Long term fire scar monitoring with remote sensing in Northern Namibia: relations between fire frequency, rainfall, land cover, fire management and trees.

Running title: Fire monitoring Namibia

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Abstract

A cost-effective method was developed to map fire scars on Quicklooks of Landat TM imagery. The method was compared with a full resolution Landsat image using visual interpretation and supervised classification using the Maximum Likelihood procedure, resulting in a high degree of agreement between methods. A long time series of fire scars was developed using all available Landsat Quicklooks between 1989 and 2001 for an area of 63000 sq km in North East Namibia.

Between 27 and 51 % of the study area burns annually, while only 10 % of the area did not burn between 1989 and 2001. Not burned areas were mainly settled areas and permanent wetlands. 33 % of the area burned between 5 and 7 times during the 13 years indicating a high frequency overall. Rainfall and livestock had little influence on burned areas.

In 1996 formal fire management started in a portion of the study area consisting of building firebreaks and holding awareness programs. A comparison of burned areas before and after the intervention started allowed evaluating its effectiveness. The area where the formal fire management program was undertaken showed a significant decrease in burned area. It is suggested that awareness campaigns rather than firebreaks contributed to this decrease.

Selected tree population data were compared with fire frequencies. Differences in tree occurrence, regeneration, and stem diameter distributions between low and high fire frequencies could be detected and explained with known responses of the species to fire. This suggests that the observed time series is representative of a longer term fire regime in the area.
keywords: fire, remote sensing, monitoring, forestry, GIS, Namibia

1. Introduction

Fires affect millions of hectares in arid to semi-arid Namibia every year. It appeared that close to 5 million hectares burned countrywide in 2001 (NRSC, 2001), much higher than the 0.5 million hectares estimated by Grégoire et al. (2003a) for 2000. These are a mixture of natural fires at the onset of the rainy season and anthropogenic fires set by humans during the dry season. A first assessment of burning (Trigg, 1998; Mendelsohn and Roberts, 1997) found that 60 % of the Caprivi region had burned during the course of 1996. The large area affected meant that it was highly probable that many areas would be burning every year, with possible detrimental effects to woodland biodiversity and regeneration as most fires become crown fires at daytime due to the dry climate and prevailing easterly winds in the dry season.

It is generally thought that within the last century, human induced changes in the environment (clearing land for agriculture, logging of forests, hunting, livestock raising) had a major effect on long-term stable fire regimes that existed in the past (Trollope, 1999). The general view is that repeated and uncontrolled burning of Namibian environments is leading to economic losses and unwanted changes to the vegetation (Trollope and Trollope, 1999). However, the situation is very complex, as fires have positive and negative consequences to the environment (Kruger, 1984; Tainton and Mentis, 1984; Smit et al., 1999). Annual burning in woodlands, even at low intensity, can cause damage to the regeneration of many species and the prevention of trees growing into the canopy. However, some species, including a commercially very important tree species Pterocarpus angolensis are fire resistant after the sapling stage (Geldenhuys, 1977; Stahle et al.,2002), but possibly at much lower frequencies than currently is the case in most of Namibia's woodlands as growth is affected at high fire frequencies (Coates Palgrave, 2002). It is also known that changes in precipitation regime, whether part of a long term cycle or not, together with land use changes and fire affect vegetation structure and composition in some semi-arid areas (Frost, 1996; Graz, 1996; De Luis et al.,2001).

There is traditional fire management in the area, but this is largely considered to be broken down under weakening traditional leadership under a colonial regime, population pressures and other socio-economic changes. The traditional fire management in the survey area has not been thoroughly researched (Kamminga, 2001), but was likely a burning of patches of woodland to improve hunting grounds. All available information suggests that the vast majority of fires are of anthropogenic origin (Trollope and Trollope, 1999).

The colonial government followed a policy of establishing cut-lines along park and forest reserves to exclude fires, but these were not regularly maintained, certainly not after Namibian independence. While in the past, the policy of forestry departments may have been the full prevention of fires, this concept has changed into promotion of the use of fire as a forestry management tool (Goldammer, 1999). In the Namibia Forestry Strategic Plan (MET-DoF, 1996) it is stated that the occurrence and severity of uncontrolled and accidental forest fires has to be reduced.

A main problem for forest management is that little is known of current fire frequencies and affected areas (Geldenhuys, 1996). Therefore the main objective of this paper is to detect fires and explore a fire regime over 13 years in a portion of Namibia between 1989 and 2001.
In 1996 a fire management project was started in a pilot area to reduce wildfires and shift towards early dry season burning with the following main approaches: (1) the establishment of community firebreaks and (2) awareness campaigns in schools and community meetings. In reality mainly a reduction in fires was aimed for in the first stage.

Although the government has between 1996 and 2001 contributed 500,000 N$ annually with about 200,000 N$ for community firebreaks in a portion of the study area, with the Finnish government contributing about 3 million € and mechanisms for monitoring were provided, it has proved to be very difficult to assess the effectiveness of the followed approaches (Kamminga, 2001). One concern was the lack of longer term fire data and a sustainable fire monitoring program.

To address these concerns a study was initiated to develop a Fire Monitoring System as part of a management information system in 1997 (Trigg, 1998; Le Roux, 2000). There are many remote sensing instruments available to detect fires (Grégoire et al., 2001), but NOAA satellite imagery acquired by a local ground receiving station was used to develop a GIS based fire mapping procedure, which provided management with a tool for the continuous monitoring of project outputs. While the approach has its drawbacks (Silva et al., 2003), also several technical problems were encountered including a two year gap of data.

In view of the above, it was decided to change the method into one that would be relatively inexpensive and sustainable. The new method is entirely based on public domain Landsat derived data obtainable from the Internet and requires a limited number of processing steps.

Regarding fire management the objective was to establish a reliable long time series of burned areas encompassing several years before the fire management project started and several years afterwards. The developed method is tested with Landsat TM satellite imagery.

The study tests then if there were any significant changes in fire frequency over time and consequently assesses if changes could be attributed to any of the following hypotheses that could influence changes in fire frequency: the establishment of firebreaks, changes in rainfall, changes in the livestock population, infrastructure, settlement or a general effect of awareness campaigns. The objective here is to evaluate fire management initiatives.

The study then proceeds to use field data on regeneration of tree species in the area (Chakanga et al., 1998) in a GIS to detect if different fire frequency classes were associated with different abundance, stem distribution and regeneration of main tree species. The shape of the stem diameter distribution is suggested to be related to fire tolerance, (Geldenhuys, 1993) where P. angolensis and Burkea africana are suggested to be fire-tolerant and Baikiaea plurijuga less tolerant (Geldenhuys, 1977). This ecological knowledge is used to test the hypothesis that the established fire regime over 13 years is too short to be representative for the density, diameter distribution histograms and regeneration of these long-lived species.

