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Monitoring Land-use Change in Northwest Nigeria by an Analysis of Multisensor Data – Corona, Landsat MSS, TM and ETM+

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Zusammenfassung: *Landnutzungsmonitoring im Nordwesten Nigerias durch Auswertung von Multisensordaten – Corona, Landsat MSS, TM und ETM+*. Das im Zuge der „Global Change"-Forschung zunehmende Interesse an Informationen über Landnutzungs- und Landbedeckungsveränderungen steht im Widerspruch zu der schmalen raumbezogenen Daten- und Wissensbasis über historische und aktuelle Veränderungen in den Trockengebieten Afrikas. Ein Beispiel ist die Ausdehnung von Ackerflächen zu Lasten natürlicher Trockensavannen und Weidegebiete im Sudan–Sahel. Der folgende Beitrag beschreibt die Herausforderungen für die satellitenbildgestützte Erfassung von Ackerflächen und das Monitoring von Ackerflächenausdehnung im Sudan–Sahel anhand eines Fallbeispiels. Die Landnutzungskategorie „Ackerflächen" setzt sich aus verschiedenen Flächenbedeckungen mit unterschiedlichen spektralen Eigenschaften zusammen. Die visuelle Auswertung der verfügbaren Multisensordaten erweist sich als praktikable fernerkundliche Methode. Die quantitative und räumlich konkrete Darstellung des Landnutzungswandels zwischen 1965 und 2002 gibt Aufschluss über Phasen schneller Veränderungen und mögliche Steuerungsgrößen.

Summary: The growing interest in land-use and land-cover change information in the context of global change research contrasts with the scarcity of spatial data and information on historical and recent changes in African drylands. One example is cropland expansion at the expense of natural vegetation areas and rangelands in the Sudano–Sahelian zone. The present article provides an overview of cropland characteristics and the implications for change detection and monitoring of cropland expansion in the Sudano-Sahel with remotely sensed data. The case study example shows that the thematic class "cropland" consists of different land covers with vastly different spectral properties. The use of these seasonally variable properties alone cannot distinguish cropland or cropland expansion. Visual image interpretation is a feasible approach to change detection with the available multisensor data. The quantitative and spatially explicit information on land-use change between 1965 and 2002 reveals the periods of rapid land-use change and illuminates possible driving causes behind land-use changes.

1 Introduction

Land-use and land-cover change is recognised as a key driver of global change and land-use and land-cover information has become a major research focus (LAMBIN et al. 1999). Before the land-use/cover change processes and their ecological impacts can be understood, the changes must be accurately characterised and quantified. Remote sensing-derived data are increasingly used to assess and monitor land-use and land-cover. Data on changes in drylands are less complete than data on other types of land-use/cover change. Geographic information is scarce, interpretation of remotely sensed data is complicated and human-induced changes are difficult to distinguish from climate-driven changes (FOODY 2001, LAMBIN & EHRLICH 1997, LEPERS et al. 2005). Local-

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scale changes in land-cover and land-use patterns in close-settled dryland landscapes are just a fraction of change detected in regional- or continental-scale studies yet their impacts on ecosystems and sustainability of livelihood might be significant (LAMBIN & EHRLICH 1997).

This information gap is particularly obvious for cropland expansion, which is one of the most prominent types of land-use change in the semi-arid Sudano-Sahelian zone (HIERNAUX & TURNER 2002, STÉPHENNE & LAMBIN 2001). Population growth is estimated at more than 2 per cent annually and annual cropland expansion rates ranging from 3% to 5.8% (1961–1989) and 1.4% to 4.8% (1984–1997) were observed in local studies throughout the Sudano-Sahelian zone (STÉPHENNE & LAMBIN 2001, p. 157). Most of this expansion happens at the existing extensive technological level and at the expense of natural vegetation areas or rangeland (HIERNAUX & TURNER 2002).

Cropland expansion has complex social and environmental dimensions. Monitoring cropland expansion reveals significant shifts in resource management strategies and changing balances between crop and livestock production. The clearing of natural vegetation for crop production may initiate soil nutrient depletion and may lead to overstocking of the shrinking rangelands (GEIST & LAMBIN 2004, HIERNAUX & TURNER 2002, POWELL et al. 2004).

