

The macro-charcoal signature in Bwabwata National park, north-east, Namibia

Calibrating surface macro-charcoal with
environmental variables

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Abstract

Fire is a major driver of vegetation patterns in the savanna biome of southern Africa and is hypothesized to allow for the tree-grass co-existence. However, to better understand the drivers of the savanna vegetation structure, more research is required. Furthermore, fire management can benefit greatly from the knowledge of fire history and vegetation change. Palaeo-ecological studies endeavour to fill this knowledge gap by investigating past ecological changes through the use of paleo-proxies. Charcoal – burned pieces of vegetation – is a proxy for fire and vegetation history. However, little is known about the relationship between charcoal found in sediment and environmental features in the savanna biome.

This study aims to fill the knowledge gap by investigating the links between macro-charcoal ($> 150 \mu\text{m}$) from surface samples and fire history and physical characteristics of the landscape, vegetation composition and settlement density. Sediment surface samples (top 2cm) were taken from six sample sites in Bwabwata National Park (BNP), Namibia and analysed for macro-charcoal pieces using the *swirling method*. Here we show that there is a strong relationship between charcoal abundance and burned area, as well as charcoal abundance and grassy vegetation density. Thus broad inference can be made about the past vegetation composition and burned area by looking at long-term charcoal data. This information is useful for fire management, as past burn history can act as a reference point for current burn policy. This calibration work will inform long-term palaeo-data from sediment cores.

Introduction

Fire is a major driver of vegetation patterns in the savanna biome of southern Africa (Bond et al., 2005). It has been hypothesized that fire allows for the co-existence of trees and grasses (Higgins et al., 2000b). By burning young tree saplings with the surrounding grasses, it prevents the establishment of woodlands in places of grassland. However, if the interval between successive fires is too long, the saplings can occasionally grow past the threshold at which they are burnt to ground level. The sapling thus 'escapes the fire trap' (Bond and Keeley, 2005) and can grow into a tree.

The dynamics in the savanna biome are complex, and involve the interactions between fire, water, herbivory, soil texture and nutrients (Higgins et al. 2000). It is this complexity which accentuates the mystery of tree-grass coexistence occurring over a wide range of conditions. It is so intriguing that it has been termed the 'Savanna problem' (Sarmiento, 1984). Multiple explanations have been proposed in order to explain the 'savanna problem' by invoking mechanisms such as competition for water and nutrients, demographic bottlenecks to tree recruitment, and disturbances (fire and herbivory). One approach to studying long-term relationships between tree-grass dynamics and fire is to use palaeo-ecology, using fossil pollen and charcoal as proxies for vegetation and fire history. However, the relationship between fire regime and the charcoal record is poorly understood and further calibration work is required. The aim of this study is to contribute to this knowledge gap.

Savannas can also be seen as a patch mosaic, a collation of woodland and grassland patches which can transition in response to fire, grazing and rainfall (A. Ekblom and Gillson, 2010). Feedback loops allow for rapid transitions, e.g. from a grass – to a forest-dominated system, but also regulate the system, maintaining the intricate balance between grasses and trees (Duffin et al., 2008). The Hierarchical Patch Dynamics Paradigm is a conceptual framework which seeks to explain holistically the patterns and processes in the savanna ecosystem (Gillson, 2004). Gillson (2004) found that the patterns of vegetation change differ with spatial scales of observation, suggesting that different ecological processes determine tree abundance at micro, local and landscape scales. Thus, the interactive forces between differing variables such as plants themselves, disturbance (fire and herbivory), climate and edaphic factors, change and thus regulate tree density at variable spatial and temporal scales (Gillson, 2004).

However, the mechanisms of these processes are mostly not understood (Sankaran et al., 2005), revealing a field requiring considerable further research. One way of addressing this lack of knowledge is to use palaeo-proxies, which are preserved physical characteristics linking past processes to present processes (Blackford and Innes, 2006; Gillson and Duffin, 2007; Gillson, 2004). Past literature has focussed on pollen as a proxy for vegetation abundance and composition (Bradshaw and Thompson, 1985; Broström et al., 1998). Others have used coprophilous spores (Innes & Blackford 2003, 2006; Baker et al. 2013) to reveal past changes in herbivore abundance.

Another important proxy is charcoal which can be used derive information of past fire events (Blackford, 2000; Innes et al., 2004). The understanding is that when fire scorches a landscape, it leaves behind a trail of evidence that manifests itself in small pieces of burnt material – charcoal. The charcoal fragments fall to the ground and collect in basins and are deposited in the sediment. As time progresses and the cycle of vegetation regrowth and burning have run over the decades, even millennia, sedimentary layers record these events, indirectly, through the successive accumulation of charcoal. We can extract the sediment and given certain assumptions and through informed interpretation, reconstruct the vegetation and fire history. However, the accurate interpretation of these charcoal records hinges on four main assumptions: 1. Sedimentary layers with charcoal abundance above some background amount (i.e. a charcoal peak) are evidence of a historical fire event in the landscape. 2. Most sedimentary charcoal is from primary fallout during or shortly after a fire; secondary or redeposited charcoal is a relatively minor component. 3. Large particles are indicative of local fires because they cannot be transported long distances. ‘Large particles’ or macro-charcoal is distinguished from micro-charcoal on the bases of size. Macro-charcoal is somewhat arbitrarily defined as charcoal particles $> 150 \mu\text{m}$ and micro-charcoal are charcoal particles $< 150 \mu\text{m}$. 4. The charcoal pieces can be reliably extracted and quantified from sediments (Blackford, 2000).

To improve the interpretation of the charcoal record, one is required to calibrate various charcoal features, such as size, shape and abundance to present surrounding factors possibly contributing to these features, such as known fire history and vegetation structure (Archibald et al., 2013, 2012). Few studies have aimed to calibrate charcoal records against known fire events and those that have, most often looked at mid- to high latitude regions (e.g. Millspaugh and Whitlock, 1995; Enache and Cumming, 2006; Tinner et al., 2006; Peters and Higuera, 2007 as cited in Duffin et al. 2008). Very little work has been done in low-latitude ecosystems for e.g. semi-arid savanna biomes. The main focus has been on temperate and boreal forest ecosystems, leaving savanna ecosystems still largely unexplored, though see Duffin et al. (2008) for charcoal calibration work in the Kruger National Park, South Africa. The question is whether the same taphonomic processes are at work in savannas as they are in forests, and whether the charcoal signature will thus be similar. The key differences between savanna ecosystems and forest ecosystems is that grass is the dominant fuel type, that it is extensively available for burning and that fires are frequent and impact large areas (Duffin et al., 2008).

