# Monitoring the Magnitude of Land-Cover Change around the Southern Limits of the Sahara

G.M. Foody

## Abstract

*Studies of land-cover change using satellite remote sensing are often constrained to depict land-cover conversions only, with the equally important modifications undetected or misrepresented, resulting in significant error. Desert fluctuations within the Sahel were examined using an approach that indicated the magnitude of land-cover changes. This showed that the conventional post-classification comparison method of change detection appeared to underestimate the area of land-cover change and, where a change was detected, typically overestimate its magnitude. At the regional scale, the land-cover changes detected were strongly related to rainfall variability. This relationship did not, however, explain changes at a finer spatial scale and indicated that dryland degradation, and its causes, may remain far from understood.*

## Introduction

Land-cover change is a major component of global change with an impact greater than that of climate change (Skole, 1994; Vituosek, 1994). Land-cover changes lie on a scale of severity that ranges from no alteration through modifications of variable intensity to a full transformation or conversion of class membership. At regional to global scales, the only practical means to map and monitor land cover is through satellite remote sensing (Tucker *et al.*, 1985; Townshend *et al.*, 1991; Skole, 1994; DeFries *et al.*, 1998). Due primarily to the constraints imposed by cloud and those of data cost and volume, such activities are inevitably constrained to use coarse spatial resolution imagery. Additionally, from the vast array of change-detection methods available (Singh, 1989; Collins and Woodcock, 1996; Ridd and Liu, 1998; Yuan and Elvidge, 1998; Abuelgasim *et al.*, 1999; Dai and Khorram, 1999; Mas, 1999), land-cover change tends to be evaluated through the comparison of sequential land-cover maps derived from imagery with a conventional (hard) supervised image classification technique. These factors may, however, introduce significant error into the analysis; contributing significantly, for example, to the ~50 to 70 percent error in deforestation estimates (Skole and Tucker, 1993; Skole, 1994). An issue of particular concern is that hard class allocations allow only a crisp or binary assessment of change and so can only indicate land-cover conversions (Lambin, 1997; Foody and Boyd, 1999; Nepstad *et al.*, 1999). Hard class labels are, therefore, inappropriate and effectively useless when partial changes or modifications, that do not involve a change in class label, are important (Foody and Boyd, 1999; Cochrane *et al.*, 1999). This applies also to situations in which small, sub-pixel, conversions occur that result in a modification of the cover in the area represented by a pixel. Thus, while remote sensing is the only practical means of observing change over large areas, it is difficult to measure change accurately, and most attention has focused on relatively drastic land-cover conversion with the equally important modifications rarely being studied (Lambin, 1997). Unfortunately, land-cover modifications, such as those relating to environmental degradation or rehabilitation, are of major concern but poorly understood due to the paucity of reliable data. This has been the situation with drylands (Daily, 1995; Agnew and Warren, 1996), particularly in the context of contentious desertification issues (Thomas and Middleton, 1994; Stiles, 1995; Hutchinson, 1996).

The ability to map land-cover modifications and/or sub-pixel scale conversions may help fill significant gaps in knowledge, including the assessment of the extent as well as the rate and severity of change in dryland environments (Daily, 1995; Agnew and Warren, 1996). A major advance in understanding dryland change was provided by satellite observations of fluctuations in desert extent (Tucker *et al.*, 1991) which helped challenge previously held views on desertification (Hulme and Kelly, 1993; Thomas and Middleton, 1994). The binary approach used may, however, have masked detail on the extent and magnitude of change that could be revealed by the use of other change-detection methods.

A variety of approaches have been used to indicate the magnitude of land-cover change (Singh, 1989; Hame *et al.*, 1998). If sites of known class membership change are available, it is possible to use these to train an analyst to directly map the magnitude of change (Gopal and Woodcock, 1996). Often such data are unavailable or insufficient, and other change-detection procedures are adopted. Perhaps the most popular are change-detection techniques that focus on alterations in image radiometry (Singh, 1989; Lambin and Ehrlich, 1997). These, however, are divorced from the classes of interest and can be sensitive to a variety of external confounding variables. A simple alternative, however, is to replace the hard classifications in the post-classification comparison method with fuzzy/soft ones that allow multiple and partial class membership (Foody and Boyd, 1999). This allows the detection of land-cover changes of all magnitudes, thus enabling the severity of land-cover change to be mapped and monitored (Figure 1). The output of a fuzzy classification may also be treated as fraction images that depict sub-pixel land-cover composition. Comparison of such images may, therefore, reveal changes in the fractional coverage of classes within the area represented by a pixel (Kressler and Steinnocher, 1999).

