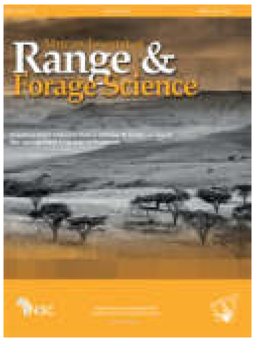

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Woody cover change in relation to fire history and land-use in the savanna-woodlands of north-east Namibia (1996–2019)

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Vegetation cover estimates for trees, shrub-grass mosaics, and grassland and bare ground, were quantified in the savanna-woodland of Bwabwata National Park, north-east Namibia. Changes in woody cover were analysed using repeat photographs in combination with aerial photographs and recent satellite imagery taken between 1996 and 2019. Cover estimates for each vegetation type were obtained using object-based classification techniques and a non-parametric random forest classifier algorithm in eCognition Trimble software. Results show that over the two decades under investigation (1996–2019), trees declined (−10.6%), and the shrub-grass mosaic vegetation type increased (8.1%) across the park. The largest decline in trees occurred in the western land use areas (−36%), which also experienced the greatest increase in the shrub-grass mosaic (17%), when compared with areas in the east (11%). Variation of woody cover estimates is attributed to different seasonal fire management practices in the east versus the west of the park. The fire history (2000–2018) revealed that late dry season fires were frequent in the west, whereas in the east, early dry season fires were frequent. The stages of encroachment recorded in this study have consequences for biodiversity, people's livelihoods, and tourism.

Keywords: bush encroachment, Bwabwata National Park, fire seasonality, repeat photography, vegetation structure

Supplementary material: available at https://doi.org/10.2989/10220119.2021.2005145

Introduction

The balance between grass and trees, as well as the structure of woody vegetation is central for managing and understanding the biodiversity and ecosystem services of savannas (O'Connor and Stevens 2018). For the past century woody plants have increased in many grasslands and savannas worldwide and this phenomenon is termed 'shrub/woody encroachment' or 'woody thickening' (O'Connor et al. 2014; O'Connor and Stevens 2017). Beyond a threshold (50%), encroachment reduces the potential for the coexistence between grass and trees causing a shift in ecosystem structure and composition (Scholes 2003; Staver et al. 2011). This in turn has significant implications for biodiversity and people through the consequential alteration of ecosystem services, such as climate regulation, provision of food resources, grazing and nature-based tourism (Gibbes et al. 2010). Fire is one of the most important management tools used to control woody biomass in savannas (Smit et al. 2016). In certain instances, fire suppression has led to homogenised, overconnected landscapes where fuel build-up leads to large intense fires. In these landscapes, heterogeneity can be restored with prescribed fires, grazing management, and fuel manipulation (Gillson et al. 2019). Quantifying change in vegetation structure in savannas can inform fire management policies and help to ensure the sustainable use of resources.

In southern Africa, tropical, and subtropical savanna biomes are characterised by a mixture of growth forms of primarily trees, shrubs and grasses and traditional pixel-based classification schemes cannot differentiate across vegetation class types, due to high levels of heterogeneity (Gibbes et al. 2010; Gessner et al. 2013; Mishra and Crews 2014). For example, high-resolution historical aerial photographs and/or satellite imagery (e.g. ≤1 m – 30 m) that have been taken in savanna landscapes have a higher density of pixels that show greater variation, which are then used to statistically classify and/or group features that are similar in a spatial context. The multiresolution segmentation approach (Baatz and Schäpe 2002) uses a combination of both spectral values and spatial characteristics (e.g. size, shape, texture, association with neighbouring objects) in the imagery to identify features and create objects to characterise different vegetation class types (Huttich et al. 2009). Furthermore, remote measurements using ground-based photographs of past landscapes can be used to document change over time (Scott et al. 2021).

Historical photographs present evidence of past conditions and repeat photography offers an opportunity to describe changes in vegetation composition and structure, as well as changes in land-use over time (Rhode and Hoffman 2012). With the use of repeat photographs the following vegetation dynamics can be established at a species-specific level: i) change in density and structure of trees and shrubs in savanna-woodlands; ii) vegetation establishment, resprouting plant traits stimulated by fire, and mortality events of tall, large trees, and iii) spatial differences in vegetation changes (Gessner et al. 2013; Ward et al. 2014).

In this study, we use an integrated method consisting of repeat photography (1999 and 2019) and remote sensing data comprising historical aerial photograph (1996) and recent satellite imagery (2019) to assess woody cover change and fire history across Bwabwata National Park (BNP). We propose that this approach presents novel and powerful monitoring tools for assessing long and short-term environmental change in BNP and elsewhere. This period under study in the park includes a change in policy from fire suppression to early burning, which was implemented in the park in 2006. The study area includes multiple land uses; protected core areas and multiple-use zoned areas, where indigenous communities inhabit the landscape in a 'Multiple Use Area' (MUA). The core conservation areas are the closest 'control' systems available in BNP, as the natural and human processes of frequent fires and moderate herbivory (grazers and browsers) are mostly maintained. Early season fires are a regular occurrence in the MUA of the park. There is a need to establish the extent of bush encroachment in the park, as Namibian stakeholders expressed mixed perceptions of whether encroachment has occurred (2015) and questioned whether the change in fire policy from suppression to early burning has influenced vegetation patterns in BNP (Humphrey et al. 2021).