The contributing factors of the charcoal signature include vegetation type (e.g. grassy-savanna), vegetation density (proportion of grasses to trees), rainfall, settlement density, dryness and lightening frequency. The main fuel for fire in savanna ecosystems is grass (Higgins et al. 2000; Duffin et al. 2008). The wet season stimulates grass production which is then followed by an extended dry period allowing for a continuous cover of fuel (i.e. grass layer) (Higgins et al. 2000). The conditions in the dry season are thus ideal for fire, since there is a ready source of ignitions both natural (lightening) and anthropogenic (Higgins et al. 2000). Furthermore, grass biomass depends on previous season’s rainfall, therefore there is a strong correlation between rainfall and area burned (Van Wilgen et al., 2004). Given these factors we expect more fire in higher rainfall, grassy environments that are near human settlement and we

expect most of the charcoal to derive from grassy vegetation. The aims of this study are to test these hypotheses.

More specifically, the objectives of this study are to investigate the links of macro-charcoal from surface samples to fire history and physical characteristics of the landscape, vegetation composition and settlement density. This calibration work will inform longer term palaeo-data from sediment cores.

The following hypotheses will be tested:

H₁: Charcoal abundance will reflect area burned over the past five years.

H₂: The area burned and charcoal abundance will be affected by distance to nearest village and rainfall.

H₃: Tree density will vary with rainfall and charcoal abundance will be higher in high rainfall areas

H₄: Charcoal morphology (length:width ratio) will reflect the proportion of trees and grasses in the landscape.

Although past studies have sought to elucidate the charcoal signal of various environmental variables such as fire intensity and rainfall (see (Duffin, 2008); and proximity, area and intensity (see Duffin et al. 2008), none to my knowledge have looked at macro-charcoal morphology or settlement density and its signal in the charcoal record in the savanna context. The importance of this study is embedded within a much greater context – fire management. The long-term records of fire and vegetation change and their accurate interpretation aid in our understanding of how fire impacts different vegetation types (a. Ekblom and Gillson, 2010). Furthermore, understanding past responses of vegetation to fire will allow us to predict future changes in the savanna ecosystem in light of climate change (2008, 2005). The results of this study will aid in the interpretation of long-term charcoal records from sediment cores collected in the study area (Humphrey, in prep).

Methods

1. Study Area

The study area is located in the north-east of Namibia within the Kavango East and Zambezi Regions (Figure 1.1). Kavango East, formerly known as the Caprivi Strip, is approximately 200 km long from east to west and 32 km wide (Brown and Jones, 1994). The study area consists of gently undulating palaeo dune fields and lies at an altitude of about 1000 metres above sea level (Trollope and Trollope, 1999). Kavango East is surrounded by Angola to the North, and by Zambia and Zimbabwe to the north-east, and Botswana to the south and lies in the nexus of the Kavango/Upper Zambezi Transboundary Conservation Area (KAZATFCA).

The Kavango Region is marked by a sub-tropical climate and experiences the highest rainfall in Namibia (600 to 700 mm Mean Annual Rainfall)(Moore et al., 2002). The area is bounded by the great floodplains of the Zambezi, Kwando-Linyanti and Kavango Rivers and is located on the Kalahari Basin, within the broad leaf tree-shrub savanna biome of the miombo eco-region of southern Africa (Jones and Barnes, 2009). Although most of the area comprises communal land designated as a multiple use area (MUA), a great portion of it is a wildlife conservation area, Bwabwata National Park (Moore et al., 2002). The vegetation is thought to be driven mostly by three factors soils, floods and fire (Trollope and Trollope, 1999). The Kavango East area is characterized by dry, semi-arid to open woodlands and is nationally and officially classified as dry forests (MWAf, 2011). As a region, the Kavango has the highest density and variety of trees and plants in Namibia (Ashley and Lafranchi, 1997). The dominant tree species occurring in the deep aeolian Kalahari sands belong to the subfamily Caesalpinioideae and comprise species typical of these ecosystems, of which are *Baikiaea plurijuga* (Zambezi Teak), *Burkea africana* (Wild syringa), *Guibourtia colesoperma* (False mopane) and *Colospospermum mopane* (Mopane) (MWAf, 2011). Other species of relevance to the region are *Pterocarpus angolensis* (Kiaat), *Sclerocarya birrea*, *Terminalia sercica* and *Schinziophyton rautanenii* (Mangetti) (MWAf, 2011). Historically, *P. angolensis* and *B. plurijuga* were commercially harvested from the dry woodlands (MWAf, 2011), but currently no formal or commercial logging is allowed (Mendelsohn and Roberts, 1997)



Figure 1.1. Location of the Caprivi strip, Namibia.

The soils vary from Kalahari sand to hydromorphic and organic clay soils in areas that are regularly flooded by the Zambezi, Chobe, Linyanti and Kwando River systems (Mendelsohn and Roberts, 1997a). The area falls within Mega-Kalahari sand sea that reflects major relic linear dunes with a roughly east-west orientation (Moore *et al.* 2012). Today these dunes are highly degraded, and in places only diagnosable by vegetation contrasts between the crests, which support tall trees separated by grass intervening layers (McFarlane and Eckardt, 2007) (see Figure 1.2 to see paleo-dunes).

2. Field and laboratory work

Surface sediment samples (top 2 cm of sediment) were collected from six water basins from eastern and western parts of the BNP within the Kavago East and Zambezi Regions (Figure 1) (April/May 2014). At each of the six sites four subsamples of sediment were taken at different points in the same basin.

In the laboratory, each processed using the swirling method (see Finch and Marchant (2011) for details on the method) sediment sample was sieved through a 150 µm sieve separating micro- (<150 µm) and macroscopic (>150 µm) charcoal. The sieved material was then added to a Petri dish which was subdivided into eight wedges. To avoid confusing organic material as charcoal, all samples were bleached with a 6 % solution of Hydrogen Peroxide (H₂O₂). This process bleaches all organic matter and leaves the charcoal pieces black for a clear contrast. All visible (macro-) charcoal pieces were counted in every second wedge (i.e. four wedges per petri dish). The number of charcoal pieces was thus doubled for each subsample as an estimate for the total number of charcoal pieces in 1 cm³ of sediment. The charcoal pieces were counted using a LEICA EZ4 dissecting microscope where the magnification ranged from 2.5 to 10. We measured each charcoal particle in terms of length and width.