As with any change-detection study based on post-classification comparison methods, the accuracy of the individual classifications used is of paramount importance. Unfortu-

Department of Geography, University of Southampton, Highfield, Southampton SO17 1BJ, United Kingdom (gmf@soton.ac.uk).

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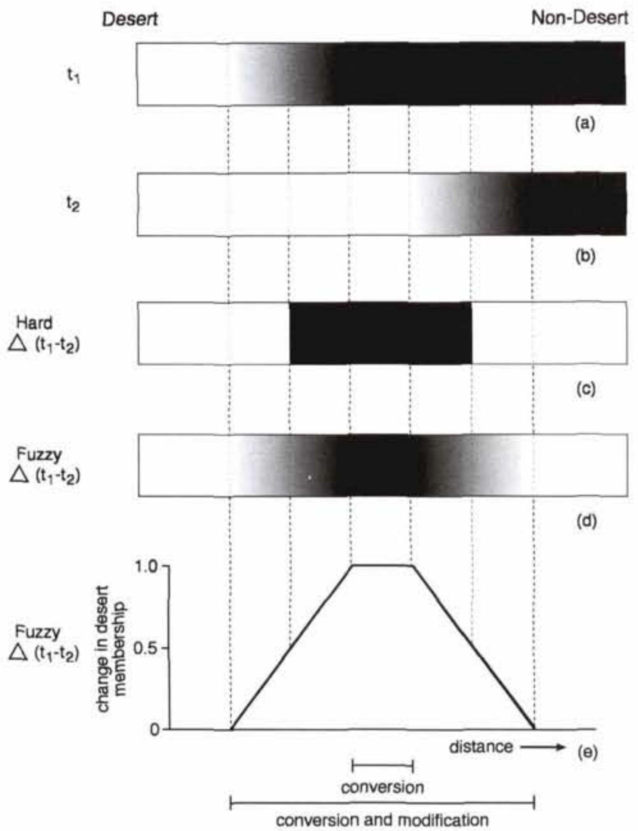


Figure 1. A simplified model of land-cover change. (a) Distribution of desert (light tone) and non-desert (dark tone) at time $t_1$ along a transect perpendicular to the desert boundary. Note that the classes are continuous and inter-grade so that the boundary is not sharp. (b) Distribution of the classes at time $t_2$ when the desert has advanced from its earlier position. (c) Change detected by a conventional post-classification comparison. Areas of land-cover conversion are shown in black. (d) Change detected by the modified method. The grey scale indicates the magnitude of change. (e) Graphical relationship of the change in membership magnitude highlighting areas of conversion and modification.

nately, many factors affect the accuracy of classifications, both hard and fuzzy. Even if appropriate image and ground data sets have been acquired and the classes of interest are spectrally separable, the accuracy of a classification and its suitability for use in change detection may be degraded by the failure to satisfy key assumptions underlying the analysis. Classification techniques make many assumptions and are often inappropriate for land-cover mapping applications (Foody, 1999; Mather, 1999). One fundamental assumption is that the classes to be mapped have been exhaustively defined. This is often not the situation. Regions of untrained classes (those not included in the training stage of the classification) are frequently observed, especially in imagery of very large areas. These regions can only display membership to the set of classes defined in the training stage and so, with a conventional hard classification rule (in which each case is allocated to the class from a given set with which it has greatest similarity to), must be erroneously allocated to one of the defined classes. Similarly, in a fuzzy classification, class membership is commonly partitioned among the set of trained classes. Consequently, untrained classes can significantly degrade the accuracy of hard and fuzzy classifications (Foody, 2000). The problem of untrained classes is especially common in the situation when attention is focused on one or a few classes (Jeon and Landgrebe, 1999), as is the case in many investigations, including those addressing major issues such as those related to deforestation, desertification, and urbanization. An approach to reducing this problem is to adopt a possibilistic rather than probabilistic approach (Foody, 2000). With a possibilistic approach, the degree of membership a case has to each class may be calculated independently of all other classes and membership is not constrained to sum to unity over all defined classes. The class membership values derived are absolute rather than relative values that indicate the typicality or degree to which a case belongs to a selected class (Foody, 2000). Post-classification change detection based on fuzzy classifications depicting the typicality of class membership may be one means of studying important land-cover changes such as those associated with dryland degradation. The aim of this article is to evaluate land-cover changes that may be detected through a post-classification comparison method to change detection based on fuzzy classifications of the Sahara-Sahel transitional region.

