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Use of remotely sensed data in the analysis of soil-vegetation changes along a drying gradient peripheral to the Okavango Delta, Botswana

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This work determines the value of remotely sensed imagery in developing drying impacts which occur as a result of internal and/or external factors in the Okavango catchment. Three sites provide a preview of the consequences of Delta margin drying as depicted over historical, intermediate and geological timescales. Initially, supervised classification resulted in the identification of sequences of islands and flood plains and their associated vegetation cover on ETM+ imagery, with a classification accuracy of 74–77%. Comparative results, augmented by patch analysis, suggest that through time, island woody vegetation cover has invaded the flood plains and locally developed protected ecotonal areas (extensions) which are densely treed, relative to adjacent, non-protected flood plains. Over longer time periods, protected areas between extensions became infilled with woody vegetation leading to, in effect, island enlargement or agglomeration. Disadvantages of long-term Delta drying in terms of natural resource management include a reduced availability of wetland-based construction and agricultural resources. If natural regeneration (island agglomeration) is allowed to take place, these resources may ultimately be replaced by dryland timber and potential cropland.

1. Introduction

Assessments of global change with respect to drying gradients were a major goal of the SAFARI 2000 project (Otter *et al.* 2002). The expansion and contraction of wetlands in response to changes in inflow are noted in the literature (Mitsch and Gosselink 1993, Tooth 2000, Junk 2003). These changes are highly dynamic and, in the case of the Okavango Delta, have taken place since the late Cretaceous and are continuing at present (Thomas and Shaw 1991, Moore and Larkin 2002). Regional wetting and drying cycles are thought to occur over approximately 23 000 years due (*inter alia*) to the precession of the equinoxes (Partridge *et al.* 1999) which led to an expanded Delta some 7000 years ago (Ringrose *et al.* 2003a). Since then, a contraction of the wetland area has occurred, and landforms indicative of a drying sequence are prevalent throughout the present wetland periphery but are

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particularly evident on the southern and western margins (McCarthy *et al.* 2002). Vegetational successional changes consequent upon drying throughout the Okavango system form a major priority for the Water and Ecosystem Resources in Regional Development (WERRD) project funded by the European Union (www.okavangochallenge.com). This is because coping strategies of local people depend on the suitability of the bush and availability of water for the continuance of livelihood support (Bendsen and Gelmoth 1983). A significant requirement at the present time is to determine the topographic and soil–plant responses to change as protracted drying including increased water abstraction appears inevitable (Bonyongo *et al.* 1996, Masundire *et al.* 1998, Ashton and Neal 2002). Changes to the Okavango system are characterized in terms of their driving agents and comprise: climatic changes (with inputs of rainfall and solar energy); geological changes (neotectonic inputs); hydrological changes (surface and subsurface water inputs); vegetational-geomorphological changes (island–flood plain building inputs); zoological activities (wildlife inputs) and anthropogenic changes (fire and land-use inputs) (McCarthy and Ellery 1993, Geiske 1996, McCarthy *et al.* 1998a, b, Ringrose *et al.* 1997, 2003c, Government of Botswana 2002a, Wolski *et al.* 2003).

Characterizing the process of drying requires carefully located areas which collectively represent a temporal drying gradient. This was achieved as specific parts of the Delta periphery have become dry over geological time periods, while other areas dried out in historical times. The hypothesis proposed here is that soil–plant relationships prevalent in peripheral Okavango Delta areas which have been dry for at least 7000 years (geological time) will differ from those which occur in areas which have been dry for 150 years (historic time). Furthermore, these relationships may be regarded as being demonstrative of the effects of continual drying. Drying here is taken to mean not only an absence of inflow but also water-table drawdown effects due to lack of recharge and continuing evapotranspiration by deeper-rooted trees (Ringrose 2003). In this context, soil–plant relationships along a known temporal drying gradient are undertaken so that responses in space can be substituted for responses in time (Matheson and Ringrose 1994, Ringrose *et al.* 1998, Steffen 2000). This assumes that field sites of a given size and relatively consistent soil background, chosen along a spatial gradient, will reflect temporal adaptive changes taking place over different broadly known time periods (e.g. Scholes and Walker 1993, Ringrose *et al.* 1994, 2003b).

Much of the Okavango Delta falls within the Zambezian regional centre of endemism (White 1983), and while locally the biodiversity is high, there are no endemic species (MLGLH 1989). The Okavango Delta shows progressive degrees of inundation throughout its length and is subdivided into the Panhandle, Permanent swamp, Seasonal swamp and Occasional (or Intermittent) swamp (McCarthy and Gumbricht 2002). Recent work using multi-date Landsat and AVHRR imagery and contextual analysis has shown that over the past 30 years, the permanent swamps are flooded >80% of the time, the seasonal swamps 30–80% of the time, regularly flooded occasional swamps 10–30% of the time, and sparsely flooded occasional swamps 5–10% of the time (Andersson *et al.* 2002, McCarthy and Gumbricht 2002). Responses to drying on former flood plains may include localized species extinctions leading to changes in community function (Thibodeau and Nickerson 1984, McCarthy and Ellery 1993, Benke *et al.* 2000, Fonseca and Ganade 2001) and bush encroachment (Sekwhela and Dube 1991, Ringrose *et al.* 1997). This is frequently exacerbated by the impact of repeated burning (Ellery *et al.* 1989, Heinl 2001). The influence of fire, along with herbivory, nutrients and moisture regime are regarded as basic savannah determinants (Scholes and Walker 1993) which play an integral part in the processes whereby vegetation cover on well-watered Delta flood plains changes to rain-fed semi-arid bush cover. Hence, overall (macro) changes (whether due to fire, herbivory or reduced soil moisture) are believed to undergo natural successional stages which can be compared so as to depict what may eventuate from the passage of time, in otherwise uniform areas.

Little previous work has been undertaken on characterizing wetland drying using remote sensing techniques (Butera 1983, Shaikh *et al*. 2001), although other similar gradients have been considered (Ringrose *et al*. 1994, 1998, Shoshany *et al*. 1995). Previous examples of wetland mapping have involved either the use of relatively high spatial resolution (SPOT) data (Blasco *et al*. 1992, Michener and Houhoulis 1997, Ringrose *et al*. 2003c) or Landsat TM/MSS imagery (Ringrose *et al*. 1988, Breininger *et al*. 1991), sometimes in association with SPOT data (Jensen *et al*. 1995). More detailed ecological work has involved the application of colour infrared aerial photography (e.g. Dale *et al*. 1991) or high-resolution imaging spectrometers (e.g. Gross and Klemas 1981, Choudhury 1987). Often, the strengths of remotely sensed data lie in their abilities to detect soil reflectance (Baumgardner *et al*. 1985, Elvidge and Lyon 1985, Frazier and Cheng 1989) including soil organic matter (Henderson *et al*. 1989, Wilcox *et al*. 1994, Ringrose *et al*. 1996, 2002). Increasingly, emphasis is being placed on satellite sensor systems using active or passive radar to map specific features in wetland areas (Ewe and Church 1995). This is because the cloud-penetrating abilities of radar are useful in mapping wet season flooding. However, flooding in the Okavango Delta takes place in the dry season as it results from rain in Angola, some 800 km to the north. As the water takes 6 months to arrive in northern Botswana, ETM+ imagery is satisfactory because of the clear skies at this time of year. The use of remotely sensed data along with spatial analytical techniques such as patch analysis is also beneficial in terms of landscape fragmentation (Rempel and Carr 2003). The converse of this, landscape (or island) agglomeration, is demonstrated here for the first time. The present work tests the validity of using Landsat data to assess soil and vegetation adaptations to long-term drying in three stages along the west side of the Delta. Specific aims of the research reported here are:

1. to determine whether single-date Landsat Enhanced Thematic Mapper Plus (ETM+) imagery is useful in defining vegetation structural changes resulting from differential exposure representing drying gradient trends peripheral to the Okavango Delta;
2. to assess whether topography–soil–plant successional relationships support the hypothesis of drying gradient change; and
3. to provide a preliminary working model from initial conditions which can predict likely results of ecosystem change resulting from drying in the Okavango system.

