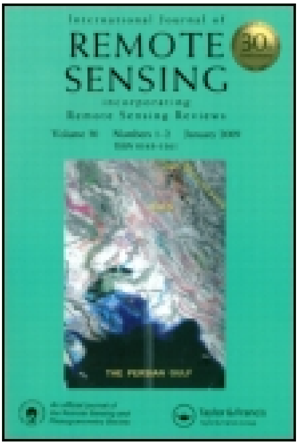
This article was downloaded by: [OARE Consortium]
On: 19 September 2013, At: 02:40
Publisher: Taylor & Francis
Informa Ltd Registered in England and Wales Registered Number: 1072954 Registered office: Mortimer House, 37-41 Mortimer Street, London W1T 3JH, UK



International Journal of Remote Sensing
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/tres20

Assessment of environmental impacts of river basin development on the riverine forests of eastern Kenya using multi-temporal satellite data

J. K. Maingi & S. E. Marsh

Published online: 25 Nov 2010.

To cite this article: J. K. Maingi & S. E. Marsh (2001) Assessment of environmental impacts of river basin development on the riverine forests of eastern Kenya using multi-temporal satellite data, International Journal of Remote Sensing, 22:14, 2701-2729

To link to this article: http://dx.doi.org/10.1080/01431160010031298

PLEASE SCROLL DOWN FOR ARTICLE

Taylor & Francis makes every effort to ensure the accuracy of all the information (the "Content") contained in the publications on our platform. However, Taylor & Francis, our agents, and our licensors make no representations or warranties whatsoever as to the accuracy, completeness, or suitability for any purpose of the Content. Any opinions and views expressed in this publication are the opinions and views of the authors, and are not the views of or endorsed by Taylor & Francis. The accuracy of the Content should not be relied upon and should be independently verified with primary sources of information. Taylor and Francis shall not be liable for any losses, actions, claims, proceedings, demands, costs, expenses, damages, and other liabilities whatsoever or howsoever caused arising directly or indirectly in connection with, in relation to or arising out of the use of the Content.

This article may be used for research, teaching, and private study purposes. Any substantial or systematic reproduction, redistribution, reselling, loan, sub-licensing, systematic supply, or distribution in any form to anyone is expressly forbidden. Terms & Conditions of access and use can be found at http://www.tandfonline.com/page/terms-and-conditions

Downloaded by [OARE Consortium] at 02:40 19 September 2013

INT. J. REMOTE SENSING, 2001, VOL. 22, NO. 14, 2701–2729

Assessment of environmental impacts of river basin development on the riverine forests of eastern Kenya using multi-temporal satellite data

J. K. MAINGI† and S. E. MARSH‡

Arizona Remote Sensing Center, Office of Arid Lands Studies, University of Arizona, Tucson, Arizona 85750, USA

(*Received 23 February 1999; in final form 1 October 1999*)

Downloaded by [OARE Consortium] at 02:40 19 September 2013

Abstract. The utility of Landsat MSS (Multispectral Scanner) and SPOT XS data in monitoring the impacts of river basin development on a riverine forest located in the lower Tana River Basin of eastern Kenya was evaluated. Land cover change maps derived from Landsat MSS indicated little change in total forest area between 1975 and 1984. Land cover change maps derived from SPOT XS data indicated a 27% decline in forest area between 1989 and 1996. Mean patch size and area–perimeter ratio of the closed riverine forest remained virtually unchanged whereas these parameters for the open forest class decreased by 31% and 4% respectively. In addition, the average extent of the open riverine forest from the river channel declined by about 200 m between 1989 and 1996. This decline was attributed to decreased extent of floods along the floodplain following construction of dams in the upper river basin, and increased exploitation of the forests for fuelwood, especially in the vicinity of the established Bura Irrigation and Settlement Project. The greater lateral movement observed in the location of the river channel for the 1975–1985 period, compared to the 1985–1996 period, was also attributed to construction of dams in the upper river basin.

1. Introduction

High population growth rates in many developing countries have led to an increased demand for food, fibre, energy and raw materials. In an attempt to meet these demands, many of these countries have turned to the development of water resources in their river basins. The creation of dams and the establishment of irrigation schemes have become a widespread method of developing water resources in river basins (Sparks 1992, McCully 1996). In Africa, there are dams on virtually all major rivers, and many of these rivers have been targets of other development activities, particularly irrigation schemes (Obeng 1981, Adams 1985, Scudder 1989).

The construction of dams has led to a myriad of complex and interconnected environmental disruptions that have tended to: (1) fragment riverine ecosystems; (2) isolate populations of species living upstream and downstream of the dam; (3) cut

---

† Present address: Institute for Regional Analysis and Public Policy (IRAPP), Morehead State University, Morehead, Kentucky, USA.

‡ e-mail: smarsh@ag.arizona.edu

International Journal of Remote Sensing
ISSN 0143-1161 print/ISSN 1366-5901 online © 2001 Taylor & Francis Ltd
http://www.tandf.co.uk/journals
DOI: 10.1080/01431160010031298

off migrations and other species' movements. Because almost all dams reduce normal flooding, they also fragment ecosystems by isolating the river from its floodplain. The elimination of the benefits provided by natural flooding may be the single most ecologically damaging impact of a dam. This fragmentation of river ecosystems has undoubtedly resulted in a massive reduction in the number of species in the world's watersheds (McCully 1996).

In Africa, elimination of downstream flooding through dam construction has devastated many local production systems. Riverine habitats for floodwater farming (flood recession agriculture) and livestock management have been adversely affected, and fisheries' productivity and hence fish landings for consumption and commercial purposes have been greatly reduced (Adams 1985, Scudder 1989). Where indigenous production activities have been disrupted, the affected communities have responded by adopting self-insurance options to minimize food insecurity and livelihood. Coping options towards food insecurity for many rural populations frequently rely on natural resources outside their usual production system or, alternatively, intensifying exploitation of resources used habitually (Longhurst 1986, Corbett 1988). As a result, many riverine forest ecosystems have been devastated not only through a reduction in floods, but also through increased exploitation by the indigenous populations.

It is important that accurate and timely information on the changing pattern of land cover types be documented in order to better understand the physical and human processes at work. Monitoring land use change is basic to almost any resource management, planning or regional policy programme. Detailed ground-based surveys of large, relatively inaccessible and ecologically complex tropical areas are difficult to accomplish. Remote sensing offers an ideal tool for the mapping and monitoring of such areas, particularly as a means of complementing or updating conventional data gathering techniques (Weaver 1984, Nellis 1986, Baker *et al.* 1991). In these regions, satellite remote sensing may be the only feasible technique to monitor forest clearing, shifting cultivation and land use conversion trends. Access to remote tropical wetlands by surface roads is usually limited, and aerial photography is either non-existent or outdated. Given these conditions, high-resolution satellite imagery can be a valuable source of information on current and changing land use patterns (Sader 1995).

In this work, multi-date Landsat MSS and SPOT HRV XS data, and single-date Landsat Thematic Mapper (TM) data, were analysed to quantitatively document the extent and continuity of the riverine forests and associated land covers along the Tana River floodplain in eastern Kenya. The analysis covered a 21-year period, during which a number of dams were completed in the upper river basin and a large irrigation scheme was initiated in the vicinity of the study area.

2. Study area

The study area is approximately 2400 km^2 and covers the lower floodplain of Kenya's largest river, the Tana. The area includes a 60 km stretch of the river between Nanighi and Makere (figure 1). Rainfall in the study area is bimodal with the long rains occurring in March–May and the short rains occurring in November–December. Rainfall is highly variable and averages about 370 mm per annum. The mean annual temperature is about 28°C.

A riverine forest extending 0.5–3.0 km on either side of the river covers the lower floodplain of the Tana River. The depth of the water table, which drops off rapidly from the edge of the river (Marsh 1978, Hughes 1985), apparently determines the extent of this forest. A drought-deciduous bushland dominated by thorny shrubs

Downloaded by [OARE Consortium] at 02:40 19 September 2013

Downloaded by [OARE Consortium] at 02:40 19 September 2013

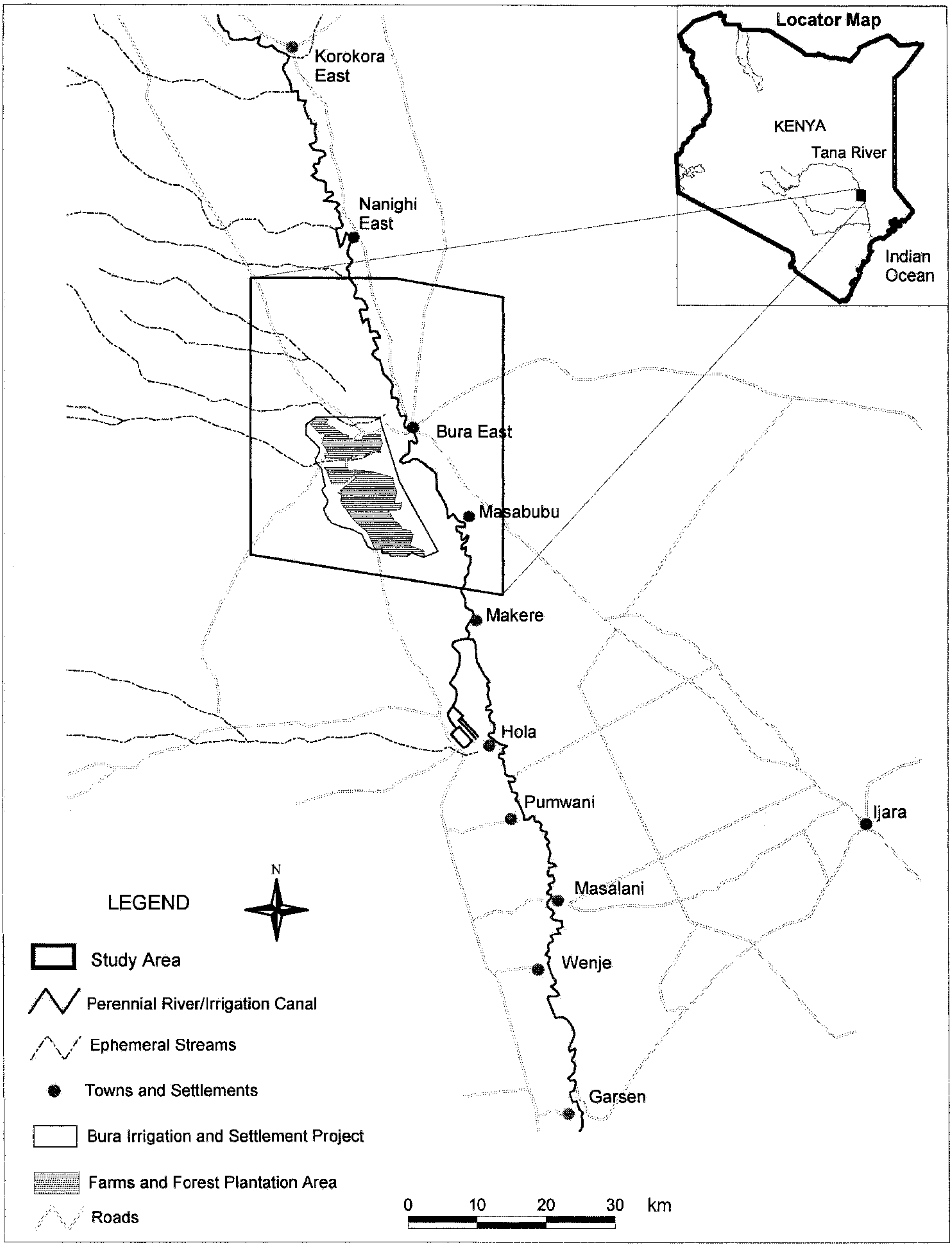


Figure 1. Location and extent of study area and the Bura Irrigation and Settlement Project.

with scattered annual grasses covers extensive areas away from the floodplain. The riverine forest is unique because of its great diversity and occurrence in an otherwise arid environment. The forest is an isolated remnant of a once continuous rainforest belt that extended between the Congo Basin and the eastern coast of Africa during moister periods of the Pleistocene (approximately 31 000–26 000 and 8000 Before Present) (Livingstone (1975) and adapted from Medley (1990)). Severe climatic drying after the hypsithermal (approximately 4000 BP) isolated east African evergreen forests in the highlands and riverine localities (Hamilton 1974, Livingstone 1975).