## Data and Methods

To evaluate the potential to observe land-cover modifications associated with desert fluctuations, a time series of remotely sensed data was acquired for the Sahara-Sahel transitional region (Figure 2). This has been an area of intense interest and study using remote sensing (Tucker *et al.*, 1991; Lambin and Ehrlich, 1997; Nicholson *et al.*, 1998; Prince *et al.*, 1998). For relation to a pioneering earlier study by Tucker *et al.* (1991) (that was used as a benchmark) and newly available precipitation data (New *et al.*, 1999), attention focused on inter-annual desert fluctuations during the period 1982 to 1990. Normalized difference vegetation index (NDVI) imagery of the site were used to indicate the amount of green vegetation cover which, in turn, can be used to characterize the land-cover classes of interest in the region (Fuller, 1998). The NDVI simply expresses the observed remotely sensed response in red and near-infrared wavelengths as an index that is positively related to vegetation amount. The data used were extracted from the NOAA/NASA Pathfinder data archive that contains NDVI data derived from radiometrically calibrated NOAA AVHRR imagery with an 8-km spatial resolution (Smith *et al.*, 1997). From this archive, the monthly composite NDVI images for each year were acquired and used to form an annual (maximum value) composite image. This type of composite imagery has been used in other studies of the region and is useful in reducing distortions in the data due to atmospheric and viewing geometry effects (Fuller, 1998).

Guided by a map depicting global land cover in 1984 (DeFries *et al.*, 1998) and other ancillary data, the desert class was characterized statistically in the NDVI imagery for 1984 from a $\sim 2.1 \times 10^6$-km$^2$ training region. As in other studies (e.g., Tucker *et al.*, 1991; Nicholson *et al.*, 1998), the desert class was defined broadly and included regions that may be considered to be part of the Saharan-Sahelian transition zone. Defining the desert by the remotely sensed response derived from the training site is clearly a simplification. It does, however, provide a basis for the mapping and monitoring of fluctuations in desert extent. Other definitions of desert could be used, or the observed fluctuations could be attributed to variations in land condition or status that need not be considered land-cover changes. None-the-less, throughout this article the temporal fluctuations of the desert class observed will be discussed in terms of land-cover change.

The derived training statistics describing the desert class were used to generate a fuzzy classification of the imagery for each year that depicted the degree of membership or typicality to the desert class (Figure 2). Class membership may be quantified in a variety of ways and ultimately this will impact on the