3. Settlement Density

In order to quantify the impact of humans on the charcoal signature we calculated the average distance of each sample site to all villages within a 35 km radius. I reasoned that any village beyond 35 km from the sample site will not have a direct effect on the charcoal signature since it has been found that the relevant source area for charcoal with diameters <50 µm is 10 to 15 km (Duffin et al., 2008).

4. Vegetation Density

The woody vegetation density was quantified with the help of Google Earth version 7.1.2.2041 and ArcGIS version 10.2. At each charcoal sampling site, five concentric circles were created in ArcGIS (see Figure 1.2) at intervals of 200 m to a maximum radius of 1 km. All rings were then populated with 50 random points for which I categorized the vegetation beneath each point, as either 'grass' or 'tree'. This allows one to derive the vegetation density around the charcoal sampling site, at variable distances from the center from each sampling site. The purpose of this is to find out at which distance the relationship between charcoal features (morphology and abundance) and vegetation density is strongest. The Google Earth image dates from October 2013.

5. Burnt Area

Burnt area data for the study area was retrieved from the MODIS Land Collection 5 product (MCD14ML) suite (data available at: <https://earthdata.nasa.gov/node/5323>). The total burnt area was calculated within a 5 km radius of each sample site for years 2009 to 2013. For each 5 km circle, the area burnt by fires was measured within the circle radius by using ArcGIS to cut out the area burnt inside the 5 km circle. A 5 year time window was chosen based as most relevant to savanna charcoal deposits, based on work by Duffin *et al.* 2008.

6. Rainfall

The rainfall data was derived from the TRMM (Tropical Rainfall Measuring Mission) data base (data available at: <http://mirador.gsfc.nasa.gov>). TRMM makes use of both satellite and sample data in all tropical regions from Latitudes 60°N-S, March 2000 to present. The data is scaled at a resolution of 0.5 °

and measurements are taken every 3 hours. We display the Mean Annual Precipitation (MAP) from the year 2000 to 2011 (Figure 5).

Results

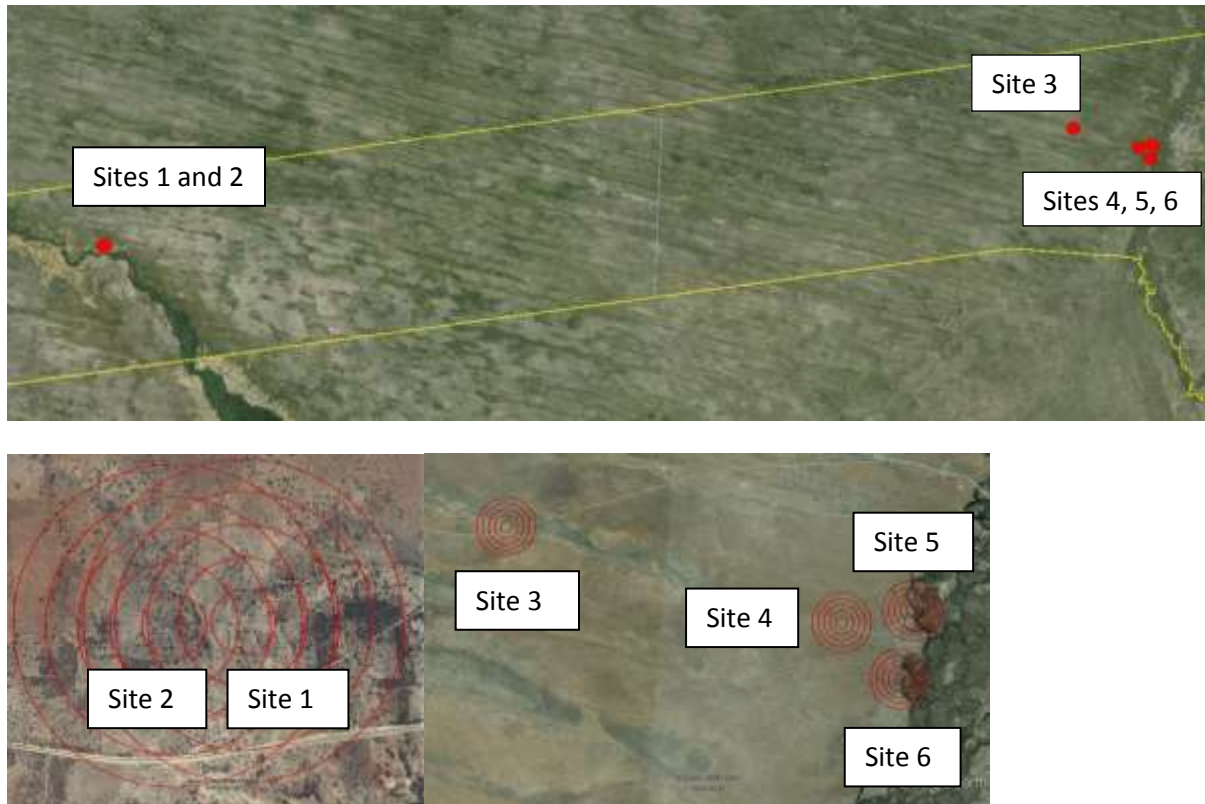


Figure 1.2 Map showing the six sample sites indicating a 1km surface area radius used to calculate vegetation density for each site within the BNP. Notice the linear dune patterns with a roughly east-west orientation. The dunes are recognizable by vegetation contrasts between crests, which support tall trees separated by grass intervening layers (McFarlane and Eckardt, 2007).

Basic Descriptive Statistics: Displaying patterns in morphology, rainfall, charcoal abundance and remoteness.

1. DESCRIPTIVE STATISTICS

1.1 Charcoal concentration (or abundance)

The charcoal concentrations between 'neighbour' pairs (see Figure 2) are not significantly different from one another ($p < 0.05$). This means that the charcoal concentrations between sites which are geographically close to another (see Figure 1 for orientation) are similar above the 95 % level. Interestingly, site 3, although quite remote from all other sites, is not different from site four ($p=0.535$). One can observe that sites far away are generally different in their charcoal concentrations. For example, site 1 has a higher charcoal concentration than sites 3, 4, 5 and 6. Site 1, thus seems to have an exceptional charcoal peak since site 2 (its close neighbour) only has a higher concentration than sites 4 and 6 and not site 5.