The overall aim this study was to investigate interdecadal woody cover dynamics to inform fire and land use management plans. The first objective was to use repeat photographs in combination with historical aerial and recent satellite imagery (1996–2019) to assess changes in woody cover. A second objective was to determine the different woody cover states in relation to the fire and land use history in BNP. To explore these objectives, two questions were addressed: i) Is there a change in woody cover over time in the land use areas representing different management strategies (protected areas versus community-inhabited areas) in BNP? ii) Do different fire histories (i.e. fire seasonality) result in different woody cover states (e.g. trees; shrub-grass mosaic; grassland and bare ground) in BNP? We expected that in the land use areas where late dry season fires were frequent, that tall trees would decline, and shrubs would increase, as fire stimulates stems to resprout repeatedly after being burnt back, as well as prevents the recruitment of trees into adult size classes. However, in land use areas where early season fires were frequent, we anticipated mixed vegetation structure of tall trees, together with shrubs, and grassland, as early season fires limit the damaging effects of intense fires and burn in patches, which results in vegetation of various post-fire age size classes to establish. Moreover, we expected to find mixed vegetation height structure (i.e. combination of trees and shrubs) in the MUAs where burning is more frequent in the early season than the late season. Alternatively, in the Core Area (CAs) we expected a more homogenous stand of shrubs and less tall trees, as fires are more pronounced in the late dry season (MET 2016).

Study area

Bwabwata National Park in north-east Namibia is 6 247 km^2 (18°06′56.52″ S, 21°40′10.56″ E) and lies within the centre of the Kavango Zambezi-Transfrontier Conservation Area (KAZA-TFCA) in southern Africa (Figures 1a and b). It is located in the Kavango East and Zambezi Regions, and is bordered to the north by Luiana Partial Reserve in Angola, and to the south by the Okavango Delta in Botswana. The park experiences the highest rainfall (average 650 mm) in the country and supports a tropical ecosystem with two major rivers, the Kwando River in the east and the Okavango River in the west. BNP lies within the Zambezian domain of the Sudano-Zambezian Floristic region (White 1983) and is on the southern limit of broadleaved tree-shrub savanna biome of the 'Miombo Eco region' of southern Africa (Timberlake et al. 2018), an important vegetation type threatened by the extent of fire and human activities (Frost 1999). Characteristic species in the savanna-woodlands include *Burkea africana, Baikiaea plurijuga, Guibourtia colesperma, Ochna pulcra, Terminalia sericea, Erythrophleum africanum, Combretum hereoense, C. collinum, Schinziophyton rautanenii*, and *Pterocarpus angolensis* (Tinley 1966). There is an absence of Miombo genera in the study area (i.e. *Brachystegia; Julbernadia*). The topography of the area is characterised by palaeo-landforms, which consist of dune fields with low-lying omiramba grasslands, which are fossil drainage lines covered in grass that lie between remnant dune crests (i.e. degraded dunes) that are now stabilised by savanna-woodlands (Tinley 1966; MacFarlane and Eckardt 2007). The primary drivers of the ecological patterns in the park are the climate, flooding regimes, herbivores, soil types, fire (Mendelsohn and Roberts 1997; Trollope and Trollope 1999), and human activities. The park is unusual in that people coexist with wildlife and live in villages in an area called the Multiple Use Area (MUA). This area is flanked by three core conservation areas designated for special protection to support key government constitutional biodiversity objectives, and controlled tourism. The three areas are called the Kwando Core Area (CAs) in the east and the Mahango and Buffalo CAs in the west of the park (Figure 1c). For the purposes of this study, the Buffalo CA and Mahango Game Park areas were combined into a single area called the Western CA. Because of their proximity, the land use sites share similar climate, geology, and vegetation.

Historical context of fire management in Bwabwata National Park

Colonial fire suppression held precedence from 1884 and persisted until after Namibia's independence (1990). In 2006, early burning strategies were formally implemented in the park (Ministry of Environment and Tourism [MET] 2013). Yet, prior to the 1700s the inhabiting indigenous (Khwe-San) and traditional communities (Hambukushu) used seasonal burning practices to support their livelihoods and maintain the landscape before the establishment of the national park (Humphrey et al. 2021). In 2016, a revised Fire Management Strategy for Namibia's Protected Areas was published, which