2. Materials and Methods

2.1. Study Area

As fire frequencies were reported to be highest in the North Eastern part of Namibia, and the formal fire management project was located there, two adjacent regions were selected that cover most of the high-risk fire areas, while allowing a comparison between areas affected and not affected by formal fire management measures. Figure 1 presents the location of the Caprivi regions and Kavango. The total area surveyed covers approximately 63,000 square km. The climate is semi-arid, soil is mainly Kalahari sand with dunes, dune valleys and river floodplains along the Okavango and Zambezi rivers. The mean volume of trees over 5 cm diameter is 21.4 m3/ha (Chakanga et al., 1998) with an average cover of 12 % for Caprivi Region (251 samples). This low volume and low cover indicates generally open woodland. The herbaceous biomass in the wet season of 2000 was on average 2300 kg/ha, while in the less grazed areas outside settlements it is 3700 kg/ha based on 126 samples from Trollope et al., 2000). Although the rainfall in 2000 was slightly above average, these values indicate a generally sufficient fuel load during most years throughout the area. Fires are widespread, affecting herbaceous and shrub cover and very often reach the crowns of the mainly semideciduous tree species. Due to the low cover of trees and the crowns often being affected, fires and burned areas (called fire scars in this study) are highly visible on remotely sensed imagery in the study area.

2.2. Rainfall

Figure 1 locates the three main rainfall stations, Rundu, Katima Mulilo and Andara (incomplete). There are no other long term rainfall stations in the study area. Available rainfall data were collected from the Weather Bureau in Windhoek. Annual rainfall is calculated from the end of the dry season starting from 1 September and ending on 31 August. This ensures that the total rainfall fallen before the subsequent burning season is taken into account. Figure 2 demonstrates that the annual rainfall fluctuates highly in all stations with long term trends of high and low rainfall periods. This is common for Southern Africa (Tyson, 1986). Numerous droughts have occurred in the last decades, largely related to El Nino phases of the El Nino Southern Oscillation. Because of the large fluctuations it is possible that changes in total burned area in a region are related to a trend in rainfall. A moving average of 9 years was applied to analyze the long term trend. This conventional procedure (Suppiah and Hennessy, 1998) allows filtering out year to year variations to reveal long-term trends (Wheeler and Martin-Vide, 1992). Figure 2 shows that for the rainfall stations the study period of 1989-2001 is situated in a period with generally lower rainfall than the long term averages. For trend analysis of climatological variables non-parametric techniques are advised (Clark and Hosking, 1986; Sneyers, 1992). Mann-Whitney U tests (Siegel, 1956) were carried out to assess if there were changes in the rainfall between the period before the fire management project started and thereafter. Pearson correlation tests were used to assess the influence of rainfall amounts on the total area burned annually after carrying out a test of normality of the distribution of burned areas using Shapiro-Wilks' W-test (Shapiro et al., 1968).

2.3. Fire scar mapping

Grégoire et al. (2003a) concluded that Landsat TM is a reliable instrument to map fire scars in semi arid environments in Southern Africa, but there are no published studies on the use of resampled Landsat images. It is therefore necessary to test the agreement between fire scar mapped on Quicklooks and those mapped on original resolution Landsat TM. From the South African Applications Centre (SAC) or the United States Geological Survey (USGS) Data catalogue websites, different Quicklooks are available. The SAC website provides the clearest ones for the purpose of fire scar mapping. The total number of Landsat scenes required to cover the area is 10. The images are viewed from May onwards until December or later, depending on the rainfall in the study area. All 680 available cloudless images between 1989 and 2001 were used. All fire scars observed from May until the end of July, although mapped, were not included in the analysis as they could be controlled early dry season fires, part of the fire management program. In fact less than 10 early dry season fires were observed throughout the whole period, indicating that controlled burning is still not common.

2.4. Accuracy assessment

2.4.1. Registration

This study used an archive of registered LANDSAT images in the Directorate of Forestry. These were registered with a Root Mean Square error (RMS) of less than 30 m using recent Global Positioning System (GPS) data and existing Geographical Information System (GIS) data from 1:50,000 topographic maps. As not all the Quicklooks capture exactly the same area, each image had to be separately registered.

For any time series analysis accurate registration of imagery is very important to reduce mapping errors. The accuracy on the ground depends on the accuracy of the registration. The location errors are less than 100 m for those images that are based on well-referenced Landsat images. Current errors of GPS data are within the 30 m of the ground resolution of Landsat images and this ensures a sufficient quality for the time series analysis, as the resolution of the Quicklooks is about 350 x 350 m.

2.4.2. Other errors

Fire-affected areas on registered images were delineated using on-screen digitizing. Clearly identifiable fire scars were digitized on the first image and new fire scars were added on when identified on a more recent image. This was continued for all images until no more new fire scars were observed. At least 12 images were available for each scene each year. During the dry season often 2 images per month are available. This was sufficient to produce the time series as fires scars only fade after a few months.

The following methods were compared: (1) supervised classification of a registered dry season Landsat TM image of 4 October 2000 with a ground resolution of 30 x 30 m using training sites of burned and not burned areas, using the maximum likelihood procedure, (2) on screen digitizing of burned areas on the same Landsat TM image and (3) on screen digitizing of a registered Quicklook at a resolution of 350x350 m of the same date. 10 training sites of known burned areas based on information from field forestry staff were used for the supervised classification. These were distributed widely over the fire management area and were at least a 1000 ha large, although precise boundaries were not provided as the areas are mostly impenetrable, some due to ongoing warfare. Trigg (2002) published a detailed ground based error analysis for the same TM image and Trigg and Flasse (2000) used in situ spectroradiometry and infrared thermometry of a fire event in the study area to characterize the spectral-temporal response of the burning vegetation to develop algorithms for detecting fires with Landsat TM imagery and other imagery. Ground-based error analysis of Landsat TM is therefore accomplished in the study area, and the use of Landsat TM to evaluate fire scar maps from coarser resolution remote sensing data is an accepted method and has been developed on images of southern Africa, including the one used in this study (Boschetti et al.,2001 a,b; Trigg, 2002; Grégoire et al., 2003a).

To compare fire scars using different methods, image analysis was carried out with a raster based GIS package after vector to raster conversions in the case of digitized fire scars. The degree of overlap (this is the same area mapped as burned in both methods multiplied by 2 and then divided by the total area not mapped in both methods as burned) is used as a measure of agreement between the methods (Barbosa et al., 1999).

