Remote Sens. **2014**, *6*, 658-676; doi:10.3390/rs6010658

OPEN ACCESS

remote sensing

ISSN 2072-4292

www.mdpi.com/journal/remotesensing

Article

Land Cover Change Monitoring Using Landsat MSS/TM Satellite Image Data over West Africa between 1975 and 1990

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Received: 28 October 2013; in revised form: 17 December 2013 / Accepted: 18 December 2013 / Published: 7 January 2014

Abstract: Monitoring land cover changes from the 1970s in West Africa is important for assessing the dynamics between land cover types and understanding the anthropogenic impact during this period. Given the lack of historical land cover maps over such a large area, Landsat data is a reliable and consistent source of information on land cover dynamics from the 1970s. This study examines land cover changes occurring between 1975 and 1990 in West Africa using a systematic sample of satellite imagery. The primary data sources for the land cover classification were Landsat Multispectral Scanner (MSS) for 1975 and Landsat Thematic Mapper (TM) for the 1990 period. Dedicated selection of the appropriate image data for land cover change monitoring was performed for the year 1975. Based on this selected dataset, the land cover analysis is based on a systematic sample of 220 suitable Landsat image extracts (out of 246) of 20 km × 20 km at each one degree latitude/longitude intersection. Object-based classification, originally dedicated for Landsat TM land cover change monitoring and adapted for MSS, was used to produce land cover change information for four different land cover classes: dense tree cover, tree cover mosaic, other wooded land and other vegetation cover. Our results reveal that in 1975 about 6% of West Africa was covered by dense tree cover complemented with 12% of tree cover mosaic. Almost half of the area was covered by other wooded land and the remaining 32% was represented by other vegetation cover. Over the 1975–1990 period, the net annual change rate of dense tree cover was estimated at −0.95%, at −0.37% for the other wooded land and very low for tree cover mosaic (−0.05%). On the other side, other vegetation cover increased annually by 0.70%, most probably due to the expansion of agricultural areas. This study demonstrates the potential of Landsat MSS and TM data for large scale land cover change assessment in West Africa and highlights the importance of consistent and systematic data processing methods with targeted image acquisition procedures for long-term monitoring.

Keywords: West Africa; land cover change; Landsat; sampling; change detection

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1. Introduction

Over the last decades, West Africa experienced major disturbances on its land surface caused both by natural processes, as well as human activities. Each of these processes influenced requirements for land use with subsequent effects on natural vegetation cover, biodiversity, socio-economic stability and food security [1]. In particular, the anthropogenic impact—mainly in the form of agriculture expansion—driven by a strong increase in population has become an issue of major concern and even conflict among the rural and pastoral population in the West Africa region [2]. To capture the potential range of impacts of these dynamics in land cover requires therefore accurate monitoring of land cover changes over time.

Extensive data about forest cover and agriculture extent are available through the Food and Agriculture Organization (FAO) [3,4]. However, uncertainty around these estimates is relatively high [5]. Remote sensing images provide data about land cover and its changes over large and inaccessible areas repetitively for a period of more than 40 years. For applications at the global or continental levels, coarse spatial resolution images with pixel size from 250 m to 1 km and more, large swath width and high revisiting period, such as Advanced Very High Resolution Radiometer (AVHHR), Satellite Pour l'Observation de la Terre (SPOT), Medium Resolution Image Spectrometer (MERIS), and Moderate Imaging Spectrometer (MODIS) have been considered as the only sources of image data, regularly delivering information about large areas. Although covering large spatial extents, *i.e.*, whole continent (continental) or even the world (global scale), their coarse resolutions mainly focused on the detection of broad scale land cover change patterns, hence failing to monitor changes like deforestation and land degradation which usually occurs on a smaller scale [6]. To overcome these limitations and acquire more detailed information of the Earth's land surface, medium resolution satellite images (*i.e.*, 30–80 m pixel size) such as Landsat TM and Landsat MSS, with greater spatial accuracy but lower revisit cycle, have been used for mapping and monitoring land cover and its changes [6–9]. Full cover surveys—also called "wall-to-wall" mapping—over larger areas using Landsat imagery would require a huge amount of satellite data and resources for processing. An alternative technique adopted in land resource inventories is provided by statistical sampling which offer a time-efficient approach [10]. Stratified sampling of medium resolution images has been applied to monitor land cover changes at different scales: on the pan-tropical level [11], continental level [1] and even the national level [9].

Several studies were conducted especially over West Africa using satellite images and adopting land cover change detection techniques. While the analysed time period is extended to 50 years, the covered area is usually limited to the national (up to 1 million km^2) [9] or sub-national level (often based on single scene) [12–15]. However, despite the high diversity and dynamic of land cover in West Africa [2,16], this region received little attention and has been poorly mapped at the sub-continental scale. An extensive Landsat dataset combined with a robust image analysis technique able to accurately identify land cover changes over the entire West Africa is therefore highly needed.

In the early 1990s, the Joint Research Centre (JRC) of the European Commission established forest and land cover monitoring systems based on Landsat sample sites over the tropics within the Tropical Ecosystem Environment Observation by Satellite (TREES) project [17,18]. A regular sampling of Landsat image extracts based on a rectangular grid has been developed and applied by the JRC in collaboration with the Food and Agriculture Organization's (FAO) Remote Sensing Survey (RSS) of the Forest Resources Assessment (FRA) [19,20]. The current TREES-3 project is assessing deforestation rates for the period 1990–2000–2010 [21]. However, the latter study does not analyse the earliest records of satellite images as provided by the first Landsat satellite with the Multispectral Scanner (MSS) launched in 1972. Additionally, in many cases, the Landsat MSS imagery of the early 1970s is the only reliable source of information on land cover dynamics in that early time period. Also, in many countries of West Africa, more significant changes in land cover took place in the 1970s, and even before, due to specific development policies related to land practices, especially in forest exploitation [2].