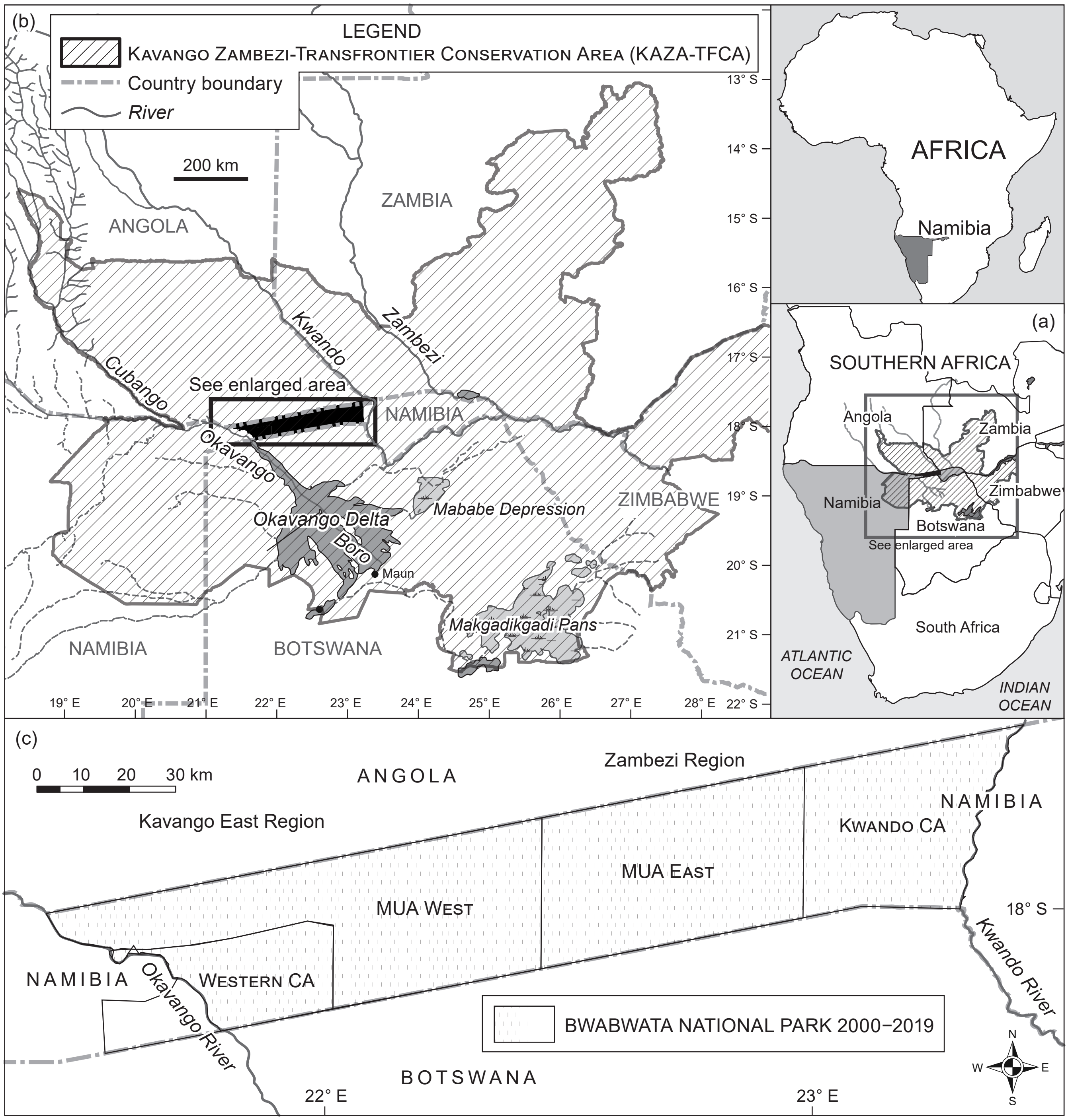

Figure 1: (a) Location of Namibia and Kavango Zambezi-Transfrontier Conservation Area (KAZA-TFCA) delineated by a bolder black outline. (b) Location of Bwabwata National Park in north-east Namibia centred within the KAZA-TFCA. (c) Land use areas (Western CA, MUA West, MUA East and Kwando CA) in the Bwabwata National Park

recognised traditional burning practices in the park (MET 2016). This was an important turning point in the acknowledgement of socio-cultural burning practices within current fire management plans. Early dry season fires (April to July) are typical in the east of the park (i.e. MUA East and Kwando CA), whereas fires in the west (Western CA and MUA West) generally occur in the late dry season between August and October (MET 2016, Humphrey et al. 2021). Differences in seasonal burning patterns are associated with cultural burning practices between groups living in the park and because of contrasting management approaches between the Kwando and the Western CAs (Humphrey et al. 2021).

Materials and methods

In 1999, thirty-seven fixed-point repeat photograph sites were established to monitor vegetation change in the BNP in north-east Namibia (D. Ward, pers. comm). In 2019, the same sites were revisited to take a second pair of repeat photos. Accordingly, in this study three independent data sources are used: (i) repeat photographs (1999 and 2019) (Eastment et al. in press), (ii) historical aerial photographs (1996 and 2007) and (iii) recent satellite imagery (2019). Image rectification and georeferencing was performed in Arc-GIS v10.7 (ESRI) and eCognition Trimble Developer® 9 platform (Definiens) was used for the assessment of the spatial and temporal change in woody cover through Object-based-image analysis (OBIA) of the aerial and satellite imagery. A systematic sampling design was used matching the established repeat photography vegetation monitoring sites (Eastment et al. in press; Figure 1c).

Data acquisition

Data included i) a very high-resolution colour orthophoto from 2007 at 1 m resolution, ii) aerial photographs from 1996 at 2–2.5 m resolution obtained from the Directorate of Mapping and Surveys in Namibia and iii) high-resolution Sentinel 2A satellite imagery from 2019 (https: //sentinel.esa.int/) at 10 m resolution (Supplementary Table S1). These images were taken over the dry season (June–August) and were used to determine estimates of woody cover change. Historical images were scanned with an Epson V850 Pro scanner and printed as A4 images for field use.

The aerial and satellite images were georeferenced and orthorectified in the GIS software with the high-resolution colour orthophoto (2007) and enhanced by using levelling histograms. Five Sentinel-2A-tiles were mosaicked to form a single image. A 3 × 3 highpass filter was used on the raster files prior to the supervised classification to accentuate the comparative differences between neighbouring pixels and produce more homogenous image objects for the OBIA analyses.

Vegetation classification

Three vegetation classes were selected using the high-resolution (1 m) imagery; i) trees, ii) shrub-grass mosaic and iii) grassland and bare ground. These classes were considered appropriate, given the high resolution of the imagery (2007) and the identification of trees versus shrubs and open grassland. These three classes were comparable to the woody cover categories (i.e. <3 m; >3 m; and total woody cover) used in the analysis of repeat photos (Eastment et al. in press). Less than 3 m woody cover category was documented as shrubs, whereas >3 m woody cover as tall trees. Several vegetation classification hierarchies were tested in eCognition prior to final selection of the classes through visual assessment in combination with accuracy assessments (i.e. error matrices) produced by eCognition.