The Tana riverine forests have a high conservation value since they are home to two endemic subspecies of primate: the Tana River Red Colobus (*Colubus badius rufomitratus*) and the Tana River Mangabey (*Cercocebus galeritus galeritus*). These are classified as 'rare' and 'critically endangered' respectively by the The World Conservation Union (IUCN) (1978). The Tana River poplar (*Populus ilicifolia*) is endemic, occurring in small patches along the Tana, Athi and Ewaso–Nyiro river systems (Dale and Greenway, 1961). It is classified by the IUCN as 'threatened' (IUCN 1978).

The indigenous residents of Tana River basin are the pastoral Orma and the Malakote agriculturalists. The Orma occupy the semi-arid savanna scrubland, but frequently take their livestock to the Tana River to drink water. They are largely dependent on cattle, with lesser numbers of other stock and virtually no camels (Ensminger 1987). On the other hand, the Malakote grow fruits, rice and maize along the point-bars and ox-bow lakes of the Tana River floodplain. The size of area cultivated depends on the magnitude of floods received (Bunger 1979). In addition to the indigenous population, there is a recent settler population of mainly cotton farmers at Bura Irrigation and Settlement Project (BISP).

Recent concern over the condition of the Tana riverine forests of eastern Kenya following a sustained programme of dam building in the upper river basin and the development of the Bura Irrigation Scheme adjacent to the riverine forests indicated a need to assess and monitor this important resource. These developments, coupled with an increasing local population in the study area, have lead to increased pressure on the riverine forests.

3. Background

Satellite data have been used to map forest resources since the inception of the Landsat satellite programme in 1972 (e.g. Newland *et al.* 1980, Likens and Peterson 1981, Khorram 1982, Kouris and Barker 1982, Bucheim *et al.* 1985, Brockhaus and Khorram 1992). The use of multi-spectral satellite images to extract forest attribute information (such as species composition, crown closure, age and forest productivity) has yielded mixed results. These results have ranged from highly successful (Tom and Miller 1980, Congalton *et al.* 1983) to marginally successful (Niemann 1993), depending on the nature of the terrain, forest cover, and study objectives.

Many tropical areas are located in remote locations that are difficult to access by road, and aerial photography is non-existent or outdated. Under such conditions, satellite remote sensing may be the only feasible means of monitoring forest clearing, shifting cultivation and land use conversion trends (Sader 1995). Although heavy cloud cover, common in many tropical regions, has hampered data acquisition from optical satellites, the joint use of data from different operational satellite sensors such as Landsat MSS, Landsat TM and SPOT HRV may provide a solution to partially overcome the acquisition problems. However, a drawback to the multiplicity of data sources is more complicated operational procedures for data analysis.

There have been many remote sensing studies of tropical and subtropical regions since the launch of the first Landsat satellite (e.g. Eden and Parry 1986, Sader *et al.* 1990). Salo *et al.* (1986) used multi-date Landsat MSS images to examine changes on the Ucayali and the Amazon Rivers and associated floodplains in Peru, between 1979 and 1983. In another study of northern Guatemala, multi-date Landsat TM

Downloaded by [OARE Consortium] at 02:40 19 September 2013

Downloaded by [OARE Consortium] at 02:40 19 September 2013

data were used to monitor the spatial characteristics of forest clearing and infer contributing socio-economic factors (Sader 1995).

Jensen *et al.* (1986) found that the timing of image acquisition may be more important than higher spatial and spectral resolution in differentiating wetland areas. In mapping a temperate hardwood forest, Wolter *et al.* (1995) were able to increase classification accuracy from 80.1% to 93.6% by aggregating classes from a species to a forest type level classification. Singh (1987) found that Landsat MSS data could usually be used to distinguish forest from non-forest, but could not differentiate reliably between forest types, grassland and shifting cultivation, or scrub and open forest. In another study of forest deforestation in the Guinea Highlands of west Africa, Gilruth and Hutchinson (1990) found Landsat MSS data inadequate in distinguishing between gallery forests and dense stands of dry forest. Other studies have demonstrated the utility of SPOT HRV and Landsat TM data in the inventory of forest resources with classification accuracies ranging between 70% and 89% (Brockhaus and Khorram 1992, Bauer *et al.* 1994).

The ability to use remotely sensed data to classify land cover accurately is dependent on a robust relationship between the remote sensing signature and actual surface conditions. However, factors such as Sun angle, Earth–Sun distance, detector calibration differences between the various sensor systems, atmospheric condition and Sun–target–sensor (phase angle) geometry will affect pixel brightness value (Jensen, 1996). Image normalization reduces variation in pixel DN (digital number) variation caused by non-surface factors, so that variations in pixel DNs between dates may be related to actual changes in surface conditions. Since quantitative comparisons are mandatory for monitoring changes in Earth's reflectivity, multiple sensor approaches require radiometrically calibrated images (Hill and Aifadopoulou 1990).

4. Methods

4.1. *Data*

A pair of Landsat MSS and SPOT XS data, and a Landsat TM image, were used for this study. These images represented about the only usable satellite data for the study area because of the presence of heavy cloud cover for most of the period under study. The limited availability of usable remotely sensed datasets for the study area meant that it would be impossible to obtain images acquired on exact anniversary dates (for example, June 2 1975 and June 2 1996). Using anniversary date imagery removes seasonal Sun angle and plant phenological differences that can destroy a change detection project (Jensen *et al.* 1993). The discrepancy in seasonal coverage is bound to complicate the change detection process, especially in the areas away from the floodplain that are most greatly impacted by the changing seasons. Fortunately, the riverine forest is mostly evergreen and is not affected significantly by seasonal change. Table 1 lists the sensors and acquisition dates for each of these datasets. Due to the spectral and spatial resolution differences between the Landsat MSS and SPOT XS, only pairs of data from the same sensor were utilized for classification change detection. The Landsat TM data were used in an analysis of changes in the river channel.

4.2. *Satellite data processing*

4.2.1. *Radiometric correction, atmospheric correction and geometric rectification*

All image processing work was performed using ERDAS IMAGINE software (ERDAS 1996). As a first step each satellite image was subjected to radiometric and

Table 1. Satellite data used in this study.

Data type	Satellite	Pixel resolution	Acquisition date
Landsat MSS	Landsat 2	56.5 m × 79.0 m	2 June 1975
Landsat MSS	Landsat 5	56.5 m × 79.0 m	23 April 1984
Landsat TM	Landsat 5	28.5 m × 28.5 m	22 January 1985
SPOT XS	SPOT 1	20.0 m × 20.0 m	12 May 1989
SPOT XS	SPOT 3	20.0 m × 20.0 m	28 March 1996

Downloaded by [OARE Consortium] at 02:40 19 September 2013

atmospheric corrections. The atmospheric and radiometric correction method used in this study was based on the dark object subtraction (DOS) technique discussed by Moran *et al.* (1992) and the COS(TZ) or COST method proposed by Chavez (1996). TZ is the angle of incidence of the direct solar flux onto the Earth's surface (solar zenith angle, theta z). This method is entirely image-based and has been found to be as accurate as those generated by models that use *in situ* atmospheric field measurements and radiative transfer codes (Chavez 1996).

An image-to-map rectification was first performed on a subset (60 km × 40 km) of the 1975 Landsat MSS image covering the study area. A total of 28 Ground Control Points (GCPs) with a total root mean square (RMS) error of 0.474 pixel were located both in the image and on a set of four 1:50 000 topographic maps covering the study area. These reference maps were prepared in 1979 based on aerial photography acquired in 1975, and were therefore current with the 1975 Landsat MSS image. A first-order polynomial and a nearest-neighbour resampling technique were used to rectify the Landsat MSS image.

The rest of the images were all rectified to the georeferenced Landsat MSS sub-scene using a first-order transformation and nearest-neighbour resampling. The Landsat MSS image for 1984 was georefernced using 30 points and a total RMS error of 0.269. The SPOT XS image for 1989 was georeferenced using 29 points and a total RMS error of 0.230, while the 1996 image was registered using 27 points and a total RMS error of 0.281.

4.3. *Land cover classification*

An unsupervised classification of the digital satellite images was used to produce land cover classes. Supervised classification techniques were found to be inadequate because of the extreme complexity of the forest cover. Multi-temporal Principal Components Analysis (PCA) was also performed but the resulting principal component images were not easily interpretable.

The Iterative Self-Organizing data Analysis Technique (ISODATA) (Tou and Gonzalez 1977, Sabins 1987, Jain 1989) was the clustering algorithm used in the unsupervised classification. All spectral bands in each image were used in the unsupervised classification. Before land cover classification could begin, clouds and shadows present in the Landsat MSS data had to be removed. An unsupervised classification of the Landsat MSS images with eight clusters resulted in optimum discrimination of cloud and cloud shadow. Both SPOT images were cloud-free and therefore did not require cloud masking.

Each Landsat MSS and SPOT XS image was then subjected to an unsupervised classification to produce four separate land cover maps. The production of each land cover map involved at least three separate steps: (1) an initial unsupervised classification of the entire image; (2) an unsupervised classification of the floodplain area; and (3) combining the results of the two separate classifications into a final land cover map.

In the first step, a classification of the entire image was performed and each of the resulting clusters evaluated and assigned to one of our targeted land cover classes (table 2). An initial 16 and 20 clusters were requested for Landsat MSS and SPOT XS images respectively. The majority of clusters in each classified image were found to belong to the non-floodplain area, while only up to three clusters were from the river floodplain. When the number of clusters requested in the unsupervised classification was raised to 30, the majority of the resulting classes still remained non-floodplain and therefore we decided not to request more clusters than our initial 16 Landsat MSS and 20 SPOT XS images. After the initial classification, the few clusters

Table 2. Land cover types for satellite-derived land cover maps.

Land cover	Code	Description
River	1	Includes the Tana River, associated meander scars and ox-bow lakes
Closed Riverine Forest	2	Generally closer to the river channel than open forest and has a higher density of trees; little light filters to the forest floor; little or no understorey vegetation
Open Riverine Forest	3	Lower density of trees compared to the closed forest; more sunlight reaches the forest floor; much further from the river channel than closed floor; *Acacia elatior* common with a perennial grass understorey
Transitional Woodlands	4	Lies to the outside of the open forest away from river channel; has species characteristic of both the riverine forest and the dense scrub/bushland class; trees rarely above 9 m; perennial grass understorey
Dense Scrub/Bushland	5	Common especially in non-floodplain areas; typically stands of *Acacia* and *Commiphora* spp.; less than 3 m in height. Ground layer covered by grass; bushland describes an impoverished woodland towards the edge of the floodplain that flood through Laga overflows; typical species include *Salvadora persica*, *Dobera glabra*, *Lawsonia inermis*, and *Grewia* spp.
Low Scrub/Herbaceous Vegetation	6	Sparsely distributed low-lying scrub species usually less than 1 m; typical species include *Acacia mellifera*, *A. reficiens* and *Salsola dendroides*; ground usually bare or covered by annual grasses
Bare Ground	7	Has mostly exposed soil and only briefly covered by herbaceous vegetation immediately following the biannual rains
Flooded Areas/Earth dams	8	Floodplain areas flooded through ephemeral streams; laga areas; earth dams and water storage reservoirs; freshly irrigated fields
Cultivated Riverine Areas	9	Identifiable in SPOT (XS)-derived land cover maps; typically within 100 m of river channel

Downloaded by [OARE Consortium] at 02:40 19 September 2013

Downloaded by [OARE Consortium] at 02:40 19 September 2013

that included the floodplain were re-coded and used to mask out the non-floodplain classes from the original 4-band and 3-band Landsat MSS and SPOT images respectively.