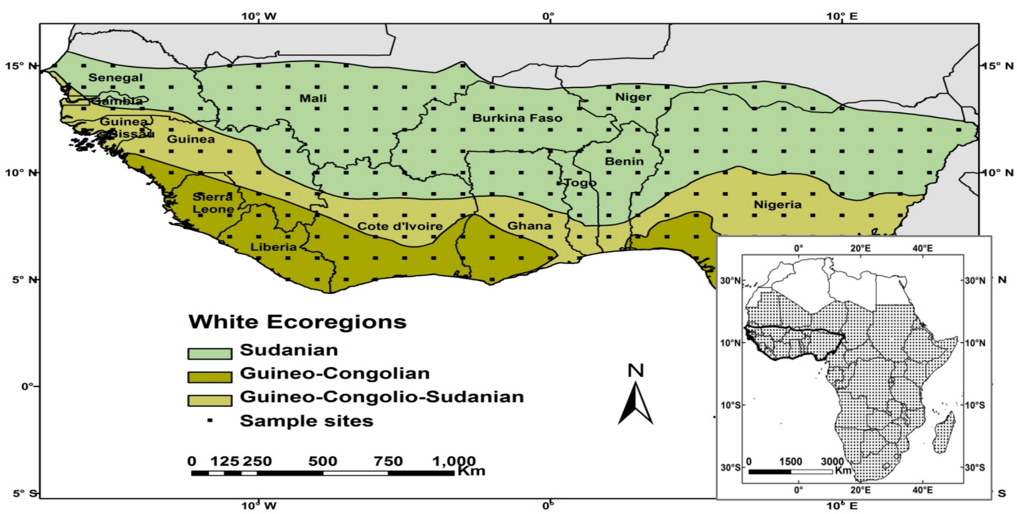
This study analyses Landsat MSS data from the early 1970s for monitoring land cover changes over the period 1975–1990 in West Africa. The analysis is based on a systematic sampling of image extracts of 20 km × 20 km at each one degree latitude/longitude intersect. A first preliminary assessment of MSS image suitability is performed over the whole of sub-Saharan Africa for the year 1975. The satellite image dataset is evaluated in respect to its overall availability and its spatial and radiometric compatibility with Landsat Thematic Mapper (TM) images for the reference year 1990. This preliminary assessment is followed by a detailed land cover change analysis over the West Africa, where the 1975 Landsat MSS image extracts are classified and compared to 1990 land cover maps to provide figures of land cover changes for the period 1975–1990. The 1990 land cover information is derived from a previous study [21]. Finally, main trends of land cover changes are described and analysed within West Africa.

2. Study Area

Covering humid to semi-arid parts of West Africa, the study area is characterized by a diversity of ecological regions from south to north. Humid tropical forest is occurring near the southern coast while semi-arid grassland and shrubland is more typical for regions towards the north. The area covered in this study is restricted to the Sudanian, Guineo-Congolio-Sudanian and Guineo-Congolian ecoregions as defined by White [22] and regionally limited to West Africa by the eastern border of Nigeria

(Figure 1). Ecoregions are ecologically similar areas, assuming that land cover classes are also relatively similar within each eco-zone (despite that land cover change magnitudes can be very different). The Guineo-Congolian as the most southern ecoregion extends along the coast from Guinea to Ghana. The dry "Dahomey" gap at the south of Togo and Benin separates a smaller part of the area at the southern coast of Nigeria. Its vegetation cover is characterized by remains of rainforests, secondary grassland and areas of forest regrowth. Towards the north, as a narrow band stretching from Senegal in the west to central Nigeria in the east extends the Guineo-Congolio-Sudanian ecoregion. The area is mostly covered with secondary grasslands, secondary wooded grasslands, and swamp/riparian forests near the western coast. The largest, the Sudanian ecoregion, comprises the northern part of the study area with its limit extending from the northern coast of Senegal through Mali, Burkina Faso and Niger towards northern Nigeria. The natural vegetation is here mostly presented by various types of grasslands and woodlands. In all of the ecoregions within the study area, cultivation takes place in different intensities, but is mostly represented in the Sudanian ecoregion. Tree plantations such as teak and fruit trees are replacing croplands moving towards the more humid southern ecoregions.

Figure 1. Study area and sampling scheme covering three ecoregions in West Africa.



3. Materials and Methods

3.1. Data Sources and Preparation

3.1.1. Satellite Image Data Sources

The imagery data source for the 1975 reference year is the Landsat MSS data acquired between 1972 and 1980. The MSS sensor on-board Landsat 1 and 2 satellites acquired images through four spectral bands with 80 m spatial resolution. The revisiting period for each satellite is 18 days. For the 1990 reference year, Landsat TM images acquired by Landsat 4 and 5 satellites between 1985 and 1995 have been used. TM images are acquired in six spectral bands with a spatial resolution of 30 m (and a thermal band at 120 m which has not been used in this study) and a revisiting period of 16 days [23,24].

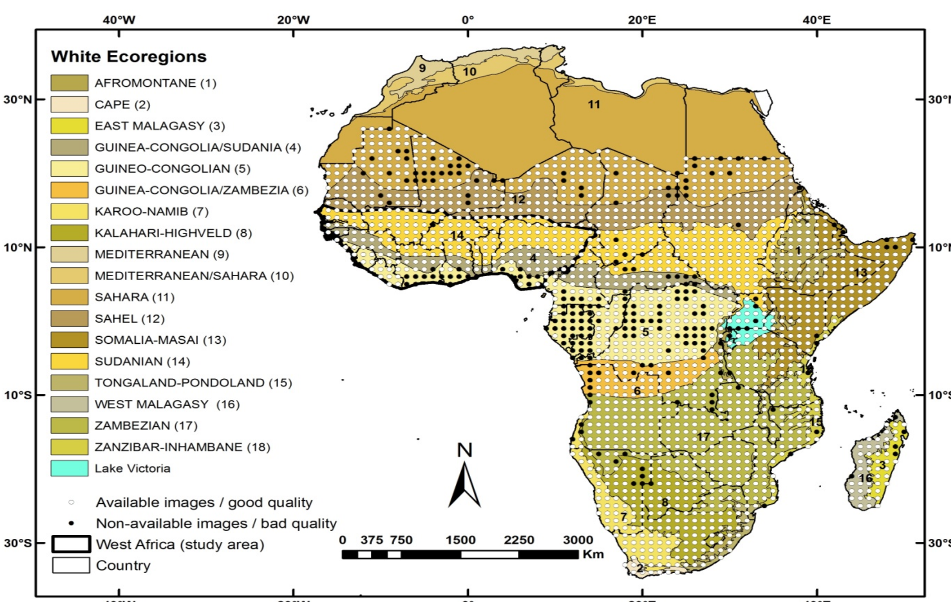
The most remarkable differences between Landsat MSS and TM sensors are recognized in spatial resolution and spectral properties.

The primary data source for this study was the National Aeronautics and Space Administration's Global Land Survey (GLS) image database, which was supplemented with image data from the United States Geological Survey (USGS) Landsat archives. The GLS database is free of charge and also provides time/cost effective image data in terms of pre-processing since the images are orthorectified. The database designed in our study specifically for the image pre-processing steps is filled with the most suitable data according to the following criteria: minimal cloud cover across the scene, maximum data quality (no missing scan lines, pixel drop outs, saturated or missing bands) and acquisition date matched with peak greenness [25]. Image data archive from the USGS available online contains several thousand scenes from Landsat MSS, TM and ETM sensors, which can be accessed and downloaded through the USGS Global Visualization Viewer (GLOVIS) interface. The advantage of this application is that it allows data searching in specific areas (*i.e.*, polygons), which can be defined by the user. In our case, the sampling sites have been overlaid on top of the quick look images of each scene and the image quality has been preliminarily examined prior downloading [26].