Repeat photographs

Data from 37 fixed-point repeat photographs were used in the analysis (Eastment et al. in press). At each repeat photo site, vegetation transects were carried out to record cover estimates for woody plants <3 m, >3 m and total woody cover. Species identification and density estimates of trees and shrubs were recorded for each height category. At each site, a general ecological description was recorded, which included altitude, evidence of herbivory and the presence of fire. These observations collected in late September and early October in 2019 were used to ground truth the repeat photos taken in 1999 by the Integrated Rural Development and Nature Conservation (IRDNC) organisation. In total, the repeat photo sites covered an area of 0.16 km^2 (16 hectares), which, when summed, covers a total area of about 5.92 km^2 (59 200 ha) or <1% of the park area. An additional 319 ground truth points in 2019 were recorded at the repeat photo locations for verification of the classification of the 2019 Sentinel 2A image. A GPS coordinate and description of the woody vegetation was recorded (e.g. tree and shrub species and estimate of the density of species) and used for verification with the automated OBIA output of vegetation classes. Additionally, the 2019 Sentinel 2A images for each repeat photo site were used as reference materials in the field. The visually classified points on the images were tested against the automated OBIA output by means of an error matrix to assess the overall classification accuracy (Supplementary Table S2).

Fire history

The Moderate Resolution Imaging Spectroradiometer (MODIS) Collection 6 burned area product (https://modis-land.gsfc.nasa.gov/burn.html) (MCD64A1) was used to extract the fire frequency and fire seasonality for each site (Eastment et al. in press). The MCD65A1 fire product maps the approximate day of burning for each calendar month for each 500 m grid cell, however, often fails to map small (≤ 100 ha) burns (Giglio et al. 2018). A 500 m buffer shapefile was created around each repeat photo site located north and south of the B8, the Trans-Caprivian highway that bisects the centre of BNP. The shapefiles were then split into two hemispheres to remove the effect of the road (i.e. B8).

Supervised classification: multiresolution approach

Each site was classified into the vegetation classes using multiresolution segmentation approach, which creates objects (i.e. polygons) on each image through the aggregation of pixels together with shape and colour characteristics (Supplementary Table S3) using a customised algorithm process tree. The mean, standard deviation and pixel brightness values were used for pixel classification. A non-parametric random-forest (RF) algorithm classifier was used for the classification (Breiman 2001; Gessner et al. 2013). A flow-chart of the procedure followed in this analysis, as well as additional detailed methods are provided in the supplementary material and in Supplementary Figure S1.

Following classification, the high-resolution images (1996 and 2007) were spatially aggregated (i.e. degraded) to 10 m to match the resolution of the 2019 Sentinel 2A image and used as learning and validation data to create a continuous training dataset for estimating woody cover (Gessner et al. 2013). All site images (n = 100) were transformed from raster to vector files to create polygons for the estimation of the area covered by each polygon in each vegetation class.

Data analyses

Assessment of woody cover change over time (1996–2019)
The change in woody cover in the aerial photographs and satellite images was calculated from four indices: number of fragments, index of dominance, mean area of each vegetation class: (i) trees, ii) shrub-grass mosaic and iii) grassland and bare ground), and mean annual expansion rate (Puyravaud 2003; Atsri et al. 2018).

The number of fragments of a vegetation class: N*i:* Refers to the number of polygons for each vegetation class for the year of interest. The index of dominance *Dj* (*a*)*,* expressed as a % refers to the proportion of an area occupied by the largest fragment with regard to the total area occupied by a given vegetation class *j* (McGarigal and Marks 1995). SPmaxj refers to the area of the largest fragment of a given vegetation class and *atj* to the sum of all fragments of the same vegetation class (i.e. trees, shrub-grass mosaic, and grassland and bare ground). The *Dj* ranges between 0 and 100 and the lower the value the more fragmented a given vegetation class.

$$Dj\left(a\right)=\frac{SPmaxj}{atj}\times 100$$

The mean area of a vegetation class $\bar{x}j$ (%) is calculated as follows: where *atj* refers to the sum of all the fragments' areas of a given vegetation class and to the number of the fragments of a given vegetation class (i.e. polygon count).

$$\bar{x}j=\frac{atj}{Nj}$$

The mean annual expansion rate (*T*) expressed as a percentage was used to assess changes in areas between years (1996, 2007 and 2019) (Puyravaud 2003). This index was calculated as:

$$T=\frac{\ln\left(S2\right)-\ln\left(S1\right)}{t\times\ln\left(e\right)}\times 100$$

where S1 and S2 refer to the area of a given vegetation class in the first and second years considered, respectively, and *t* refers to the number of years between the first and the second dates considered (note that ln-natural logarithm and *e* is a constant of 2.71828).

To assess changes between years (1996, 2007 and 2019) in the aerial photographs and satellite images the percent of change was determined for each vegetation class, based on the area classified for each vegetation class.

Accuracy assessment
The accuracy estimation is one of the most important aspects to assess reliability of the classifications prepared from remotely sensed images. The producer accuracy, user accuracy, overall accuracy, and kappa coefficient (KIA) were used to indicate how well the classified image represented the actual features on the ground. Thomlinson et al. (1999) set a target of an overall accuracy of 85% with no class less than 70%. The classification results were tested against the automated OBIA classification results by means of an error matrix to assess the classification accuracy of the automated technique (Supplementary Table S2). The 1996 dataset produced an overall accuracy 79%. The accuracy of both the 2007 and 2019 datasets were 84% and 91%, respectively. This suggests that they provide a good platform from which to explore woody cover estimates from the automated classification results. Overall, there was good congruence in the qualitative assessment between the ground-truthed repeat photographs and the vegetation classifications from the 1996 aerial and 2019 satellite imagery, which supports the authenticity of the woody cover changes observed in the east and west of BNP. The average error-estimate matrices for each of the vegetation classes (1996, 2007 and 2019) are summarised in Supplementary Table S4.