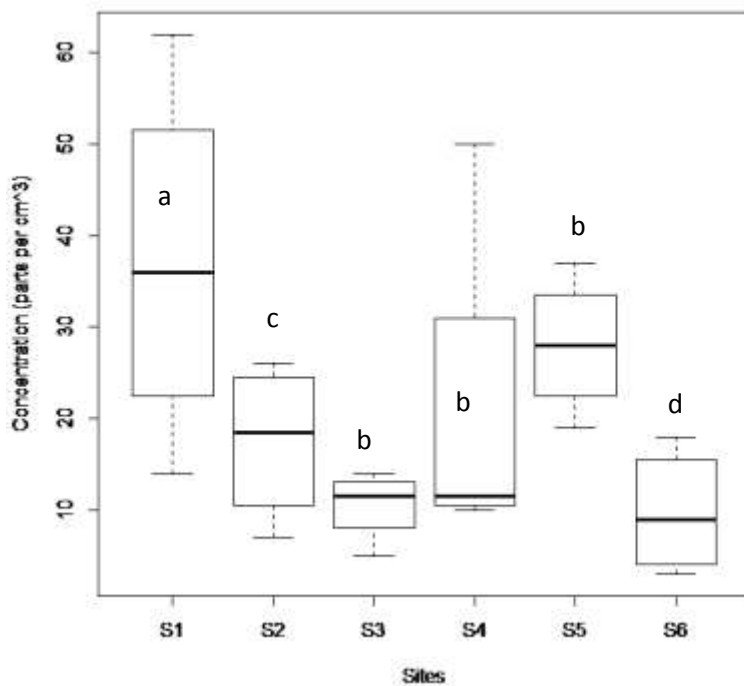


Figure 2. Boxplot displaying the concentration of charcoal for each sample site. Sites sharing a letter in the group label are not significantly different at the 95% confidence level.

1.2 Morphology: Width to length Ratios

Sites 1, 2 and 3 all have a significantly ($p < 0.05$) higher charcoal width to length ratio (W:L) compared to sites 5 and 6. Furthermore, sites 1 and 2 are significantly different from site 5. It is evident that the W:L ratio in the West (S1 and S2) have a higher W:L ratio when compared to the East (S4, S5 and S6). Site 3 (S3) which is unique in its location, being neither on the far East or West, and has a lower W:L ratio than the sites from the West (S1 and S2) and a higher W:L ratio than the sites from East except form site 4 .

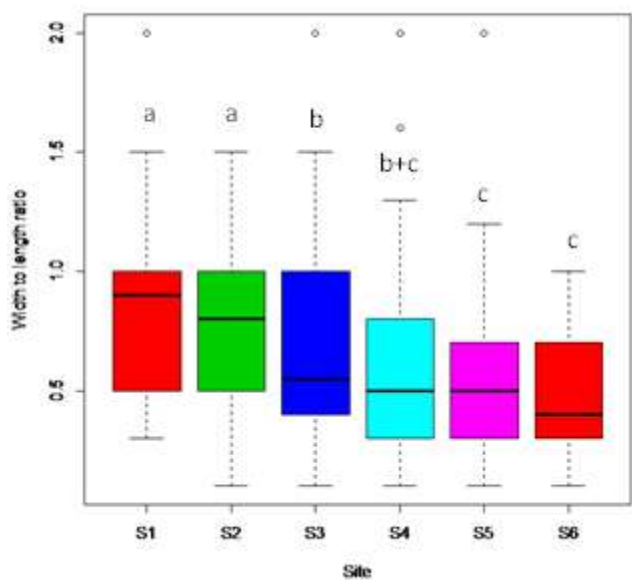


Figure 3. Boxplots of the charcoal width to length ratios. Letters represent significant difference at 95% confidence level.

1.3 Remoteness: “Distance to Nearest Village”

Figure 4 indicates the average distance to nearest settlement which approximates the “remoteness” of each sample site. The most conspicuous feature is the clustering of sites 4, 5 and 6. They are all geographically close to another (not more than 12 km from center to center), so the results comes as no surprise. The average distance to the nearest settlement is roughly 10 km for sites four to six. Site three is the most remotes with an average distance of roughly 20 km. Conversely, site 1 is the least remote, having settlements in its vicinity of less than 2.5 km. Site two is the second least remote of the sample sites with a median distance of roughly 5 km.