3.1.2. Sampling Strategy

Although some may argue that image analysis at the full spatial extent (wall-to-wall) for any area on the land surface may be the best approach, it may not always be the optimal solution. Even with free data acquisition, significant requirements for storage and analysis are needed, especially if the study area is large. Moreover, it would be difficult to maintain consistent image quality across diverse geographic regions. As an example, the inconsistent cloud coverage can be mentioned which can lead to difficulties in estimation of the resulting statistics [26].

Figure 2. Availability of good quality Landsat MSS images for the 1975 reference year over sub-Saharan Africa (including our study area over West Africa) overlaid on White's ecoregions [22].



In this study, the sample based approach considers the analysis of image subsets extracted over 20 km × 20 km at each degree latitude and longitude intersects for the reference years 1975 and 1990. The whole sub-Saharan Africa is covered by 2,045 sample sites as shown on the small map of Figure 1 and in Figure 2. For covering an area with diverse biomes and to perform an assessment on a limited area with sufficient good quality image availability, the selected processing steps and land cover change assessment in this study were focused on the area covering West Africa. The selection of this restricted area, containing 243 sample sites (Figure 1), was based on the results of data availability and suitability assessment of all Landsat MSS scenes covering sub-Saharan Africa. Selection of this area was determined by the high diversity of ecological regions and total number of available good quality sample images, which is crucial for further statistical estimates of land cover dynamics.

3.1.3. Dedicated Image Selection for Land Cover Change Assessment in West Africa

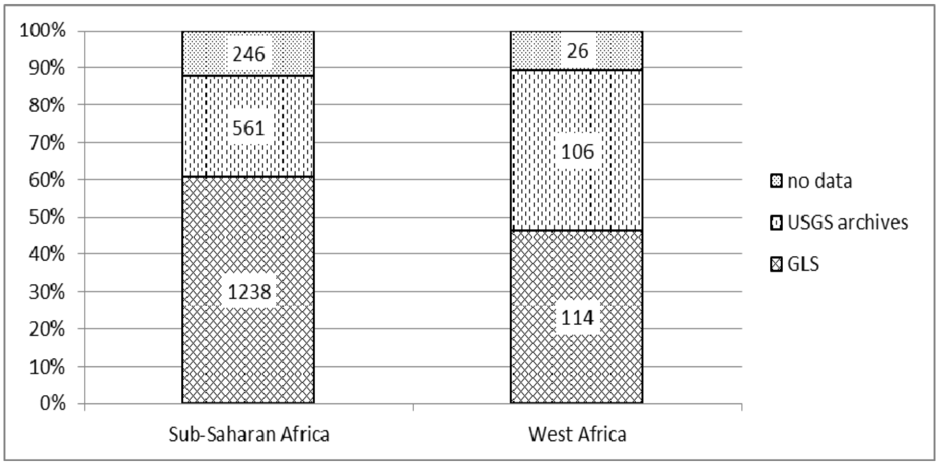
In order to cover the sample sites for the reference year 1975, subsets of 20 km × 20 km size of Landsat MSS were extracted and processed. To find satisfactory images in terms of cloud cover and seasonal/radiometric characteristics, all available Landsat MSS scenes were visually screened for the reference year 1975. In addition, available Landsat TM scenes were considered for the reference year 1990.

The best images available were evaluated for each sample site with the Graphic User Interface (GUI) developed by the JRC [27]. The image selection was following this hierarchy of data source: first choice was GLS image archive; when GLS data was of low quality, cloud covered or even missing, USGS archives were investigated to find alternative images. In case of no suitable images, the sample was labelled with "No Data" status. Each image extract was assessed according to three parameters: (1) quality; (2) usage; and (3) priority. "Image quality" depends on the presence of clouds, haze, linear errors and bad geo-location. "Usage" describes the coverage of the sampling area by the Landsat scene. "Priority" explains the suitability of available Landsat scene for the selected sample site related to image acquisition date and land-cover monitoring purpose. The scenes with the highest score in the above mentioned criteria were selected for further analysis. The dedicated image evaluation tool also allows the assessment of the geo-location (relative geo-location between two image tiles). Significant differences in image location (shifting) were expected at image samples without GLS orthorectification.

The Landsat MSS image data availability was evaluated for the entire sub-Saharan Africa (Figure 2). Good quality images were selected for multi-date image analysis with TM images for the 1990 reference year. The obtained figures were used to evaluate general patterns and distribution of image data in larger areas, and for examining the potential impact of data availability on the results of land cover change assessment. While previous studies were focused on general image availability assessment over large areas [28–30], this study provides a dedicated image selection to source suitable images for land cover change assessment.

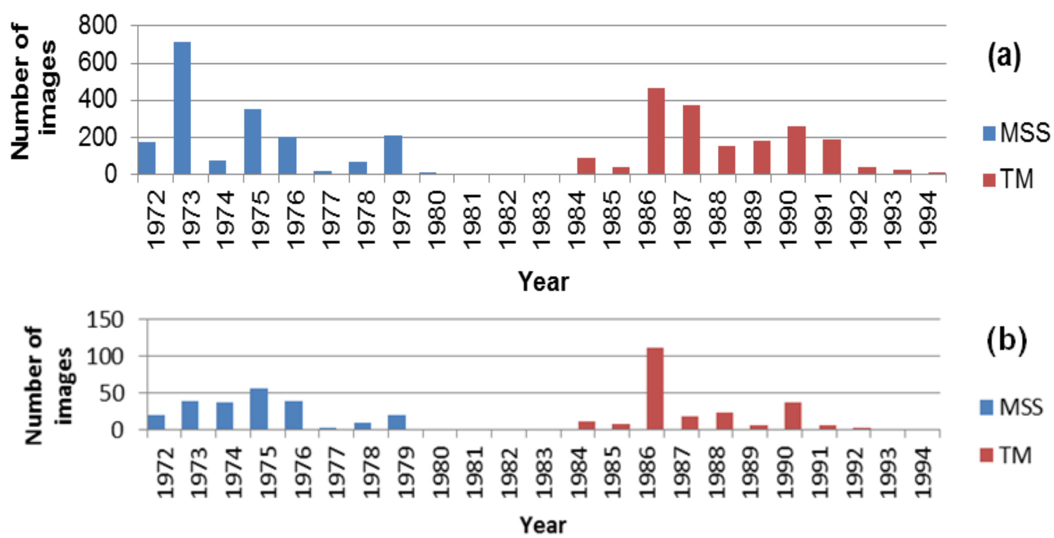
Over sub-Saharan Africa (our extended study area for data suitability assessment), Landsat MSS data quality from the GLS archive for all 2,045 confluence points of our sampling scheme results in 1,238 image extracts (out of 685 different scenes) of good quality (Figure 3). In addition to this dataset, 561 image extracts (out of 266 scenes) were downloaded from USGS archives (Figure 3). For the remaining 246 image extracts, there were no good quality images found. In total, 951 Landsat MSS scenes have been used as a data source from which the 1,799 image extracts in sub-Saharan Africa were extracted.

