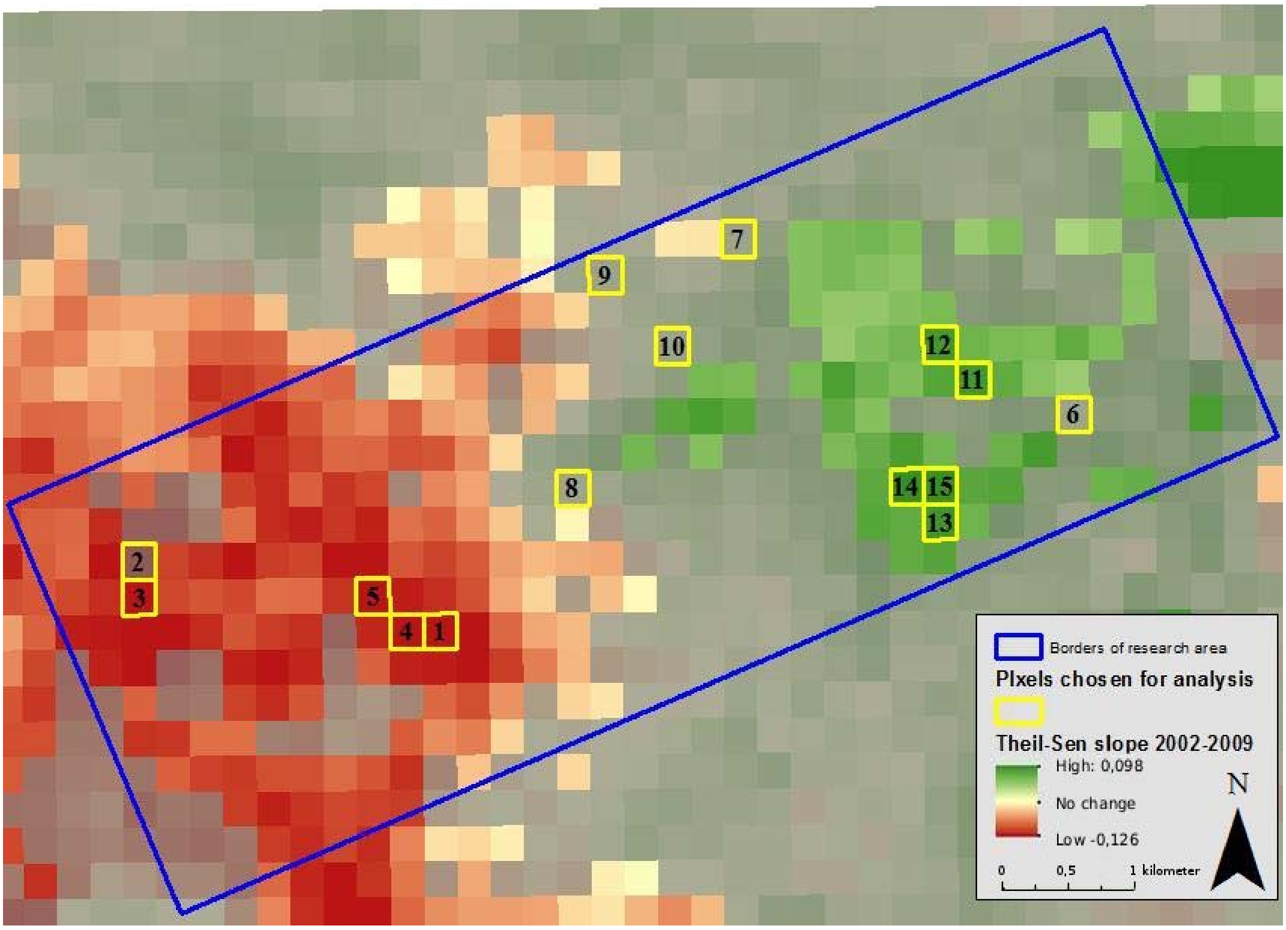


Figure 4. Quick Bird images of pixels 1, 8 and 15; images in the top row are from 27 October 2002; images in the bottom row are from 29 September 2009. Pixel 1, on the left, shows the highest negative Theil-Sen slope (−0.126) of MODIS iNDVI values. Pixel 8 in the center showed a Theil-Sen slope of 0.000, and pixel 15 on the right showed the highest positive Theil-Sen slope (0.069).