Remote sensing data are an important land-cover data source in the African context of poor geoinformation (Committee on the Geographic Foundation for Agenda 21 et al. 2002). The fact that land-cover changes caused by human activities generally occur at scales finer than 1 km (TOWNSHEND et al. 1991) limits the applicability to medium resolution remote sensor data. In terms of cost, temporal and spatial scope of remote sensing data, the Landsat archive lends itself to monitoring and retrospective land-use change research. However, the Landsat archives (USGS 2003) reveal a limited data availability for West African drylands that is corroborated by other studies (LEPERS et al. 2005, LOVELAND et al. 1999). Time series approaches (HOSTERT et al. 2003) or digital change detection methods (JENSEN 2005) are of limited value for change analysis in drylands if the choice of data and observation dates is limited (LAMBIN 1996, TAPPAN et al. 2000).

In such cases, the inclusion of multisensor data is a necessary and practical approach to successive mapping and change detection (TAPPAN et al. 2000). Visual image interpretation may prove the most feasible and appropriate approach to the detection of thematic land-use conversion at the local scale (SOHL et al. 2004, TAPPAN et al. 2000).

The present paper pursues three objectives: (1) to outline the characteristics and interpretability of cropland expansion in the Sudano-Sahelian zone; (2) to demonstrate the monitoring of cropland expansion with multisensor data for a case study example; (3) to briefly discuss the influence of data characteristics on thematic classification and area statistics.

2 Cropland characteristics and implications for change analysis in the Sudano–Sahelian zone

In the Sudano–Sahelian zone, the small field sizes, low vegetation cover within and outside croplands and spectral similarities between fallows and cropland complicate the mapping of agricultural land-use (REENBERG 1994, TURNER & CONGALTON 1998). With respect to change detection, spectral, seasonal and thematic characteristics of croplands are of particular interest.

Spectral heterogeneity results from low vegetation cover, spectral ambiguity and mixed pixels in the fine-grained Sudano-Sahelian landscape (LOVELAND et al 1999). The crop phenological cycle and the practice of intercropping influence the spectral variability of croplands. A variety of crop species at different stages of development is intercropped in the individual fields. Harvest of the different crop species starts in August and ends in late November (MORTIMORE & ADAMS 1999). This is exacerbated by the fact that different land-covers are associated with the thematic land-use class "cropland"

and these covers have different spectral signatures. Cropland may consist of abandoned cropland, recently cleared cropland, crop-fallow-cycle, and permanently cultivated land (Mortimore & Adams 1999).

Measured in terms of the Normalized Difference Vegetation Index (Jensen 2005), the heterogeneity of vegetation response in the Sudano–Sahelian zone is lowest during the time of highest vegetation development at the end of the wet season (September) or during the dry season when vegetative growth ceases (December to April). The heterogeneity of vegetation response reaches a maximum in October or November when the cultivated land has been mostly harvested while the natural vegetation is still green (Lambin 1996).

Taking these spectral, seasonal and thematic characteristics into consideration, remotely sensed data acquired in October or November can be expected to be optimal for mapping different land-use categories in the Sudano-Sahelian zone (Lambin 1996). Anniversary dates can be compared for the detection of complete land–cover conversion as a result of land–use change (Sohl et al 2004, Tappan et al. 2000).

With a focus on permanently cultivated cropland and the appropriation of uncultivated land for cropping, only full land-conversion conversion trajectories (natural vegetation-cropland) are considered cropland expansion (land–use change) in the following example. The study is based on the available multisensor data over the largest area of reserved Sudanian savanna woodland in northwest Nigeria for a period of 37 years.

3 Study area and datasets

The Zamfara and Runka reserves (3300 km^2) are located in the Sudano-Sahelian bioclimatic zone of northwest Nigeria (Fig. 1). The semi-arid climate is characterised by a single wet season (May to September) with a precipitation peak in July and August, and a distinct dry season from October to April. Long-term average annual rainfall ranges from 650 mm to 850 mm along a north–south gradient in the reserves. The coarse textured, predominantly sandy soils have developed from pre-Cambrian basement complex granites. They are low in nitrogen, phosphorus and organic matter content. Based on aerial photographs and ground surveys (RIM 1991), the vegetation of the reserves has been described as undifferentiated Sudanian savanna woodland with a tree canopy cover of 5 to 8 % and more than 90 % shrub/grassland cover in the Zamfara Reserve and 50–75 % shrub/grassland cover in the Runka Reserve (Fig. 1).