In the second step, the image containing only the floodplain area underwent an unsupervised classification to produce 12 clusters. These clusters were then evaluated, and each assigned to one of the floodplain land cover classes (e.g. river, closed riverine forest, open riverine forest, transitional woodland). The last step involved joining the two separate classifications into a land cover map with eight classes.

For the Landsat MSS classifications, aerial photographs acquired in 1975 at a scale of 1:50 000 were used to aid in labelling the clusters. In addition, a Modified Soil-Adjusted Vegetation Index (MSAVI) was computed for each image (Qi *et al.* 1994) and used to calculate the mean and standard deviation of MSAVI values of each cluster. The MSAVI statistics for the clusters were used as an additional aid in identifying clusters that represented various levels of vegetated and non-vegetated areas.

A major goal of the land cover characterization was to map cultivated areas within the riverine forest. Although spatially distinctive, cultivated areas within the riverine forest were found to be spectrally indistinct, and were invariably classified as dense scrub. However, because such cropped areas are always next to the river or around ox-bow lakes, a 100 m buffer was applied to the river class in the SPOT images. Any dense scrub class that fell within this buffer was re-classified as cultivated land. Because of the coarser Landsat MSS spatial resolution, it was not possible to try to separate cultivated areas from dense scrub in the manner described for the SPOT HRV XS images.

Nine land cover classes were targeted for mapping in the SPOT XS data and eight for Landsat MSS data. Eight of the classes were common to both data types but the SPOT classified images had an extra class: cultivated riverine areas. Table 2 lists and describes these classes. The classification scheme described in table 2 was developed during a 1-year ecological survey in the study area by the primary author in 1995 (Maingi 1998). Ultimately, the dense scrub and low scrub classes could not be distinguished consistently due to the seasonal differences in their appearance and were therefore combined into a general scrub class.

4.4. *Classification accuracy assessment*

Once the final land cover classes were obtained, each image was filtered using a 3 × 3 majority filter in order to reduce noise in the classification. A classification accuracy assessment was then performed on the land cover maps for 1975, 1989 and 1996. The accuracy assessment for 1975 was carried out using aerial photographs acquired in 1975 at a scale of 1:50 000. Another set of photographs acquired in 1989 at a scale of 1:20 000 was used for accuracy assessment of the 1989 SPOT land cover map. The classification accuracy of the 1996 land cover map was evaluated using a random sample of GCPs selected during fieldwork in 1995 and located using a hand-held global positioning system (GPS).

An accuracy assessment was performed for the following land cover classes; river, closed and open forest, transitional woodland, scrub class (with the dense scrub and low-density scrub classes merged), bare ground, and cultivated area. Twenty random points were generated for each class to conduct the accuracy assessment. This brought the total number of random points in the Landsat MSS image to 120, and that for each of the two SPOT land cover images to 140 points. The result of the

Downloaded by [OARE Consortium] at 02:40 19 September 2013

classification accuracy assessment was a matrix showing errors of omission (producer's accuracy) and commission (user's accuracy) and a Kappa coefficient (Cohen 1960, Congalton *et al.* 1983, Rosenfield and Fitzpatrick-Lins 1986).

Overall map accuracy is computed by dividing the total correct (obtained by summing the major diagonal of the error matrix) by the total number of pixels in the error matrix. The accuracy of individual categories is computed by dividing the number of correct pixels in a category by either the total number of pixels in the corresponding row or the corresponding column (Congalton 1991). When the number of correct pixels in a category is divided by the total number of pixels in the corresponding row (i.e. the total number of pixels that were classified in that category), the result is an accuracy measure called 'user's accuracy', and is a measure of commission error. 'User's accuracy', or reliability, is indicative of the probability that a pixel classified on the map actually represents that category on the ground (Story and Congalton 1986). On the other hand, when the correct number of pixels in a category is divided by the total number of pixels in the corresponding column (i.e. the total number of pixels for that category in the reference data), the result is called 'producer's accuracy'. 'Producer's accuracy' indicates the probability of a reference pixel being correctly classified and is really a measure of omission error.

Overall accuracy uses only the main diagonal elements of the error matrix, and, as such, it is a relatively simple and intuitive measure of agreement. On the other hand, because it does not take into account the proportion of agreement between datasets that is due to chance alone, it tends to overestimate classification accuracy (Congalton and Mead 1983, Congalton *et al.* 1983, Rosenfield and Fitzpatrick-Lins 1986). Kappa coefficient (KHAT) is another measure of accuracy or agreement. KHAT accuracy has come into wide use because it attempts to control for chance agreement by incorporating the off-diagonal elements as a product of the row and column marginals of the error matrix (Cohen 1960). Verbyla (1995) gives a formula for computing KHAT:

$$\hat{K} = \frac{\text{Overall Classification Accuracy} - \text{Expected Classification Accuracy}}{1 - \text{Expected Classification Accuracy}} \qquad (1)$$

Each pair of land cover images obtained from the same sensor was then compared class-by-class for changes. The resulting change image was colour coded to display changes that were of interest in this study. These changes involved the forest classes, the transitional woodlands and cultivated areas within the floodplain. A summary of area changes (in hectares) for each change image class was produced. Change images for the 1975–1984 and the 1989–1996 periods were produced separately because of the great differences in spatial resolution of Landsat MSS and SPOT XS.

5. Results

5.1. *Classification accuracy assessment*

Results of the 1975 land cover map classification accuracy assessment are presented in table 3. Overall classification accuracy was 85% and the overall Kappa statistic was 0.82. Although the producer's accuracy for the closed forest is high (93.3%), the user's accuracy is much lower (70%). This means that, although 93.3% of the closed forest pixels were correctly identified as closed forest, only 70% of the areas labelled closed forest were actually closed forest. The open riverine forest class has a producer's accuracy of 73.9% but a higher user's accuracy (85%). This can be interpreted in the same way as that for the closed forest class. The implication of

Table 3. Error matrix of the 1975 land cover map derived from Landsat MSS data.

	Reference data						
Classified data	1	2	3	4	5	6	Classified total
1. River	**20**	0	0	0	0	0	**20**
2. Closed Riverine Forest	0	**14**	6	0	0	0	**20**
3. Open Riverine Forest	0	1	**17**	2	0	0	**20**
4. Transitional Woodlands	0	0	0	**20**	0	0	**20**
5. Scrub	0	0	0	0	**20**	0	**20**
6. Bare Ground	0	0	0	0	9	**11**	**20**
Reference total	**20**	**15**	**23**	**22**	**29**	**11**	**120**

Land cover class	Reference totals	Classified totals	Number correct	Producer's accuracy (%)	User's accuracy (%)	Kappa statistics
1. River	20	20	20	100	100	1
2. Closed Riverine Forest	15	20	14	93.3	70.0	0.66
3. Open Riverine Forest	23	20	17	73.9	85.0	0.81
4. Transitional Woodlands	22	20	20	90.9	100	1
5. Scrub	29	20	20	69.0	100	1
6. Bare Ground	11	20	11	100	55.0	0.50
Total	120	120	102			

Overall classification accuracy = 85.0%

Overall Kappa statistics = 0.82

Downloaded by [OARE Consortium] at 02:40 19 September 2013

these figures is that there are a significant amount of mis-classified pixels in the forest class with a larger number of such pixels in the closed forest class. As a result, the area classified as closed riverine forest is exaggerated. This result has implications in the results obtained from the change detection procedure discussed in §5.2.

Although the bare ground class has a perfect producer's accuracy (100%), it has the lowest user's accuracy (55%). This means that all pixels belonging to the bare ground class were correctly identified as bare ground, but only 55% of the areas labelled bare ground were actually bare ground. Wet irrigated fields and flooded areas along ephemeral streams were most probably mis-classified as bare ground.

Classification accuracy assessment results for the 1989 land cover map are presented in table 4. The overall classification accuracy and Kappa statistics are very similar to those observed for the 1975 map. Producer's and user's classification accuracy for both closed and open riverine forest classes are 90% and 80% respectively. The accuracy for the forest classes is therefore better than was the case with the Landsat MSS derived land cover map. The lowest user's accuracy is for the transitional woodland class (65%) and the bare ground class (70%).

Although 92.9% of all transitional woodland pixels were correctly identified as transitional woodland, only 65% of the areas called transitional woodland were actually transitional woodland. Likewise, 100% of bare ground pixels were correctly identified as bare ground, whereas, only 70% of all areas called bare ground were actually bare ground.

Downloaded by [OARE Consortium] at 02:40 19 September 2013

Table 4. Error matrix of the 1989 land cover map derived from SPOT HRV-1 XS data.

	Reference data							
Classified data	1	2	3	4	5	6	7	Classified total
1. River	**20**	0	0	0	0	0	0	**20**
2. Closed Riverine Forest	0	**18**	1	0	1	0	0	**20**
3. Open Riverine Forest	0	2	**16**	1	1	0	0	**20**
4. Transitional Woodlands	0	0	2	**13**	5	0	0	**20**
5. Scrub	0	0	0	0	**20**	0	0	**20**
6. Bare Ground	0	0	1	0	5	**14**	0	**20**
7. Cultivated Riverine Areas	0	0	0	0	1	0	**19**	**20**
Reference total	**20**	**20**	**20**	**14**	**33**	**14**	**19**	**140**

Land cover class	Reference totals	Classified totals	Number correct	Producer's accuracy (%)	User's accuracy (%)	Kappa statistics
1. River	20	20	20	100	100	1
2. Closed Riverine Forest	20	20	18	90.0	90.0	0.88
3. Open Riverine Forest	20	20	16	80.0	80.0	0.77
4. Transitional Woodlands	14	20	13	92.7	65.0	0.61
5. Scrub	33	20	14	60.6	100	1
6. Bare Ground	14	20	14	100	70.0	0.67
7. Cultivated Riverine Areas	19	20	19	100	95.0	0.94
Total	140	140	120			

Overall classification accuracy = 85.7%

Overall Kappa statistics = 0.83

Results for classification accuracy assessment of the 1996 map derived from SPOT XS data are shown in table 5. The overall classification accuracy was higher (93.6%) than that obtained for the 1989 map. User's accuracy for all land class categories was 85% and above. All classes are well classified. The most likely explanation for the higher classification accuracy compared to that for the 1989 map is the absence of flooded ground in the 1996 image. The 1996 image was acquired towards the end of the dry season (March). During that time, there was neither local rainfall, nor was the Tana River flooded. These results confirm that the best satellite imagery for mapping land cover along the Tana River floodplain is that from the dry season.

5.1.1. *Sample size for accuracy assessment*

An additional task related to the classification accuracy assessment described in §5.1 was to determine the confidence intervals of the overall accuracy values obtained for each land cover map. An equation based on binomial probability theory that relates classification accuracy assessment sample size to overall classification accuracy and allowable error was used to calculate the error on the accuracy of each land

Downloaded by [OARE Consortium] at 02:40 19 September 2013

Table 5. Error matrix of the 1996 land cover map derived from SPOT HRV-3 XS data.

	Reference data							
Classified data	1	2	3	4	5	6	7	Classified total
1. River	**20**	0	0	0	0	0	0	**20**
2. Closed Riverine Forest	0	**18**	1	0	1	0	0	**20**
3. Open Riverine Forest	0	2	**17**	0	1	0	0	**20**
4. Transitional Woodlands	0	0	3	**17**	0	0	0	**20**
5. Scrub	0	0	0	0	**20**	0	0	**20**
6. Bare Ground	0	0	0	0	0	**20**	0	**20**
7. Cultivated Riverine Areas	0	0	0	0	1	0	**19**	**20**
Reference total	**20**	**20**	**21**	**17**	**23**	**20**	**19**	**140**

Land cover class	Reference totals	Classified totals	Number correct	Producer's accuracy (%)	User's accuracy (%)	Kappa statistics
1. River	20	20	20	100	100	1
2. Closed Riverine Forest	20	20	18	90.0	90.0	0.88
3. Open Riverine Forest	21	20	17	86.0	85.0	0.82
4. Transitional Woodlands	17	20	17	100	85.0	0.82
5. Scrub	23	20	20	87.0	100	1
6. Bare Ground	20	20	20	100	100	1
7. Cultivated Riverine Areas	19	20	19	100	95.0	0.94
Total	140	140	131			

Overall classification accuracy = 93.5%

Overall Kappa statistics = 0.93

cover map (van Genderen and Lock 1977, Fitzpatrick-Lins 1981, Marsh *et al.* 1994). The equation is:

$$N = \frac{Z^2 pq}{E^2} \tag{2}$$

where N is the number of samples, Z is the standard normal deviate for the 95% two-tail confidence level (1.96), p is the expected or calculated accuracy (in per cent), q is $100-p$ and E is allowable error.