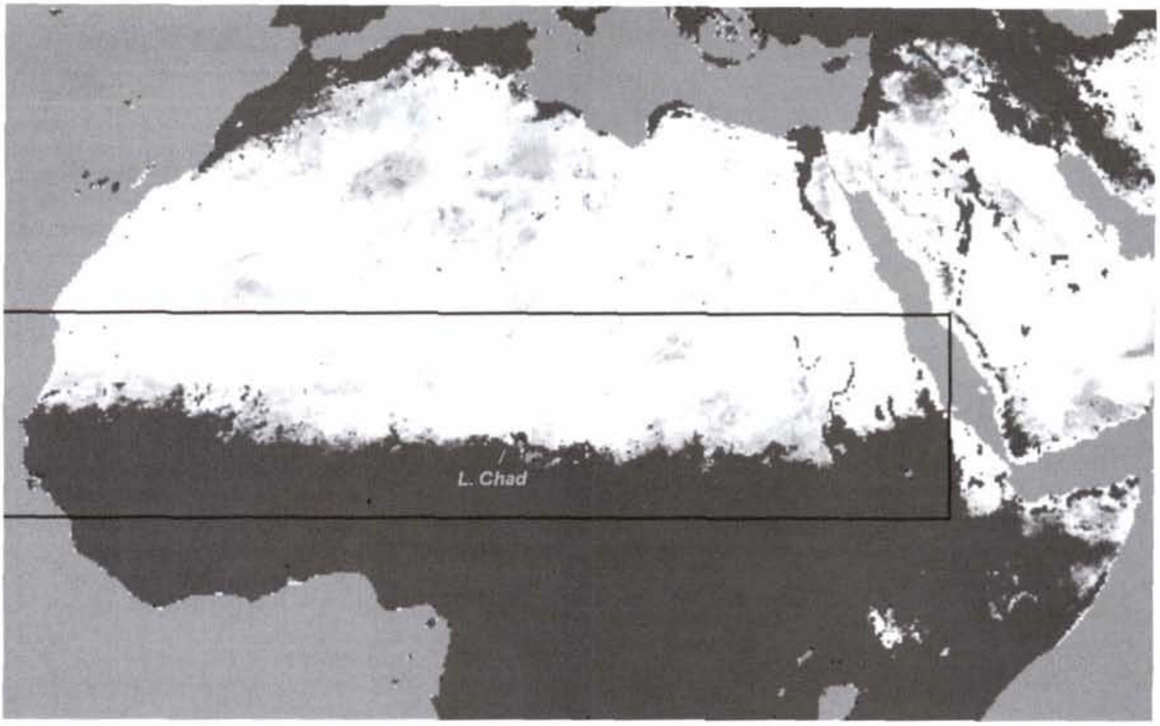


Figure 2. Fuzzy classification illustrating the distribution of desert membership in 1984. The classification used a montonically decreasing sigmoidal function of the annual NDVI with full membership (white) associated with NDVI ≤ mean desert response and zero membership (black) with NDVI ≥ 3 standard deviations above the mean (see Figure 3). A similarly defined function was used to map the vegetation of the Sahel. Box highlights the extent of the region studied.

magnitude of the changes detected. Here, the absolute strength of membership to the desert class was calculated from a simple decreasing function of NDVI (Figure 3). Note that class membership was determined with respect to the single class of interest and that the values derived indicated the possibility of class membership. The difference between two such classifications from sequential years was used to represent the inter-annual fluctuation in desert membership. This approach to change detection is referred to as the modified method in the rest of this article.

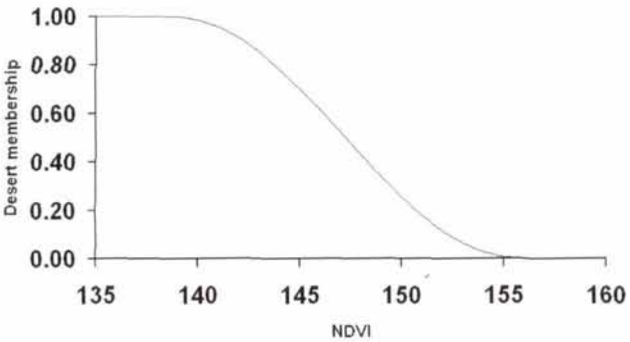


Figure 3. The class membership function used in generating the fuzzy classification of the desert class. Note that here the NDVI was expressed in DN extracted from the maximum value composite imagery.

To allow comparison against a conventional post-classification comparison of land-cover change, a class representing the bush and shrubland vegetation of the Sahel depicted on the global land-cover map presented by DeFries *et al.* (1998) was also characterized statistically in the NDVI imagery for 1984. These training data were used to classify the NDVI imagery relating to each year. These classifications, together with those for the desert class, were used to derive conventional hard classifications of the imagery for each year by allocating each pixel to the class with which it had the highest membership. Comparison of these classifications revealed land-cover conversions. Due to the presence of "dropped pixels," a modal filter with a 3- by 3-pixel window size was applied to the change images derived from both the conventional and modified methods.

## Results and Discussion

Inter-annual conversion of land cover was manifested through the comparison of the conventional hard classifications. The trends in desert expansion and contraction matched those reported in the benchmark study (Tucker *et al.*, 1991). In particular, the area of inter-annual change in desert extent was strongly correlated with that reported by Tucker *et al.* ($r = 0.98$) and, over the eight-year period, was strongly related to the inter-annual difference in rainfall over the region ($r = -0.84$). The comparison of the fuzzy classifications, however, revealed a greater richness of information about the land-cover changes.