2.5. Analysis of the time series data

The digitized fire scars for each year were converted to a raster image in a GIS package and added year by year to produce a fire frequency time series for the 2 regions with 0: never burned and 13: burned annually. The resulting frequency image was then converted back to a vector format to integrate with fire break data to investigate influences of fire breaks on the fire regimes.

2.6. Fire management

Fire break data were collected in the field using GPS by field based Forestry staff. These point and tracking data with ancillary data on condition were integrated with the GIS on fire scars.

In order to explore the effect of firebreaks on fire frequencies, the time series of fire scars was used to compare the fire frequencies between the period 1989-1996 and 1997 to 2001. Although in 1996 the project on fire management was started in East Caprivi, any effect in the field is likely to have taken place only from 1997. Two images were prepared: one including all fires between 1989 and 1996 were added (and then divided by 8 as this period covers 8 years) and another where all fires between 1997 and 2001 were added (and then divided by 5 as this period covers 5 years). Both images have values between 0 and 1. These values indicate the relative frequency that each pixel was burned during the period. The first image was then subtracted from the second image to detect changes in fire frequencies.

Negative values in the resulting image indicate areas where the relative frequency of fire has decreased in the second period, while positive values indicate where fires have increased in relative frequency. This image was overlaid with the firebreaks of Eastern Caprivi to investigate whether firebreaks were associated with areas where a decrease in fire scars took place. The image was re-classed for ease of interpretation with 1: a decrease in frequency between -0.75- -1.0, 2: a decrease between -0.25- -0.75, 3: an increase between 0.25- 0.75 and 4: an increase between 0.75- 1.0.

2.8. Tree species occurrence, regeneration and diameter distribution

A forest inventory, covering all tree species was carried out in Caprivi Region in 1997 (Chakanga <u>et</u> <u>al</u>., 1998) and in the Caprivi State Forest in 1999. Stratified systematic sampling was used on the basis of vegetation maps to stratify the area with a higher sampling density in more dense forests. Each cluster consisted of 3 plots 60 m apart in north-south direction. A plot consisted of three concentric circles with 10, 20 and 30 m radii respectively. All trees with a diameter larger than 5 cm were measured. The size of the plot depended on the size of the tree to be measured. Regeneration, considered all tree species with a diameter less than 5 cm was measured using two 3.99 m radii circular plots located in the first plot of each cluster. This included the number of stems and height class with 50 cm intervals. For the analysis all height classes up to 3 m were included in the class regeneration. The plots were located with GPS. The tree and the regeneration sample data were converted in a GIS and intersected with the fire frequency data layer to assess the fire frequency in the plots. Frequency of occurrence of trees and regeneration frequency per species was calculated as the percentage of occurrence out of all samples falling in each fire frequency class. A total of 364 woodland plots were available and analyzed. Mann Whitney U tests were used to test differences between high fire frequency classes (from 7 – 13 times burned in 13 years) and low fire frequency classes (from 0 – 6 times burned in 13 years) in tree occurrence and regeneration. Wilcoxon matched pairs tests were used to test differences between stem diameter distributions for the two fire frequency classes (Siegel and Castellan, 1988).

3. Results

3.1. Accuracy of fire scar mapping

Table 1 presents an overview of the comparison of the different methods tested with the total area mapped as fire scars for each method and with the size of areas that were not recognized when comparing method by method. On screen digitizing of the same Landsat TM scene of the same date of a resampled quicklook and on an image at resolution of 30 x 30 m (3,5,4 RGB band combination) resulted in an 80.5 %

agreement between the two (a total of 770,706 ha was mapped as fires in both methods and therefore overlapping while a total of 150,921 ha were mapped differently when comparing the two images). The differences are due to smaller fire scars being overlooked in the low resolution quicklooks and due to edge effects caused by registration errors and boundary differences during digitizing. The lower resolution images appear to result in simplification of the fire scars digitized.
The comparison with digitizing at 30 x 30m resolution on the TM image and a supervised classification of the same image using selected fire scars as training sites resulted in 84 % agreement between digitized areas and classified areas (704,378 ha were mapped as fire scars in both methods and therefore overlapping while a total of 134,136 ha were mapped differently in both methods).

In the supervised classification some fields and rivers were classified as fire affected areas, although training sites of rivers and fields were put in as not affected by fires (Figure 3). The area classified as affected by fires is lower than in the digitizing methods, because small unburned patches in a burned area are usually included in the fire-affected areas while digitizing.

The comparison of the supervised classification of fire-affected areas with on-screen digitizing of the Quicklooks resulted in a lower agreement of 68.7 % overlap (a total of 672,204 ha mapped as fires in both methods and therefore overlapping while 210,223 ha were mapped differently). With an area of 144,684 ha digitized as areas affected by fire that were not classified as such and 65,549 ha classified as fire-scars but not digitized as such on the Quicklooks it appears that digitizing on Quicklooks results in an overestimate of fire scars. However, it is likely that the areas within larger burned areas that do not seem to be scarred are affected by the fires. In addition, as larger interpretation uncertainties appear for older scars, errors will be smaller when a time series is used, instead of only one Quicklook as was used for this test. The actual digitizing was done while comparing with older images to detect changes between the two images that appeared to be due to fire scarring.

3.2. Fire history of Kavango and Caprivi Regions

Table 2 shows that between 1989 and 2001 between 27.6 and 51 % of the area burned annually with a mean of 38 %. Figure 4 indicates the fire frequency during the period by calculating the size of the area that burned in each frequency class. One third of the study area burned around 50% of the time (between 5 and 7 years out of 13). 33 % of the area burned more than 50 % of the time. Only 10% of the total area did not burn once during this period.

Figure 5 shows the fire frequency maps for both Kavango and Caprivi regions. These maps show the pattern of the accumulated burned areas and locate the "hot spots" or areas with very high fire incidences. In Kavango the presence of title deed farms in the South West is associated with much lower fire frequencies in comparison with the communal lands. In the Southeast fire frequencies are also lower than elsewhere. Fire frequencies are in general lower around settlements, except in the North East where there are several settlements in an area with high fire frequencies.

In the Caprivi region fire frequencies are much lower around the settled area, especially in the East. There is a positive correlation between increasing distance from settlement and higher fire frequency ($r = 0.37$) but the low correlation coefficient indicates that this trend is not always there. Notable exceptions are the portion South

West of East Caprivi where south of a settled area there are high fire frequencies, but not to the north of the same settled area. There is also one remote area where the fire frequencies are much lower than other areas where settlement density is very low.