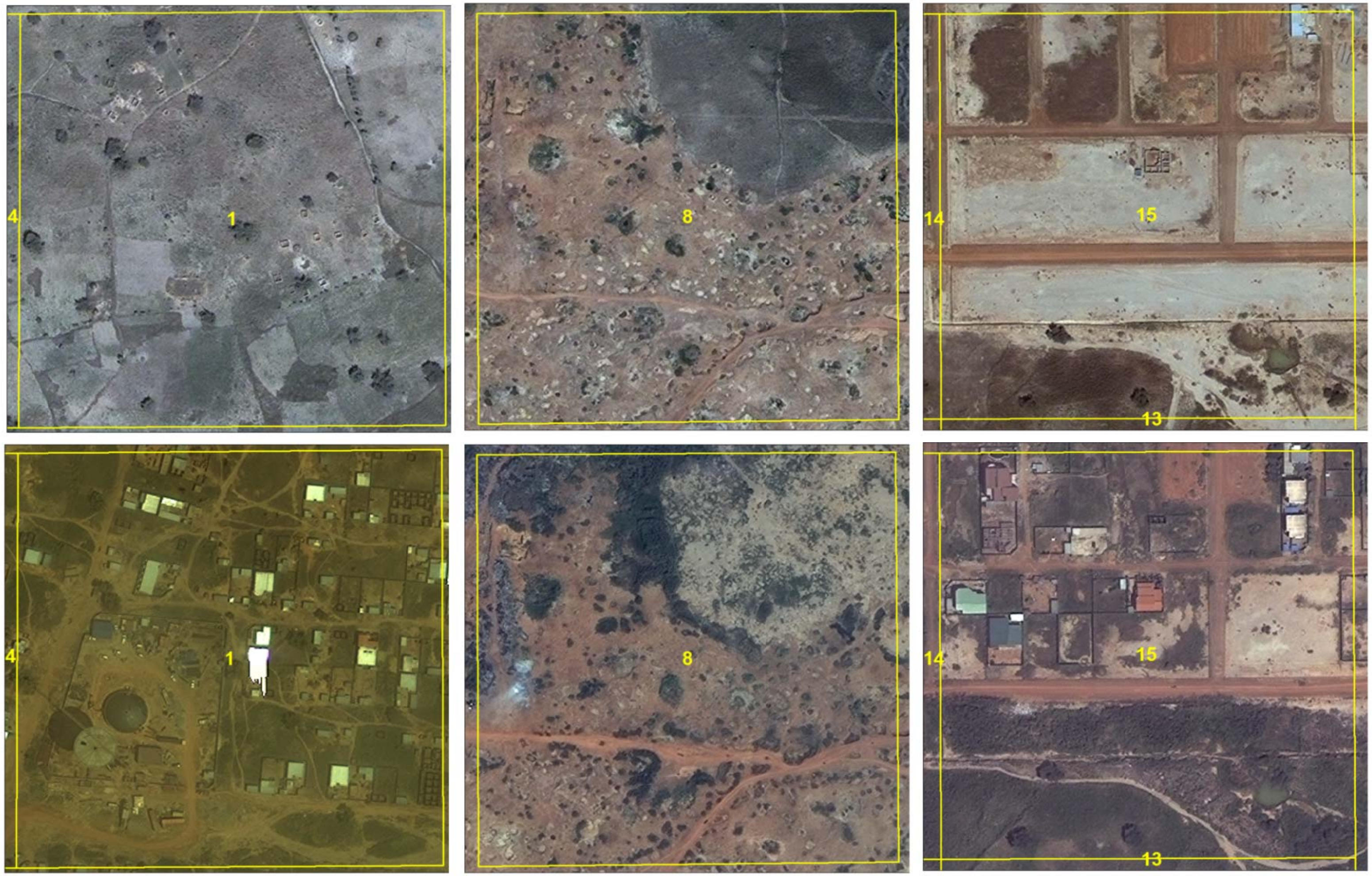


Table 3. The results of analysis of association between LCC and trends of MODIS iNDVI.