The conventional approach indicated land-cover conversions only. In the areas of conversion identified, the degree of class change was depicted as both uniform and full (i.e., magnitude of class membership change at each site = 1.0). The modified method revealed changes of variable magnitude. Over the region, the mean inter-annual change in membership to desert

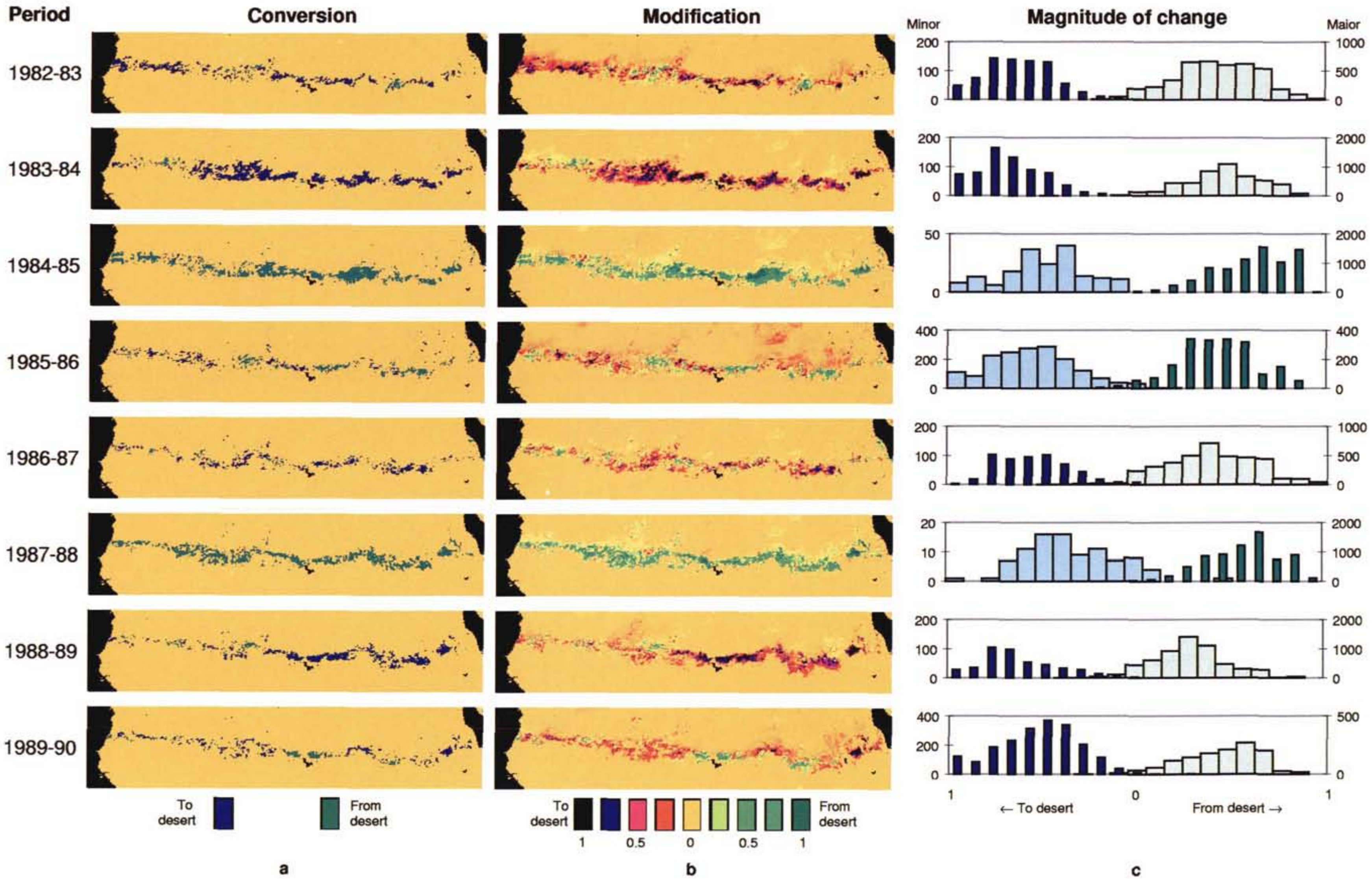


Plate 1. Land-cover changes detected. (a) Conversions from the conventional post-classification comparison method. (b) Modifications from the modified method. (c) Magnitude of change in desert membership in the area of land-cover conversion. In (a) and (b), water bodies have been masked in black. Note, that desert expansion was apparent in 1982–83, 1983–84, 1986–87, 1988–89, and 1989–90 while desert contraction was evident in 1984–85, 1985–86, and 1987–88. The histograms indicate the magnitude of land-cover change determined by the modified method in the area of conversion identified by the conventional method. They show the number of pixels (each representing 64 $km^2$) undergoing changes of differing magnitude, with the major direction of change indicated by dark toned narrow bars (use right axis) and the minor direction of change by light toned wide bars (use left axis). The color scale indicates the degree of change with conversions to and from desert indicated by dark blue and dark green colors, respectively.

derived from the modified method was strongly correlated with the associated change in rainfall ($r = 0.87$). The representation of change derived also differed from that provided by the conventional method in two important respects. First, relative to the modified method, the conventional method underestimated the area of land that had undergone change. The total area of land undergoing a change in membership of greater than 0.2 was, for example, on average 69.7 percent larger than the area of change indicated by the conventional method. Second, where change was detected by the conventional method it was, in keeping with the predictions from the simple theoretical model of land-cover change (Figure 1), located between areas that had only been modified and its magnitude was generally overestimated. For example, in the area of conversion indicated by the conventional method, much of the change was found to be partial, with an average change in membership of 0.52 (Plate 1).

Past studies have sought to explain the fluctuations in desert extent in terms of regional rainfall variations and attribute the residual variance to other agencies, notably those associated with human activity (Hulme and Kelly, 1993). There are, however, problems in interpreting and using the relationships between desert and rainfall fluctuations. The estimates of desert extent and change over time used, for example, have typically been derived using a conventional change-detection approach that indicated only land-cover conversions and so may poorly represent the changes in the vegetated land cover associated with dryland degradation. These land-cover changes are also treated in aggregate over the region. Additionally, while Sahelian rainfall is known to vary significantly in space and time, it is common for rainfall data to be aggregated over very large areas, including the entire Sahel, and the region treated as if homogeneous (Nicholson and Palao, 1993). Scale-dependent relationships may, however, exist. This was evident here because, while the land-cover changes detected (Plate 1) were generally located within and around the zone with rainfall of a transitional magnitude between that of desert and the Sahel (Plate 2), they were not fully compatible with the rainfall trends. Thus, although there was a strong correlation between the inter-annual fluctuations in desert extent and rainfall at the regional scale, the relationship may not be transferable between scales.