3.3. Effects of Rainfall

Figure 6 shows the annual rainfall in Katima Mulilo and Rundu from 1988-1989 to 2000-2001. The data from Andara cannot be used for comparison as there were no data after 1995. The median rainfall from September-August is 622.8 mm for Katima Mulilo, based on the period 1945-2000. The median rainfall in Andara is 525 mm for the period 1961-1995. The median rainfall in Rundu is 557.7 mm for the period 1940-2000. There is no significant change in total rainfall in the period 1989-1996 and 1997-2000 (Mann-Whitney $U = 15$ $p=0.46$ for Rundu, Mann-Whitney $U = 10$, $p=0.14$ for Katima Mulilo). Rainfall pattern differences between the stations are expected to be relatively small as the area is influenced by the Intertropical Convergence Zone.
Fire scar size and annual rainfall (September-August) did not show any significant correlation ($r= -0.04$ for East Caprivi , $r = 0.15$ for West Caprivi). In Kavango a satistically significant positive correlation was found in only one constituency with an $r=0.58$ ($p=0.046$).

3.4. Changes in fire frequencies

The annual fire scar sizes are normally distributed (Shapiro Wilks' $W=0.93$ $p=0.33$) and hence the Student t-test was applied to test if fire scars changed in size after 1996. Only for East Caprivi there was a significant change: the mean size of fire scars decreased from 648,953 ha to 430,167 hectares ($t=2.87$, df 11, $p=0.015$). There were no changes in West Caprivi ($t= 1.08$, df 11, $p=0.3$) and Kavango ($t=0.45$, df 11, $p=0.66$) in the same period. There was no change in early dry season fires indicating that management by controlled burning is not common.

Figure 7 shows the areas of decrease and increase in fire frequency in East Caprivi since 1997 in comparison with the previous period of less fire management. The firebreaks, settlements and roads have been superimposed. From the analysis of change classes it appeared that 71 % of East Caprivi had changed little in fire frequency, while 25.5 % decreased (of which 1 % sharply) and 3.5 % increased in fire frequency since 1997 in comparison with 1989-1996. The map shows that the 200,000 ha burned less since 1997 are mainly in areas where there are fewer fire breaks. A GIS analysis of dividing all firebreaks between change classes revealed that out of 6651 km of firebreaks, the density of firebreaks were: for a high decrease in fire frequency 90 m/km^2; for a medium decrease in frequency 85 m/km^2; for a medium increase in fire frequency 100 m/km^2 and for a high increase in fire frequency 900 m/km^2. Firebreaks seem to have been placed in high fire frequency areas but apparently not with the expected results. The map also demonstrates that some of the community firebreaks are very short and many do not enclose an area fully, especially in view of the prevalence of easterly winds. Visual observations in the field confirmed the information obtained by key informants that most firebreaks were not maintained after establishment and little used for fire-fighting or controlled burning.

3.5. Tree occurrence, regeneration and stem diameter distribution in Caprivi

Figure 8 shows the frequency of occurrence in percentage of <u>Baikiaea plurijuga</u>, <u>Burkea africana</u> and <u>Pterocarpus angolensis</u> trees in the different fire frequency classes for 364 woodland plots in Caprivi. B. plurijuga is an abundant tree species and occurrence is not affected by fire frequency (Mann Whitney U = 20, p=0.56), but both B. africana and P. angolensis are more frequent in areas that burned from 7-13 times in 13 years than in less frequently burned areas (resp. Mann Whitney U = 8.5, p=0.04; U = 3, p= 0.006).

Figure 9 shows the frequency histograms in percentage of incidences of regeneration in all inventory samples falling within a fire frequency class. 73 plots had regeneration of B. plurijuga (20 %) and 44 plots regeneration of B. africana (12%) Only 13 plots had regeneration of P. angolensis (4%). B. plurijuga and B. africana regeneration frequencies were not different between high and low fire frequencies (resp. Mann-Whitney U = 14, p =0.18; U = 16, p =0.28), while regeneration of P. angolensis was significantly higher in high fire frequency classes (Mann-Whitney U = 7, p=0.02).

Figure 10 shows the stem diameter distribution in stems/ha over different diameter classes of trees in low and high fire frequency situations. Although the distribution curve for B. plurijuga is similar, the density is significantly lower in high fire frequency conditions (Wilcoxon Z = 3.05, p=0.002). The diameter distribution for both B. africana and P. angolensis in high fire frequency conditions is much different from low fire frequency conditions (Wilcoxon Z= 2.24, p=0.025, Z= 2.4, p=0.017). Both species show higher stem density at low diameter classes in high fire frequency conditions.

4. Discussion

The methodology using visual interpretation of fire scars on multi-temporal quicklooks resulted in burned area maps with high agreement (80%) when compared with burned area maps derived from 30 m resolution Landsat Enhanced Thematic Mapper (ETM+) and Thematic mapper (TM) imagery. With NOAA imagery Barbosa et al., (1999) found 71% accuracy compared to Landsat TM. Gregoire et al., (2003a) found variable accuracy using Vegetation (VGT) 1 km resolution burned area maps dependent on vegetation type and on the spatial pattern of the burned areas in comparison with ETM+ data. Boschetti et al. (2001a), using 3 Landsat TM images from Southern Africa, including the one used here, found variable levels of accuracy when testing SPOT vegetation data for fire detection found an omission error of 20% and a commission error of 40% for central Namibia and a strong omission error of 50 % for the image used in this study. They noted an influence of very small fires and very dry vegetation with low reflectance in the infrared as contributors to the high error level.

Besides Barbosa et al., (1999) using 5x5 km resolution data, there are few published records on fire regimes outside the largely fire-controlled National Parks (Siegfried, 1981; Trollope and Potgieter, 1985; Du Plessis, 1997; Grégoire et al., 2003b) and scientific experiments (Geldenhuys, 1977) in similar environments in Southern Africa. In that sense the information presented here could prove a valuable reference for further studies of areas of Namibia, Botswana, Angola, Zambia and Zimbabwe where mainly informal fire management occurs.

Chakanga et al., (1998) assessed fire effects in the forest inventory of Caprivi region and found that 88.2 % of the total area was affected by fire. This estimate is very close to the 90% affected by fire in the two regions over the 13 years of this study.

These results suggest that the observed time series of fire scars can be used to detect some effects of formal fire management.

While the fire scar time series demonstrated that in East Caprivi burned areas decreased roughly by 200,000 hectares between the periods 1989-1996 and 1997-2001, no significant decreases in burned areas were detected in the areas where no formal fire management intervention took place, there were no significant differences in average rainfall in the period before fire management commenced and the period after the intervention took place. This has however to be seen in the light of a low number of rainfall stations, although both showed similar trends. There was no clear relationship between total annual rainfall and total burned area in the subsequent dry season.