2. Study areas

The study focuses on one 180 km^2 (Gumare) and two 250 km^2 (Shakawe and Etsha) areas on the west side of the Okavango Delta (figure 1). The three areas are located to encompass recent to advanced drying characteristics in terms of soil-vegetation

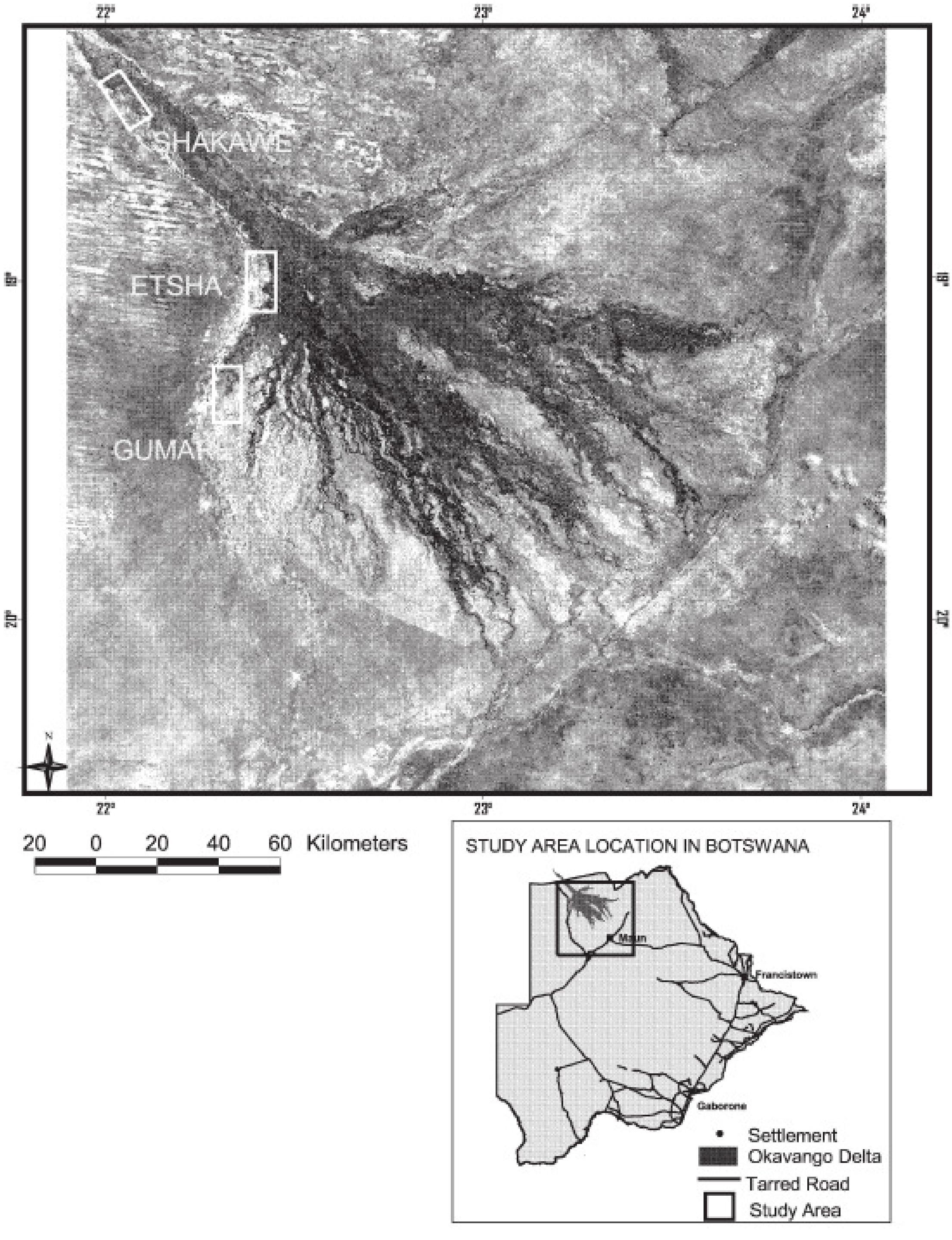

Figure 1. Okavango drying gradient study areas: Shakawe (250 km^2), Etsha (250 km^2) and Gumare (180 km^2).

successional trends. The Gumare area represents a currently drying flood-plain system resulting from channel blockages approximately 150 years ago on the westernmost Okavango distributary, the Thaoge system (Tlou and Campbell 1984, Ellery *et al.* 1995). The Etsha area exemplifies locations where the Delta margin has receded and exposed a series of flood plains in recent geological time about 2000–3000 years ago (Ringrose *et al.* 2003b). The Shakawe area occurs peripheral to the Panhandle, where tectonic events have exposed a series of flood plains from the geological past estimated from regional multi-proxy data around 7000 years ago (McCarthy *et al.* 1997, Partridge *et al.* 1999, Ringrose *et al.* 2003a). The Okavango Delta in total is underlain by medium fine sand and is characterized by a semi-arid climatic regime with an annual average rainfall in Maun of 460 mm. Much of the rainfall is localized in extent with frequent droughts. Potential evapotranspiration rates vary from 1000 to 1500 mm year^{-1} (Hulme 1996) such that geochemical precipitates (within clastic sediments) are characteristic of the soils. Only generalized maps were previously available for the study area representing soils (Soil Mapping and Advisory Services Project 1991; 1 : 250 000) and vegetation cover (Soil Mapping and Advisory Services Project 1990, 1 : 1 000 000). Terms used in this work are defined as follows. Flood plain here refers to a dry (never flooded) depression comprising extensive low gradient elongate basins (flood plains) within which islands (higher, smaller areas) protrude at irregular intervals (McCarthy and Gumbricht 2002). Channels are mostly dry elongate features, incised into the flood plains (figure 2).

Problems arise in analyses of this nature in differentiating between changes caused by anthropogenic and natural processes. Much of the land in the three areas is (like much of Botswana), however, relatively pristine (Ringrose *et al.* 1996, Scholes *et al.* 2002). Landuse, now and in the past, in all the study areas is predominantly cattle grazing (Tlou and Campbell 1984). The predominant (and relatively rapid) change brought about by cattle is bush encroachment, a process which is identifiable by specific shrub species (Moleele *et al.* 2002, Ringrose *et al.* 2003b). Soil changes are also minimal as impacts by hoofed animals on medium-fine textured sand are not severe. Human impacts such as extensive tree felling are negligible in all three areas.

Figure 2. Dry Okavango Delta mosaic of floodplains, channels and islands.

The Shakawe and Etsha areas have only recently been populated (including refugees from Angola, 20 years ago), and the Gumare population has only moved into the Tubu (Gumare study area) in the recent past (Larsson 1998). A further possibly significant influence is that of fire which is known to change the nature of the vegetation cover in parts of the Delta (Heinl 2001). However, fire is regarded as a relatively constant factor (as fires occur repeatedly over 3- to 4-year intervals throughout much of the Okavango), so it may have similarly affected the vegetation cover in all three areas. Although peat fires are presently prevalent in the Gumare area, the process of burning off recently dried flood plains is widespread and has likely occurred in all areas in historic times (Ellery *et al*. 1989).

3. Data

Satellite data were obtained over the Delta dated April 2000 from the SAFARI 2000 NASA collection. The imagery used consisted of two Landsat 7 ETM+ scenes from April 2000 over the western Okavango Delta and environs (Path 175 row 073, Path 175 row 074), acquired on 10 April 2000. The two scenes were initially mosaiced using the Image Correction and Mosaicer tools of Erdas Imagine (Erdas 1999). The mosaic was georectified (RMS 6.9 m range 3.5–10.6 m) using regional road data obtained from ground Global Positioning System locations by Government of Botswana (2002b), projected to UTM grid Zone 34 South. Within the mosaic, a total of 86 points were used, spread throughout path 175 row 073 along the main and subsidiary road networks. A first-order polynomial stretch method was used to re-locate the pixels. The images were acquired under clear blue skies with negligible haze prior to the fire season, so no atmospheric correction was undertaken (Otter *et al*. 2002). Within-season temporal variations were considered negligible because of the protracted wet season in northern Botswana in 2000 justified on the basis of follow-up work in the Kalahari (Ringrose *et al*. 2003b). Only small-scale soils and vegetation maps (Soil Mapping and Advisory Services Project 1990, 1991) were available for these three study areas which are mapped here in terms of relatively detailed soil and vegetation cover for the first time. Hence, there is an absence of basic spatial and contextual data at the scale required. Landuse–landcover change mapping over time was not attempted, as this forms part of ongoing work being undertaken under the Okavango Delta Management Plan (ODMP; Government of Botswana 2002a).