Three key observations can be made that limit the ability to relate the regional scale relationship to finer scales. First, both the conventional and modified methods revealed that the desert did not move uniformly in a single direction. Each change image (Plate 1) showed desert advances and retreats, perhaps a consequence of patchy rainfall (Hellden, 1991). These results support the view that the Sahara has not been consistently migrating southwards along a single front (Nicholson *et al.*, 1998). Second, the net change in desert area used in regional scale analyses provided an inaccurate measure of the area of land undergoing change. Because inter-annual changes were in both directions, the gross area of land conversion was higher. On average, the gross area of conversion was 2.25 times larger than the net area of conversion, with a maximum of 7.84 times higher for 1985–1986 (Plate 1), and was not strongly related to rainfall fluctuations at the regional scale. Moreover, the area of land experiencing a modification of cover would be even larger. Third, the magnitude of change in desert membership indicated by the modified method was not closely related to the associated difference in annual rainfall. Numerous factors limit the ability to accurately relate the two data sets in terms of fluctuations in desert extent (e.g., differences in spatial resolution (8 km for the NDVI and 0.5° for the rainfall data), geometric misregistration, interpretation of membership values, etc.), but some discrepancies were large. Most noticeable was that many areas of change detected occurred at sites where the trend in rainfall was the opposite of that expected. Over the period studied, an average of 29.1 percent of the area of inter-annual land-cover conversion identified involved the class label changing in the direction opposite to that expected by the change in rainfall (Plate 2). Undoubtedly, problems in data acquisition, reliability, and interpolation may account for some of these occurrences. With the NDVI data, for instance, key concerns relate to the temporal stability of the sensor, the effect of variable soil backgrounds, and the misregistration in the data sets that can significantly distort the results (e.g., Cihlar *et al.*, 1998; Roy, 2000). There are also uncertainties in the rainfall data (New *et al.*, 1999), time lags in the response of vegetation to rainfall fluctuations (Goward and Prince, 1995), and problems in using a surrogate measure such as vegetation amount derived from the NDVI as an indicator of degradation (Hutchinson, 1996; Thomas, 1997; Nicholson *et al.*, 1998). However, the size of the area affected suggests that the simple link between inter-annual fluctuations in desert extent and rainfall may, at sub-regional scales, perhaps not be as strong as previously believed. Application of the strong relationships observed at the regional scale to finer scales may thus fall foul of the ecological fallacy because the results indicate a significant heterogeneity in the spatial distribution of change intensity and dependence on rainfall. This has implications for the evaluation of the residual variance in the regional scale relationships and consequently the identification and separation of natural and human driving variables of environmental change in drylands.