Livestock populations increased in both regions (Mendelsohn and Roberts 1997; Mendelsohn and El Obeid, 2003), but no distribution data are available. As goats rarely venture beyond 2 km from a settlement (Verlinden et al., 1998) they do not explain the decrease in fires in East Caprivi. For cattle it is possible that a decrease in fuel biomass caused a decrease in fire frequency in localized areas around settlements. However, as no significant relationship was found in most areas between rainfall and total size of burned areas, suggesting that fuel loads (on average 3700 kg/ha in less disturbed areas in the year 2000) are in most cases sufficient for fires to burn, it is not likely that cattle played an important role in the overall observed decrease in burned areas.

The data suggest that the established firebreaks have not contributed significantly over time to the decline in wild fires in East Caprivi. Although insufficient data were available in 2001, Kamminga (2001) reports that key informants indicated during interviews that this was a likely situation. In view of the high cost of firebreak establishment and management this is of high concern. Initial investigations of the fire scars and infrastructure suggested that not well maintained firebreaks or cut-lines have no effect on long term fire regime and it seems that annual maintenance and early dry season burning is necessary to have functional firebreaks. The fire scar patterns also show that fires even jump main roads, suggesting that firebreaks, like is the practice in neighbouring Botswana, may have to be very wide and cleared annually to stop fires without early burning management. This increases the costs of establishment, ecological impact and maintenance even more. It has to be noted that maintenance requirements are less when the firebreaks are used to facilitate firefighting, such as to backburn from and gain access along.

This study demonstrated also that the design of some of the firebreaks lacked planning. Many community firebreaks are situated in areas that did not show a decline in burned areas and no clear increase in early dry season burning, possibly demonstrating that they are established for other reasons. Possible reasons include tenure (safeguarding smaller areas around the homestead from grazing or people harvesting thatching grass), territory protection in general like demarcation of village areas or also regarding firebreak making as a way to get an income.

It seems that firebreaks should only be constructed in communities where a high risk of wild fires exists that threaten various resources around settlements and where a policy of controlled burning and firebreak maintenance is likely to be adopted. Allocation of resources should therefore take place according to a priority plan and objectively verifiable and transparent selection criteria. In view of this, it is recommended that more attention is given to existing fire management practices in a

regional land use context to better understand which options are likely to be adopted under what circumstances.
It seems that the awareness campaigns in East Caprivi are a large contributor to the decrease in burned area observed. But this is still a far cry from formal fire management with clearly stated objectives.

The tree and regeneration sample data suggest that the density, diameter distributions and regeneration of selected tree species with known fire ecology is related to the fire regime established in this study. While overall regeneration is low, B. plurijuga and B. africana regeneration seems not to be affected by higher fire frequencies but P. angolensis has more regeneration in high fire frequency areas. Both B. africana and P. angolensis trees are more abundant in high fire frequency areas. While stem density of B. plurijuga is lower in high fire frequency conditions, stem density at lower diameter classes is much higher in both B. africana and P. angolensis at high fire frequencies.

The data suggest that B. plurijuga density is lower in high fire frequency conditions while high fire frequencies do not seem to suppress regeneration of P. angolensis or B. africana. This is in agreement with experiments in Kavango region (Geldenhuys, 1977, 1996). Kent Burger (1983) found that high fire frequencies in northern Botswana caused a decline in B. plurijuga and P. angolensis, the latter also under influence of elephant damage. Controlled experiments in Africa demonstrate that B. africana and P. angolensis withstand repeated burning better than others (Rutherford, 1981; Geldenhuys, 1996).
Mushove (1996) found inverse J shaped stem diameter distributions in some forests for P. angolensis, but other distributions in other forests. In this study B. plurijuga seems to have a bimodal (bell-shaped) curve with lower stem densities of smaller diameters, while B. africana and P. angolensis follow a not very pronounced inverse J- shaped diameter distribution, although the 5-10 cm classes have lower stems ha^{-1} in all species It is remarkable that these patterns for the three species was also reflected in Kavango region (Geldenhuys, 1991, 1993). Although other factors than fire may influence the regeneration of the tree species, Geldenhuys (1996) suggests that in woodlands the typical inverse J-shaped diameter distribution may indicate that the species is fire tolerant and responds well to frequent uncontrolled fires. The fact that the bell-shaped curve is also found in areas with low fire frequencies for the less fire tolerant B. plurijuga may mean that regeneration for this species is depressed at even low fire frequencies or that fire has little to do with regeneration for this species.
The surprisingly good explanation of tree population structure by monitoring fires over only 13 years suggests that the fire regime is representative for a much longer period.

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Fig. 1. Bottom right map shows the location of Namibia in Africa. Bottom left map shows the Kavango and Caprivi regions in Namibia and the top left map shows the two regions with the main rainfall stations Rundu, Andara and Katima Mulilo.

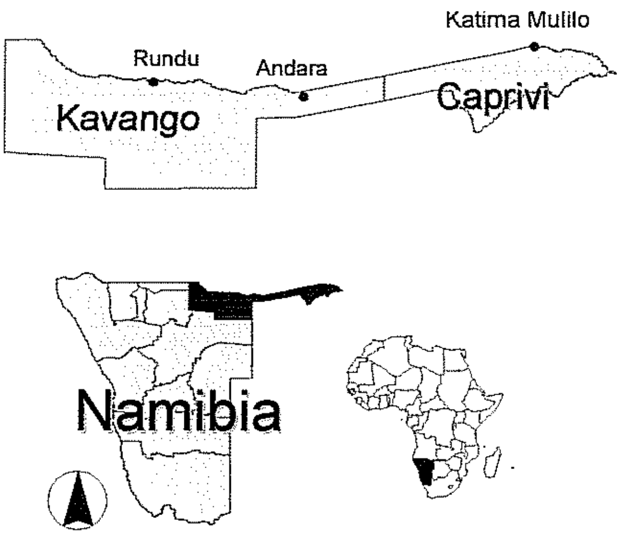
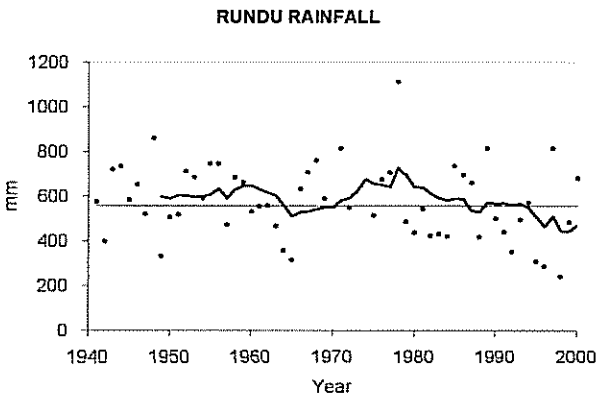
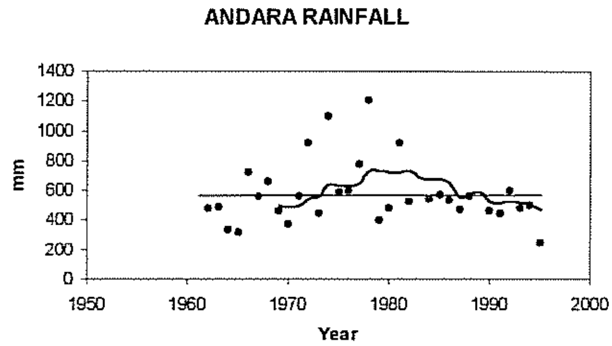