The Zamfara and the adjacent Runka reserve were part of a series of Nigerian national projects in the 1960s to convert forest reserves into grazing reserves. Due to the status as reserves, cropland is restricted to the four encapsulated farming enclaves in Zamfara Reserve: Dumburum, Shamushalle, Tsabre and Aja (Fig. 1). Besides for livestock of the sedentary farmers, the reserves are an important transhumance grazing area for the livestock of nomadic and transhumant livestock-keepers. Based on 1991 census data the areas bordering on the reserves had an estimated population density of 124 persons km^{-2} (CIESIN et al. 2000). Population density within the reserves is much lower (approximately 15 persons km^{-2}).

Altogether 31 Landsat TM and ETM+ scenes (path/row 189/51) were available for

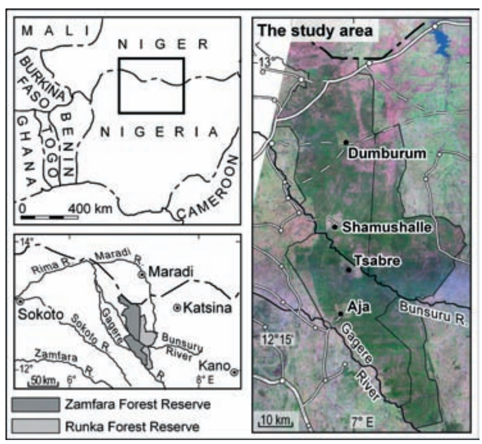

Fig. 1: The location of the study area in northwest Nigeria and Landsat 7 ETM+ subset of October 1999, bands 742 (RGB).

Tab. 1: Multisensor data used for monitoring land-use change.

Platform and sensor	Acquisition date	Nominal spatial resolution of bands mapped (m)
Corona KH-4A	04 November 1965	2.74×2.74
Landsat 2 MSS	29 January 1976	79×79
Landsat 4 TM	23 February 1988	30×30
Landsat 7 ETM+	19 October 1999	30×30
Landsat 7 ETM+	20 May 2002	30×30

the period 1982–2002 (USGS 2003). Cloud-free dry season Landsat scenes covering optimal time intervals were selected for analysis (Tab. 1). In addition, a Landsat MSS scene (GLCF 2005) and three Corona satellite photographs (USGS 2001) were used to extend the monitoring as far back in time as possible (Tab. 1).

The Landsat MSS, TM and ETM+ data were rectified by the data distributor to the desired map projection (UTM zone 32 North, WGS84 spheroid and datum). Because digital format was not available at the time of order, Corona positive films were ordered and scanned with a Vexcel Imaging Austria UltraScan 5000 photogrammetric scanner at 20 μm (1270 dpi) resolution to acquire a pixel ground resolution of approximately 6 m.

In the absence of topographic maps of the study area, the scanned Corona images were registered to the panchromatic bands of the level 1-G Landsat 7 ETM+ images (1999) and bilinear interpolation resampled into UTM projection with an output pixel size of 6×6 m. For the northern and southern Corona scenes, a positional accuracy of 1.3 pixel was achieved with 26 and 25 ground control points, respectively, and a second order polynomial transformation. Due to severe geometric distortion of the centre scene a nonlinear rubber sheeting model was applied using 31 ground control points. The resulting positional accuracy was within one pixel (3 metres) when overlaid with the panchromatic Landsat 7 ETM+ band. Co-registration and atmospheric correction of the different Landsat images (Tab. 1) was not performed as a per-pixel change analysis was not carried out (Jensen 2005). Changes in spectral response between two dates of calibrated images indicate some form of surface change, but this change often is not a thematically defined land-use change (Sohl et al. 2004).

4 Analysis of multisensor data

The present study avoids problems of data fusion or image calibration by relying almost exclusively on visual interpretation. Given the unavailability of anniversary-date data from the same sensor, seasonality influences, the geographic context and the use of multisensor data, this change detection methodology was considered to be most feasible and effective (Sohl et al. 2004, Tappan et al. 2000).