Figure 3. Repartition of Landsat MSS image extracts availability depending on the data source comparing sub-Saharan and West Africa (figures correspond to the number of concerned sample sites).



Over West Africa (our study area), 220 MSS image extracts (out of 243 sample sites) were suitable for the analysis. From this dataset, 114 good quality images extracts were provided by the GLS archives. From the USGS archives, good quality images were extracted over 106 sample units. The 220 MSS image extracts were derived from 153 Landsat MSS scenes. Missing data were not distributed randomly, but concentrated in the humid areas located at the southern coast, known to be affected by high cloud coverage (Figure 3).

Figure 4. Comparison of the acquisition years of the best candidates selected for Landsat Multispectral Scanner (MSS) (around 1975) and Thematic Mapper (TM) images (around 1990) for (**a**) the whole sub-Saharan Africa (n = 1,799), and only for (**b**) West Africa (n = 220).

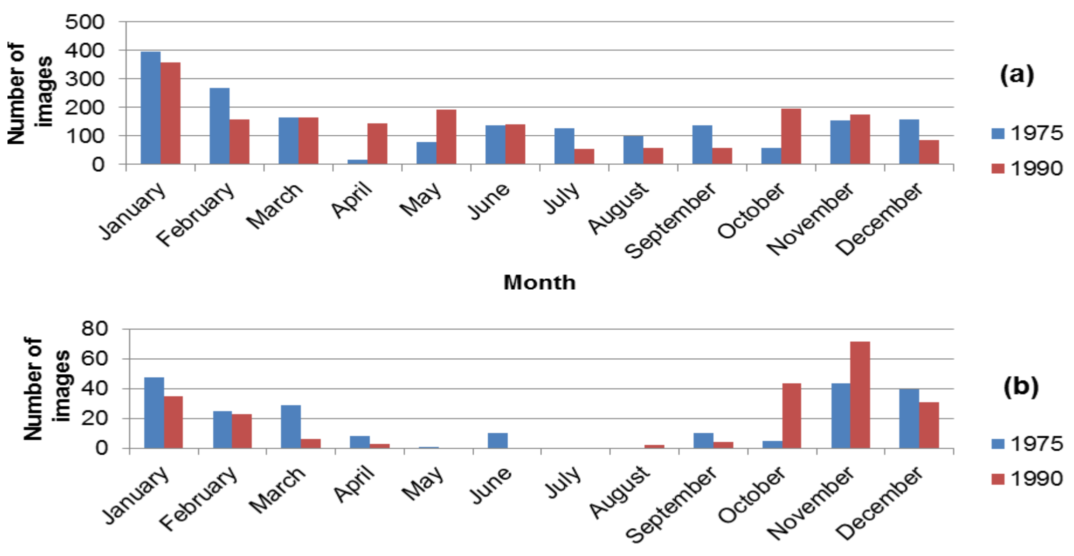


In the data selection process, we tried to select images acquired as close as possible to the reference years: 1975 for Landsat MSS and 1990 for Landsat TM. Figure 4 provides an overview of acquisition dates of the selected image samples comparing the whole sub-Saharan Africa and West Africa (our study area).

In order to avoid erroneous interpretation of land cover changes due to seasonality, image pairs (Landsat MSS for 1975 and TM for 1990) were selected to correspond as close as possible to the same vegetation phenology stage. Images should then be acquired at the same acquisition period for the two reference years (1975 and 1990). For this purpose, the differences in julian dates of acquisition were computed for each site regardless of the year. The average acquisition dates difference for the two selected images of 1975 and 1990 reference years was 43 days over the whole sub-Saharan Africa, while accounting for 50 days in West Africa. Figure 5 shows the number of images for each month of both reference years in (a) sub-Saharan Africa and (b) West Africa.

According to this Landsat data availability evaluation, the selected image dataset was considered suitable for the 1975–1990 land cover change assessment since the risk of combining images from different seasons is minimized, and the data availability of West Africa is representative of the situation for the whole sub-Saharan Africa.

Figure 5. Comparison of acquisition months of the best candidates selected for Landsat MSS (around 1975) and TM images (around 1990) for (**a**) the whole sub-Saharan Africa (n = 1,799), and only for (**b**) West Africa (n = 220).



3.2. Methodology

3.2.1. Pre-Processing

Based on the selected MSS dataset over West Africa, a series of pre-processing has to be performed prior to the classification and change detection procedures. These steps include (1) co-registration and (2) radiometric calibration. In fact, change detection requires that image extracts pairs for 1975 and 1990 have to be as comparable as possible in terms of geometric and radiometric qualities.

As non-GLS MSS data could have a shift in X and Y up to 1,500 m when compared with the 1990 GLS TM corresponding data, a co-registration is thus compulsory prior to any other processing.

In order to achieve accurate spatial co-registration between image pairs (acquired respectively in 1975 and 1990), a relative image to image location was performed over West Africa. The 1990 image extract was considered as master and the 1975 image extract was matched by linear shift on the master image. In case of large displacement between image pairs, a new image sample of 20 km × 20 km was extracted from the original Landsat MSS scene.

In order to reduce differences caused by changing illumination conditions and instrument errors, radiometric calibration has to be performed on images [23]. Calibration is first achieved by converting raw Digital Numbers (DN) into at-sensor spectral radiance, which is subsequently converted into top-of-atmosphere reflectance. Additionally, techniques to reduce the noise introduced by the variation in atmospheric conditions were applied [27]. A recent study [24] explains that new radiometric properties were adapted to the Landsat MSS data on an absolute radiometric scale based on the Landsat-5 TM sensor. This means that for Landsat MSS scenes used in this study and downloaded after 1 April 2011, new rules for calibration procedures were applied.

3.2.2. Land Cover Classification and Change Detection Procedures

The 1975–1990 land cover monitoring over West Africa was achieved by integrating several data: (1) the 1975 pre-processed MSS images extracts, (2) the 1990 pre-processed TM image extracts and (3) the existing 1990 land-cover classification. Whereas the first dataset has been produced in this study, the two following datasets were provided by a previous work [31].