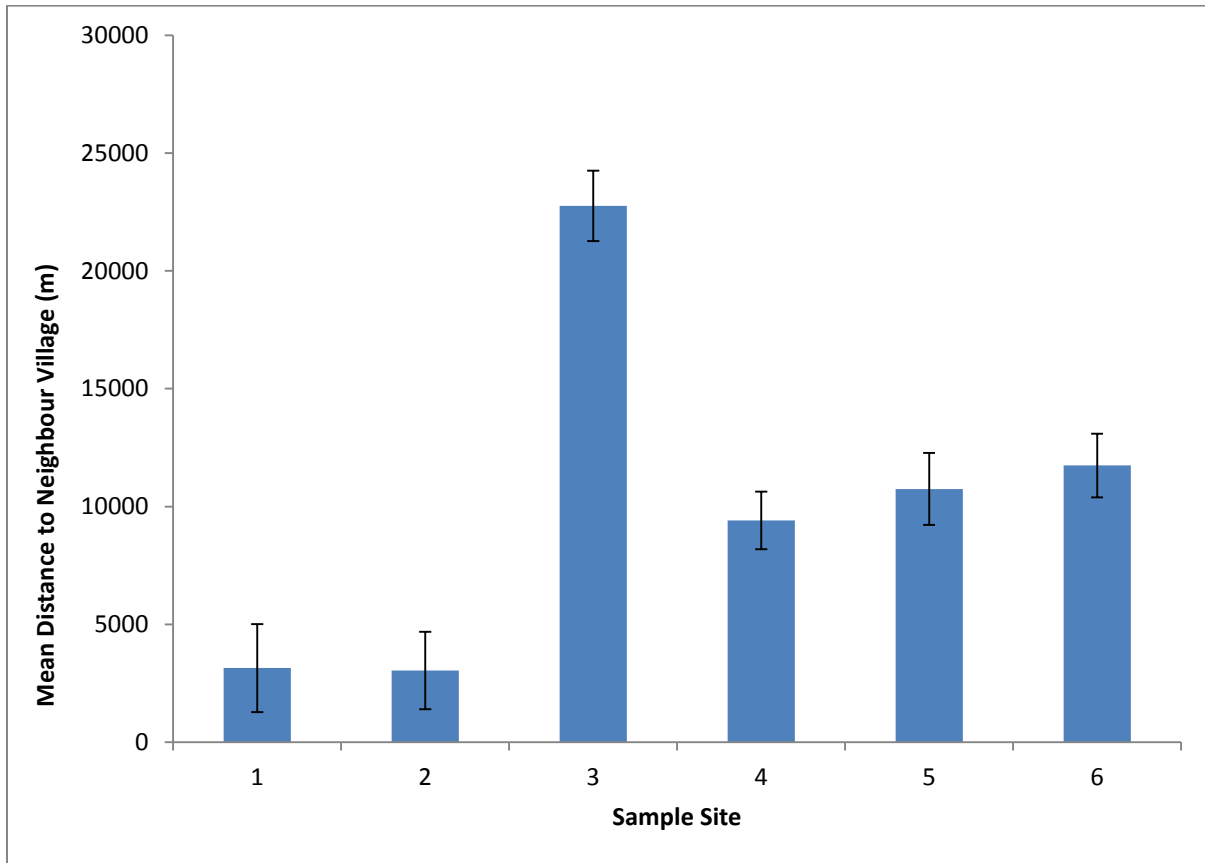


Figure 4. The average distance to the nearest settlements. The error bars indicated mean \pm SE.

1.4 Rainfall

The sites were collated into three categories according to their relative position: West, Middle and East (Figure 5). The data revealed an increasing rainfall gradient going from the west to east. The differences in rainfall between the sites are relatively small with approximately 100 mm range between West (571 ± 53 mm) and East (664 ± 45 mm) and Middle falling in between at 639 mm (± 43 mm). So the mean annual rainfall ranges between 571 and 664 mm/yr. The rainfall occurring in the Kavango East is thus comparable with that of the Kruger National Park (KNP) where the rainfall has been reported to range between 459 and 650 mm/yr (A. Ekblom and Gillson, 2010).

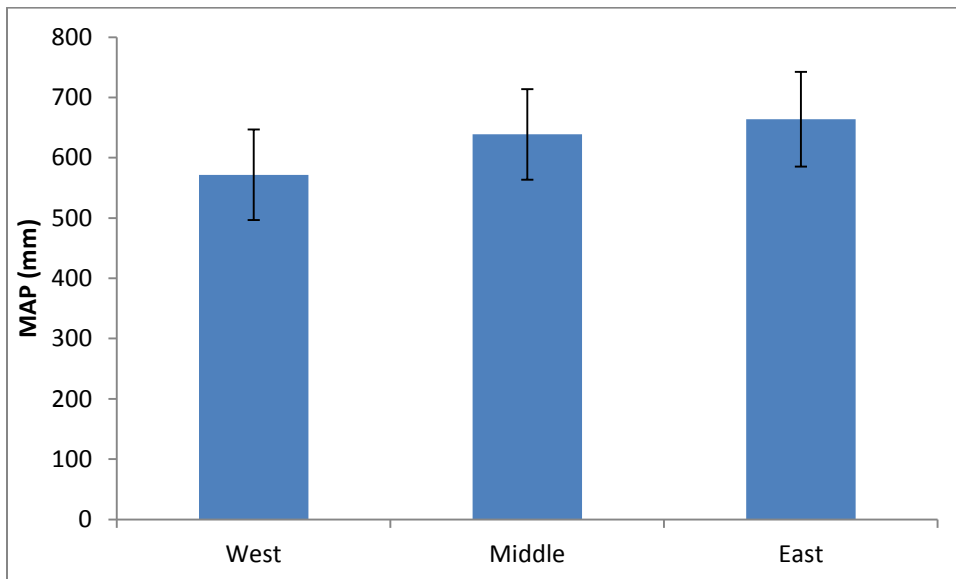


Figure 5. The mean annual precipitation (MAP) for years 2000 to 2011 of all sample sites. Sites 1 and 2, and 4 to 6 have been collated because the rainfall data did not yield a resolution fine enough to show differences between them. Error bars indicate \pm SE.

Correlations: Displaying patterns relationships between charcoal morphology, rainfall, charcoal abundance and remoteness.

2. CORRELATES

2.1.1 Charcoal concentration versus Burned Area

Figure 6 shows the relationship between charcoal concentration and burned area. The correlation coefficients ($r = -0.186$, $\rho = 0.2$) and associated p-value ($p > 0.05$) do not suggest that there is a strong relationship between the two variables. However, I think the statistics in themselves is misleading since there seems to be an outlier – site 3 (see Figure 6). By justifying the removal of site 3 from the data set, statistically significant results emerge as seen in Figure 7 below.