Results

Woody cover change (1996–2019) derived from the aerial photographs and satellite images
Over the two decades under investigation, between 1996 and 2019 trees declined (−10.6%), and the shrub-grass mosaic vegetation class increased (8.1%) across the entire park (Table 1, Table 2). The largest decline in trees occurred in the MUA West (−36.3%) and Western CA (−36.1%), when compared with the Kwando CA and MUA East. Furthermore, the Western CA and MUA West areas also experienced the greatest increase in the shrub-grass mosaic (17%) vegetation class between 1996 and 2019, whereas shrub cover in the east of the park increased by 11%.

Over time, habitat fragmentation increased for all vegetation classes (Table 2), but it was most prominent in the shrub-grass mosaic and the grassland and bare ground classes for the entire BNP (from 4 500 to 26 000 fragments: 5 000 to 27 000, respectively). This pattern was evident to a greater extent in the west versus the east of the park. This indicates that shrubs have become dominant over the past two decades in the Western CA and MUA West (Table 2) where late season fires were observed as frequent, where subsequently trees have declined in response. The opposite was observed in the MUA East and Kwando CA where mixed vegetation height structure was prevalent with a higher number of trees interspersed within the shrub-grass mosaic class (Table 2) yet under a more prominent early season fire regime. The dominance index (*Dj*) revealed an increase in shrub-grass mosaic and a decrease in the trees across the entire BNP and for all land use areas, except in the Kwando CA.

The mean annual expansion rate calculated for each vegetation class showed that over the decade 2007–2019 there was an increase in trees in the MUA East and Kwando CA (8–10%), and overall over the entire two decades (1996–2019) by ≥2%. However, the mean annual rate of expansion showed a negative trend (−6%) for trees in the MUA West and Western CA over the past two decades. Notably, the grassland and bare ground class type was higher by 10% in 2019 in the west, when compared with the east of the park (Figure 2). Figure 2 provides an estimate of the annual woody cover estimates for all the vegetation classes, which would be influenced by regional and local rainfall patterns and the frequency of fire.

Table 1: Percent of change and mean annual expansion rate between 1996 and 2019 for the different vegetation classes for Bwabwata National Park (BNP) and for each land use area derived from the aerial and satellite images

Land use	Vegetation type	Percentage change			Mean annual expansion rate (%)		
		1996–2007	2007–2019	1996–2019	1996–2007	2007–2019	1996–2019
BNP	Trees	−11.6	1.0	−10.6	−10.5	8.6	−0.5
	Shrub and grass mosaic	0.5	7.5	8.1	−0.6	2.3	1.8
	Grassland and bare ground	11.0	−8.5	2.5	−2.9	2.2	2.2
Kwando CA	Trees	−1.9	−8.8	−10.7	−4.5	8.7	2.4
	Shrub and grass mosaic	−1.7	13.0	11.2	−1.0	0.3	2.3
	Grassland and bare ground	3.6	−4.2	−0.5	3.4	−0.7	1.3
MUA East	Trees	−3.9	−11.0	−14.9	−7.7	9.8	1.4
	Shrub and grass mosaic	−7.1	18.4	11.3	1.4	−3.6	2.3
	Grassland and bare ground	11.0	−7.5	3.6	0.7	1.2	1.3
MUA West	Trees	−21.1	−36.3	−36.3	−15.5	1.5	−6.6
	Shrub and grass mosaic	7.9	9.1	17.0	0.2	−5.9	3.6
	Grassland and bare ground	13.3	6.1	19.3	5.1	−1.2	1.8
Western CA	Trees	−4.4	−31.7	−36.1	−7.3	−5.0	−6.1
	Shrub and grass mosaic	−3.8	19.8	16.0	0.8	0.4	1.8
	Grassland and bare ground	8.2	11.9	20.1	2.0	3.7	2.9

The repeat photographs revealed an increase in trees in the MUA East and Kwando CA of the park (>3 m) and less shrub cover (<3 m), whereas in the Western CA and the MUA West woody cover (i.e. trees) >3 m declined, and shrub cover (<3 m) increased (Figure 3; Eastment et al. in press). The results derived from the repeat photo sites corroborate the woody cover change estimates revealed in Table 1.

Discussion

The overall aim this study was to investigate interdecadal woody cover dynamics to inform fire and land use management plans. To do this, we first analysed repeat photographs in combination with historical aerial and recent satellite imagery (1996–2019) to assess changes in woody cover. The results showed that woody cover has increased since 1996, indicating that woody encroachment is occurring in Bwabwata National Park (Figure 3). Overall, the shrub-grass mosaic vegetation class increased by 8% over the past two decades with a mean annual expansion rate of ≤2% across the entire BNP, with a positive increase of this vegetation class across all land use areas in the park. These findings are consistent with similar studies of the woody thickening occurring in southern African savannas (Moleele et al. 2002; Wigley et al. 2010; O'Connor et al. 2014; Stevens et al. 2016; Mogashoa et al. 2021).

We then analysed the results in terms of fire and land use history in BNP. In answer to the question: *Is there a change in woody cover over time in the land use areas representing different management strategies (protected areas versus community-inhabited areas) in BNP?* The results showed clear differences in woody cover between the community inhabited areas (MUA East and MUA West) and the core conservation land use areas (Kwando CA and Western CA).

The results show a considerable increase in the shrub-grass mosaic vegetation class. In the tree size class, there were decreases, particularly in the MUA West and Western CA of the park (Figure 2).