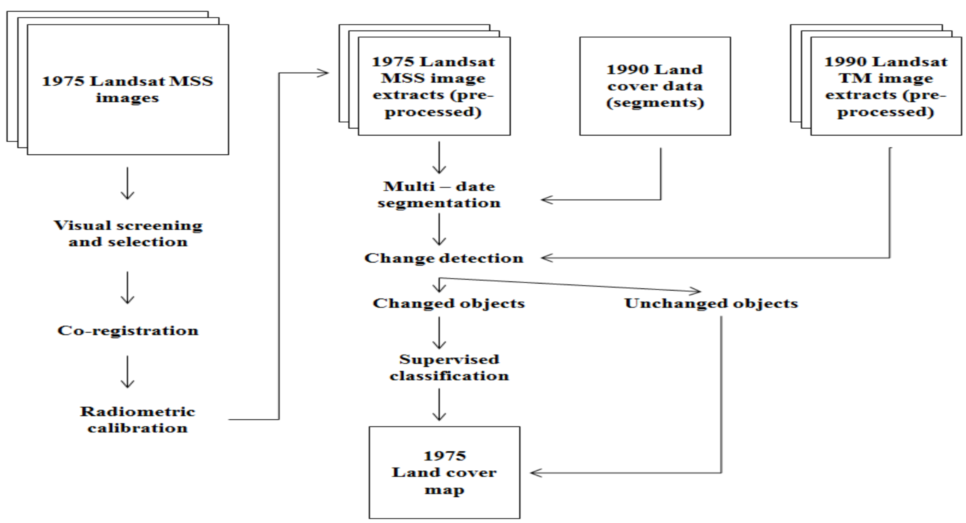
The 1990 land cover maps have been produced using the 1990 pre-processed TM image extracts and an object based classification approach, originally dedicated for the 1990–2000 land-cover monitoring exercise [32]. Image segmentation, an important step in the processing chain, was performed on all image extracts using the eCognition tool. Objects (or image segments) are created by grouping pixels which are spectrally similar and spatially adjacent. A multi-date segmentation was applied which means the two image extracts were stacked together. As the segmentation tool (also called multi-resolution) can combine images with various spatial resolutions for the segments delineation, there is no need for preliminary image resampling. Multi-date objects were then classified by supervised classification using a spectral library and then change detection was performed by post-classification comparison. The final land-cover maps were then validated by regional and national experts. The original processing chain, still only based on Landsat TM/ETM data, has been adapted for the 2000–2010 exercise in order to exploit the already validated 2000 land-cover maps and has been automated using a Tasseled Caps change detection step [33].

In order to exploit multi-sensor images (SPOT, DMC/Deimos and even MSS data), the processing chain has again been adapted to be more flexible to spectral content differences and by using the most appropriate object features for the supervised classification [34]. Derived from this last approach, our 1975–1990 processing chain is working in three steps: (1) multi-date segmentation; (2) change detection; and (3) 1975 land cover classification (Figure 6). Based on the 1990 object-based classification, the multi-date segmentation is using stacked 1975 and 1990 image extracts for defining new objects with a Minimum Mapping Unit of 5 ha. The next step is the change detection which separates multi-date objects between “changed” and “unchanged” using thresholding in Euclidean distance derived from red, NIR and SWIR bands (respectively, Landsat TM channels 3, 4 and 5).

As no SWIR band is available in MSS data, the closest band in terms of spectral range was used. The selected channels were MSS bands 2, 3 and 4. Finally, the 1975 supervised classification is performed combining two different parallel ways. The 1990 land-cover information of "unchanged" objects (as defined by the change detection step) is copied onto the 1975 land-cover map. For the "changed" objects, a supervised classification is performed using the spectral signature defined by "unchanged" objects (considered as training sets). It is important to note that the spectral signature is recomputed for each sample site and the supervised classification is then adapted for each 1975 image extract. The final result is an object-based thematic map with the predefined land cover classes for the years 1975 and 1990. Land cover classes were established based on the following criteria:

- Tree Cover (≥70% of tree cover);
- Tree Cover Mosaic (70%–30% of tree cover);
- Other Wooded Land (≥70% of other wooded land);
- Other Vegetation Cover (including areas of bare ground);
- Inland Water (≥50% of water and previous criteria do not apply).

Figure 6. Scheme of TREES data processing chain with adaptation for Landsat MSS images.



Object labels obtained from the automatic classification were visually checked and corrected when necessary [32]. The objective of this validation step using the dedicated TREES validation tool is to eliminate misclassification and to provide better consistency over the whole area. The 1990 dataset has followed an evaluation of regional experts and an independent validation procedure, in addition to an internal rigorous quality control [31]. Accuracy assessment was carried out for the land cover maps of the period 1990–2000 [31] where 338 random 20 km × 20 km sample sites were selected over sub-Saharan Africa. Within these primary units, five points were systematically selected and reinterpreted by an independent expert. Overall agreement between classification results and the re-interpretations (considered as reference information) reaches 94% for the tree-cover classes and 87% for the six land-cover classes.

As the 1975 classification was derived from the 1990 independently validated data, the validation procedure for 1975 did not undergo a time-consuming independent validation procedure and was limited to an internal quality control and consistency check. Following the previous work and experience in image classification within the TREES project, the validation was conducted at a reduced area of the sample sites (10 km × 10 km) [31]. The close correspondence between the two estimates—20 km × 20 km and the central 10 km × 10 km portion of the image extracts—enables us to validate the classification with significant savings in time and resources.

3.2.3. Derivation of Land Cover Change Statistics

Based on the area of the classified objects (derived from the segmentation and classification process), land cover statistics were computed for all 220 sample units at reduced area (10 km × 10 km) and separated by land cover class. Furthermore, changes in land cover for entire West Africa were derived by post-classification comparison of 1975 and 1990 land-cover maps. This analysis provides the figures of land cover area distribution within each sample site and the estimates of change between the two reference years. From this information, the results of land cover changes and the final matrix indicating the changes between each of the defined land cover classes were obtained. Additionally, during the statistics extraction, data normalization procedures were applied: (1) a linear adjustment from the real acquisition date to the target reference date (1975 and 1990) and (2) an application of weight based on latitude for compensating the earth curvature. These procedures are explained in more detail in Eva *et al.*, 2012 [35].