4. Methodology

4.1 *Image classification*

The Shakawe area falls in path 175 row 073, while Etsha and Gumare fall into path 175 row 174 (both acquired on 10 April 2000). The three areas were classified independently because of local differences in topographic, soil and vegetation characteristics (Hill and Curran 2002) using supervised maximum likelihood supervised techniques (Lillesand and Kiefer 1987). All eight Landsat ETM+ bands were used in the classification, as earlier work implied that the thermal bands provided a useful separation of aquatic features (Ringrose *et al*. 1988). Classification was intended to provide mapped information with respect to the spatial distribution of flood plains and islands, and the extent to which they are vegetated (Jellema *et al*. 2002). The species composition of the different landscape elements was defined in terms of spectral differentiation, while specific species were defined later using field data. Because of the focus on the drying parts of the Delta, most of the wet Delta (to the east) and drier Kalahari dunes (to the west) were masked out of the classification. Training pixels were selected for a number of locations in all three areas known to represent typical islands and flood plains. Once these locations were identified, polygons were created manually to ensure pixel homogeneity. Signatures were evaluated using standard procedures, including histogram analysis to ensure homogeneity and the use of the Transformed Divergence Separability Measure to minimize overlapping training areas (Erdas 1999). Signature statistics were revised until a high degree of separability of the resultant ellipses was apparent throughout the available feature space. This was achieved mainly by merging and deleting some of the original training signatures, so that island, dryland and flood-plain classes were merged into identifiable entities. In all cases, emphasis was placed on differentiating islands and flood plains in terms of their respective vegetation cover and background soils. A 3×3 majority filter was applied to smoothen the classification in all cases. Accuracy assessment was undertaken with reference to a series of colour aerial photographs obtained by the Tawana Land Board (2000) for the Shakawe and Etsha study areas. Older panchromatic aerial photographs and recent fieldwork (December 2002) were used in the Gumare area. From the aerial photographs, a random sample of 110 or 111 points was taken for each study area, visually interpreted and categorized according to the classes of the classification. By overlaying this data set with the classification, producers, users and overall accuracies were produced for each site (Congalton 1991).

4.2 *Spectral trend analysis*

Spectral trends were explored to gain further insight into the evolution of the flood plains and the apparent influence of the island nucleus areas in recolonizing flood plains. As the two images from which the pixel values were taken were obtained almost simultaneously (on 10 April 2000) these values were considered comparable. For this work, the pixel values (DNs) were converted to radiance values to ensure between image comparability (Landsat 7 Science Data User's Handbook 2004). Hue analysis of the flood plains and islands showed that the flood plains in particular are depicted as darkened vegetation types. This is a noticeable characteristic of semi-arid vegetation cover which, although relatively dense and actively growing, absorbs electro-magnetic energy in both visible and near-infrared bands (Robinove 1983, Ringrose *et al*. 1989, Chavez and MacKinnon 1994). Further work has indicated that a greater range of semi-arid vegetation cover types (relative density) can be discerned using a darkening ratio (TM5/TM3) in Botswana to define vegetation spectral trends (Moleele *et al*. 2001). Hence, an attempt was made to explore relationships between ETM5 and ETM3 to determine the extent to which the relative density of vegetation cover differed in the three study areas. A total of 22 points (Gumare 7, Etsha 7, Shakawe 8) were obtained from each of the study areas intended to depict comparable island and flood-plain sites and thereby infer their relative antiquity.

4.3 *Patch analysis*

Patch analysis was used in conjunction with the classified images in each of the study areas to gain further insight into the processes and responses of flood plain and island revegetation using the patch analysis extension in ArcView (Rempel and Carr

2003). Patch analysis is normally undertaken to demonstrate increased fragmentation of landscapes over time (Sharma *et al*. 2001) and is frequently used to depict areas wherein clearing for agriculture has fragmented wildlife habitats, for instance in Europe (Winkler 1993). In this case, the converse is anticipated for the peripheral Okavango drying stages which entails revegetation and species changes. Patch analysis involved the development of several patch indexes using polygons from the classified sub areas. During this process, different classes representative of the agglomeration of islands (Island, Island Extensions, Flood plain Infill) were clumped together into distinct patches, excluding other classes. Because fields are generally created in former island areas, patch analysis was carried out twice for the Shakawe area, first without the fields as part of the island agglomeration and second taking the fields as part of the agglomeration process.

4.4 *Topographic profiling and vegetation analysis*

Topographic profiling took place specifically to determine whether landform changes through time could be discerned as a result of this work. The general concept stems from the fact that newly formed features such as flood plains and islands generally have a sharper topography (more overall relief) than older features which have been subject to erosion and deposition through time (Goudie 1992). Soil transect data were generated to determine whether variations in pedogenic processes could be observed as a result of long-term drying. This is based on the assumption that increased soil profile development takes place over time, causing variations in macro soil properties (Brady 1983, Miles 1985). A vegetation-transect data analysis was undertaken to determine whether woody vegetation from the islands had colonized adjacent flood plains during the drying process, thereby causing an enlargement of the area with former island type woody vegetation–soil characteristics (Tivy 1993).

4.5 *Field and laboratory work*

Fieldwork at the three locations took place during the wet season (February and December 2002) and was aimed at facilitating image interpretation and characterizing flood plains and islands in terms of evolutionary trends (Walker and Menaut 1991). Satellite images examined in the field also provided a basis for the selection of transects which were used to establish topographic profiles, soil profiles and associated vegetation identification. The profile and vegetation work took place adjacent to existing tracks in Etsha and Shakawe where the vegetation cover was relatively thick. This facilitated access in terms of personnel and equipment. The Gumare profile is shorter than the other two profiles because of the lack of continuous access brought about by underground cavities, which are the result of subsurface peat fires. The profiles generally ran east–west, consistent with the local lateral sub-drying gradient. It should be noted that the south–north drying gradient encompasses the totality of drying results at each site.

Topographic profiling took place using a Trimble 4700 Global Positioning System, through the establishment of a base station and roving techniques at approximately 250 m intervals to determine relief variation. As base-station data were not tied into the national topographic survey, the heights are only relatively correct. An average of 10 soil pits were dug per study area and augured (to 1.75 m) along the topographic profile and sampled systematically through the top and sub-soil. Soil pits were located with respect to the landform(s) requiring characterization; hence, a number were dug in the islands, flood plains and channels. Specific transects for woody cover analysis were undertaken every 2 km along the topographic profile using techniques described in Kent and Coker (1996) and structure/composition following Grunblatt *et al.*'s (1989) nomenclature for east Africa. Tree and shrub species were identified using standard texts for the region specifically Roodt (1995), Palgrave (1996) and Ellery and Ellery (1997). Soil texture and Munsell Colour were identified, and 226 samples analysed for soil moisture, electrical conductivity (EC) and pH (Andersen and Ingram 1989). Carbonate content was estimated by noting the amount of effervescence when 6N HCl was added to the samples. An estimate of the undecomposed organic litter was obtained by sieving the weighed dried topsoil through a 2 mm sieve and weighing the organic fraction.

5. Results

5.1 *Image classification*

The original images and results of classification for the three study areas are shown in figures 3–5. Spectrally, the Gumare area shows mixed characteristics such that certain flood plain and island features are easily identifiable, while others are confused. Two classes, Channel/*Cyperus papyrus, Phragmites australis* and Island nucleus/Dense Woodland, proved very difficult to separate spectrally, although they appear spatially distinct in the Gumare area (figure 3(*a*)). Both the actively growing channel vegetation and the dense broadleaved island woodlands show high responses in the near-infrared. Hence, misclassified Woodland in the *C. papyrus* channel was reclassified as *C. papyrus* resulting in 10 classes (table 1). Channel areas are to some extent misclassified with flood plains 1 and 4 (FP1 and FP4) as the channel areas comprise both light bare soil and peat soil, which are both found in the dry flood plains. Flood plains 1 and 2 (FP1 and FP2) are also difficult to separate because of confusion over the density of grasses relative to the proportion of peat remaining on the mainly burnt flood-plain areas. Spectrally distinctive are flood plain 3 (FP3) on account of the sparse cover and high proportion of bare sandy soil, the palm islands and dense grasses (FP4) and island nuclei (I1). The Gumare area was classified with an overall accuracy of 77% (table 2).