The woody cover patterns in the MUA East and the Kwando CA land use areas showed a mixed vegetation structure consisting of trees and the shrub-grass mosaic vegetation type. These woody cover patterns were corroborated by the repeat photographs at a local landscape scale (Eastment et al. in press) (Figure 3).

In answer to the question: *Do different fire histories (i.e. fire seasonality) result in different woody cover states (e.g. trees; shrub-grass mosaic; grassland and bare ground) in BNP,* we attributed the changes in woody vegetation cover and structure to local fire management strategies and seasonal burning patterns, which differ between land use areas in the east and the west of BNP (MET 2016; Eastment et al. in press; Humphrey et al. 2021).

In the Western CA and MUA West, where shrubs increased and trees declined, analyses of fire history revealed that between 2000 and 2018 late season fires were prevalent.

In contrast, in the MUA East, and in the Kwando CA park management area, where there was a mosaic of trees and shrub-grass mosaic vegetation structure, early dry season fires were common (Eastment et al. in press). In MUA East, the Khwe-San people historically and still to this day use early dry season fires to sustain their livelihoods (e.g. maintain the productivity of important plant food resources), as well as to prevent the spread of the intense, late dry season fires in the park landscape. Their burning strategies have likely contributed to the patch-mosaic vegetation structure evident in the MUA East where the Khwe-San population is largely resident. Moreover, the early dry season management fires implemented in 2006 in the Kwando CA have also likely contributed and helped maintain the population of tall trees; and thus a combination of both park management and local burning strategies have influenced the vegetation patterns observed in this study.

The difference in seasonal burning patterns has affected the vegetation structure in the park, with large hot fires, prevalent in the Western CA and MUA West, contributing to reducing fire-sensitive tall trees (e.g. *Baikiaea plurijuga*), with a concurrent increase in low multistemmed shrubs in the west.

In the MUA East and Kwando CA (Table 1), tall trees persisted, a finding consistent with long-term research showing that early season fires allow persistence of a much broader range of fire resistant and fire sensitive species (Higgins et al. 2007; Bond and Zaloumis 2016). In the east of the park, where early season fires dominate, trees >3 m included *Dialium engleranum*, *T. sericea* and *Burkea africana* (Eastment et al. in press).

Eastment et al. (in press) showed that there were no clear trends in rainfall where Mean Annual Precipitation (MAP) varied between 430 mm and 890 mm over the 20-year period, with a mean of 612 mm over the study period. Though the east of the park is marginally wetter than the west rainfall is not significant between the two areas, suggesting that management not rainfall is important in causing differences in changing vegetation structure.

With regard to management implications, the results show the interacting effects of global and local drivers. At the local level, use of early burning to manage vegetation by the communities in the park, as well as by park management (Humphrey et al. 2021) has reduced late season fires and protected fire sensitive tall trees. Nevertheless, the par wide increase in woody cover suggests the influence of global drivers, which may ultimately supersede the influence of early season burning on vegetation. This pattern corresponds to other studies in grassy woodland systems where the fertilising effects of CO_2 on savanna trees has a more regional influence on woody tree recruitment, versus rainfall and grazing at the landscape scale (Wigley et al. 2010; Buitenwerf et al. 2012; O'Connor et al. 2014; Stevens et al. 2017).

It is widely recognised that woody encroachment can be reversed through frequent fires. For example, in north-east Swaziland, woody encroachment was managed with a high fire frequency and low grazing pressure in a lowland savanna (Roques et al. 2001), and similarly in Kruger National Park (Smit et al. 2016) though other research suggests late season, intense fires might be more effective in curbing woody cover in encroached areas (Smit et al. 2016).

The park would benefit from an adaptive management plan that recognises the uncertainty in environmental variation, in particular of rainfall that is typically related to burn area in southern African systems (Archibald et al. 2010). Such an adaptive approach would regularly reassess the effectiveness of early season burning and adjust management burns in response to changes in woody vegetation cover and antecedent rainfall. Adaptive management has been established in Kruger National Park, South Africa, whereby a learning approach was adopted to actively manage fire in the park through experimentation with different approaches for the conservation of biodiverse and heterogeneous savannas (Van Wilgen et al. 2011; Smit et al. 2016; Nieman et al. 2021). For example in BNP, managers could increase the fire frequency in the early dry season fires (i.e. between April and June) in the Western CA and the MUA West to test its efficacy in reducing the late dry season fires, to protect the remaining tall trees in this area, as well as to allow shrubs to grow into trees (i.e. escape the fire trap). The use of early dry season fires would facilitate a

Table 2: Trends in spatial structure indices for the different vegetation classes and years and for Bwabwata National Park and for each land use area (1996, 2007 and 2019) derived from the aerial and satellite images

Land use	Vegetation type	*n*1996	Dj(*a*)1996	αj1996	*n*2007	Dj(*a*)2007	αj2007	*n*2019	Dj(*a*)2019	αj2019
BNP	Trees	6 867	6.74	4.57	5 649	10.41	2.17	10 281	11.12	3.02
	Shrub and grass mosaic	4 547	4.39	21.93	4 834	5.49	23.06	26 001	7.91	7.57
	Grassland and bare ground	5 466	8.35	6.35	7 695	7.41	7.18	27 334	7.63	6.73
Kwando CA	Trees	955	39.08	5.87	1 438	24.82	2.38	2 988	34.81	3.23
	Shrub and grass mosaic	899	20.56	5.20	1 357	19.67	15.02	5 659	17.33	3.74
	Grassland and bare ground	1 036	33.44	9.55	1 824	22.64	7.92	4 721	24.15	2.81
MUA East	Trees	2 573	18.94	0.84	2 201	23.14	2.20	4 620	21.03	3.40
	Shrub and grass mosaic	1 897	12.24	16.55	1 355	12.58	27.13	7 759	19.75	3.07
	Grassland and bare ground	2 206	13.08	6.38	2 804	15.56	5.41	7 153	24.25	2.45
MUA West	Trees	2 680	16.67	5.13	1 529	22.39	1.64	2 270	17.37	1.33
	Shrub and grass mosaic	1 311	10.19	31.98	1 813	12.79	23.68	8 316	26.65	2.53
	Grassland and bare ground	1 681	15.14	7.16	2 512	17.76	8.44	10 163	27.58	1.80
Western CA	Trees	659	44.65	5.00	481	59.23	3.07	403	38.37	2.02
	Shrub and grass mosaic	440	42.88	23.61	309	40.13	36.89	4267	45.53	2.80
	Grassland and bare ground	543	40.97	6.61	555	58.03	8.03	5297	95.03	1.31