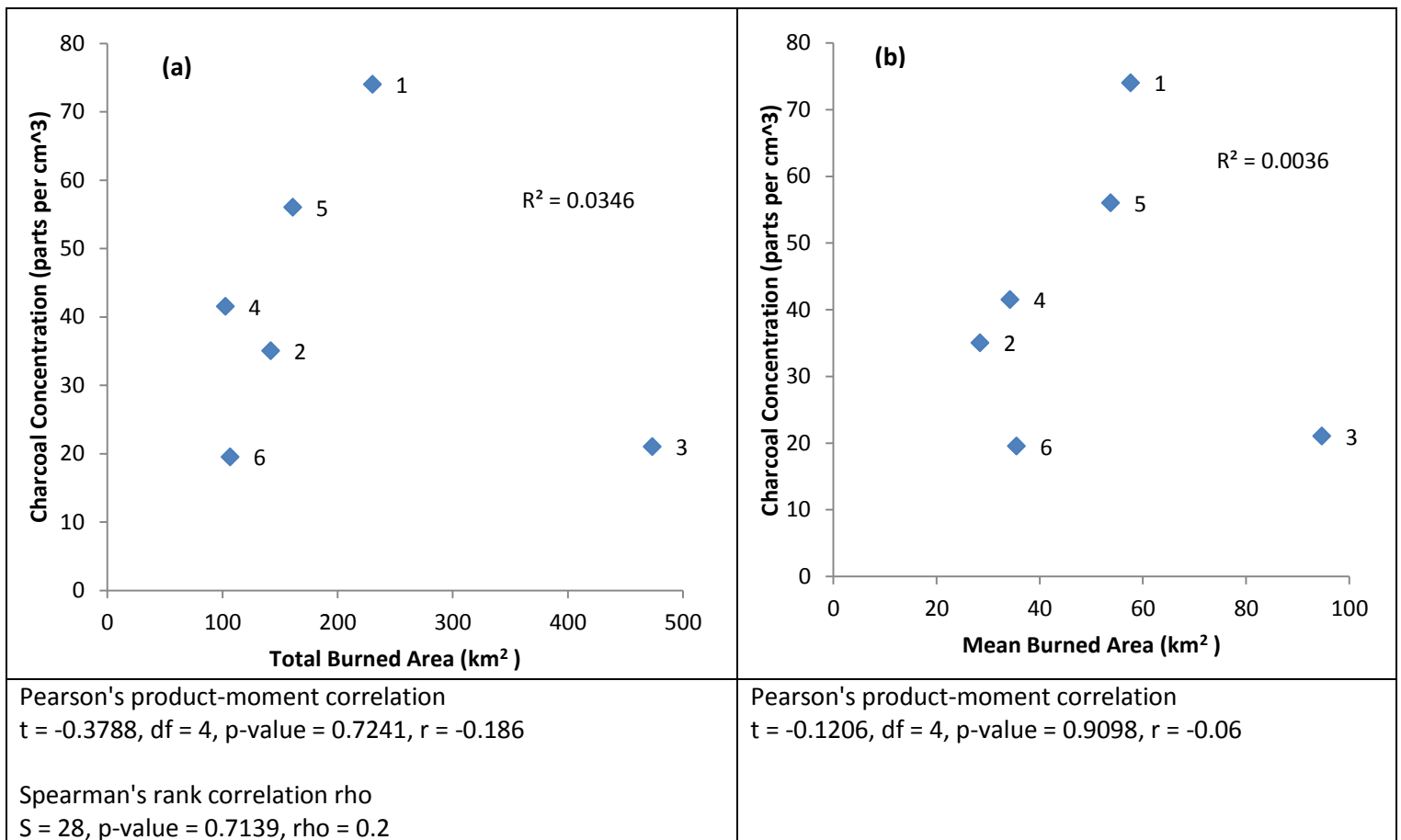


Figure 6. Correlating Burned Area with Charcoal Concentration. Notice the outlier, site 3 which is removed in Figure 7.

2.1.2 Charcoal concentration versus Burned Area (Outlier Site 3 removed)

A clear pattern emerges when site 3 is excluded. The data suggests a strong correlation between charcoal concentration (or abundance) and burned area (Figure 7). Of all correlates tested, this is the only **statistically** significant result and therefore is a weighty piece of evidence for a link between the two variables. I have included both total and mean burned areas (for the five year period – 2009 to 2013), although total burned area probably makes more sense to use since it is expected to leave a strong charcoal signature.