In conjunction with the results of vegetation fieldwork, it was found that the Gumare area is characterized by intermittently flooded channels with *C. papyrus* and *P. australis* flanked on the east by a zonation of former flood plains (table 1). Seven classes show the flood-plain charactersitics in terms of vegetation cover, which, in this case, is mainly grass cover (figure 3(*b*)). The classified image shows that the classes beside the channel comprise sparse and dense grass cover with sparse grasses occurring over recently emerged burnt peat (FP6—62 km^2) and over bare soil, which shows aspects of wind erosion (FP3—8 km^2). The image shows a gradation away from the channel with initially more grassland merging into shrubland further east. Significantly, a number of small islands are depicted on the classified image which form densely wooded island nuclei (I1—14 km^2). The classified image underlines the significance of grassland in this area, much of which is underlain by burnt peat soil and the relative isolation of remaining islands (17 km^2, table 1).

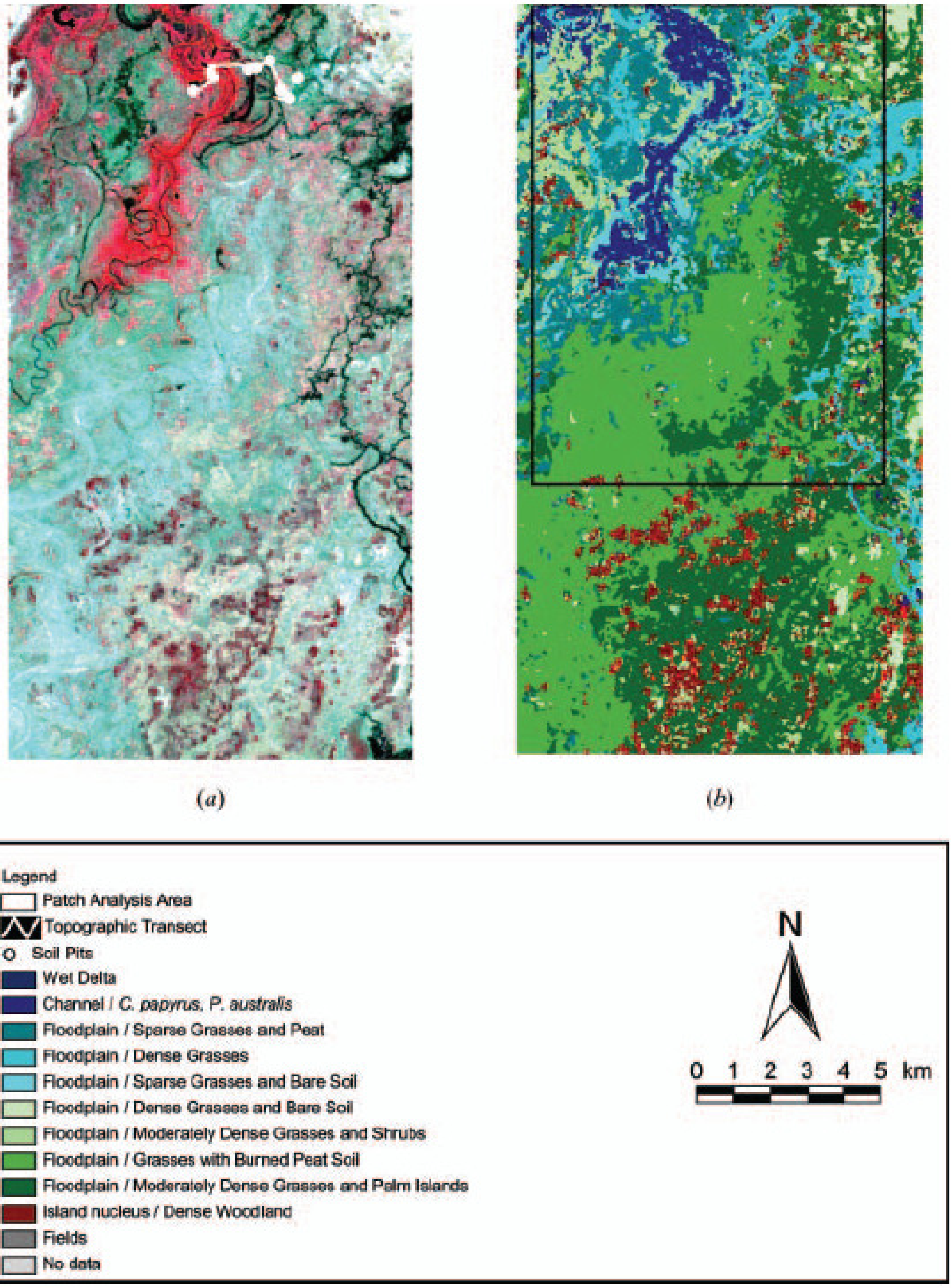

Figure 3. Gumare area (*a*) original Landsat ETM+ imagery (bands 2, 3 and 4 displayed as blue, green and red) and (*b*) results of supervised classification.

In the Etsha area, fewer flood-plain classes could be discerned, along with one island class and two classes of high NIR reflectance which appear to extend from the island nuclei, and so are called island extensions 1 and 2 (figure 4(*a*)). The two flood-plain types (FP1 and FP2) show little overlap, as they are readily distinguished on the basis of the relative densities of woody cover. The island classes are more problematic, especially the I1 (Island nucleus) class, which is

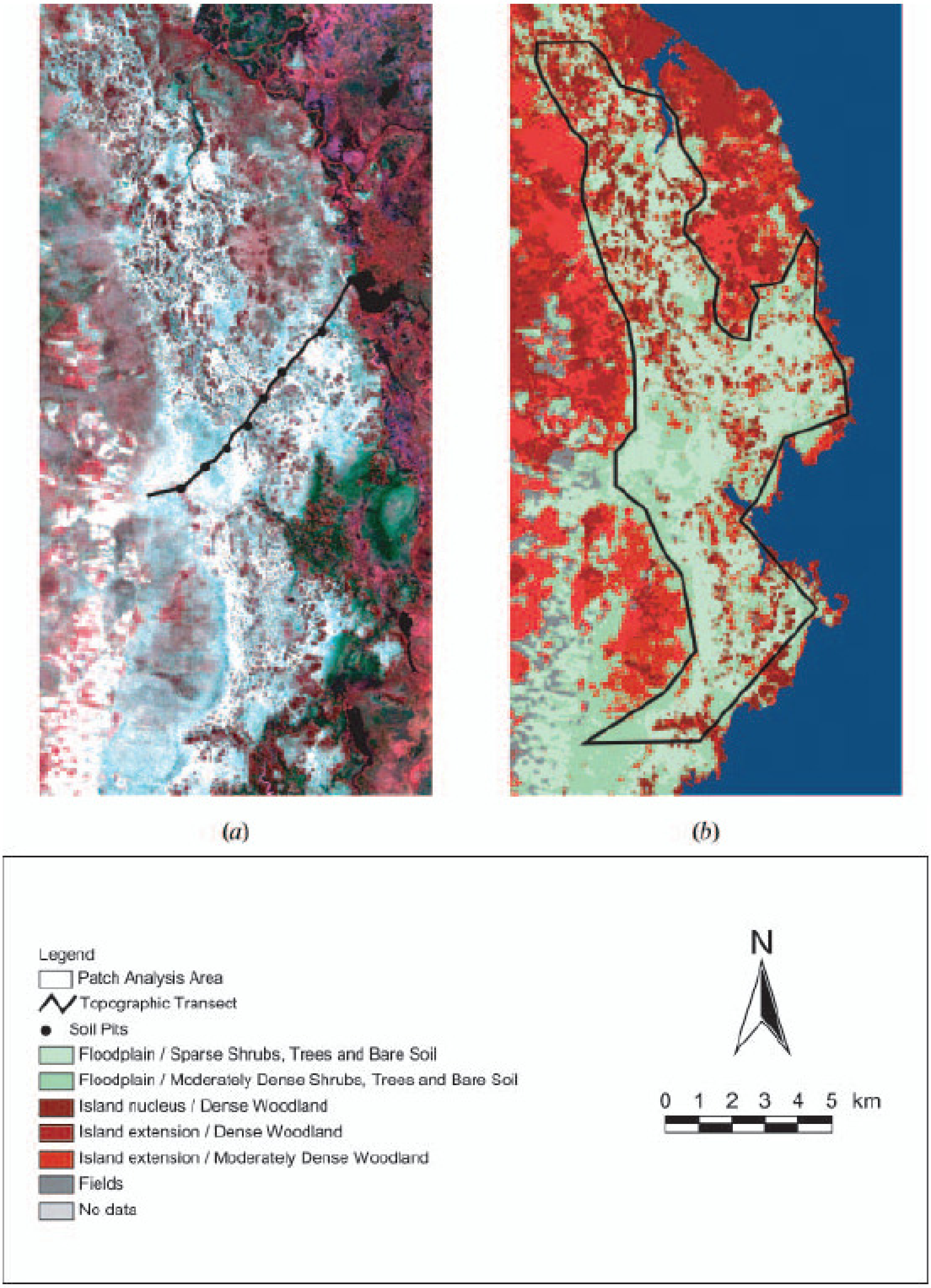

Figure 4. Etsha area (*a*) original Landsat ETM+ imagery (bands 2, 3 and 4 displayed as blue, green and red) and (*b*) results of supervised classification.