Land-use change as a discontinuous process with periods of rapid change is exemplified with the development of Shamushalle enclave (Fig. 1, Fig. 2). Cropland expansion is patchy which has implifications for the analysis of multisensor data. Cropland expansion is periodic but the development can be ascribed to a single settlement. This is important for exploring the linkages between ground data on human activities and remote sensing data.

The various elements of visual image interpretation (Jensen 2000) were applied to the high-resolution Corona images and the Landsat images (Fig. 2). In the early dry season images (November 1965 and October 1999), the thematic land-use class "cropland" is a mixture of agricultural land with crops and harvested agricultural land (Fig. 2). In the late dry season images (January 1976 and February 1988), all the cropland is harvested (Fig. 2). This seasonal in-

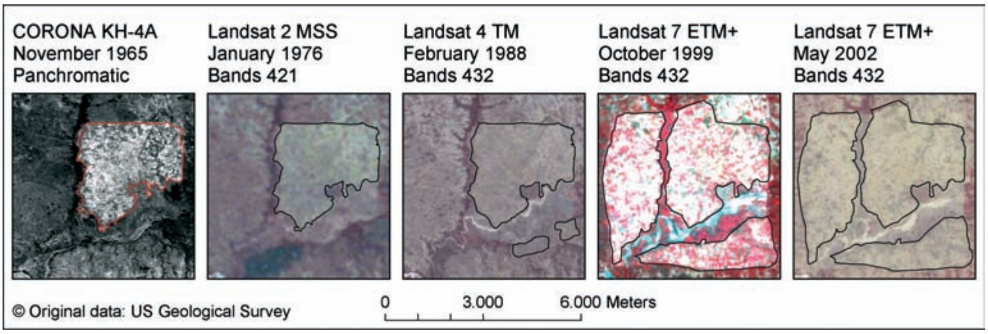

Fig. 2: Cropland expansion in Shamushalle enclave 1965–2002.

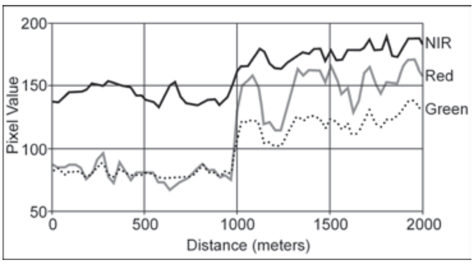

Fig. 3: Spatial profile of reflectance values across an uncultivated land-cropland interface (October 1999).

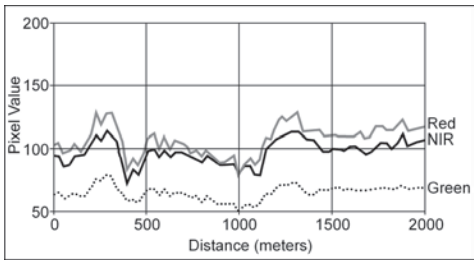

Fig. 4: Spatial profile of reflectance values across an uncultivated land-cropland interface (February 1988).

fluence is reflected in the spatial profile of the near-infrared (band 4) red (band 3) and green (band 2) spectrum of Landsat ETM+ data of October 1999 (Fig. 3). The differences between uncultivated land and cropland show as increase in brightness values as the profile line enters the enclave cropland at the 1000 m mark (Fig. 3). At that time of year, cropland reflects relatively higher amounts of incident red light, causing the NDVI to be much lower than for uncultivated land (Fig. 3).

The same spatial profile over the late dry season Landsat TM image (February 1988) shows the low spectral contrast between uncultivated land and cropland as well as the low vegetation response of both land-use classes (Fig. 4).

The use of spectral information alone cannot distinguish cropland expansion. In all datasets, tone/colour, brightness, site (location of cropland around settlements) and association (neighbourhood of settlements, cropland and watercourses) are additional key variables that are used in land-use mapping and change detection (Fig. 5). Croplands are distinct from uncultivated land both in the pattern and colour of pixels in the Landsat colour composites. Like in the Corona images, the field pattern is recognisable due to a relatively systematic arrangement of tonal patterns (Fig. 5). The combinations of these spectral properties (tone/colour and brightness) with other interpretation elements enable the image interpreter to map cropland or land-cover conversion, i. e. cropland expansion.