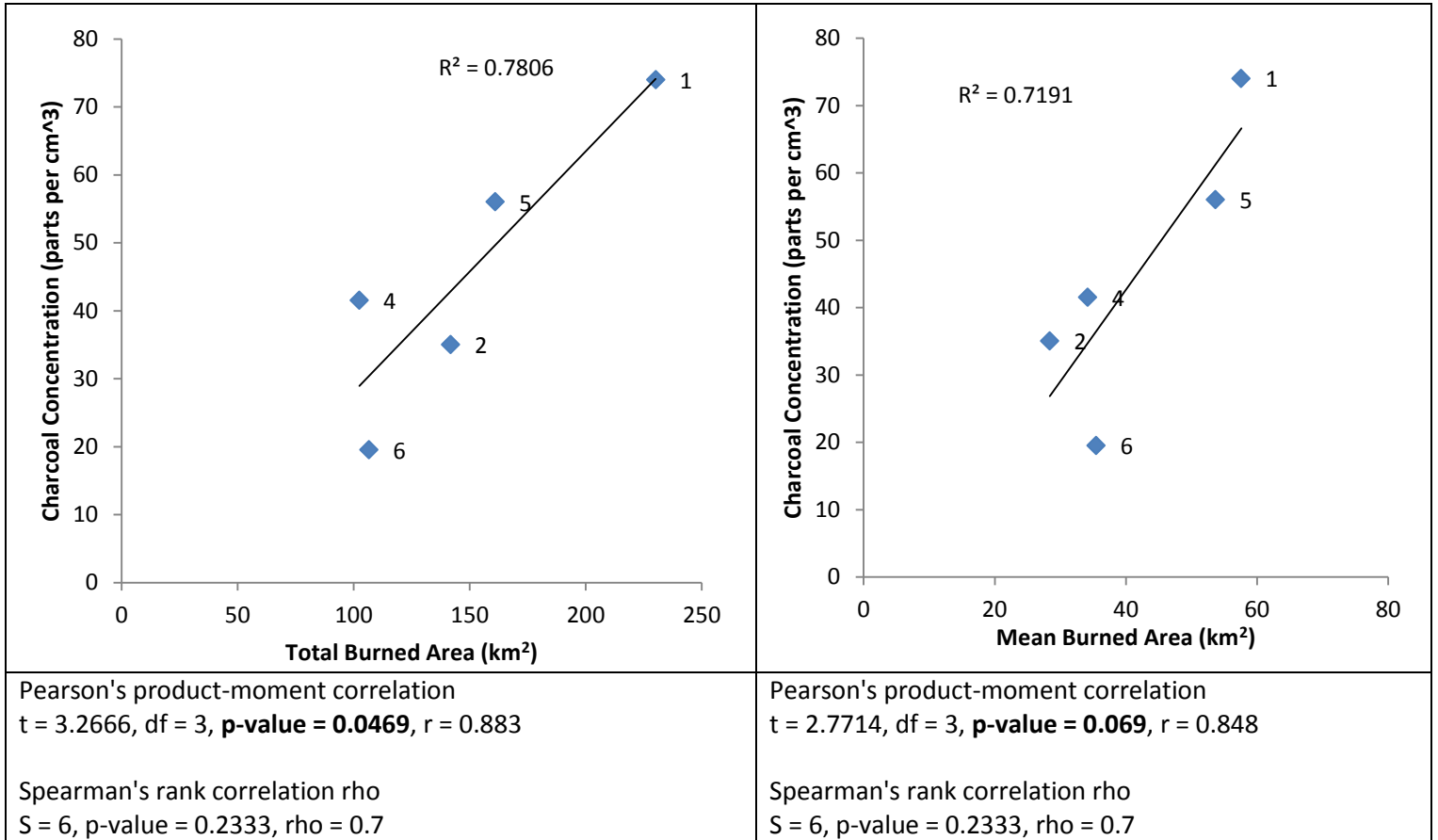
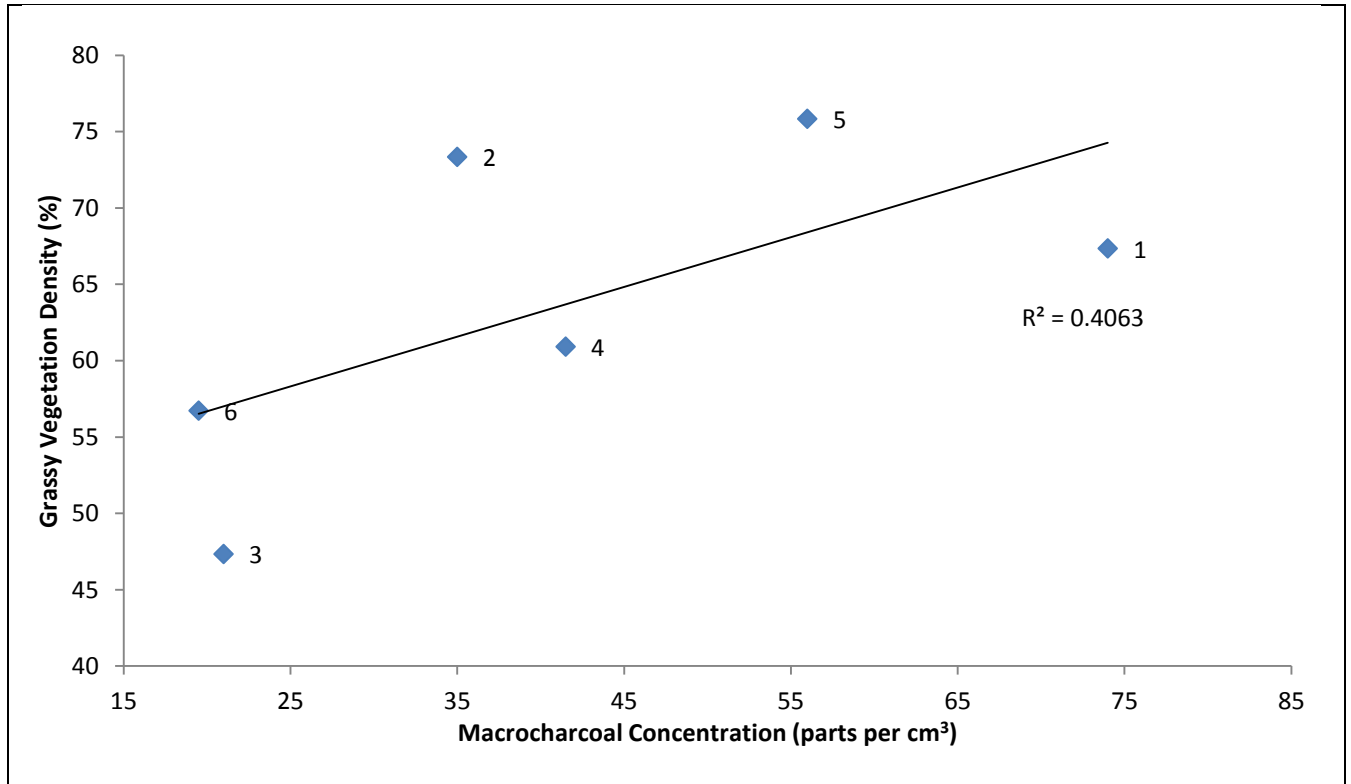


Figure 7. See Figure 6, but outlier 'Site 3' removed.

2.3 Vegetation density versus macrocharcoal concentration

There is a relatively strong positive relationship between charcoal concentration and grassy vegetation density at a distance of 600 meters from the center (Figure 8)(p-value = 0.1736, $r^2 = 0.406$, $r = 0.637$). At a distance closer to the sample point or between 600 and 1000 metres, the relationship remains positive but weakens in both cases.



Statistics Summary:

$t = 1.6532$, $df = 4$, $p\text{-value} = 0.1736$, $r^2 = 0.406$, $r = 0.637$ (Pearson's product-moment correlation)

$S = 12$, $p\text{-value} = 0.175$ (Spearman's rank correlation rho)

Figure 8. The correlation between macrocharcoal concentration (parts per cm^3) and the corresponding grassy vegetation density (expressed as percentage contribution). The vegetation density is derived from the first 600 meters from the sampling point, and represents the greatest correlation coefficient. The strongest correlation is at 600 meters from the sample sites, as depicted here (see Figure 9 for comparison).

2.4 The correlation strength between vegetation density and morphology at different radii from point of sampling

Figure 9 shows the degree to which W:L ratio and vegetation density at variable distances from the sampling center. Notice the peak at 600 meters revealing the strongest relationship between the two variables ($r^2 = 0.41$).