In this case, what needed to be determined was the allowable error, E, for the sample points used and the calculated overall classification accuracy assessment. For the 1975 land cover map, 120 sample points were used for classification accuracy assessment, while 140 sample points per land cover map were used for the 1989 and 1990 maps. Allowable errors (at the 95% confidence interval) for the classification accuracy assessment samples of the various land cover maps were:

$$E = ((1.96^2 \times 85.0 \times 15.0)/120)^{-0.5} = 6.39\% \text{ (1975 land cover map)}$$

$$E = ((1.96^2 \times 85.7 \times 14.3)/140)^{-0.5} = 5.80\% \text{ (1989 land cover map)}$$

$$E = ((1.96^2 \times 93.5 \times 6.5)/140)^{-0.5} = 4.08\% \text{ (1996 land cover map).}$$

Downloaded by [OARE Consortium] at 02:40 19 September 2013

Determination of the overall classification accuracy of each land cover map, at the 95% confidence interval, is therefore:

$$(85.0 \pm 6.39)\% \text{ (1975 land cover map)}$$

$$(85.7 \pm 5.80)\% \text{ (1989 land cover map)}$$

$$(93.5 \pm 4.08)\% \text{ (1996 land cover map).}$$

5.2. *Land cover change*

5.2.1. *Landsat MSS 1975–1984*

Results of the 1975 and 1984 land cover mapping and change analysis are summarized in table 6. The results indicate that between 1975 and 1984, there was ≈32% decline in closed riverine forest and ≈20% increase in open riverine forest. However, these changes are more of a reflection of the inability of Landsat MSS data to reliably discriminate between the two forest types than actual changes. This assertion is supported by the higher errors of omission and commission observed in the closed and open forest classes for the land cover maps (1975 and 1984). When the two forest classes are merged, there is only a 2% decline in total area. Land cover maps derived from the 1975 and 1984 Landsat MSS images are not shown in this paper because there was little change in overall forest cover.

Transitional woodlands show an increase of 3.8% between 1975 and 1984. Most of this increase is from open riverine forests changing to transitional woodland and some of the areas within the floodplain that were mapped as dense scrub developing into an open riverine forest.

There was a 13.5% decline in the dense scrub class between 1975 and 1984. Most of the loss was to the low scrub or bare ground classes. One likely explanation for the observed decrease is the construction of the BISP. Contractors for the project cleared about 10 000 ha of dense scrub/bushland class to make way for the irrigation scheme. Another factor likely to contribute to the apparent reduction in the dense scrub class is the prevailing drought towards the end of 1983 and in the beginning of 1984.

The area classified as bare ground increased by about 40% between 1975 and 1984. Most of this increase is from the low scrub/herbaceous vegetation. However, because of the low user's accuracy for this class (55%), it is clear that there are many areas incorrectly identified as bare ground. The most likely explanation is flooding within various land cover types causing them to be mis-classified. Where increases in bare ground are real, the likely explanation is the construction of the BISP and the prevailing dry conditions in 1984. Farmers and workers interviewed at the irrigation scheme during the field phase of this study in 1995 said they recalled frequent dust storms in the period 1981–1985.

5.2.2. *SPOT HRV XS 1989–1996*

The 1989 SPOT XS image was acquired in the middle of the long rainy season in 1989 and therefore vegetation in the non-floodplain area was very lush. On the other hand, the 1996 SPOT XS image was acquired in the dry season, just prior to the long rainy season. As a result most of the non-floodplain areas had very little actively growing vegetation. This means that some of the changes in the non-floodplain classes between 1989 and 1996 could be attributed to differences in season. Fortunately, the riverine forests, which are of the greatest interest in this study, are

Downloaded by [OARE Consortium] at 02:40 19 September 2013

Table 6. Land cover (in hectares) change matrix for the 1975 and 1984 maps derived from Landsat MSS data.

	1984								
1975	1	2	3	4	5	6	7	8	Total
1. River	466.4	80.3	134.8	59.8	241.9	87.9	28.6	43.3	1143.1
2. Closed Riverine Forest	134.8	1146.2	1190.4	260.2	187.5	25.4	6.2	18.3	2969.1
3. Open Riverine Forest	137.0	488.8	1789.4	840.0	519.1	103.1	6.2	141.9	4025.6
4. Transitional Woodland	35.3	92.8	982.0	1481.9	808.3	154.4	4.9	452.2	4011.8
5. Dense Scrub/Bushland	180.3	215.6	615.1	960.5	49 889.4	25 125.5	16 660.9	824.0	94 471.3
6. Low Scrub/Herbaceous Vegetation	10.7	5.8	69.6	185.2	19 240.8	14 014.5	10 437.4	1697.5	56 661.6
7. Bare Ground	4.0	0.9	6.7	7.1	7591.5	8571.7	11 781.9	114.3	28 078.1
8. Floodeed Ground/Earth Dams	5.8	1.3	40.2	370.0	3216.4	2335.3	381.2	1506.9	7857.1
Total	974.4	2031.8	4828.2	4164.9	81 695.0	50 417.9	39 307.4	4798.3	188 217.8

Land cover type	1975	1984	Change	Per cent change
1. River	1143.1	974.4	−168.7	−14.8
2. Closed Riverine Forest	2969.1	2031.8	−937.3	−31.6
3. Open Riverine Forest	4025.6	4828.2	802.5	19.9
4. Transitional Woodland	4011.8	4164.9	153.1	3.8
5. Dense Scrub/Bushland	94 471.3	81 695.0	−12 776.3	−13.5
6. Low Scrub/Herbaceous Vegetation	45 661.6	50 417.9	4756.3	10.4
7. Bare Ground	28 078.1	39 307.4	11 229.3	40.0
8. Flooded Ground/Earth Dams	7857.1	4798.3	−3058.8	−38.9
Total Forest (Closed and Open)	6994.8	6860.0	−134.8	−1.9

evergreen and therefore are not as affected by differences in season of acquisition of satellite imagery.

Land cover maps derived from the 1989 and 1996 SPOT XS images are shown in figures 2 and 3 respectively. These maps show the south-eastern quarter of the

Downloaded by [OARE Consortium] at 02:40 19 September 2013

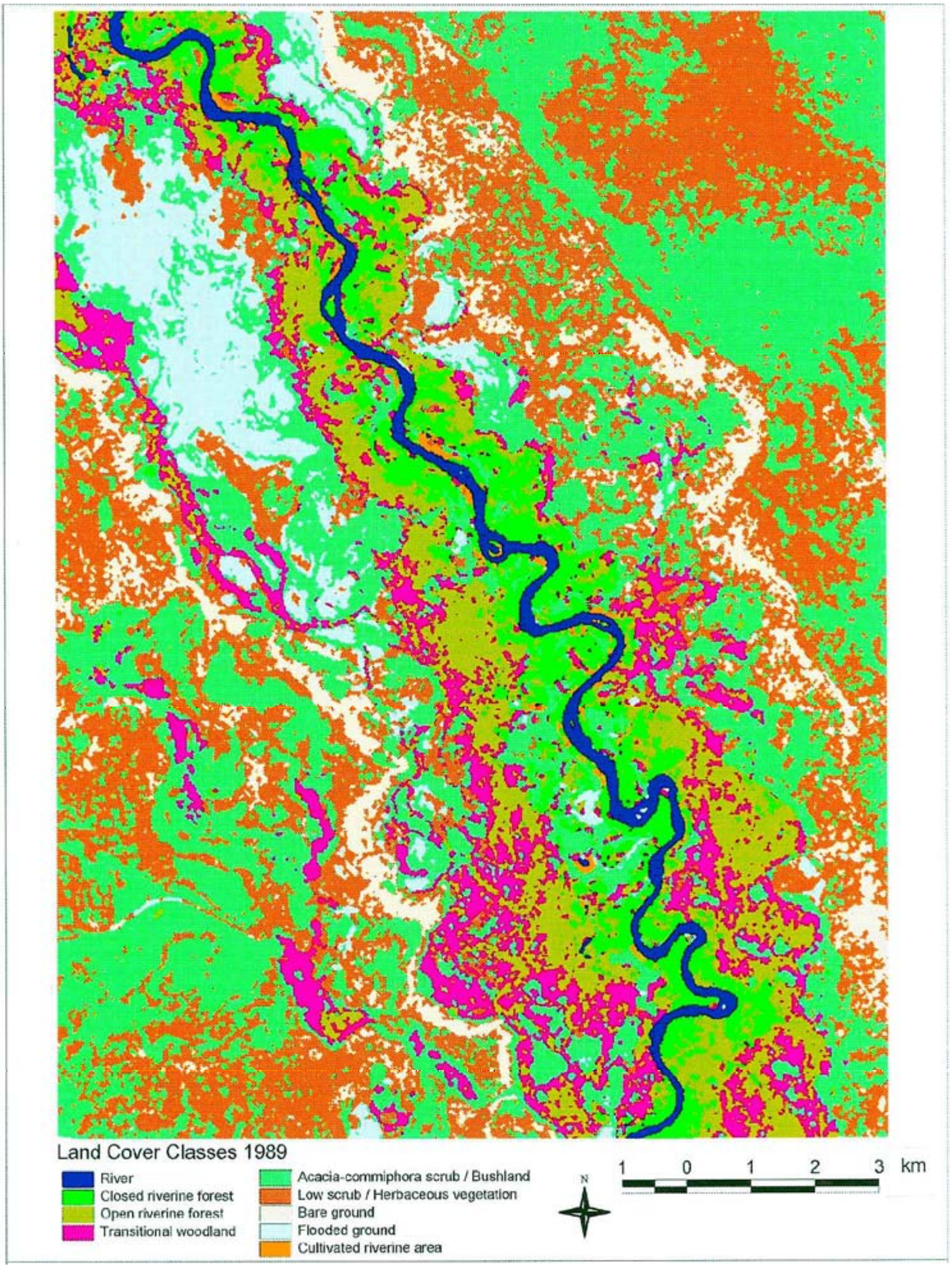


Figure 2. A subset of a land cover map for the study area derived through an unsupervised classification of a 1989 SPOT XS image.