In the early dry season Corona image, cropland was mapped on the basis of characteristic field patterns, bright tones and smooth texture. The field pattern results from small field sizes and variations in grey tones. Planted fields (mainly sorghum, *Sorghum bicolor*, and cowpea, *Vigna unguiculata*) appear darker and alternate with bright fields where pearl millet (*Pennisetum*

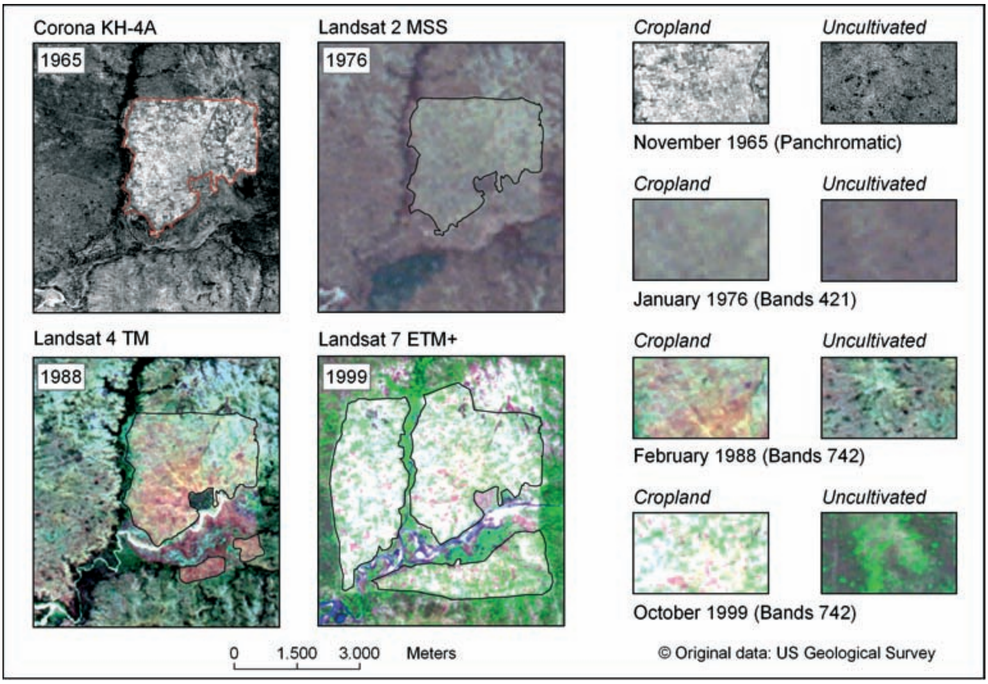

Fig. 5: Cropland characteristics represented on multisensor imagery.

ssp.) and groundnut (*Arachis hypogaea*) are already harvested. Cropland appears in brighter tones than uncultivated land due to its overall lower vegetation cover (Fig. 5). The smooth texture is due to uniform tones within the dark, grey or bright fields (Fig. 5). The irregular spacing of the trees combined with variations in dark tones of vegetation cover causes an intermediate to coarse texture of the uncultivated land in the Corona images (Fig. 5).

In the early dry season false-colour Landsat images of October 1999 (RGB 742), cropland exhibits lighter hues of green compared to the surrounding uncultivated land where vegetation is still vital, resulting in bright green colours. Where vegetation cover is sparse and dry soil is exposed, cropland colour varies from light to dark magenta hues (Fig. 5).

The late dry season Landsat 2 MSS (29 January 1976), Landsat 4 TM (23 February 1988) and Landsat 7 ETM+ (22 May 2002) images are more difficult to interpret. This is due to the low geometric and radiometric resolution of the MSS data and the high correlation between the signatures of cropped and uncultivated land during the late dry season (January–April) and at the beginning of the wet season (May). Nevertheless, differences in colour, brightness values and texture between the cropland and uncultivated land allow for mapping of cropland and cropland expansion (Fig. 2, Fig. 5).

The panchromatic Corona images and the multiband colour composites of the Landsat MSS, TM and ETM+ images were used as background images for GIS-based mapping. Polygons around cropland areas were digitised on-screen for all dates and area calculations were performed in ArcGIS.