partially confused with I2 (Island extension), as dense woodland characterized both classes (figure 4(*b*)). Some confusion occurred between I2 and I3, as both island extension types are classified on the basis of the relative density of the woody cover. The Etsha area has been dry for an estimated 2000–3000 years and

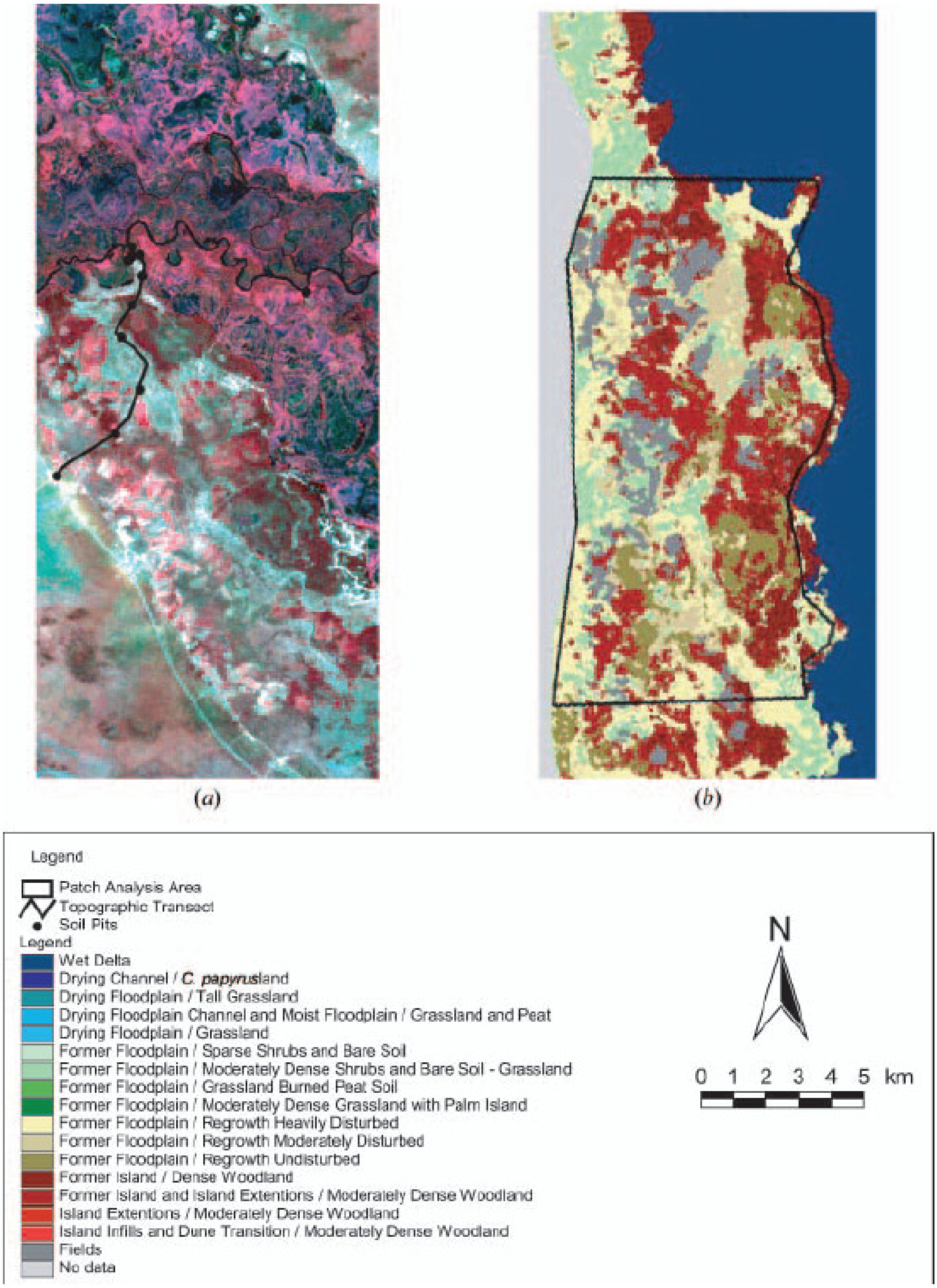

Figure 5. Shakawe area (*a*) original Landsat ETM+ imagery (bands 2, 3 and 4 displayed as blue, green and red) and (*b*) results of supervised classification.

shows on the classified image a contrasting classification result relative to the Gumare area, and yet it comprises a similar pattern of flood plains and islands. In this case, the grass flood plains have been replaced by a more uniform woody vegetation cover of varying density (table 3). Both sparse and moderately dense

Table 1. Final results of supervised classification in the Gumare area.

Class	Description	Area (km^2)
Wet Delta	Water in channels	6
Channel	Vegetated channels with *C. papyrus* and *P. australis*	11
FP1 Flood Plain	Sparse grasses and peat—*C. dactylon*	24
FP2 Flood Plain	Dense grasses—*I. cylindrica*	14
FP3 Flood Plain	Sparse grasses and bare soil—*C. dactylon*	8
FP4 Flood Plain	Dense grasses and bare soil—Mixed species	10
FP5 Flood Plain	Moderately dense grasses and shrubs—Mixed species	14
FP6 Flood Plain	Grasses and burnt peat soil—*C. dactylon*	62
FP7 Flood Plain	Moderately dense grasses and Palm Islands	17
I1 Island nucleus	Dense woodland—*C. megalobotys, A. nigrescens, A. erioloba*	14

flood-plain classes are quite extensive, covering an area of 50–60 km^2. While the island nuclei can still be identified, woodland occurs surrounding the nuclei and evidently spatially related to it (figure 4(*b*)). These are referred to for the first time in this work as island extensions. This appears as an ecotonal transition as, spectrally, the woodlands can be sub-divided into the dense (I2) woodland type, which covers 56 km^2, and the moderately dense I3 type, which covers 60 km^2. Both these comprise *Acacia erioloba* species (table 3). Fields are also beginning to be found on the edges of the flood plains (figure 4(*b*)). The Etsha area is classified with an overall accuracy of 76% (table 4).

The Shakawe area shows more overall diversity than Etsha, particularly in the form of flood-plain categories (figure 5(*a*)). The first flood-plain class (FP1) supports sparse shrubs and trees while *Colophospermum mopane* is clearly spectrally separable. There is, however some overlap with FP5 which is described as dense mixed trees and shrubs. The other flood-plain class, FP4 moderately dense mixed shrubs and trees, is classified separately from the flood-plain infill, FP5 dense mixed shrubs and trees. While I1, the island nuclei, is partly inseparable from FP4, I2 and I3, a relatively high classification accuracy is nonetheless maintained. In the Shakawe area, the number of discernible flood plains increased to five, in addition to island nuclei and two island extension classes, giving a total of eight classes (figure 5(*b*), table 5). The Shakawe area, which has been dry for several millennia, shows the same basic pattern of flood plains and islands. In this case, the FP1 and FP2 flood plains (covering 25 and 26 km^2, respectively) are distinguishable by the addition of *C. mopane* in tree and shrub forms, a species which is characteristic of most of the drier parts of the Delta (table 5). Other tree and shrub flood plains are more extensive (FP3—28 km^2 and FP4—38 km^2) with species in the form of *Baphia massaiensis* and *Ximenia americana*. The island nuclei and surrounding dense woodland extensions (I1–I3) are enlarged and more coherent (relative to the two other study areas) and appear to encircle areas of former flood plains. These comprise such species as *Croton megalobotrys* and *Garcinia livingstonei* (figure 5(*b*)). Within the encircled areas, the flood-plain vegetation has also changed to become denser and to 'infill' the extensional areas (F5—33 km^2). The image shown as figure 5 depicts for the first time the spatial distribution of dense and less dense island extension woodlands and flood-plain infills, a relationship which lends credence to the drying, successional theory which is central to this work. The Shakawe area is classified with an overall accuracy of 74% (table 6).