Downloaded by [OARE Consortium] at 02:40 19 September 2013

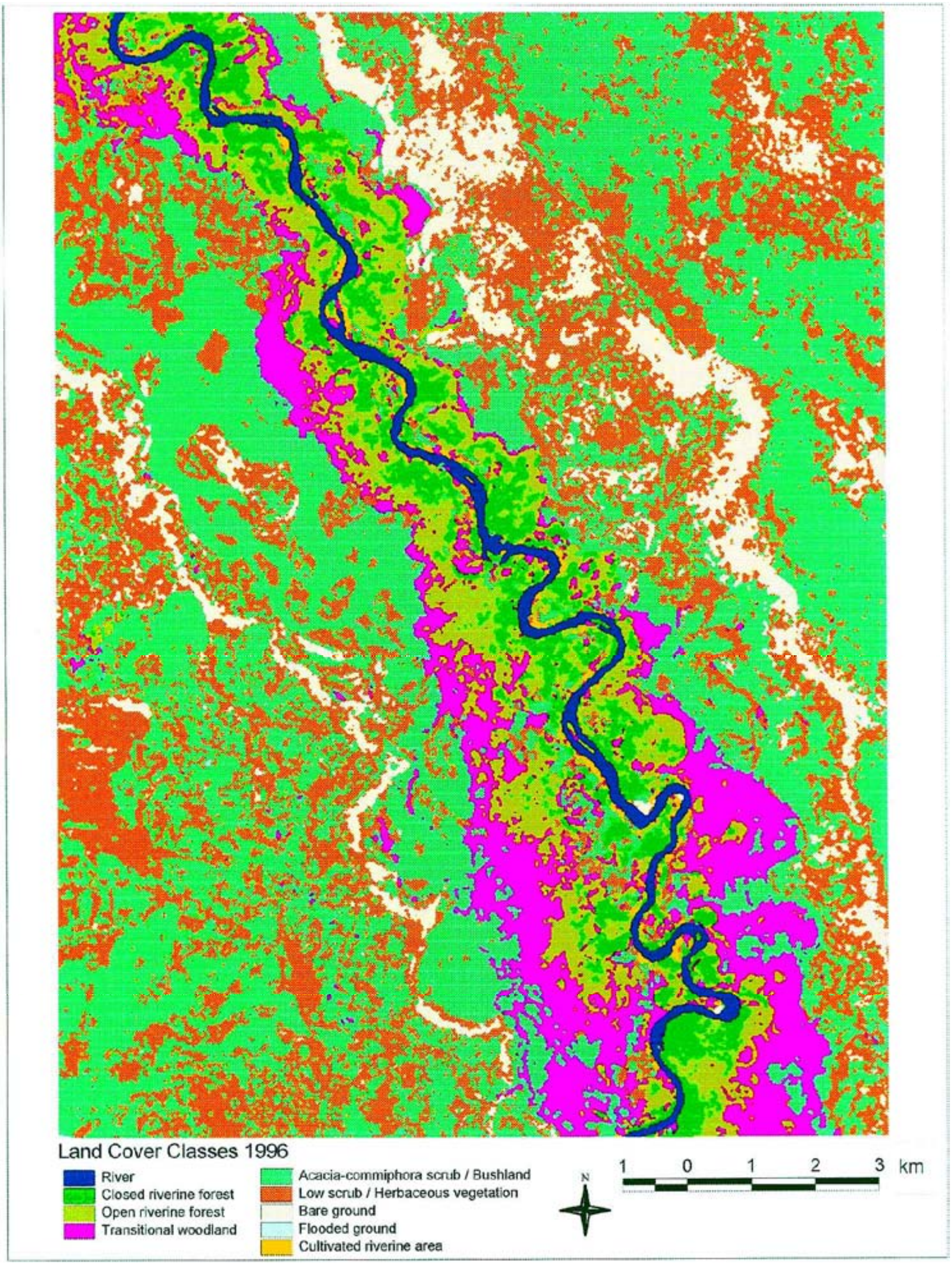


Figure 3. A subset of a land cover map for the study area derived through an unsupervised classification of a 1996 SPOT XS image.

study area (figure 1), and are displayed at a scale of approximately 1:100 000. Table 7 summarizes changes by land cover type between 1989 and 1996.

A change matrix map for the 1989–1996 period is shown in figure 4. The change map shows three types of change: (1) 'negative forest change' refers to a loss of forest (either dense or open) to any other class; (2) 'negative change in transitional

Downloaded by [OARE Consortium] at 02:40 19 September 2013

Table 7. Land cover (in hectares) change matrix for the 1989 and 1996 maps derived from SPOT HRV XS data.

	1996									
1989	1	2	3	4	5	6	7	8	9	Total
1	843.4	52.2	85.1	43.5	40.1	16.0	17.6	0.5	87.3	1185.8
2	83.6	1246.8	678.7	183.0	143.6	46.8	1.0	0.1	82.2	2465.9
3	35.3	535.6	2341.9	1933.0	682.4	48.9	0.5	0	33.0	5610.5
4	13.8	25.8	523.0	1799.0	1964.1	736.9	7.9	0	22.5	5093.0
5	20.0	96.2	242.2	889.0	28 714.4	30 597.5	4988.6	13.6	29.6	65 591.1
6	1.2	4.1	14.1	134.0	18 782.0	49 822.3	17 305.7	1.1	5.4	86 069.9
7	0.5	1.1	0.6	6.3	1199.1	4129.5	10 260.1	1.5	3.8	15 602.6
8	6.2	7.9	12.0	47.4	2271.6	3327.8	526.0	1.4	4.9	6205.2
9	26.4	11.4	60.3	25.3	25.7	14.5	1.8	0	63.0	228.4
Total	1030.4	1981.2	3958.0	5060.5	53 823.0	88 740.2	33 109.1	18.3	331.7	188 052.3

Land cover type	1989	1996	Change	Per cent change
1. River	1185.8	1030.4	−155.4	−13.1
2. Closed Riverine Forest	2465.9	1981.2	−484.8	−19.7
3. Open Riverine Forest	5610.5	3958.0	−1652.5	29.5
4. Transitional Woodland	5093.0	5060.5	−32.5	−0.6
5. Dense Scrub/Bushland	65 591.1	53 823.0	−11 768.1	−17.9
6. Low Scrub/Herbaceous Vegetation	86 069.9	88 740.2	2670.2	3.1
7. Bare Ground	15 602.6	33 109.1	17 506.6	112.2
8. Flooded Ground/Earth Dams	6205.2	18.3	−6186.9	−99.7
9. Cultivated Riverine Areas	228.4	331.7	103.3	45.2
Total Forest (Closed and Open)	8076.4	5939.1	−2173.3	−26.5

Downloaded by [OARE Consortium] at 02:40 19 September 2013

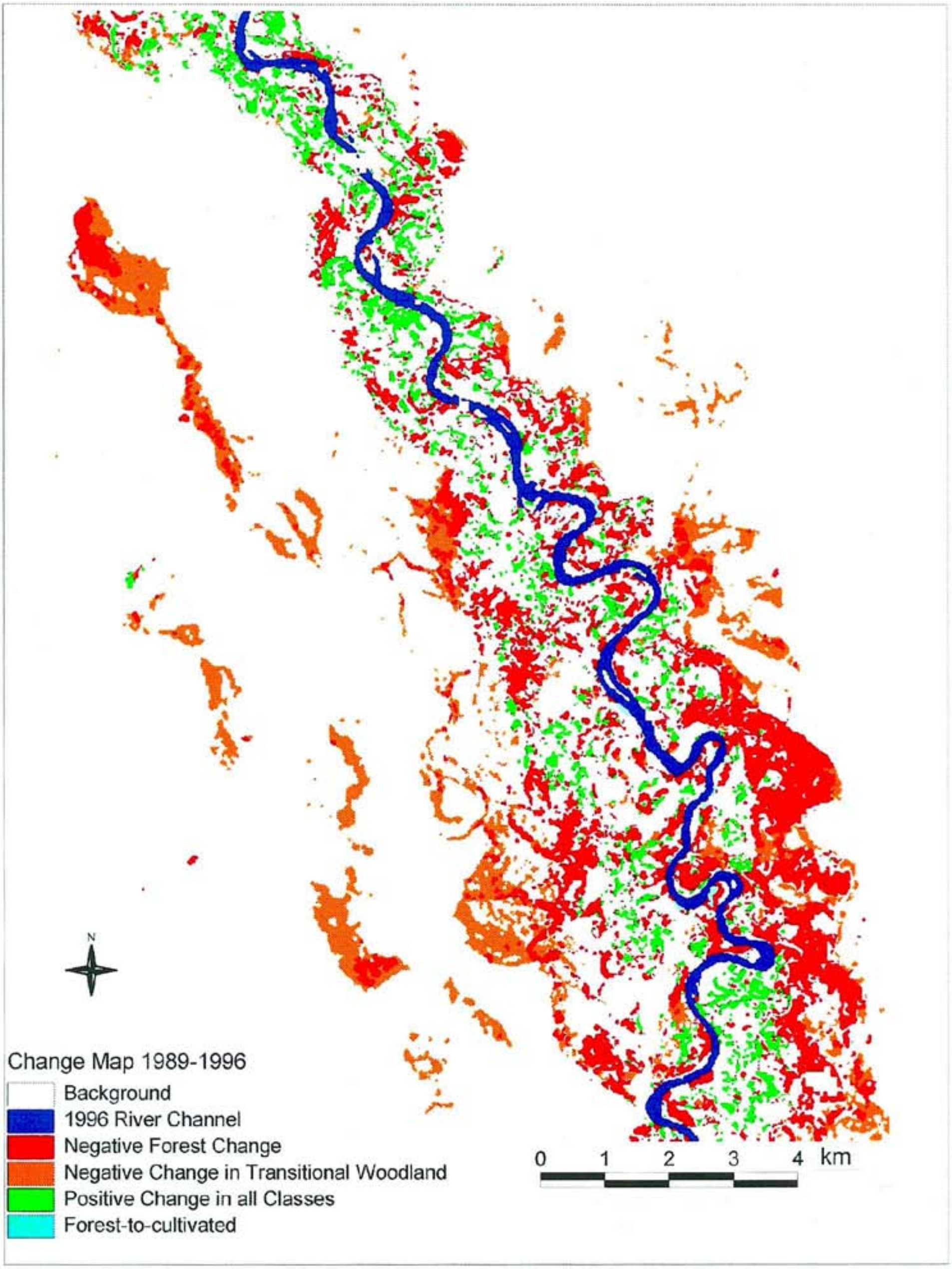


Figure 4. A subset of the 1989–1996 change map derived from 1989 and 1996 land cover maps.

woodland' refers to a loss of transitional woodland to any class other than forest, thereby resulting in a decrease in overall biomass; (3) 'positive change in all classes' refers to any change that involved an increase in biomass. Class categories 2–7 are arranged in a decreasing order of biomass (from dense forest to bare ground) and therefore any change from a lower class (for example bare ground) to a higher class

Downloaded by [OARE Consortium] at 02:40 19 September 2013

(any class from dense forest to the low scrub) would be considered a positive change. It is worth noting that the positive changes shown in figure 4 mostly involve the non-forest classes, this indicating that there has been little forest re-growth. The 'Background' category refers to pixels showing no change in land cover class between 1975 and 1984 or those that indicated changes other than those shown in the change map (figure 4).

There was a 20% decline in closed forest between 1989 and 1996. Most of this loss was to open forest. In turn, the open forest lost about 30% of its area to the transitional woodland and to the dense scrub class. However, the gain in area of the transitional woodland class was more than balanced by a loss to the dense scrub and low scrub classes. The overall change in area of the transitional woodland class remained negligible (−0.6%).

The dense scrub class showed an 18% decline between 1989 and 1996, with most of the loss going to the low scrub class. As a result, the area of the low scrub class increased by 3.1% within the same period. There was a large increase (112%) in the area mapped as bare ground between 1989 and 1996. However, some the increase in the bare ground class can be attributed to the differences in the seasonality of the images. The bulk of the increase was from the low scrub class and to a lesser extent from the dense scrub class. Cultivated riverine area increased by 45% between 1989 and 1996. Most of the cultivated area came from areas that were previously part of the river class in 1989 and the rest came from conversion from closed and open forest.

In the past, the Malakote farmers would only cultivate on suitable areas along point-bars and ox-bow lakes as the floods subsided. Field interviews (Maingi 1998) indicated that the farmers have little faith left in natural flooding of the river and have resorted to using small diesel pumps to help irrigate their crops. As a result, farmers are clearing increasingly larger areas of forest. Since these farmers have few resources with which to purchase fertilizers, it is likely that once nutrients are exhausted in these farms, they will be abandoned for new ones. Cropped areas as mapped in this study represent areas that had actively growing crops at the time the images were acquired. Most of the disturbed forest areas were also mapped, but in the general category of scrub. The new trend toward irrigated agriculture represents a major threat to the survival of the riverine forest ecosystem.

5.3. *River channel changes (1975–1996)*

River channel classes derived from the 1975 Landsat MSS, 1985 Landsat TM and the 1996 SPOT XS images were overlaid in order to map changes in channel location and morphology. The 1985 Landsat TM image was used instead of the 1984 Landsat MSS image because the latter had cloud cover on several sections of the river channel. Figure 5 shows the 1975 and 1985 river channels overlaid, whereas figure 6 shows that for 1985 and 1996 channels. Changes in river location and morphology were more pronounced in the 1975–1985 period than those observed for the 1985–1996 period. River channel locations corresponding to the period 1989–1996 are not shown here as there was very little change.