5 Results and discussion

Cropland expansion

The results show that cropland expansion is not continuous but rather a disjunct process with a period of rapid change between

Tab. 2: Cropland expansion rates in Shamushalle enclave.

	1965–1976	1976–1988	1988–2002	1965–2002
Total increase (%)	0	32.6	117.1	187.8
Average annual increase (%)	0	2.4	5.7	2.9

1988 and 2002 (Table 2). Population growth seems not to be a unidirectional driver behind cropland expansion in the different intervals (Tab. 2). If only the years 1965 and 2002 were the temporal endpoints of the study, population growth would appear as a driving cause of cropland increase (Tab. 2). This underscores the importance of including datasets at as many time intervals as possible. The annual rates and the location of cropland expansion after 1988 point to in-migration and the initial conversion of uncultivated land into cropland (Tab. 2, Fig. 5).

The temporal pattern of rapid land-use change after 1988 is characteristic of cropland expansion in all enclaves except Dumburum. The spatial pattern of cropland expansion in Shamushalle reflects official land allocations to the enclave that have led to rapid clearing of uncultivated land around the initial settlement. Cropland expansion in the study area is not random but occurs close to the already existing cropland and settlements (Fig. 5). A detailed discussion of land-use change in the reserves is provided in Hof (2006).

Mixed pixels and area statistics

In general, higher resolution data show more change than coarse resolution data. Sharp boundaries in coarse resolution data are often artefacts caused by mixed pixels rather than discrete breaks in land-use/cover (Jensen 2000). A general problem with using multisensor data of varying spatial and radiometric resolution is that the characteristics of mixed pixels and their influence on area statistics is difficult to ascertain. The magnitude of the influence can be estimated when comparing the area classified as cropland in the Corona image (1965) and Landsat MSS image (1976). The overall area mapped as cropland in Shamushalle enclave has not changed (Tab. 2). If the superior spatial resolution of the Corona image would have been exploited, excluding the visible patches of field trees, windbreaks, rock outcrops or erosion gullies from the cropland area, a total of 87 hectares (13.4%) would have been considered cropland expansion by 1976. This internal differentiation of cropland is not visible on the lower spatial resolution Landsat MSS or Landsat TM and ETM+ images. Thematic classification consistency requires generalising the observation from the higher resolution image to a minimum mapping unit of 79-metre or 30-metre pixels consistent with the lower resolution images (Tappan et al. 2000). Within the area mapped as cropland in 1965 this procedure results in "intentional" errors of commission (erroneously assigning pixels to cropland in the Corona image). When mapping the Landsat images, this error of commission is not intentional but a result of the lower spatial resolving power of the Landsat data. The magnitude of this error cannot be assessed for the areas where full thematic land-use conversion has taken place after 1965 unless higher resolution data were available for direct comparison. This also applies to the assessment of the impact of mixed pixels along the edges of cropland on area statistics. This impact could be assessed in quantitative terms if images from sensors with different spatial resolution were available for the same year.

The present information on cropland areas does not reach the accuracy of land parcel boundaries. More information than the data are capable of supplying cannot be extracted from the data. However, the analysis of the available multisensor data supplies information on cropland areas and the rate and extent of cropland expansion in an area for which agricultural references are very scarce or nonexistent. Future changes can be assessed against the established baseline dataset. The achieved accuracy can be considered sufficient for the characterisation of the process of change.

6 Conclusions

There is limited availability of repeated coverage with medium resolution remote sensing data (Landsat MSS, TM, ETM+, SPOT HRV) for the West African drylands. Data from multiple sensors can be used efficiently for the monitoring of land-use change. The use of these mutisensor data would be extremely difficult with algorithm-based approaches to change detection. Seasonality exacerbates the difficulties of relying on spectral properties for thematic classification and change detection.

This situation is not a specific of the study area but may be considered typical for local-scale change detection studies in the Sudano–Sahelian zone. Visual interpretation of data acquired by multiple sensors in different and even adverse seasons allows for the assessment of the rates and the spatial extent of cropland expansion. Land-cover conversion due to land-use change can be monitored in spatially and temporally explicit terms. This information is pertinent to linking household-level information to remote sensing data for the understanding of local-scale land-use dynamics in the Sudano–Sahelian zone.

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