Table 2. Accuracy assessment (111 samples) of the Gumare area classification (classes are defined in table 1; overall accuracy=77%).

	Image classes												
Observation points	CH	F1	F2	F3	F4	F5	F6	F7	I1	ΣC	Users' accuracy (%)		Producers' accuracy (%)	
CHH	6	1	1	0	0	0	0	0	0	8	CH	66	CH	75
F1	0	7	2	0	0	0	0	0	0		F1	50	F1	77
									9					
F2	0	4	10	0	1	0	0	0	0	15	F2	59	F2	66
F3	0	0	0	8	2	0	0	0	0	10	F3	100	F3	80
F4	2	1	3	0	7	1	0	0	0	14	F4	64	F4	50
F5	0	0	0	0	0	9	2	0	0	11	F5	75	F5	81
F6	1	0	0	0	0	2	12	0	0	15	F6	80	F6	80
F7	0	1	0	0	0	0	1	15	0	17	F7	100	F7	88
I1	0	0	1	0	1	0	0	0	10	12	I1	100	I1	83
ΣR	9	14	17	8	11	12	15	15	10	111	Average	77	Average	76

Table 3. Final results of supervised classification in the Etsha area.

Class	Description	Area (km^2)
FP1 Flood Plain	Sparse shrubs, trees and bare soil—*B. massaiensis, T. sericea*	53
FP2 Flood Plain	Moderately dense shrubs, trees and bare soil—*B. massaiensis, T. sericea*	61
I1 Island nucleus	Dense woodland—*S. cordata, D. messpiliformes*	18
I2 Island extension	Dense woodland—*D. messpiliformes, A. erioloba*	56
I3 Island extension	Moderately dense woodland—*B. massaiensis, A. erioloba*	60

Table 4. Accuracy assessment (111 samples) of the Etsha area classification (classes are defined in table 3; overall accuracy=76%).

Observation points	Image classes									
	F1	F2	I1	I2	I3	ΣC	Users' accuracy (%)		Producers' accuracy (%)	
F1	12	2	0	0	0	14	F1	75	F1	86
F2	3	14	0	0	0	17	F2	88	F2	82
I1	0	0	11	3	0	14	I1	65	I1	79
I2	1	0	6	30	5	42	I2	75	I2	71
I3	0	0	0	7	17	24	I3	77	I3	71
ΣR	16	16	17	40	22	111	Overall	76	Overall	78

5.2 *Topographic characteristics*

The results of topographic analysis varied within the different study areas generally endorsing the drying trends. The Gumare profile which covers a linear distance of about 4.5 km (12 points) is shorter and therefore may be less conclusive than the Etsha and Shakawe profiles. However, the salient though attenuated flood plain,

Table 5. Final results of supervised classification in the Shakawe area.

Class	Description	Area (km^2)
FP1 Flood Plain	Sparse shrubs, trees and bare soils with *C. mopane, A. erioloba*	25
FP2 Flood Plain	Moderately dense shrubs, trees and bare soils with *C. mopane, T. sericea*	26
FP3 Flood Plain	Sparse mixed shrubs and trees *B. massaiensis, X. americana, R. tenuinervis*	28
FP4 Flood Plain	Moderately dense mixed shrubs and trees *B. massaiensis, X. americana, R. tenuinervis*	38
FP5 Flood Plain infill	Dense mixed shrubs and trees *C. megalobotrys, T. sericea, B. massaiensis*	33
I1 Island nucleus	Dense woodland—*G. livingstonei, C. megalobotrys, B. massaiensis*	31
I2 Island extension	Dense woodland— *G. livingstonei, C. megalobotrys, A. erioloba*	38
I3 Island extension	Moderately dense woodland—*B. massaiensis C. megalobotrys, T. sericea*	33

Table 6. Accuracy assessment of the Shakawe area classification (classes are defined in table 5; overall accuracy=74%).

Observation points	Image classes												
	F1	F2	F3	F4	F5	I1	I2	I3	SC	Users' accuracy (%)		Producers' accuracy (%)	
F1	14	0	0	0	0	0	0	0	14	F1	82	F1	100
F2	0	5	4	0	0	0	0	0	9	F2	50	F2	55
F3	0	0	6	0	2	0	0	0	8	F3	43	F3	75
F4	0	0	1	6	0	0	0	0	7	F4	100	F4	86
F5	2	4	3	0	11	1	0	1	22	F5	73	F5	50
I1	0	0	0	0	2	7	2	0	11	I1	63	I1	64
I2	1	0	0	0	0	2	15	0	18	I2	83	I2	83
I3	0	1	0	0	0	1	1	18	21	I3	95	I3	86
SR	17	10	14	6	15	11	18	19	110	Average	74	Average	75

channel and island features are still captured in this profile. The more elongate lower stretches on the profile are illustrative of extensive flat flood plains which are intermittently incised by deep channel remnants. The higher topographic features form islands such that the overall relief in this area is 3.64 m. The Etsha profile covers a linear distance of about 9 km comprising 34 points along a sand track. The elongate lower stretches consist of extensive flat flood plains intermittently intersected by topographically higher islands and lower poorly formed channel remnants (figure 6). The overall relief is 3.4 m. The Shakawe profile covers a linear distance of about 11 km, comprising 34 points along a sand track extending from the base of dunes in the west in towards the Okavango Panhandle in the east. The area consists of low elongate stretches which comprise flat flood plains intersected by slightly higher islands and poorly formed channels with an overall relief of 3.11 m. Overall relief is therefore greater in the recently

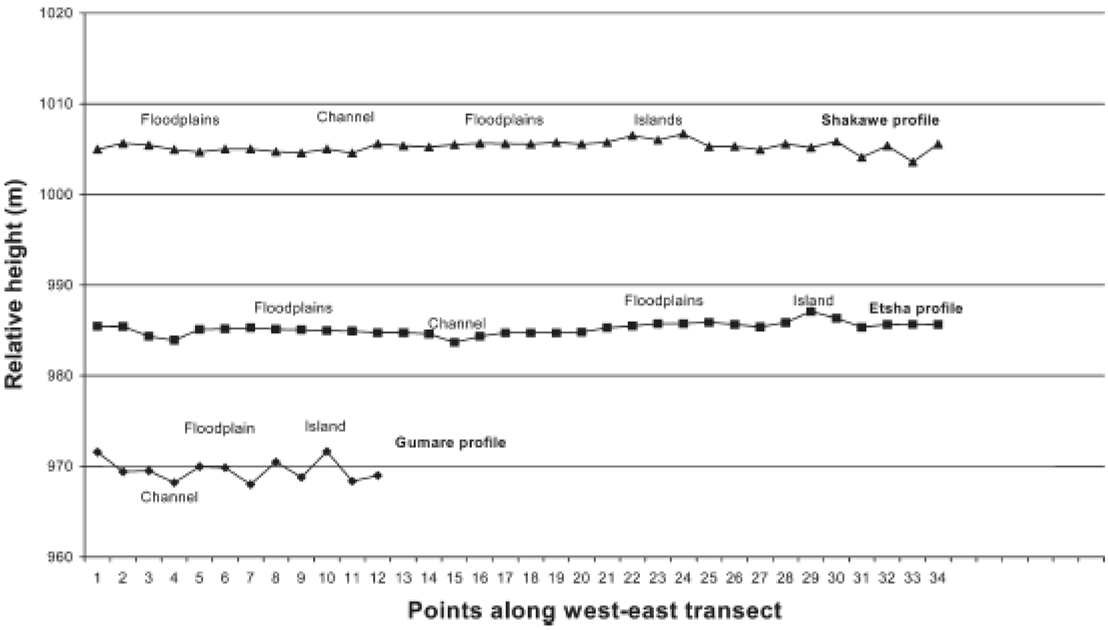

Figure 6. Variation of topographic profiles from Gumare to Shakawe showing a decrease in overall relief along the drying gradient. Each point represents a Trimble 4700 Global Positioning System record taken on major breaks of slope in the field.

dry Gumare area, drops gradually in the Etsha area and is almost level in the area with the longest drying history (Shakawe) due to continuous erosion and in-channel deposition.