The greater change in channel position observed in 1975–1985, compared to 1985–1996, could be best explained as a result of the construction of the Masinga Dam (completed in November 1981). The period 1975–1984 is mostly pre-Masinga Dam and is characterized by an active river channel meandering across its floodplain. The fewer changes in channel position observed in the 1985–1996 period are consistent with decreased meandering associated with damming of rivers.

Downloaded by [OARE Consortium] at 02:40 19 September 2013

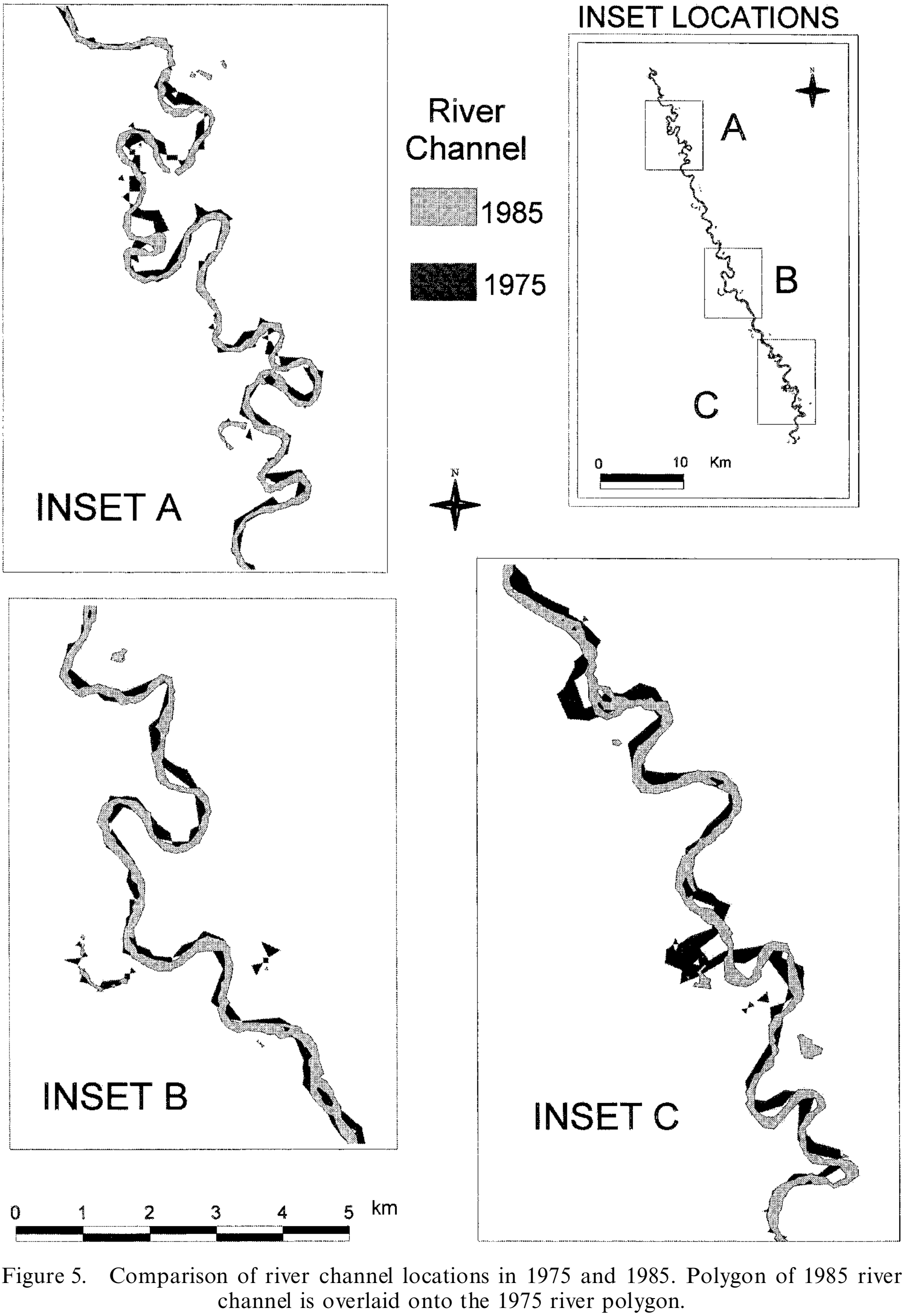


Figure 5. Comparison of river channel locations in 1975 and 1985. Polygon of 1985 river channel is overlaid onto the 1975 river polygon.

As is often the case below dams, a river lowers its bed and deepens its channel (incised) as a result of the upstream dams capturing most of the river's sediment. Lateral migration of the Tana River appears to have been reduced in the 1985–1996 period, suggesting that that some incision had taken place already. A new, deeper

Downloaded by [OARE Consortium] at 02:40 19 September 2013

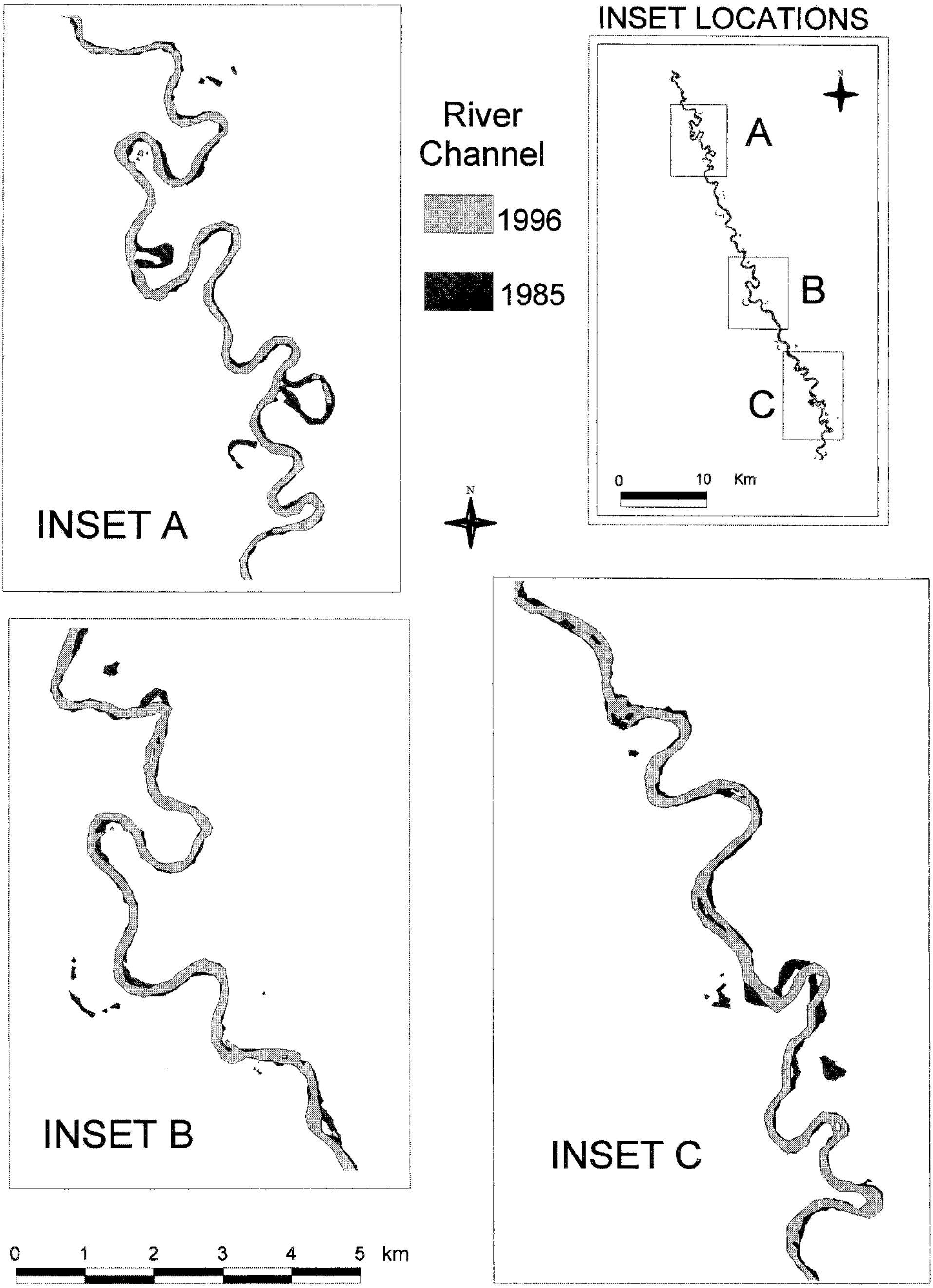


Figure 6. Comparison of river channel locations in 1985 and 1996. Polygon of 1996 river channel is overlaid onto the 1985 river polygon.

channel would require a higher discharge to overtop its banks and spill out onto the floodplain. This, in turn would result in a shorter duration of inundation, even assuming that high flows were not altered by dam operations. Related research (Maingi 1998) has shown that high flows in the Tana have been reduced by

Downloaded by [OARE Consortium] at 02:40 19 September 2013

construction of the Masinga Dam. Reduced peak flows, coupled with incision of the Tana River, are likely to exacerbate an already reduced duration and extent of flooding on the floodplain. A reduction in areal extent and duration of floodplain inundation often results in decreased species diversity. A decrease in the lateral migration of the river channel across the floodplain eventually leads to a lower heterogeneity (as the variety of geomorphic units formed through channel migration processes, e.g. ox-bow lakes, become reduced), eventually leading to a less diverse riverine forest ecosystem.

5.4. *Landscape analysis*

In this section, the areal extent and distribution of forest patches within the Tana riverine forest were quantified. Land cover maps for 1989 and 1996 were converted from a grid to a polygon coverage in ARC/INFO (ESRI 1997a). Polygons were built from groups of contiguous cells (pixels) that had the same cell values. The resulting vector coverage was then taken into ArcView (ESRI, 1997b) for analysis, and several landscape matrices were computed for the closed and open forest (table 8).

As expected, changes in total area for the two forest classes in 1989 and 1996 are about the same as those obtained in the change matrices using raster images. While the number of forest patches decreased by about 22% for the closed forest, those for open forest increased by 2%. The mean patch size remained unchanged for the closed forest class, but decreased by 31% for the open forest between 1989 and 1996. The mean area–perimeter ratio of forest patches decreased by about 4% in the open forest but remained unchanged in the closed forest.

Mean patch size and area–perimeter ratio are inter-linked and are good indicators of fragmentation. Fragmentation had occurred in the open forest, resulting in an

Table 8. Landscape distance (in metres) and area (in hectares) based matrices computed for close and open forest classes in the 1989 and 1996 Arc/Info coverages.

	Closed forest			Open forest		
Forest type	1989	1996	% change	1989	1996	% change
No. of fragments	1012	791	−21.84	1636	1668	1.96
Mean area (ha)	2.47	2.54	2.97	3.49	2.41	−31.03
Total area (ha)	2499	2011	−19.52	5712	4016	−29.68
Max area (ha)	127.36	111.76	−12.25	935.64	249.68	−73.31
SD of area	8.47	8.67	2.39	32.35	15.27	−52.63
Mean perimeter	747.98	773.55	3.42	938.88	759.52	−19.1
Min. perimeter	80	80	0	80	80	0
Max. perimeter	28 720	19 640	−31.62	183 880	63 080	−65.7
SD of perimeter	1718.12	1749.05	1.8	6415.76	3534.28	−44.91
Mean area–perimeter ratio	14.82	14.87	0.33	11.39	10.95	−3.91
Min. area–perimeter ratio	5	5	0	5	5	0
Max. area–perimeter ratio	72.04	79.01	9.68	61.29	51.73	−15.6
SD of area–perimeter ratio	11.18	11.16	−0.2	7.87	7.85	−0.33

Downloaded by [OARE Consortium] at 02:40 19 September 2013

increase in the amount of edges between the open forest and the non-forest classes and thus changing the area–perimeter of the fragments. As patch size (area) decreases, the amount of edge (perimeter) increases. The maximum forest patch size of the closed and open forest decreased by 15.6% and 73.3% respectively. Most of the statistics computed above indicate that more detrimental changes have taken place in the open forest than in the closed forest.