Fig. 2. Long term annual rainfall (September – August) with a 9 year moving average trend line and the median rainfall for the recording period for Rundu, Andara and Katima Mulilo meteorological stations.





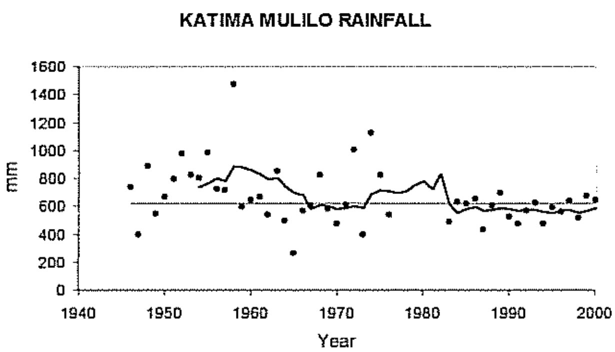


Fig. 3. Supervised Classification (Maximum Likelihood procedure) of bands 3,4,5, and 7 of Landsat TM image (path 174 rows 072-073) dating of 4 October 2000. The straight vertical boundary between a large burned area and an unaffected area in the lower left portion is a wide annually maintained firebreak in Botswana.

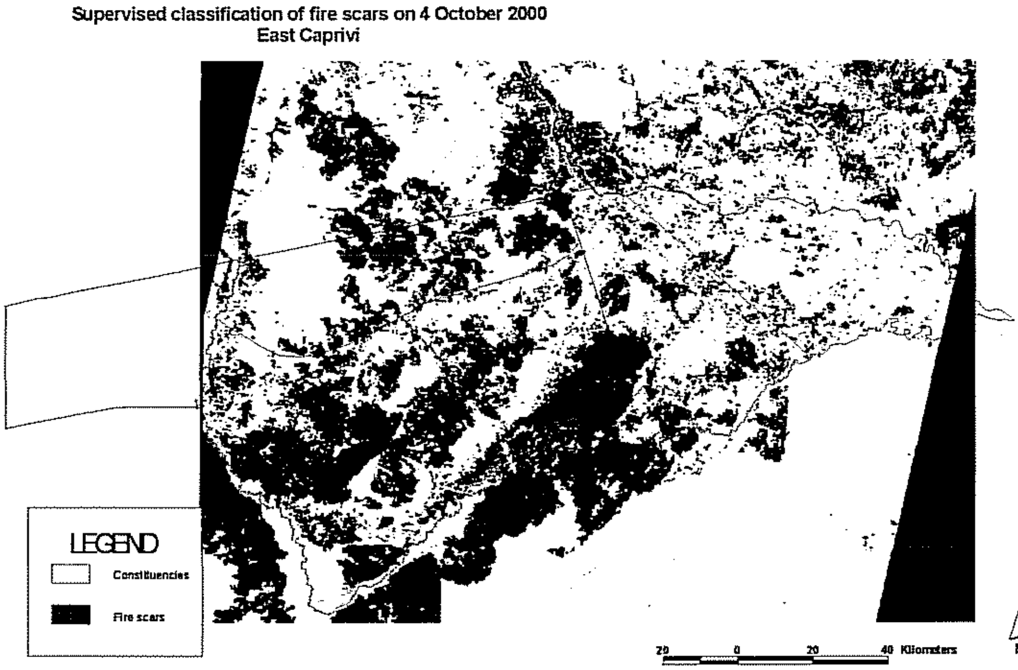


Fig. 4. Fire frequency (number of years burned) and % of total area burned in the study area (Caprivi and Kavango Regions) in 1989 – 2001. Total area is 63000 square km.

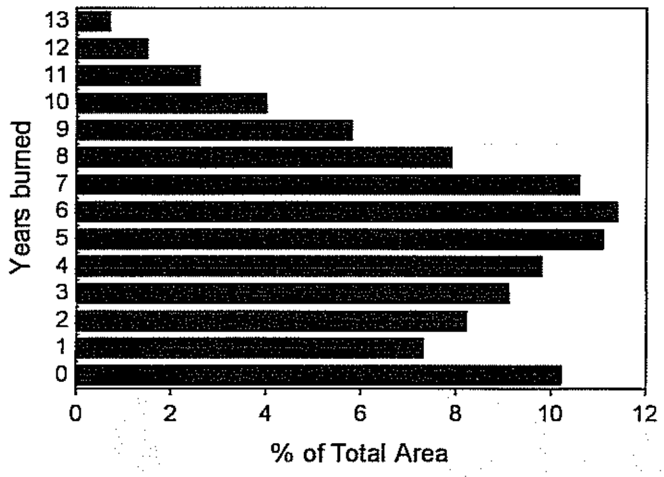
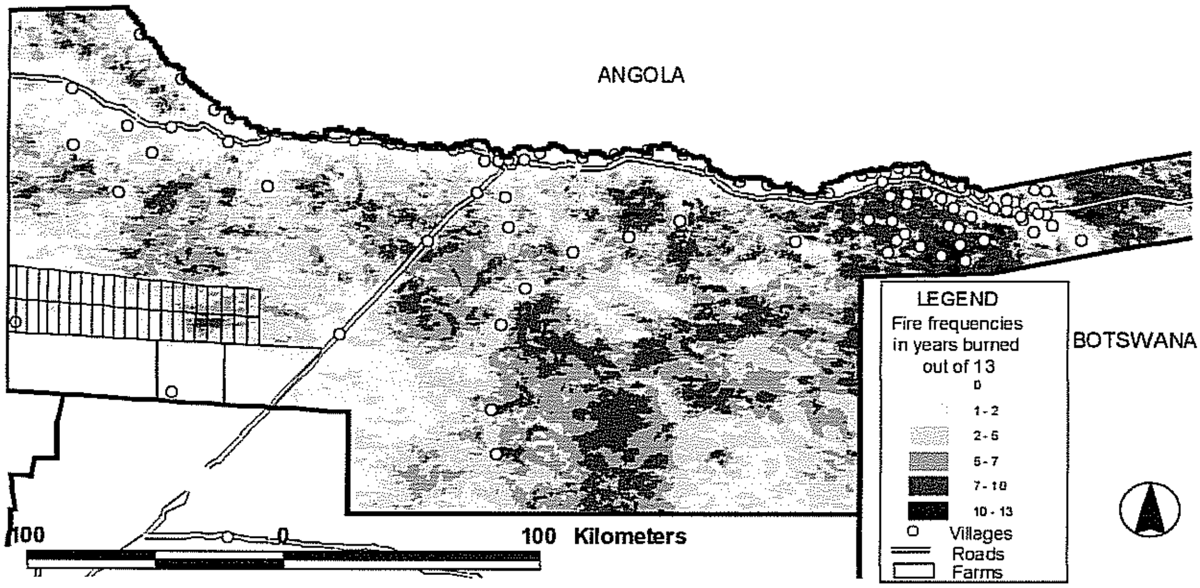