	μ_2 Monotonicity Coefficient			
	All Pixels with Insignificant Theil-Sen (n = 179)	**All Pixels with Significant Theil-Sen (n = 211)**	**Pixels with Significant Positive Theil-Sen (n = 68)**	**Pixels with Significant Negative Theil-Sen (n = 182)**
	n = 390		**n = 211**	
Mud-brick houses	−0.014	−0.145	Not enough data	−0.100
Sheds	−0.677	*−0.798*	−0.272	−0.769
Brick houses	−0.305	−0.467	−0.509	−0.436
Large trees	0.770	**0.891**	0.822	0.876
Small trees	0.727	**0.812**	0.256	0.808

Table 3 above indicates two main findings. Firstly, changes in MODIS iNDVI are mostly positively associated to changes in the vegetative features in the landscape (bolded in Table 3). Secondly, association between iNDVI changes and changes in human constructions is usually low to very low and negative. An exception to these findings is the relatively high negative association between changes in sheds in parceled areas and iNDVI trend (italic in Table 3).

A detailed look into the relationships between LCC and trends of change in iNDVI for the three categories of the pixels with different MODIS iNDVI trends (Table 2) indicate that, generally, in most of these cases, the iNDVI trend can be explained by the LCC studied in this investigation.

Rows one through five represent the five pixels with the highest negative values of Theil-Sen slopes. All these have decreases in vegetation (small and large trees) and increases in man-made construction from 2002 to 2009. Rows six to ten represent the five pixels with the lowest change in MODIS iNDVI (Theil-Sen slope closest to 0). Here, a variety of LCC combinations can be observed, ranging from relatively large increase in the number of small trees, to a decrease. The same variability can be seen for man-made infrastructure, even though these variations are smaller than for the small trees.

However, in some cases, LCC does not produce the corresponding MODIS iNDVI trend, which is expected from the results of the association analysis (Table 3). An example of this can be seen in row 11, where a decrease in small trees ($\mu_2 = 0.891$) and the construction of brick houses ($\mu_2 = -0.467$) is expected to have a negative influence on the trend of iNDVI, despite the two large trees, which were added to the pixel's area. The corresponding Theil-Sen slope indicates a high increase in NDVI. Secondly, in other cases, the MODIS iNDVI trend cannot be explained solely by the change in parameters chosen for LCC in this study. Two examples for that are rows 13 and 15, where MODIS iNDVI show a high positive trend, while LCC observed in these pixels are either minor or expected to cancel each other's influence out.

Thus, for the five pixels with the highest positive Theil-Sen slope, only rows 12 and 14 can be argued to have the expected correlation between LCC and MODIS iNDVI. In the three other pixels, other parameters must have a high influence on the trend of MODIS iNDVI.

Out of the 390 MODIS pixels that fall within the study site, 15 were chosen for detailed analysis. Rows 1–5 represent the five pixels with the highest negative Theil-Sen slope, rows 6 through 10 are the five with the lowest slopes and rows 11 to 15 are the five pixels with the highest positive slope.

Pixels 1 (highest negative MODIS iNDVI trend), 8 (no change) and 15 (highest positive MODIS iNDVI trend) are given as an example of LCC in Figure 4.

Figure 4 gives an example of LCC in three of the pixels with the most extreme trends of MODIS iNDVI. Pixel 1 (2002, top left, and 2009, bottom left) is the pixel with the highest negative trend ($\mu_2 = -0.126$). The Quick Bird images of the pixel's area show how the landscape has changed between these years. In 2002 the pixel is a peri-urban area, an open landscape with small-scale agricultural plots, some smaller trees, which seem to be anthropogenically placed, and larger, natural trees, which seem to be left by farmers to grow. In 2009, the pixel is part of a new urban area undergoing development. Most of it is covered by new, legal brick hoses, and some parcels seem to be under construction.

The open spaces, which still exist in the area, are used as small-scale urban agricultural plots, usually for growing supplementary grain (millet, maize) or peanuts (observation during field work).