Note: **n* = number of fragments (i.e. number of pixels); *Dj*(*a*): index of dominance; = mean area

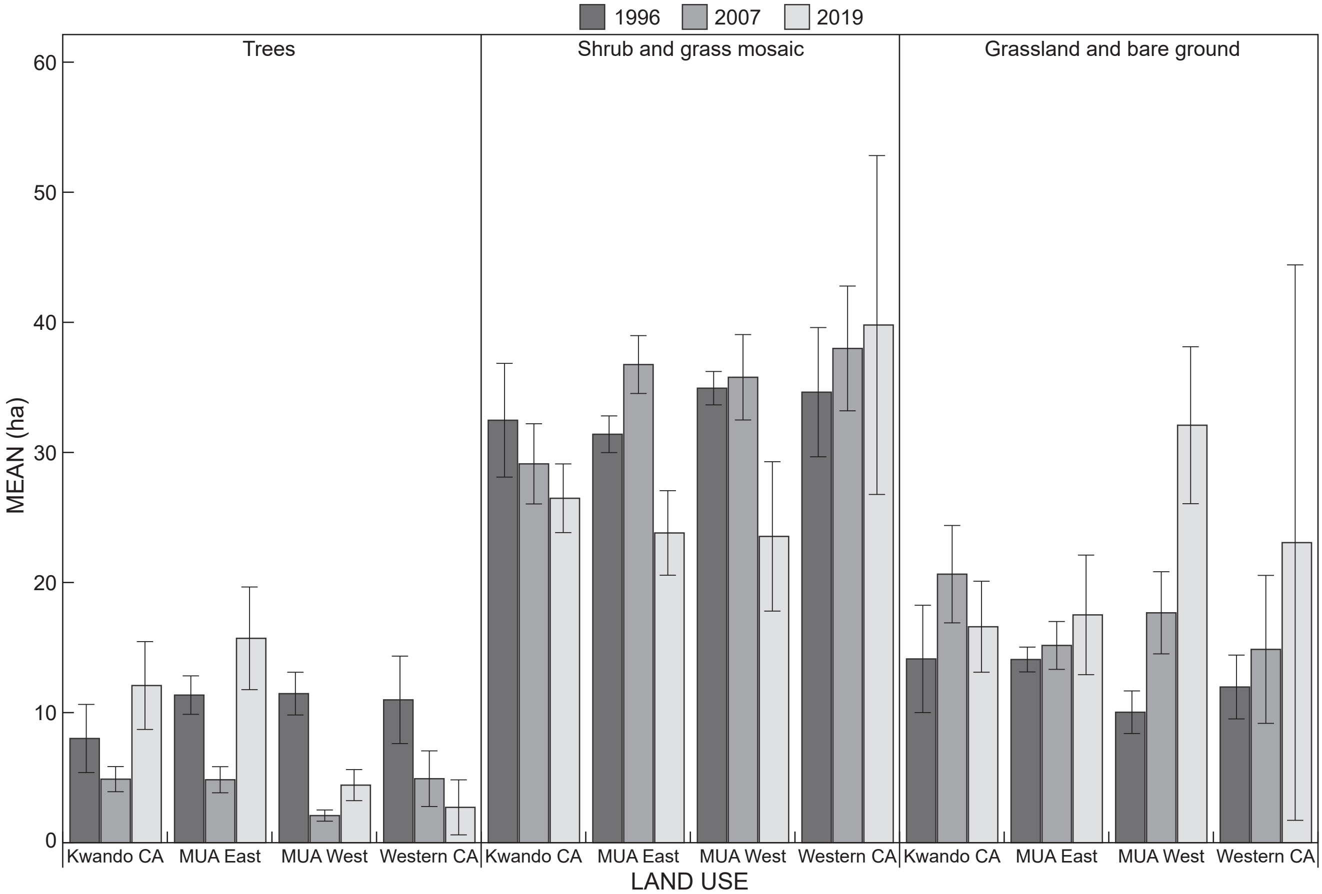

Figure 2: Annual patterns in the mean extent (ha) of trees, shrub-grass mosaic and grassland and bare ground cover estimates between land use areas in 1996, 2007 and 2019 in Bwabwata National Park derived from the aerial and satellite images. Bars represent standard error of the mean

heterogeneous vegetation height structure, as is evident in the MUA East and Kwando CA areas.

Long-term fire experiments have shown that regular early-season burning facilitate a much broader range of fire-resistant and fire-sensitive trees to occupy a savanna (Higgins et al. 2007). Yearly estimates showing change in woody cover (Figure 2) are an example of the importance of annual monitoring especially in response to changing rainfall patterns and managing prescribed burning in the different land use areas in the park. This study highlights the value of using a combination of methods for understanding change. Both the repeat photos and historical and satellite images contributed to gaining a longer-term understanding of woody cover change across the park.