Fig. 5. The map on the top shows fire frequencies in Kavango region with infrastructure and settlement superimposed. The map on the bottom shows the same for Caprivi region.



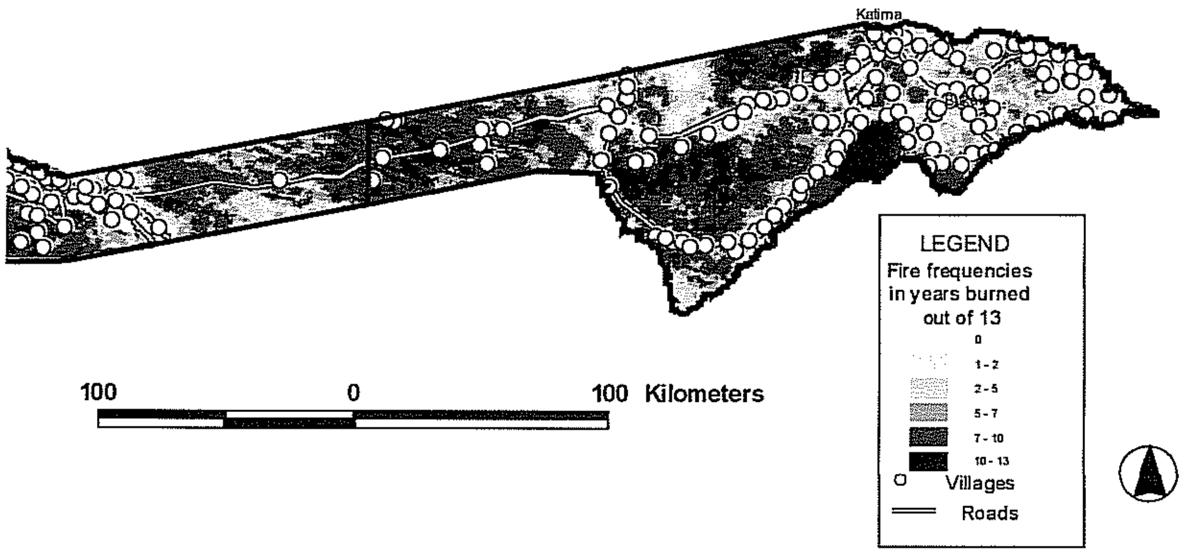
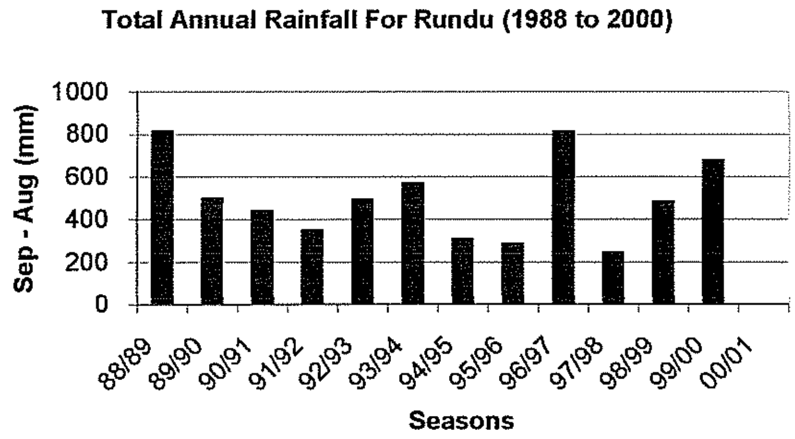


Fig. 6. Total annual rainfall (September to October) for the rainfall stations Katima Mulilo and Rundu during the 13 year fire time series between 1988-89 and 1999-2000.



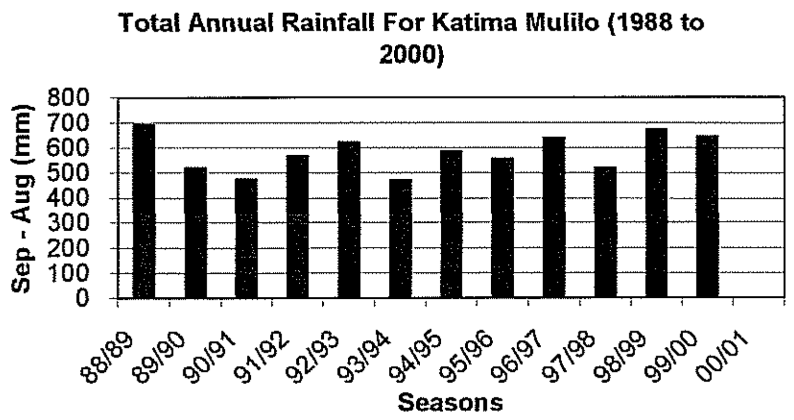


Fig. 7. Changes in relative fire frequencies between 1989-1996 and 1997-2001 in East Caprivi. Firebreaks are superimposed on the classified change image.