Pixel 8 (2002, top center, and 2009, bottom center) is located in an area, which, according to the municipal plan, is a green space or a space for sport and leisure [70]. Thus, it is not planned for construction. It seems that LCCs between 2002 and 2009 in this area are minimal. Most of it is an open landscape covered sporadically with low vegetation and small ponds, which are the result of soil erosion, which is usually the result of extraction of mud for mud-bricks.

On the right, pixel 15 covers the area that showed the highest positive MODIS iNDVI trend between 2002 (top) and 2009 (bottom). This area can be divided into two distinctive landscapes: on the northern half, development and construction of a new neighborhood is taking place, while the southern half is kept as a construction-free green space [70] dominated by natural vegetation, as opposed to pixel 1, where unconstructed areas are dominated by small scale agriculture.

6. Discussion

Our results for the association between MODIS iNDVI trends for 2002–2009 and LCC, using the μ_2 monotonicity coefficient (Table 3), indicate a strong, positive, yet not perfect, association between the Theil-Sen trend analysis and changes in LCC. The non-perfect association is most probably a combination of the influence of some of the other parameters that have changed in the study area between 2002 and 2009, influencing the MODIS iNDVI signal. These parameters can, for example, be the influence of low story, seasonal vegetation, which was not monitored in the current investigation, or the change in man-made elements in the urban and peri-urban landscape, which replace the natural or agricultural soil and vegetation.

In contrast to the strong association between trends of MODIS iNDVI and changes in tree cover vegetation in the respective pixels, association between the three types of man-made LCC is somewhat of a more mixed character. The man-made constructions in the landscape seem to have a two-fold influence on the MODIS iNDVI signal. The first influence is the direct effect on the MODIS iNDVI signal when replacing the natural or agricultural vegetation mosaic with man-made construction. The second influence is the indirect relation to different types of urban development and different stages in the urban development.

The association coefficient between the trend in MODIS iNDVI and mud-brick houses in the un-parceled areas is very low ($\mu_2 = -0.145$), due to the mixed influences of this form of development on the MODIS iNDVI signal. First of all, most of the areas in which this type of settlement are present in 2009 were also present in 2002; thus, the change in these areas between these years is minimal and mostly internal. The second reason for the low association between MODIS iNDVI and mud-brick houses can be related to the type of development attached to these areas. In many cases, these mud-brick houses are built as a temporary, illegal solution to the housing problem or as a land capture activity as a result of land speculations [59,62]. The temporary character of this type of settlement leads to minimal input into areal development, thus to minimal changes in the landscape besides the actual construction of a mud hut [58].

The second man-made element that was monitored relative to its land cover change was sheds in parceled areas. The link between the trend of MODIS iNDVI and the change in the concentration of sheds show a high negative association ($\mu_2 = -0.798$). This result might seem to be surprising, as the direct influence of these sheds on the MODIS iNDVI signal is expected to be of minor importance, due to their small size and their low density relative to the similarly sized, but much denser, mud-brick huts in the non-parceled areas. Yet, what the high negative μ_2 implies is the indirect association between the Theil-Sen trend and changes in the amount of sheds in the parceled areas. These sheds are, in many cases, the first man-made construction to appear in a parcel, which is being prepared for a larger, permanent construction. Thus, the likely reason for the negative association might be that these sheds are related to the removal of vegetation before the actual building process.

The association between the Theil-Sen trend and changes in permanent brick houses is weak and negative ($\mu_2 = -0.467$). Similarly to the two cases discussed above, this is also a combination of direct and indirect influences. The direct effect of permanent brick houses on the MODIS iNDVI signal is somewhat higher than the direct influences of sheds and mud-huts. This is due to the density and size of permanent houses relative to mud-brick houses and sheds.