4. Results

4.1. Land Cover Status in 1975

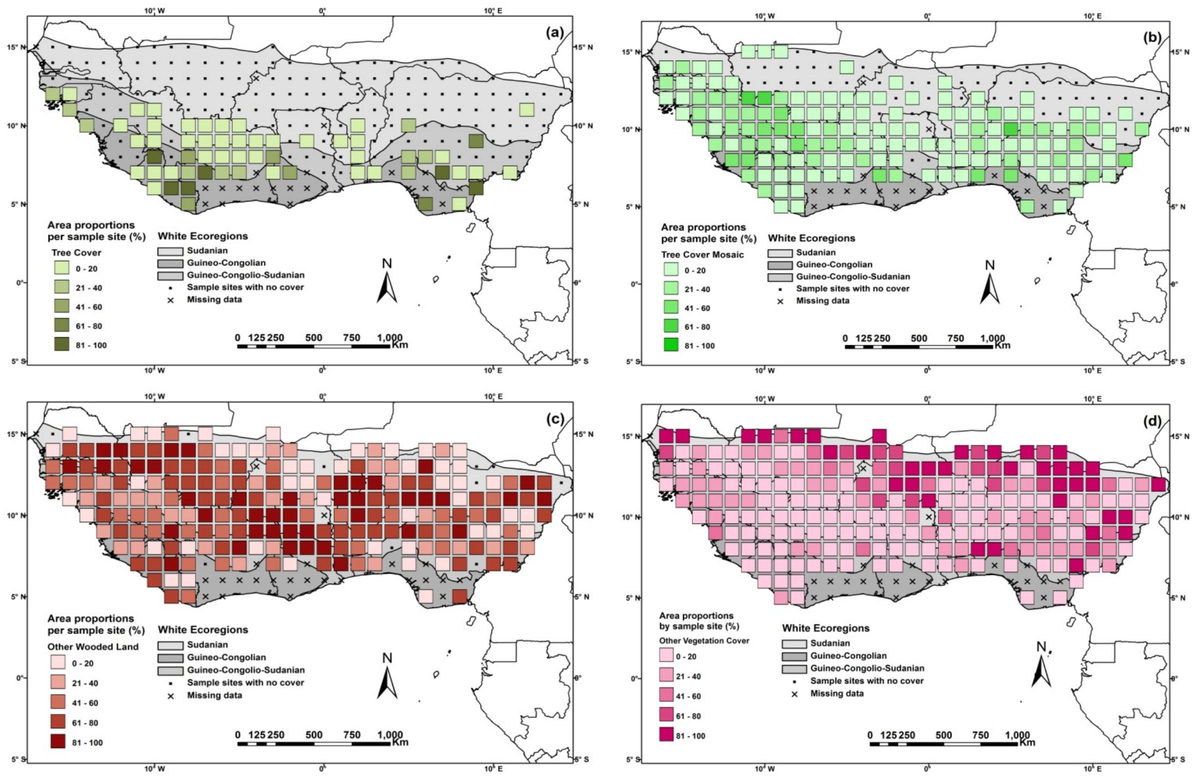
The results of the object-based image classification process at each sample site provide an overall estimate of land cover distribution in West Africa for the year 1975. From the total area of 2,899 million km^2, around 18% was covered with trees (Table 1). From this extent, approximately one third corresponded to areas with dense tree cover; the remaining areas were tree cover mosaic. Almost half of West Africa was covered with other wooded land which also holds the highest proportion from all land cover classes. Other vegetation covers represented 32% of the study area.

Areas covered with trees (Figure 7) were mostly in the south and west of the region (Guineo-Congolio-Sudanian, Guineo-Congolian ecoregion) mainly outlining the humid areas. Other vegetation cover was more frequent in the north (Sudanian ecoregion). Other wooded land is most equally distributed over the study area.

Table 1. Land cover transitions from 1975 to 1990 over West Africa (areas in thousands of km^2, and in bracket, the proportion of each value compared to the total area).

1975/1990	Tree Cover	Tree Cover Mosaic	Other Wooded Land	Other Vegetation Cover	Total 1,975
Tree Cover	155	14	6	5	180 (6.2%)
Tree Cover Mosaic	1	317	14	10	342 (11.8%)
Other Wooded Land	0	6	1,303	129	1,438 (49.6%)
Other Vegetation Cover	0	2	37	900	939 (32.4%)
Total 1,990	156 (5.4%)	339 (11.7%)	1,360 (46.9%)	1,044 (36%)	2,899 (100.0%)

Figure 7. Area proportions of land cover classes for each sample site (*n* = 220) for the year 1975 (**a**) Tree cover (**b**) Tree cover mosaic (**c**) Other wooded land (**d**) Other vegetation cover.



4.2. Land Cover Dynamics between 1975 and 1990

The various land cover change trajectories occurring during the period 1975–1990 are summarized in Table 1. For all classes, areas affected by land cover changes account for about 8% of the total area (224,000 km^2) whereas unchanged areas constituted the remaining 92%. For 1975 and 1990 years, the order of importance of each class remains the same, with reducing proportions for other wooded land, other vegetation cover, tree cover mosaic and tree cover.

When the analysis was performed for land cover, the dynamics were summarized by way of Loss, Gain and Net change (Table 2). Changes of inland water bodies are not significant in comparison to all other land cover classes and are therefore not reported. For the period 1975–1990, the loss in tree cover class covers 25,000 km^2, 24,000 km^2 for tree cover mosaic, 135,000 km^2 for other wooded land and 39,000 km^2 for other vegetation cover. This loss is compensated in various ways by a gain, mainly for the other vegetation cover class (144,000 km^2). Over the analysed period of 15 years, the net annual change is negative (reduction of surfaces) for all classes except other vegetation cover class which grows of 7,000 km^2 annually. Considering the annual rate of land-cover change has been computed following Puyravaud's formula [36], this annual rate is negative (net reduction) and quite high for tree cover (−0.95%) whereas less important for other wooded land (−0.37%) and very low for tree cover mosaic (−0.05%). This annual rate is positive and quite high (0.70%) for the other vegetation cover class.

Table 2. Land cover dynamics (Loss, Gain and Net change) between 1975 and 1990 in West Africa represented by areas of change in thousands of km^2. Annual change rates are computed comparing the areas in the 1975 and 1990 reference years.

Change 1975–1990	Loss	Gain	Net	Net Annual Change	Annual Change Rate
Tree Cover	25	1	−24	−1.6	−0.95%
Tree Cover Mosaic	24	22	−2	−0.2	−0.05%
Other Wooded Land	135	57	−78	−5.2	−0.37%
Other Vegetation Cover	39	144	105	7.0	0.70%

The net annual deforestation rate, considered as the total loss of dense tree cover and half of the tree cover mosaic, reached 0.50% for 1975–1990. The total forest area was converted annually in slightly higher proportions into other wooded land (0.28%) than into other vegetation cover (0.22%).

Figure 8a illustrates the 1975–1990 deforestation process over sample sites of our analysis. The highest net deforestation rates are recorded towards the south-western part of West Africa, particularly in Liberia and western Cote d'Ivoire, but to some extent also in Nigeria. Moving north from the south-western area, a slight regrowth of forests is observed. Figure 8b is highlighting the high dynamics of change in the other wooded land class in both directions, namely loss and gain. Highest net losses of other wooded land towards other vegetation cover appear at the southern belt of the Sudanian ecoregion where the concentration of other wooded land was the highest in 1975. Small areas of net gains of other vegetation cover towards other wooded land were recorded in the area of northern Cote d'Ivoire, western Burkina Faso, eastern Guinea and southern Mali (central-west Sudanian ecoregion).