Conclusion

This paper contributes to savanna ecology and remote sensing literature by exploring the utility of ground-truthed repeat photos in combination with high-resolution data (i.e. aerial photographs and orthophotos) and remote sensing methodologies (e.g. supervised classification) for characterizing woody cover change in southern African savannas, using Bwabwata National Park as a case study. These methods involved a multiresolution approach in determining woody cover change at the local landscape scale with the purpose of improved land cover mapping in heterogeneous vegetation, such as the savanna-woodlands of BNP.

Results showed an increase in shrub cover park-wide, and that woody cover varied according to land use and fire history. Shrub-grass mosaic increased and trees declined in the west of the park, where late season burning prevailed. In the east of the park, large trees survived, and we attributed this to the practice of early season burning in both the Conservation Area and the Multiple Use Area.

This latter finding highlights how seasonal fire practice (early versus late fires) in vegetation structure management can contribute towards the conservation of ecosystem services, biodiversity, and ecotourism. Early season fires could be used to maintain a mosaic of trees versus shrubs and therefore diverse habitat types in the east, whereas late season fires could be used for eradicating dense shrub encroachment in the west of BNP. An adaptive approach is needed that accommodates the interplay between local and global drivers. The exploration of multiple features of woody cover variation (e.g. height and density) is critical to gaining insights into spatio-temporal variability of change.

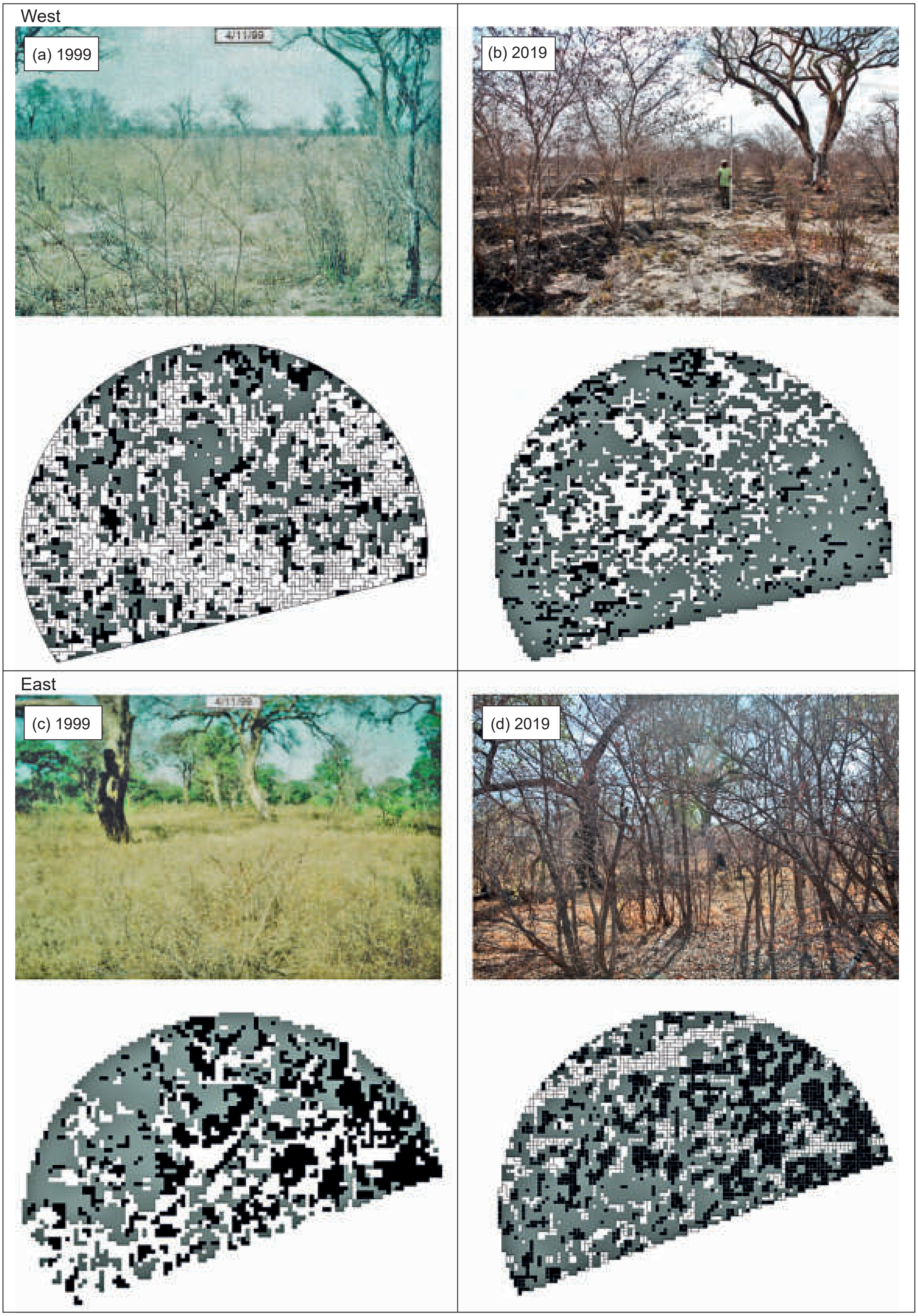

Figure 3: Selection of repeat photographs and matching woody cover class classification output (black pixels: trees; dark grey pixels: shrub-grass mosaic; white pixels: grassland and bare ground) showing the change in woody cover in 1999 and 2019 in the west (a: 1999; b: 2019) and east (c: 1999; d: 2019) in Bwabwata National park (1996–2019)

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