Construction of dams in the upper river basin has resulted in a reduction in the magnitude and extent of floods in the lower basin. Since the study area is arid, survival of the Tana riverine forest is therefore entirely dependent on the river and the associated water table. A reduction in magnitude and extent of floods is therefore likely to result in a drop in the water table, and consequently, a reduction in the extent of the forest from the river. Field observations in 1995 indicated that some of the trees near the edge of the floodplain showed signs of dieback and that the forest may once have been more abundant in these areas.

Classes for open and closed forests and river in the 1989 and 1996 land cover maps were exported as a grid and subsequently converted to polygon coverages. These coverages were then used to calculate the distances of each forest type from the river; these are summarized in table 9.

The above statistics indicate that on average, the extent of the open forest from the river had declined by about 200 m between 1989 and 1996. Dying-off of trees in the open forest is most likely a reflection of increasingly xeric conditions occurring along this part of the floodplain. The drier conditions can most probably be attributed to a reduction in the magnitude and extent of flooding and the accompanying drop in the water table.

6. Discussion and human impacts

Several explanations can be offered for the observed increase in the 'bare ground' and 'low scrub' classes in land cover maps corresponding to the periods 1975–1984 and 1989–1996. The 40% increase in bare ground between 1975 and 1984 coincided with the construction phase of the BISP, during which about 10 000 ha of dense scrub (mainly *Acacia*-*Commiphora* woodlands) were cleared to make room for the irrigation scheme infrastructure. During the same period, about 70 000 ha of land within the irrigation scheme and the surrounding area were set aside for both ongoing construction and future expansion. This land represented some of the best grazing land for the Orma pastoralists (Johansson 1993). Construction of the BISP also encouraged a less nomadic lifestyle for the Orma by providing: (1) year-round access to water in the earth-lined irrigation canals, and luxuriant pasture that would grow along the canals due to water seepage; (2) improved security from livestock

Table 9. Summary statistics of distance of forest classes from the river in 1989 and 1996.

	1989		1996	
Distance from river (m)	Closed forest	Open forest	Closed forest	Open forest
Maximum	1645.6	4181.9	1372.4	2398.4
Mean	238.0	628.8	228.6	412.4
Standard deviation	227.0	544.0	173.2	302.2

Downloaded by [OARE Consortium] at 02:40 19 September 2013

rustling by other pastoralists following the establishment of a police post; and (3) the establishment of health services, schools and supply stores throughout the BISP area.

Between 1989 and 1996 the bare ground class increased by about 112%. This is direct evidence of local overgrazing by Orma livestock following the adoption of a more sedentary lifestyle within the irrigation scheme. Mobility had been the key element in the Orma pastoral strategies. Movements of the Orma had been based on seasonally changing ecological conditions, an intimate knowledge of their environment and livestock herds. Before the construction of the BISP, the Orma had been able to utilize the full range of environments open to them, and therefore had managed to keep adverse impacts on the environment at a minimum. However, following this reduced range of environments and limited access to them, local environmental degradation has taken place.

The construction of the BISP also resulted in the introduction of a large settler population of farmers, traders and workers beginning in 1981. By 1989, the population within the irrigation scheme had risen to over 35 000 people. Anticipating a growing demand for fuelwood and building poles for the new settler population, irrigated forest plantations (of mainly *Prosopis juliflora* and *Eucalyptus* spp.) were initiated in 1984 by the Bura Fuelwood Project sponsored by the Finnish International Development Agency (FINNIDA). Unfortunately, this project was not successful because the irrigation scheme was unable to guarantee adequate and reliable water supply for the irrigated forest plantations.

This inadequate and unreliable supply of irrigation water resulted in frequent crop failures and many farmers were forced to diversify their subsistence activities. Some farmers started to keep livestock by themselves or contracted the Orma to look after their herds. This development could only further exacerbate environmental degradation within the BISP area as a result of local overgrazing. Because of an acute shortage of firewood and charcoal within the irrigation scheme, farmers started to participate in the relatively lucrative business of charcoal burning and supply of firewood for cooking.

In a firewood survey conducted in 1982 at the BISP, Hughes (1985) estimated that 0.875 m^3 of firewood was consumed per person per year. Hughes also found that the families within the riverine forest consumed twice as much firewood compared to those living in the irrigation scheme. Another study conducted within the BISP in the period 1985–1987 revealed that firewood was the main source of fuel for the tenant farmers, and that the bulk of it came from the riverine forest. Consumption of firewood was estimated at 1 m^3 per person per year (Vainio-Mattila 1987).

In 1992, firewood yields from the irrigated plantations were estimated at 2800 m^3 per year, while those from wild mesquite, which has spread virtually everywhere within the irrigation scheme, were estimated at 1700–2200 m^3 per year (Pukkala 1993). An inventory covering the riverine forest, irrigated fuelwood plantations and areas in which wild *Prosopis juliflora* was growing within the BISP was conducted (Pukkala 1993). The results indicated that the riverine forest, irrigated plantations and wild *Prosopis juliflora* could annually produce 10 000 m^3, 5400 m^3 and 2700 m^3 of firewood respectively on a sustainable basis. Total sustainable yield therefore came to 18 100 m^3, and taking a per capita firewood consumption of 1 m^3 per person per year, this yield would have provided for about 18 000 people, against an estimated population of 35 000 people in 1989. These results imply that there was a fuelwood deficit of about 17 000 m^3 in 1989 that could only have been met by unsustainable

Downloaded by [OARE Consortium] at 02:40 19 September 2013

harvesting of the riverine forest. This may partly explain the observed significant decline in the closed and open riverine forest area.

Pukkala estimated the mean volume of wood in the riverine forests to be 80 $m^3 ha^{-1}$ (1993). Another estimate based on sample plots measured in 1995 indicated the mean volume per hectare in the riverine forests to be $91.3 \pm 8.9 m^3$ at the 95% confidence level (Maingi 1998). Using these mean volume estimates for riverine forests, between 187 and 213 ha of forest would need to be cleared to satisfy a 17 000 m^3 fuelwood deficit. This calculation assumes the fuelwood was to be used only within the irrigation scheme, and was not exported commercially to the nearby towns of Garissa and Hola. However, this was not the case since riverine forests were already being exploited commercially once it became clear that prospects for irrigated agriculture within BISP and flood recession agriculture along the Tana River were poor. At the time of this research, most of the charcoal was being transported for sale to the nearby towns of Hola and Garissa. Riverine forests were also being exploited for building material but no data are currently available on this use. This means that the rate of exploitation is bound to be much higher to satisfy this demand. According to the analysis of the SPOT data, 2137 ha of forest were lost between 1989 and 1996. This means that on average, 305 ha were cleared per year. This number is quite plausible considering that the deficit calculated is for fuelwood only and the fact that, by 1994, the yield from irrigated forest plantations was almost non-existent because most of the plantations had died through lack of water. There was also a reluctance to harvest the wild mesquite that has invaded most parts of BISP since it is a labour-intensive exercise requiring great care because of its large and sharp thorns.

Agricultural activity within the irrigation scheme came to a virtual stop in 1993 after irrigation pumps failed. By the time of this study (1995), conditions had become so bad for the settler farmers that they were destitute and relying entirely on food-aid for their survival. Some of the enterprising farmers had joined hands with the Malakote flood recession agriculturalists to cultivate the most suitable floodplain sites using small diesel pumps. Other joint ventures between these groups of people now also included commercial production of charcoal and timber from the riverine forests.

The construction of the Masinga and Kiambere Dams in the upper river basin has resulted in reduction of floods and sediment within the lower basin. This development has disrupted agricultural activities of the Malakote flood recession agriculturalists. There has also been reduction in the deposition of sediment because of the reduced flooding, and the trapping of sediment behind dams in the upper river basin. This has meant a reduced opportunity for the replenishment of soil nutrients on cultivated sites during floods, and subsequently a reduction in crop yields. This problem has been aggravated by the fact that the Malakote farmers have traditionally not used artificial fertilizers in their farming. Among the coping options that Malakote flood recession agriculturalists have adopted in attempt to satisfy their subsistence needs are: (1) cutting down the large trees, especially *Acacia elatior*, in the open forest for charcoal production; (2) establishing pit-saws in several forest locations, for the production of construction timber; (3) commercial production of dug-out canoes; (4) clearing of larger tracts of forest (up to 20 ha at a time) for cooperative groups to grow crops (especially vegetables such as tomatoes, collards and onions) by irrigating by means of small diesel pumps. Most of these activities have in recent years become an integral part of the Malakote livelihood rather than a short-term response to disruption of agricultural activities. This change from exploitation of forest resources at a subsistence to a commercial level is the main reason for the extensive destruction of riverine forests that has been documented. It is reasonable that it is the open riverine forests that have been impacted most (a 30% reduction between 1989 and 1996) because it is here that the most suitable species for fuelwood are found.

7. Conclusions

Changes observed within the floodplain indicate a significant loss of riverine forest. Removal of trees on most parts of the riverine forest has been through thinning rather than clear-cutting operations. However, during fieldwork in 1995, it was observed that villagers were clearing increasingly larger portions (in tens of hectares) of the forest for new farms to be irrigated using diesel pumps. Continued removal of mature forest trees was also observed, especially *Acacia elatior* for making charcoal. Commercial exploitation of the endemic *Populus ilicifolia* had been taking place, as was indicated by bench-saw stands and remnants of felled trees. Degradation in forest stands is indicated by changes in stand density. The closed forest has the highest stand density, followed by the open forest and lastly the transitional woodlands. Changes to a more open forest and woodland have been demonstrated in this study. Die-back of trees towards the edge of the floodplain was observed during the 1995 field season, and is probably an indication of increasing xeric conditions associated with a decline in floods and water table following damming of the Tana. This would explain why some areas towards the edge of the forest were mapped as open forests in 1989, but as transitional woodlands in 1996. The transitional woodlands have also been under threat as destitute tenant farmers and villages in the riverine areas cooperate to exploit this resource commercially.

Analysis of the land cover change information shows that little change occurred in the total forest area between 1975 and 1984 (a decrease of about 2%). However, there was a substantial decline in forest area between 1989 and 1996 (about 27% for combined closed and open forest). Direct comparison of estimated forest area between Landsat MSS and SPOT HRV sensors was not made because of differences in spatial resolutions. Estimates of total forest area using Landsat MSS were lower than those by SPOT (1989) because of the lower spatial resolution of the former and resulting sub-pixel mixing of signals from different cover types.

River development activities of dam construction in the upper river basin and the construction of the BISP in the downstream area have negatively affected the riverine forests. Reduced floods and deposition of sediment have negatively impacted the livelihood of Malakote flood recession agriculturalists. The failure of the traditional agricultural production system has forced the Malakote into unsustainable exploitation of the riverine forests in an attempt to earn a livelihood. Where the focus is still on agriculture, increasingly larger patches of forest are being cleared to make way for agriculture irrigated using small diesel pumps. The large settler population of farmers and workers in the nearby irrigation scheme has increased the pressure on the riverine forest for provision of fuelwood and building material. The collapse of the BISP has meant a much lower than anticipated population, and consequently a lower pressure on the riverine forests. However, the near-destitute situation many settler farmers and Malakote families have found themselves in has forced them into activities that degrade the environment within the riverine forests. Forest exploitation is no longer for the provision of fuelwood for domestic purposes,

Downloaded by [OARE Consortium] at 02:40 19 September 2013

but rather a new and probably the only income-generating activity the farmers have left. This now represents the biggest threat to the continued survival of the riverine forests. This study has been able to document the extent of this impact on the riverine forests quantitatively using multi-temporal Landsat and SPOT data.