The same land cover dynamics are further described in Figure 9, showing the importance of loss, gain and net changes in the tree cover and other wooded land classes for each sample site. While Figure 9a is demonstrating the strong trend of tree cover loss, Figure 9b illustrates land conversions in the other wooded land class in both directions—gain and loss—indicating the high intra-site variability. In some cases, this is resulting in a net change close to zero.

Figure 8. Net land cover changes in West Africa between 1975 and 1990 focused on (**a**) forest to all other land cover classes (deforestation) and (**b**) from other wooded land to other vegetation cover.

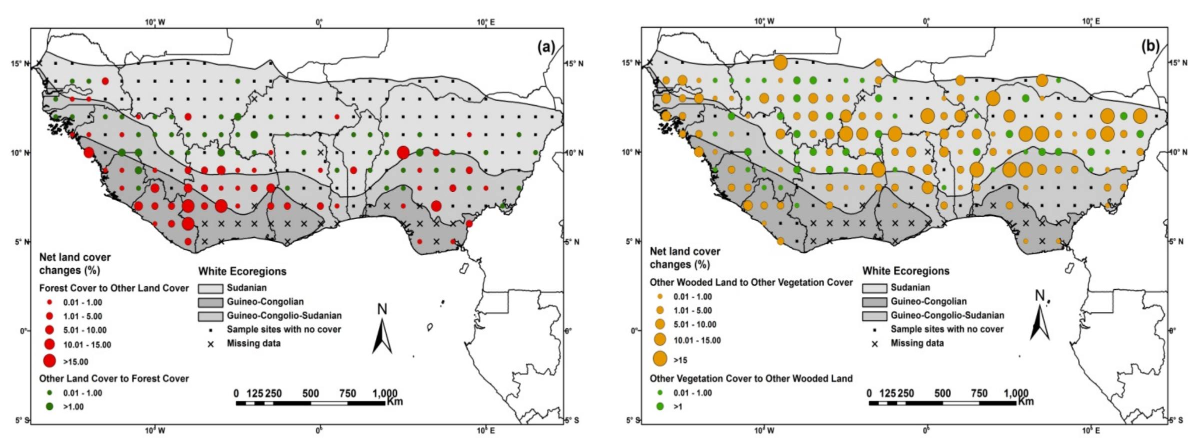
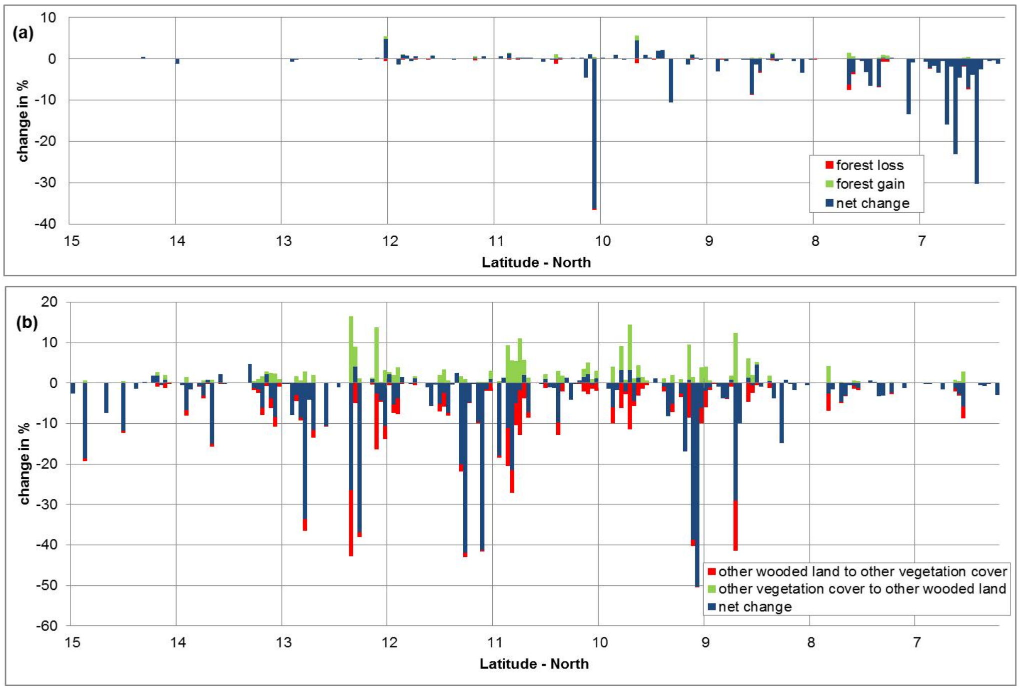


Figure 9. Loss, gain and net land cover changes for each sample site depending of its latitude and for two dynamics (**a**) forest to all other land cover classes, and (**b**) other wooded land to other vegetation cover.



5. Discussion

Land cover monitoring of West Africa over the period 1975–1990 requires a specific dataset of Landsat imageries in order to capture various local land cover changes. Whereas the 1990 data have already been produced in a previous study, a dedicated selection of available MSS data for the 1975 period has been made in order to reduce the seasonality effect and improve classification accuracy. According to our visual screening, about 90% of West African sample sites are covered with Landsat MSS imagery from the year 1975 having suitable quality for land cover change detection. However, the distribution of these suitable images is not uniform over the area. Regions with missing data are mostly concentrated at the south—the Guineo-Congolian ecoregion along the coast where cloud coverage is high and permanent.

Large scale land cover monitoring analyses dating back to the 1970s are rare. The only source of comparison at the sub-continental scale for this time period is provided by the Global Forest Resource Assessment of the FAO which offers relatively comprehensive estimates of forest cover in West Africa for the period of the 1970s [4]. FAO estimates the total forest cover for the same area at around 527,000 km^2. This is considerably higher than our estimates obtained from the classification of Landsat images (351,000 km^2). However, these differences could be explained either by the differences in forest area definitions or by the satellite image data gaps, mostly concentrated at the south of the study area where the forest cover is more abundant [2,4] (Figure 2). In our study period, the most significant changes were conversions to other vegetation cover (105,000 km^2 net gain), namely 4% of the total area converted to other vegetation cover. In most cases, these changes correspond to the extension of agricultural land where high increase rates are characteristic for this period, particularly in West Africa [1,2].