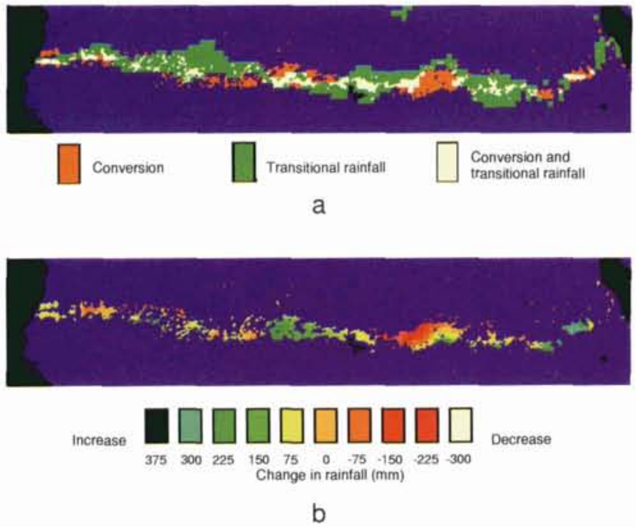


Plate 2. Location of land-cover conversion and key rainfall changes for 1984–85, a period of almost unidirectional desert contraction after the 1984 Sahelian drought with 97.6 percent of conversions being from desert cover. (a) Location of land-cover conversion relative to the zone where change may classically be expected from rainfall data. Masked-out areas in purple represent land for which rainfall was characteristic of desert (i.e., $<100$ mm yr$^{-1}$) and of the Sahel proper ($>200$ mm yr$^{-1}$) in both years. (b) Magnitude of rainfall difference 1984–85 within the area of land-cover conversion. Note that 29.6 percent of the area of land-cover conversion was in the direction opposite to that expected, with a large area of decreased rainfall (up to a 261-mm reduction) associated with lands converting from desert east of Lake Chad.

## Summary and Conclusions

Conventional change-detection studies based on post-classification comparison are constrained to indicate only land-cover conversions. Moreover, in the output of the post-classification comparison, it is implied that any change detected for a pixel applies uniformly to the entire area it represents. Conventional change detection methods, therefore, provide only a restricted view of change. In particular, the conventional approach ignores or misrepresents land-cover modifications, which may include small (sub-pixel scale) transformations. Modifying the conventional approach by replacing the hard classifications with fuzzy ones in which class membership is assessed in a possibilistic rather than probabilistic manner enables a greater degree of information on land-cover change to be detected. The results of an analysis of a time series of imagery show that land-cover changes, including modifications and sub-pixel scale conversions, may be revealed through the comparison of fuzzy image classifications. Moreover, because the approach used was based on a measure of typicality, its calculation is independent of all other land-cover classes which can be advantageous in comparison to the relative measures of class membership (e.g., posterior probabilities) generally used in analyses of remotely sensed data. The land-cover changes observed corresponded to those reported by others at a regional scale, but the spatial patterns observed highlighted dangers in transferring relationships at one scale to another and, in particular, may challenge aspects of the simple link between inter-annual fluctuations in rainfall and desert cover. It was particularly apparent that the conventional approach only indicated land-cover conversion and appeared to generally overestimate the magnitude but underestimate the area of land undergoing change.

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