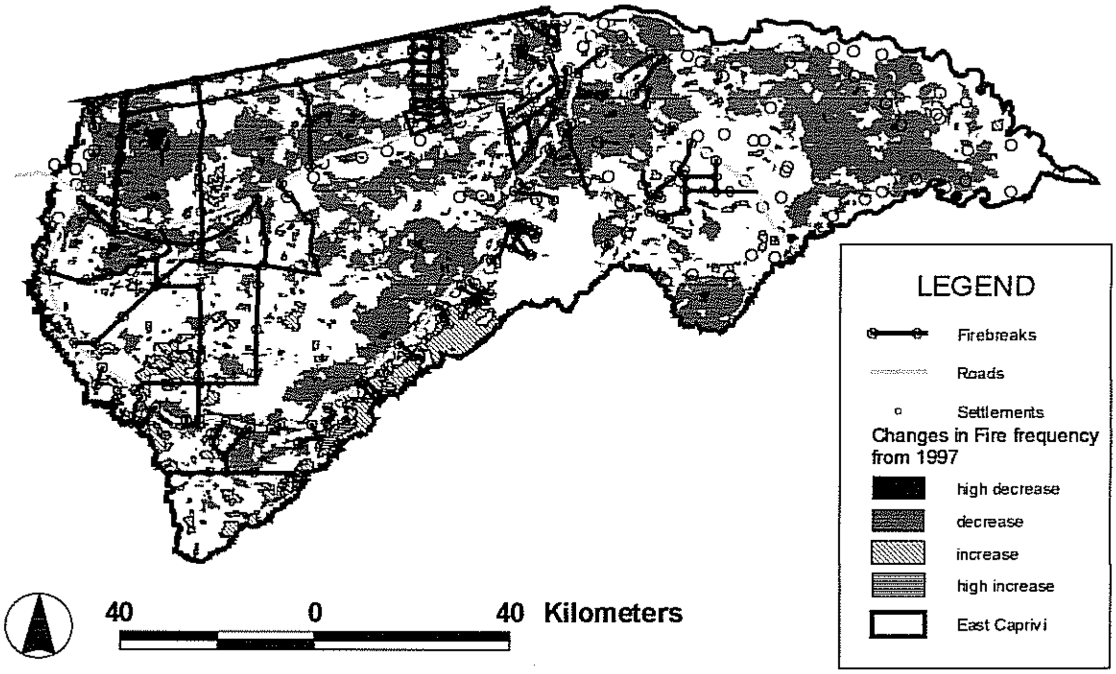

LEGEND
Firebreaks
Roads
Settlements
Changes in Fire frequency from 1997
high decrease
decrease
increase
high increase
East Caprivi
40
0
40
Kilometers

Fig. 10. Stem size distribution in stems/ha for different diameter classess of *B. plurijuga*, *B. africana* and *P. angolensis* in classes with low fire frequency (between 0 and 6 years) and high fire frequency (between 7 and 13 years). Note the differences in vertical scale for the three species.

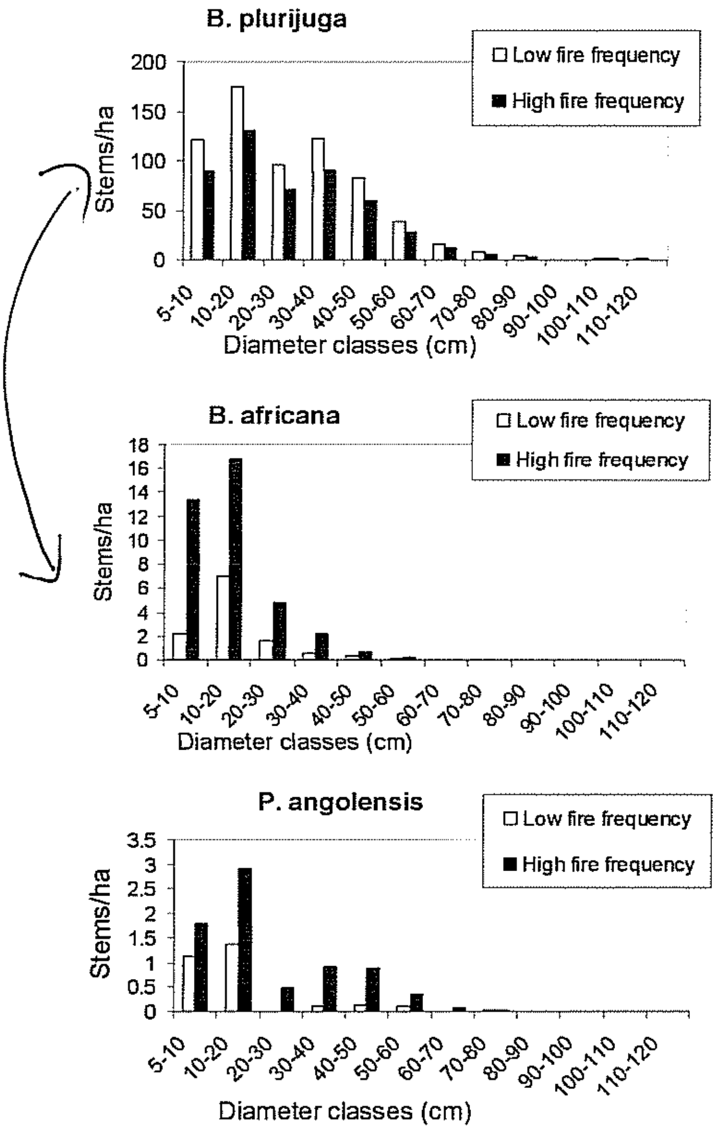


Table 1: Comparison of areas (ha) affected by fire using different methods in East Caprivi, October 2000.

Key to abbreviations: Q: fire scars digitized on quicklooks at a resolution of approximately 350 x 350m, TMd: fire scars digitized on Landsat Tm at 30 x 30 m resolution, TMc: Landsat TM image classified with supervised classification (maximum likelihood method) using fire affected and not affected areas as training sites. The total area mapped as fire scars for each method is given under Total Area. The other headings for the columns are explained as follows: - scar + TMd: area not mapped as scars in the method of the row, but mapped as scars in Landsat TM; +scar – TMd: area mapped as fire scars in the method described in the row, but not in Landsat TM and so on.

	Total Area	-scar +TMd	+scar - TMd	-scar +TMc	+scar -TMc
Q	482,355	53,919	97,002	65,549	144,684
TM d	439,272	-	-	49,462	84,674
TM c	401,652	-	-	-	-

Table 2: Area (in hectares and percentage) burned in the study area (Caprivi and Kavango Regions) in 1989 – 2001. Total area is 63000 square km.

Year	Hectares burned	Percentage of total area
1989	2,455,048	39.0
1990	2,799,759	44.4
1991	2,535,032	40.2
1992	2,985,715	47.4
1993	2,113,909	33.6
1994	3,077,275	48.8
1995	2,085,998	33.1
1996	2,199,237	34.9
1997	1,818,060	28.9
1998	2,002,291	31.8
1999	2,449,946	38.9
2000	3,213,490	51.0
2001	1,736,461	27.6