5.3 *Soil characteristics*

The Gumare area comprises recently dry flood plains incised by channels and interspersed with islands. The flood plains are characterized by up to 60 cm of burnt peat over peaty sand or clean white sand. The burnt peat has a low remaining large (>2 mm) litter content, high surface soil moisture content and conductivity, which drops rapidly over the 1.0 m profile (table 7). In contrast, channel soils subject to intermittent flooding have a higher litter content and higher soil moisture and pH

Table 7. Results of soil analyses in the Gumare, Etsha and Shakawe study areas.

	Depth	Litter		Moisture		pH		Electrical conductivity		Carbonate
	(cm)	(%)	SD	(%)	SD	pH	SD	$\mu S\ cm^{-1}$	SD	content
Gumare										
Island	0–20	3.54	7.52	11.54	6.78	7.9	0.57	591	261	+ +
(1–9, 1–3, 1–6)	21–90			27.05	5.87	8.6	0.72	930	712	+ + +
N=3	>91			10.16	1.99	8.28	0.41	839	465	+ + +
Flood Plain	0–20	0.63	0.97	18.51	5.56	4.37	0.43	1046	408	−
(1–5, 1–7)	21–90			6.43	7.89	5.47	1.44	275	235	−
N=2	>91			2.27	0.85	6.82	0.97	99	78	−
Channel (CH)	0–20	3.67	6.8	36.2	4.47	5.77	1.86	987	293	−
(1–4, 1–8)	21–90			62.37	0.02	6.96	3.03	1368	275	−
N=2	>91			21.64	3.79	5.56	0.89	194	131	−
Etsha										
Island	0–20	1.15	1.39	6.02	2.84	7.54	0.77	402	287	−
(1–5, 1–4)	21–90			3.83	1.31	7.65	1.13	419	508	−
N=2	>91			6.6	1.84	8.92	1.09	955	467	+ +
Flood Plain	0–20	0.06	0.07	2.17	0.23	6.45	0.63	70	41	−
(1–9, 1–6, 1–3, 1–2)	21–90			3.1	0.46	7.72	0.9	215	301	−
N=4	>91			3.59	3.91	6.94	1.13	99	157	−
Shakawe										
Island	0–20	0.51	1.05	3.81	N/A	7.64	0.99	357	223	−
(2–1, 2–2, 1–8)	21–90			5.6	0.99	8.68	1.43	501	133	−
N=3	>91			8.35	2.85	8.92	1.26	761	284	+
Flood Plain	0–20	0.33	0.48	1.14	1.05	5.67	0.93	140	145	−
(1–4, 1–6, 1–7)	21–90			0.82	0.09	6.24	1.43	70	51	−
N=3	>91			0.96	0.36	5.72	0.63	54	421	−
Island Extension	0–20	2.47	3.48	3.41	3.15	5.99	0.67	216	148	−
(1–2, 1–3, 1–5)	21–90			1.34	0.08	5.37	0.51	125	40	−
N=3	>91			1.95	0.97	5.94	0.59	97	39	−

−: no apparent carbonate; +: minor carbonate; + +: moderate carbonate; + + +: major carbonate.

than the surrounding flood plains. Many island soils have relatively well-developed upper organic horizons but are mainly composed of silty sand with clay and disseminated calcrete. The island soils which have rarely experienced flooding are relatively alkaline with an intermediate conductivity. Hydrolysis of basic cations is a primary source of soil alkalinity, and the elevated pH observed in these soils may well be due to the hydrolysis of exchangeable ions such as sodium.

In the Etsha area where drying has taken place over approximately 2000–3000 years, there is also a sharp distinction between soil characteristics in the islands and flood plains. Flood plains are characterized by massive brown sands with thin humic topsoils up to 20 cm in depth. These flood-plain soils have low EC values and are neutral to slightly alkaline in reaction. In contrast to the Gumare flood-plain soils, the Etsha flood plains show very low litter and soil moisture contents, although both flood plains are carbonate-deficient (table 7). Etsha island soils are characterized by deep, organic-rich topsoils over clay-rich sub-soils, whereas island edges are more sandy. The island soils support high moisture and EC values (relative to the flood plains) and are characterized by increasing pH values at depth with disseminated calcrete at about 1.0 m.

In the Shakawe area, where drying has taken place in the order of 7000 years, there is considerable variety in soil characteristics with less obvious differentiation between islands and flood plains (table 7). The Shakawe flood plains are generally characterized by orange washed dune sand overlain by 20–60 cm of brown channel sand with no significant humic soil formation. The flood-plain soils typically have low EC values (lower than Etsha), low pH values (slightly lower than Etsha), moderate litter, low soil moisture contents and a marked absence of carbonate (table 7). This suggests that in terms of flood-plain evolution, the exposed flood-plain soils become increasingly skeletal and impoverished over the millennia. In contrast, islands are characterized by silty-sand topsoil overlying either carbonate rich silt or clay rich sand. Island soils typically have lower EC values (than Shakawe and Etsha), moderate pH values and lower moisture contents. The results may suggest that the hydrolysis of basic cations is slowing at least in island nuclei as a result of ground or soil moisture transpiration by large trees as a result of continued island drying. The areas around islands, which represent the modified flood-plain soils of island extensions and infills, show mixed flood plain–island characteristics comprising mainly sand with evidence of humic soil formation suggesting transitional pedogenesis. These transitional soils typically have higher EC values, slightly higher pH values and much higher moisture contents than the adjacent impoverished flood plains.

5.4 *Spectral trends*

Results of a spectral trend plot of bands ETM+5 and ETM+3 show a clear separation with increasing incidences of darkening (decreasing reflectance) extending from the flood-plain soil-vegetation cover types to the island types (figure 7). The darkening ratio plot from the Etsha and Gumare study areas show some overlap suggesting that the soil-vegetation cover has a similar origin as they occur on the same trend line. The darkening values from the Etsha area are high relative to those from Gumare mainly because of the remnant peat-burnt peat soils which occupy extensive areas in Gumare. The Gumare and Etsha area darkening ratio trend essentially demonstrates an overall similarity in terms of

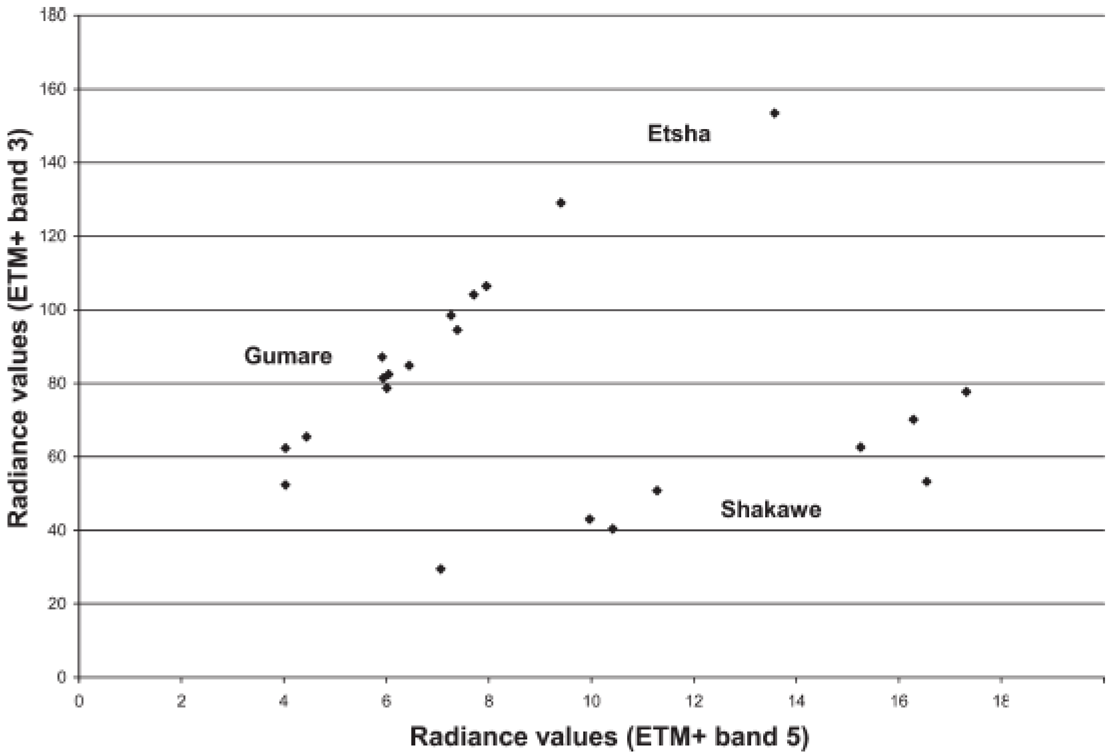

Figure 7. Spectral plot of ETM3 against ETM5 radiance values showing the differentiation of relatively reflective (hence more youthful) soil-vegetation types in Gumare and Etsha areas relative to the denser and more darkened woody cover in the Shakawe study area. Each point represents one pixel.

the relative youthfulness of the vegetation regeneration processes taking place in these two areas. In contrast, the Shakawe darkening trend forms a separate and generally darker sub-population indicative of an overall increasing density of woody cover (Moleele *et al*. 2001), and more humic soil formation both on the flood plains and islands. This suggests the relative antiquity of the vegetative regeneration processes ongoing in this area.