The indirect effect of brick-houses on the MODIS iNDVI signal is also complex. As brick-houses are considered as permanent accommodation, trees and bushes are planted and grasses are sown. Moreover, if the area is not yet fully built, then small scale agricultural activity is taking place in free parcels. Another factor that influences the MODIS iNDVI signal is the relatively high income of the inhabitants and infrastructure, which increase the availability of water in the more affluent neighborhoods of the city (pixels 6, 11, 12, 14 and 15). These allow planting and nursing of plants, which directly leads to a relatively fast increase in the MODIS iNDVI signal. Last, but not least, is the factor of time in the indirect influence on the MODIS iNDVI signal. The period since the beginning of development of blocks and neighborhoods seems to be related to the trend of MODIS iNDVI, due to the different stages in the development process. Development of parceled areas would usually begin with the removal of all the existing vegetation. Next, as houses are built, vegetation is planted as well. In the early stages, this is a mix of ornamental vegetation and some fruit trees next to the houses and some small-scale farming in free parcels, but later on, as more houses are built, the small fields are replaced by new houses and new vegetation. With time, this new urban vegetation is being established and covers larger areas, thus influencing positively on the MODIS iNDVI signal.

In this context, it is worth noticing the location of the different pixels and the grouping of pixels with a similar Theil-Sen slope in patches (Figure 2), relative to the different urban patches. Pixels with decreasing MODIS iNDVI (pixels 1–5) are concentrated in the southwest of the study area where peri-urban agriculture was replaced by new urban areas between 2002 and 2009. Pixels with increasing iNDVI (pixels 11, 12, 14 and 15) are clumped around the northeast of the study area in what is one of the most affluent neighborhoods of the city, Ouaga 2000, or as in the case of pixel 13, just south of Ouaga 2000. Pixels with no significant change in MODIS iNDVI (pixels 6–10) engulf the two other types of patches. Pixels 7–10 are all located in areas that were under development already in 2002, but of a lower economic status than Ouaga 2000. Pixel 6, on the other hand, is on the southern part of Ouaga 2000, and the area covered by it is only in its early stages of development in 2009.

What is indicated by the discussion above is that urban sprawl and development does not necessarily mean reduced vegetation relative to the peri-urban and the surrounding ecosystem. Moreover, it indicates that, due to the dynamic character of areas undergoing urban development, the temporal and spatial aspects have a significant influence on the urban vegetation.

It is clear that the results of any temporal analysis are highly dependent on the start and end points of the time series in a highly variable and fast changing urban environment this is accentuated. As it has been shown, different areas are at different points in time at different stages in the transformation process from a peri-urban vegetation mosaic to a fully developed urban neighborhood. Hence, any time series analysis neglecting to accommodate specific local conditions inherently runs the risk of basing conclusions on extreme starting points and, as such, pre-describe a certain outcome.

We have attempted to establish an understanding between long-term trends in vegetation productivity and changes in the physical environment in peri-urban Ouagadougou. It has been shown that such a relationship can be established, but only when the underlying model of explanation is based in detailed, in-depth understanding of local circumstances. Previously, we argued along the lines of Flyvbjerg's [52] critical case, that such a model of understanding then can be established also for other peri-urban environments undergoing rapid changes of the sub-continent. Indeed, we will argue that the use of detailed local knowledge applied in this study is paramount to obtaining any viable results also in other parts of West Africa, and it is likely that the models of explanations of trends in vegetation productivity only can be explained if the explanations are built on the same level of local in-depth understanding of local activities and structures.

7. Conclusion

In this study, we have calculated trends in vegetation productivity, as obtained by analyses of long-term trends of MODIS data in detail for the city of Ouagadougou. An interesting pattern of decreasing vegetation productivity is found in the peri-urban areas, whereas the center is characterized by a general greening. A detailed case study was conducted to investigate if it is possible to link changes in the observed long-term trends in vegetation productivity to physical changes in a peri-urban setting in West Africa. We have demonstrated that correspondence between trends of MODIS iNDVI and LCC overall agrees well, yet, in some cases, LCCs correspond poorly to MODIS iNDVI trends, and in other cases, it shows the opposite from what is theoretically expected. In most cases, however, these disagreements can be explained by a detailed spatiotemporal analysis of LCC within the specific pixel relative to what is known about the character of each pixel. In the case of the current study, disagreements found between satellite derived vegetation trend information and detailed knowledge on changes in LCC are directly related to temporal coverage of the MODIS time series, not necessarily covering all stages of the urban development (MODIS being launched in 2000).

Acknowledgments

The authors would like to thank the financial support provided by the Danish development cooperation (Danida) through the West African Network for Studies of Environmental Change (WANSEC) project, DFC file number 21-08-KU, and through the Danida travel fund.

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