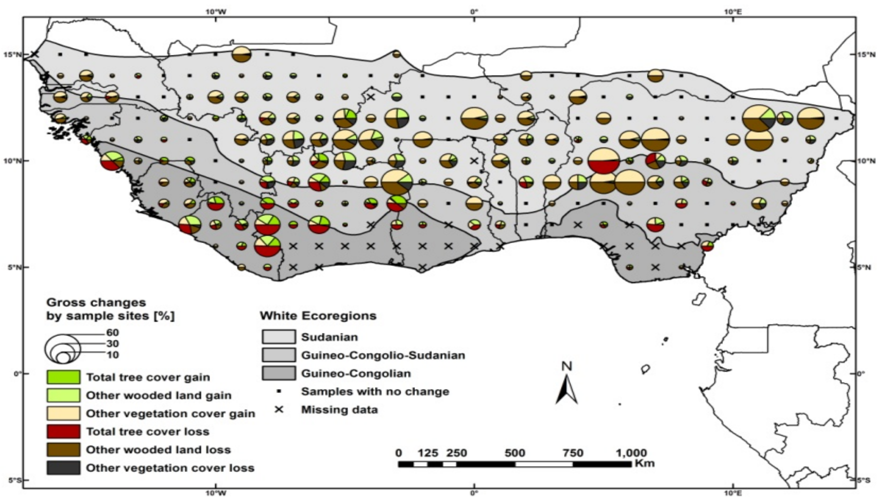
Several studies tracking changes in land cover from the early 1970s have been conducted at the national scale. Poorter *et al.* [2] describe deforestation patterns in Cote d'Ivoire in the last decades at different spatial scales. The highest rates of deforestation were reached in the 1970s and 1980s within the locations corresponding to areas with the highest rates of tree cover loss in our study. Tappan *et al.* [9] describe land cover changes over 35 years in semi-arid Senegal, where an expansion of agricultural land is dominant. This change dynamics is also higher compared to our study at the beginning of the period and slowing down in recent years. Another study [16] analysed land cover changes in an area of eastern Guinea resulting in moderate changes in deforestation towards other vegetation cover. Also here our study shows reduced land cover change figures for the corresponding area.

However, our highest forest loss was registered in the south-west of the study area (Cote d'Ivoire, Liberia, Guinea) which corresponds effectively with changes of land practices related to agricultural expansion, exploitation of wood and the role of the State [2,16,37]. It is important to note that large areas in West Africa—in particular, when moving towards the north—are characterized by shifting cultivation practices which could influence the overall land cover estimations and change statistics. In general, the compensation between loss and gain explained by the high intra-site variability (as shown in Figures 9 and 10) sometimes results in a minimal net land cover change.

Figure 10 illustrates the spatial distribution of all land cover dynamics across West Africa. Most of the changes are located in the Sudanian ecoregion whereas deforestation (tree cover loss) is mostly concentred in Liberia and Cote d'Ivoire. Certain sub-regions with high land cover dynamics are not necessarily highlighted with high overall land cover change due to the compensation between gain and loss within the same class. These areas are particularly located in Liberia, western and northern Cote d'Ivoire, southern Mali, southern Burkina Faso, western and north-eastern Nigeria. Furthermore, Figure 10 also reflects the direction of the land cover changes. In the south, natural forests are converted to croplands, but also tree plantations such as teak and fruit trees which are nowadays dominant in this region. The gain in other wooded land in the southern part is often related to forest regrowth (in most cases, forest reserves). Moving towards the north, we can either see a clear pattern of removal of other wooded land in favour of other vegetation cover (and therefore agriculture) or see the pattern of shifting cultivation.

For a more straightforward analysis we could also consider applying Landsat MSS data to the 1990 period and overcome the constraints caused by the multi-sensor approach. However, in that case, besides lower spatial resolution, we would expect lower spatial coverage and we would have to deal with less satisfactory radiometric quality of the images. By using a good quality TM image dataset, which was processed within the TREES project, we could ensure improved results by comparing MSS and TM images. An additional advantage was the adaptation of the established TREES Landsat TM processing chain considering MSS properties. Therefore, the analysis is noticeably less time consuming, and in the future, the results could be directly used to extend time period covered using the most recent image data.

Figure 10. Overall gross land cover change estimates over 1975–1990 by sample site over the West Africa. Changes are expressed by percentage of the changed area compared to total sample site area (pie chart size) and by proportion for each land cover class (pie chart distribution).



6. Conclusions

This study delivers a unique assessment of land cover changes in West Africa for the period of 1975–1990 based on remote sensing. The sample based land cover change approach using medium resolution satellite images provides a consistent method for the evaluation of land cover dynamics over large areas. The 89% overall availability of suitable data over West Africa and the relatively consistent quality of Landsat MSS imagery provides perspective for its utilization in spatial monitoring of land cover conditions. West Africa, with high diversity of land cover types, recorded strong dynamics in the past 40 years. For the period of 1975–1990, the most significant change was the tree cover loss of about 14% (from 181,000 to 157,000 km^2) and the other vegetation cover gain of 11% (from 939,000 to 1,044,000 km^2). These changes were predominantly related to forest clearing for agricultural land expansion.

This is the first detailed evaluation of land cover dynamics at a sub-continental scale for the period of the 1970s based on remote sensing image data. Research assessment from the early records of satellite data helps to assess changes in landscape when often other sources of information are missing or cannot provide broad, consistent and reliable information about land cover area and changes over time. The outcomes achieved will be a basis for related research applications at the continental scale and in specific regions of interest. Image datasets will extend the existing time series based on a regular sampling of medium to high resolution images and the figures of change provide valuable input for spatial models in various environmental disciplines. Additionally, this study will contribute to better estimate forest carbon fluxes and provide supporting information for Reducing Emissions from Deforestation and Forest Degradation (REDD+) activities demanding detailed monitoring of global forests and woodlands.

By considering the extension and intensity of changes recorded in the 1970s in West Africa, it is important to draw attention to more distant periods when figures of change can provide information about long-term development to the current stage of ecosystems. Nevertheless, monitoring of vegetation changes in a diverse environment remains a challenging task, which requires a precise methodology of image data processing. This approach should take into account not only lower radiometric and geometric accuracies, but also lower spatial resolution while using Landsat MSS image data.

Acknowledgments

The authors would like acknowledge the members of JRC scientific and technical staff particularly Frederic Achard for the scientific support and Desiree Johansson for the data acquisition and selection. The majority of Landsat image data were obtained free of charge from the Global Land Survey (GLS) partnership between the US Geological Survey (USGS) and the National Aeronautics and Space Administration (NASA) (http://gls.umd.edu/). Additionally, data outside the available GLS archives were downloaded from the USGS Landsat archive via GloVis interface (http://glovis.usgs.gov/).

Conflicts of Interest

The authors declare no conflict of interest.

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