5.5 *Patch analysis*

In conjunction with the results of image classification, an ecological process is inferred here, whereby former small tree islands act as refugia, while the Delta is flooded and as a source for certain species which later colonize dry flood plains over time (e.g. Peters 2002). For patch analysis in the Etsha area, the transition zone from the Kalahari dunes in the west of the study area and a large island in the east were excluded. In the Gumare area, the patch analysis procedure was concentrated in the vicinity of the terminal Thaoge channel. In the Shakawe area, the entire area of flood plains, island extensions and infill was used in the analysis. While the number of patches per km^2 is similar in Gumare and Etsha (approximately 5.0), the number declines rapidly to the Shakawe area (0.8). The mean patch size also increases from the Gumare to Shakawe study area as small patches (tree islands) occur in Gumare, while larger patches (island extensions) are found in the Etsha area, and finally large island agglomerations are located in the Shakawe area (table 8). The remaining statistics show similar trends, especially the Area Weighed Shape Index, while the results of fractal analysis are less clear. The fact that such indices as Mean Patch Size

Table 8. Results of patch analyses along the Okavango drying gradient.

	Gumare	Etsha	Shakawe –	Shakawe +
Number of patches per km^2	4.5	5.1	0.86	0.7
Mean patch size	0.66	4.88	16.28	25.42
Patch size standard deviation	1.31	26.09	118.36	213.27
Mean shape size	1.22	1.39	1.4	1.44
Area weighted shape index	1.63	4.29	5.91	7.43
Mean patch fractal dimension	1.04	1.05	1.05	1.06
Area weighted fractal dimension	1.09	1.19	1.21	1.23

Shakawe –: Shakawe image with the field areas removed; Shakawe +: field areas are included.

and Shape Complexity increase from the relatively recently dried Gumare area to the geologically drier Shakawe area (along the drying gradient) suggests that an overall enlargement process is taking place. Interestingly, the Patch Size Standard Deviation also increases from Gumare to Shakawe, suggesting that the island agglomeration process is relatively random and, once initiated, may stabilize as a small agglomerated island or may continue enlarging, depending on circumstances within the local environment. The processes of island ecotonal extension and flood-plain infilling combined are referred to here for the first time as 'island agglomeration'. However, with a sample of three, the results may not be regarded as being entirely conclusive.

5.6 *Island Agglomeration theory*

The Island Agglomeration theory is deduced here from observations and analyses based on ETM+ imagery interpretation augmented by independent vegetation, topographic and soil analyses. The three study areas were selected on the basis of the relative freshness of remnant flood plain and island forms. The evidence for the relative dates for the three locations is partly based on historical notes (Tlou and Campbell 1984) and partly based on Delta wide multi-proxy data (Ringrose *et al.* 2003a), which are circumstantial by nature. However, a number of different lines of evidence appear to confirm the prevalence of a series of drying changes on the western side of the Okavango Delta, over approximately 7000 years. The theory assumes (from the Gumare area) that initial conditions comprise nuclear islands which act as woody plant refugia and dried out (often burnt peat) grass-covered flood plains. After a few millennia, the flood plains become covered with shrubs, then trees and shrubs, although the actual density of cover may be controlled by burning (Heinl 2001). The island refugia provide specific woody species (notably *Croton megalobotrys* and *Acacia* spp.) which colonize out from the islands to the adjacent flood-plain ecotone. The areas where these species colonize are referred to as island extensions. Given the evidence from this work, the process of island extension appears to take a few thousand years and, while apparently retarded by burning, is rarely completely stopped by fire (Heinl 2001). After several more thousand years, protected areas within enlarged extensions become infilled by successive flood-plain trees and shrubs, which proceed to become denser as the quality of soil cover improves. The entire area of former islands, island extensions and infills is called Island Agglomerations. These appear to co-exist with tree and shrub flood plains on bare sandy soils which become increasingly impoverished, possibly because they are continually exposed to wind and fire, with little opportunity for humic soil formation and evolutionary development.

6. Discussion and conclusions

This work was undertaken to determine the value of remotely sensed imagery in the determination of drying impacts which may occur as a result of internal factors (e.g. blockages) and/or external factors in the Okavango catchment. Little previous work has been undertaken on characterizing successional changes resulting from drying peripheral to wetlands using remote sensing techniques (Shaikh *et al*. 2001, Kerr and Ostrovsky 2003). The importance of this work stems from the inevitability of increased human and naturally induced drying which will likely lead to further Delta margin contraction through time. The three sites chosen here are intended to provide a preview of the consequences of Delta margin drying as depicted over historical timescales (150 years, in Gumare), 2000–3000 years in Etsha and over periods of approximately 7000 years in the Shakawe study area. So, the three sites were chosen to try and reconstruct the nature and types of soil-vegetation changes which might be expected over forthcoming intermediate and longer time spans, while providing insights into possible future natural resource management for affected communities.

The results of satellite (ETM+) imagery interpretation in these three areas have led to the development of a preliminary theory of long-term successional change here called the Island Agglomeration theory. Results indicate that vegetation-soil changes can be detected using ETM+ imagery particularly with respect to changes in former flood plains and islands which result from sequential drying along the west side of the Okavango Delta. Initially, supervised classification resulted in the identification of sequences of islands and flood plains, and their associated vegetation cover with a classification accuracy of 74–77%. A comparison of the results from the geologically older Shakawe study area with the younger Etsha and Gumare areas infers that, through time, island-based woody vegetation cover invades the flood plains and locally develops protected ecotonal areas (extensions) which are densely treed, relative to the adjacent, non-protected flood plain. Over longer time periods, the (inter-extension) protected areas also become infilled with woody vegetation. Hence, island areas become enlarged and ultimately coalesce, as suggested by patch analysis which shows large island-like agglomerations on ETM+ images of geologically older parts of the Delta margin.

Independent evidence of drying trend changes was also sought through comparative data on soil and vegetation change. Results indicate that former islands are relatively stable features on the landscape. Islands sustain a greater number of woody species, some of which are well adapted to the drying out process either by means of root deepening or by developing lateral roots to make more efficient use of rainfall (Ringrose 2003). Flood plains are ephemeral as they loose their characteristic soil and vegetation cover relatively quickly and are readily invaded by woody vegetation species. Flood-plain margins embodied in island extension and infill appear to form relatively stable, protected, more densely treed ecotones which through time develop richer, more humic soils. In contrast, unprotected flood-plain remnants continue to be characterized by sparser trees and shrubs growing on humus poor sandy soils.

With respect to the prospects for natural resource management as the Delta dries out, a main disadvantage will be the reduced availability of *P. australis* for housing and general construction purposes, reduced opportunities for molapo (river edge) cultivation and the absence of surface water for domestic purposes. Increasing shrub dominance on drying flood plains will cause a reduction in the relative proportion of grass available for grazing by cattle. Goat populations may continue to increase as a result of their ability to browse on shrubs. After a number of millennia, if left undisturbed, the flood plains peripheral to nuclear islands may become colonized by island-type trees and therefore develop relatively good humic topsoils as a result of litter decay. At this stage, the taller trees may be useful for a range of construction activities, and importantly, the soils become humic and may be cultivated at first with minimal fertilizer. However, the non-protected flood-plain soils will remain of limited agricultural potential.

While preliminary in nature, this work reveals that not only flood-plain species change but also island agglomeration is an integral process in the drying of complex flood-plain systems. More detailed ecological work in other areas is required to characterize the drying processes further, which may well involve the application of detailed IKONOS imagery and/or ER2 photography. This could prove extremely useful as serious wetland conservation and management have to take into account the nature of ecological change consequent upon drying so that the correct interventions may be invoked.

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