References

Adams, W. M., 1985, The downstream impacts of dam construction: a case study from Nigeria. *Transactions, Institute of British Geographers*, **10**, 292–302.

Baker, J. R., Briggs, S. A., Gordon, V., Jones, A. R., Settle, J. J., Townshend, J. R. G., and Wyatt, B. K., 1991, Advances in classification for land cover mapping using SPOT HRV imagery. *International Journal of Remote Sensing*, **12**, 1071–1085.

Bauer, M. E., Burk, T. E., Ek, A. R., Coppin, P. R., Lime, S. D., Walsh, T. A., Walters, D. K., Befort, W., and Heinzen, D. F., 1994, Satellite inventory of Minnesota forest resources. *Photogrammetric Engineering and Remote Sensing*, **60**, 287–298.

Brockhaus, J. A., and Khorram, S., 1992, A comparison of SPOT and Landsat-TM data for use in conducting inventories of forest resources. *International Journal of Remote Sensing*, **13**, 3035–3043.

Buchheim, M. P., Maclean, A. L., and Lillesand, T. M., 1985, Forest cover type mapping and spruce budworm defoliation detection using simulated imagery. *Photogrammetric Engineering and Remote Sensing*, **51**, 1115–1122.

Bunger, R. L. Jr, 1979, *Islamization Among the Upper Pokomo*, 2nd edn (New York: Syracuse University, Maxwell School of Citizenship and Public Affairs).

Chavez, P. S. Jr, 1996, Image-based atmospheric corrections—revisited and improved. *Photogrammetric Engineering and Remote Sensing*, **62**, 1025–1036.

Cohen, J., 1960, A coefficient of agreement for nominal scales. *Education and Psychological Measurement*, **20**, 37–40.

Congalton, R. G., 1991, A review of assessing the accuracy of classifications of remotely sensed data. *Remote Sensing of Environment* **37**, 35–46.

Congalton, R. G., and Mead, R. A., 1983, A quantitative method to test for consistency and correctness in photointerpretation. *Photogrammetric Engineering and Remote Sensing*, **49**, 69–74.

Congalton, R. G., Oderwald, R. G., and Mead, R. A., 1983, Assessing Landsat classification accuracy using discrete multivariate statistical techniques. *Photogrammetric Engineering and Remote Sensing*, **49**, 1671–1678.

Corbett, J., 1988, Famine and household coping strategies. *World Development*, **16**, 1009.

Dale, I. R., and Greenway, P. J., 1961, *Kenya Trees and Shrubs* (Nairobi: Buchanan's Kenya Estates Ltd).

Eden, M. J., and Parry, J. T., 1986, *Remote Sensing and Tropical Land Management* (Chichester: Wiley).

Ensminger, J., 1987, Economic and political differentiation among Galole Orma women. *Ethnos*, **52**, 28–49.

ERDAS, 1996, ERDAS IMAGINE 8.2. ERDAS Inc., Atlanta, Georgia, USA.

ESRI, 1997a, ARC/INFO 7.1.1. Environmental Systems Research Institute, Redlands, California, USA.

ESRI, 1997b, ArcView 3.0. Environmental Systems Research Institute, Redlands, California, USA.

Fitzpatrick-Lins, K., 1981, Comparison of sampling procedures and data analysis for a land use and land cover map. *Photogrammetric Engineering and Remote Sensing*, **47**, 343–351.

Gilruth, P. T., and Hutchinson, C. F., 1990, Assessing deforestation in the Guinea Highlands of West Africa using remote sensing. *Photogrammetric Engineering and Remote Sensing*, **56**, 1375–1382.

Hamilton, A. C., 1974, The history of vegetation. In *East African Vegetation*, edited by E. M. Lind and M. E. S. Morrison (London: Longman), pp. 188–209.

Hill, J., and Aifadopoulou, D., 1990, Comparative analysis of Landsat-5 TM and SPOT HRV-1 data for use in multiple sensor approaches. *Remote Sensing of Environment*, **34**, 55–70.

Downloaded by [OARE Consortium] at 02:40 19 September 2013

Downloaded by [OARE Consortium] at 02:40 19 September 2013

Hughes, F. M. R., 1985, The Tana River Floodplain Forest in Kenya: ecology and impact of development. Ph.D. Dissertation, University of Cambridge, UK.

IUCN, 1978, Categories, objectives, and criteria for protected areas. IUCN/The World Conservation Union, Morges, Switzerland.

Jain, A. K., 1989, *Fundamentals of Digital Image Processing* (Englewood Cliffs, NJ: Prentice-Hall).

Jensen, J. R., 1996, *Introductory Digital Image Processing: A Remote Sensing Perspective* (Upper Saddle River, NJ: Prentice Hall).

Jensen, J. R., Hodgson, M. E., Christensen, E., Mackey, H. E. Jr, Tinney, L. R., and Sharitz, R., 1986, Remote sensing inland wetlands: a multispectral approach. *Photogrammetric Engineering and Remote Sensing*, **52**, 87–100.

Jensen, J. R., Narumalani, S., Weatherbee, O., and Mackey, H. E., 1993, Measurement of seasonal and yearly cattail and waterlily changes using multidate SPOT panchromatic data. *Photogrammetric Engineering and Remote Sensing*, **59**, 519–525.

Johansson, S., 1993, Resource planning, repercussions and retrospective–forestry and irrigation development in the Tana River Basin. *Proceedings of the Bura Fuelwood Project Research Seminar* (Nairobi, Kenya, 9 Mar–10 Mar), pp. 31–48.

Khorram, S., 1982, A remote sensing aided procedure for site specific estimation of net radiation over large areas. *Journal of Applied Photogrammetric Engineering*, **8**, 72–91.

Kouris, M., and Barker, G. R., 1982, St. Regis uses satellite technology to help manage its forestlands. *Tappi*, **65**, 33–36.

Likens, W., and Peterson, D., 1981, Statewide Landsat inventory of California forests. Report NASA-TM-81255, NASA, Moffet Field, California, USA.

Livingstone, D. A., 1975, Late Quaternary climate change in Africa. *Annual Review of Ecological Systems*, **6**, 249–280.

Longhurst, R., 1986, Household coping strategies in response to seasonality and famine. *Institute of Development Studies Bulletin*, **17**, 27–35.

Maingi, J. K., 1998, Land use and vegetation change in response to river basin development in the lower Tana basin of Eastern Kenya. Ph.D. Dissertation, University of Arizona, USA.

Marsh, C. W., 1978, Tree phenology in a gallery forest on the Tana River, Kenya. *East African Agricultural and Forestry Journal*, **43**, 305–316.

Marsh, S. E., Walsh J. L., and Sobrevila C., 1994, Evaluation of airborne video data for land cover classification accuracy assessment in an isolated Brazilian forest. *Remote Sensing of Environment*, **48**, 61–69.

McCully, P., 1996, *Silenced Rivers: The Ecology and Politics of Large Dams* (Atlantic Highlands, NJ: Zed Books).

Medley, K. E., 1990, Forest ecology and conservation in the Tana River National Primate Reserve, Kenya. Ph.D. Dissertation, Michigan State University, USA.

Moran, M. S., Jackson, R. D., Clarke, T. R., Qi, J., and Cabot, K. J., 1992, Evaluation of simplified procedures for retrieval of land surface reflectance factors from satellite sensor output. *Remote Sensing of Environment*, **41**, 203–214.

Nellis, M., 1986, Remote sensing for monitoring rangeland management strategies in the Kansas Flint Hills. *Proceedings of the Symposium of Commission IV of International Society of Photogrammetry and Remote Sensing and the Remote Sensing Society: Mapping From Modern Imagery, Nottingham, England, September 1986* (Nottingham, England, International Society for Photogrammetry and Remote Sensing and the Remote Sensing Society), pp. 370–375.

Newland, W., Peterson, D., and Norman, S., 1980, Bulk-processing of remotely-sensed data for very large areas: Landsat classification of California. *Proceedings of the 6th Annual Symposium on Machine Processing of Remotely Sensed Data, West Lafayette, Indiana, 1980* (West Lafayette, Indiana, Purdue University, Laboratory for Applications of Remote Sensing), pp. 430.

Niemann, O., 1993, Automated forest cover mapping using Thematic Mapper images and ancillary data. *Applied Geography*, **13**, 86–95.

Obeng, L. E., 1981, Man's impact on tropical rivers. In *Perspectives in Running Water Ecology*, edited by M. A. Lock and D. D. Williams (New York: Plenum), pp. 265–288.

Downloaded by [OARE Consortium] at 02:40 19 September 2013

Pukkala, T., 1993, Yield and management of the indigenous forests and fuelwood plantations of Bura. *Proceedings of the Bura Fuelwood Project Research Seminar, Nairobi, 9–10 March 1993.* Tropical Forestry Report No. 9, University of Helsinki, Department of Forest Ecology, Helsinki, Finland.

Qi, J., Chehbouni, A., Huete, A. R., Kerr, Y. H., and Sorooshian, S., 1994, A modified soil adjusted vegetation index. *Remote Sensing of Environment*, **48**, 119–126.

Rosenfield, G. H., and Fitzpatrick-Lins. K., 1986, A coefficient of agreement as a measure of thematic classification accuracy. *Photogrammetric Engineering and Remote Sensing*, **52**, 223–227.

Sabins, M. J., 1987, Convergence and consistency of fuzzy means/ISODATA algorithms. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, **9**, 661–668.

Sader, S. A., 1995, Spatial characteristics of forest clearing and vegetation regrowth as detected by Landsat Thematic Mapper imagery. *Photogrammetric Engineering and Remote Sensing*, **61**, 1145–1151.

Sader, S. A., Stone, T. A., and Joyce, A. T., 1990, Remote sensing of tropical forests: an overview of research and applications using non-photographic sensors. *Photogrammetric Engineering and Remote Sensing*, **56**, 1343–1351.

Salo, J., Kalliola, R., Hakkinen, I., Makinen, Y., Niemela, P., Puhakka, M., and Coley, P. D., 1986, River dynamics and the diversity of Amazon lowland forest. *Nature*, **322**, 254–258.

Scudder, T., 1989, River basin projects in Africa. *Environment*, **31**, 4–9, 27–31.

Singh, A., 1987, Spectral separability of tropical forest classes. *International Journal of Remote Sensing*, **8**, 971–979.

Sparks, R. E., 1992, Risks of altering the hydrologic regimes of large rivers. In *Predicting Ecosystem Risk: Advances in Modern Environmental Toxicology*, edited by J. Cairns Jr, B. R. Niederlehner and D. R. Orvos (Princeton, NJ: Princeton Scientific Publishing Company), pp. 119–152.

Story, M., and Congalton, R. G., 1986, Accuracy assessment: a user's perspective. *Photogrammetric Engineering and Remote Sensing* **52**, 397–399.

Tom, C. H., and Miller, L. D., 1980, Forest site mapping and modeling. *Photogrammetric Engineering and Remote Sensing*, **46**, 1585–1596.

Tou, J. T., and Gonzalez, R. C., 1977, *Pattern Recognition Principles* (Reading, MA: Addison-Wesley).

Vainio-Mattila, A., 1987, Bura fuelwood project: domestic fuel economy. Report 13B, University of Helsinki, Institute of Development Studies, Helsinki, Finland.

van Genderen, J. L., and Lock B. F., 1977, Testing land use map accuracy. *Photogrammetric Engineering and Remote Sensing*, **43**, 1135–1137.

Verbyla, D. L., 1995, *Satellite Remote Sensing of Natural Resources* (New York: CRS Lewis Publishers).

Weaver, R. E., 1984, Integration of remote sensing data for moorland mapping. *Satellite Remote Sensing: Review and Preview Remote Sensing Society* 191–200.

Wolter, P. T., Mladenoff, D. J., Host, G. E., and Crow, T. R., 1995, Improved forest classification in the Northern Lake States using multi-temporal Landsat imagery. *Photogrammetric Engineering and Remote Sensing*, **61**, 1129–1143.