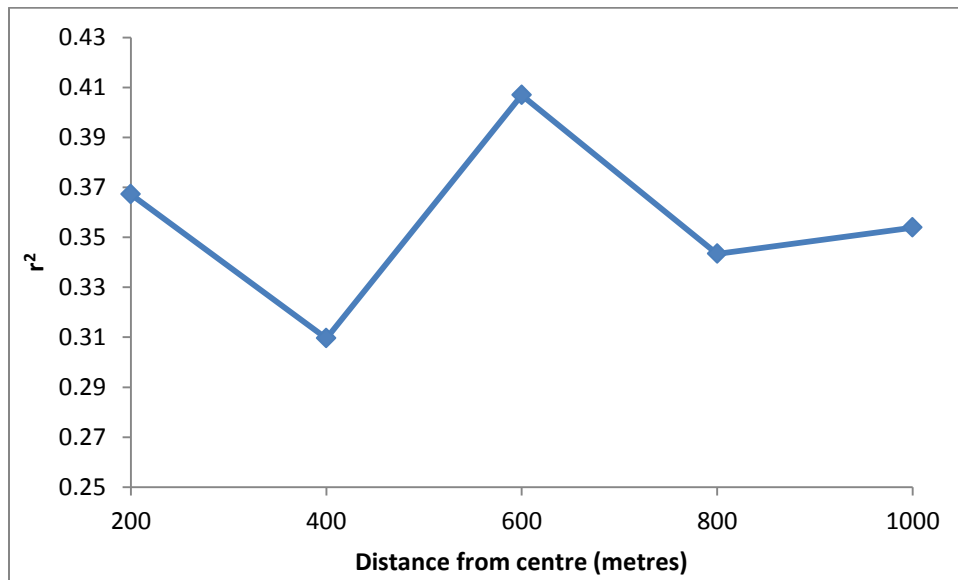


Figure 9. The correlation coefficient, r-squared, of W:L ratio and vegetation density of all sites with increasing distance from the sampling center.

2.5 Length to width ratio versus macrocharcoal concentration

The correlation between L:W and charcoal concentration is negative ($r = -0.565$), but very weak ($r^2 = 0.32$, $p = 0.24$). When correlating the inverse, W:L and charcoal concentration, the relationship becomes positive ($r = 0.482$), and a bit weaker ($r^2 = 0.23$, $p = 0.33$). Neither correlation is statistically significant ($p > 0.05$)

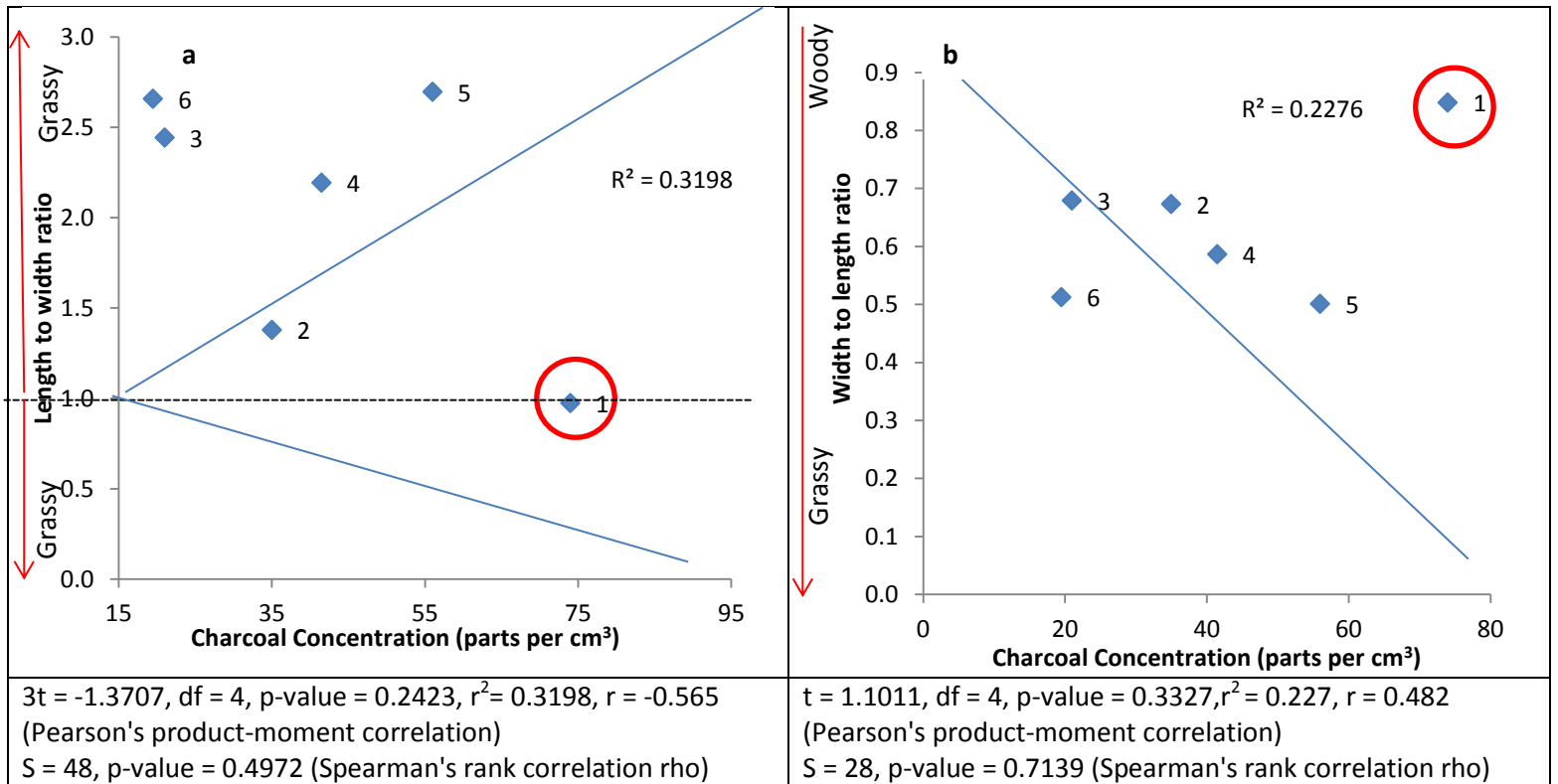


Figure 10. The correlation between macrocharcoal concentration and the corresponding average width to length ratio. (b) The same as in (a) but here the width to length ratio (i.e. the inverse) is correlated with macrocharcoal concentration. The numbers indicate the study site. The horizontal line figure 5b indicates hypothesized woody dimensions where the charcoal particles have a 1:1 relationship and are thus square-like. Grassy fragments are thought to deviate from this 1:1 ratio. The trend lines in both 5a and 5b indicate the **expected** relationship.

2.6 Width to length ratio versus vegetation density

There is a very weak relationship between fuel (here, woody vegetation density) and morphology (W:L ratio) (p-value = 0.857, $r^2 = 0.095$). The correlation was done with the vegetation density taken from within an 600 meters radius from the sampling point, since it yielded the strongest relationship (see Figure 9).

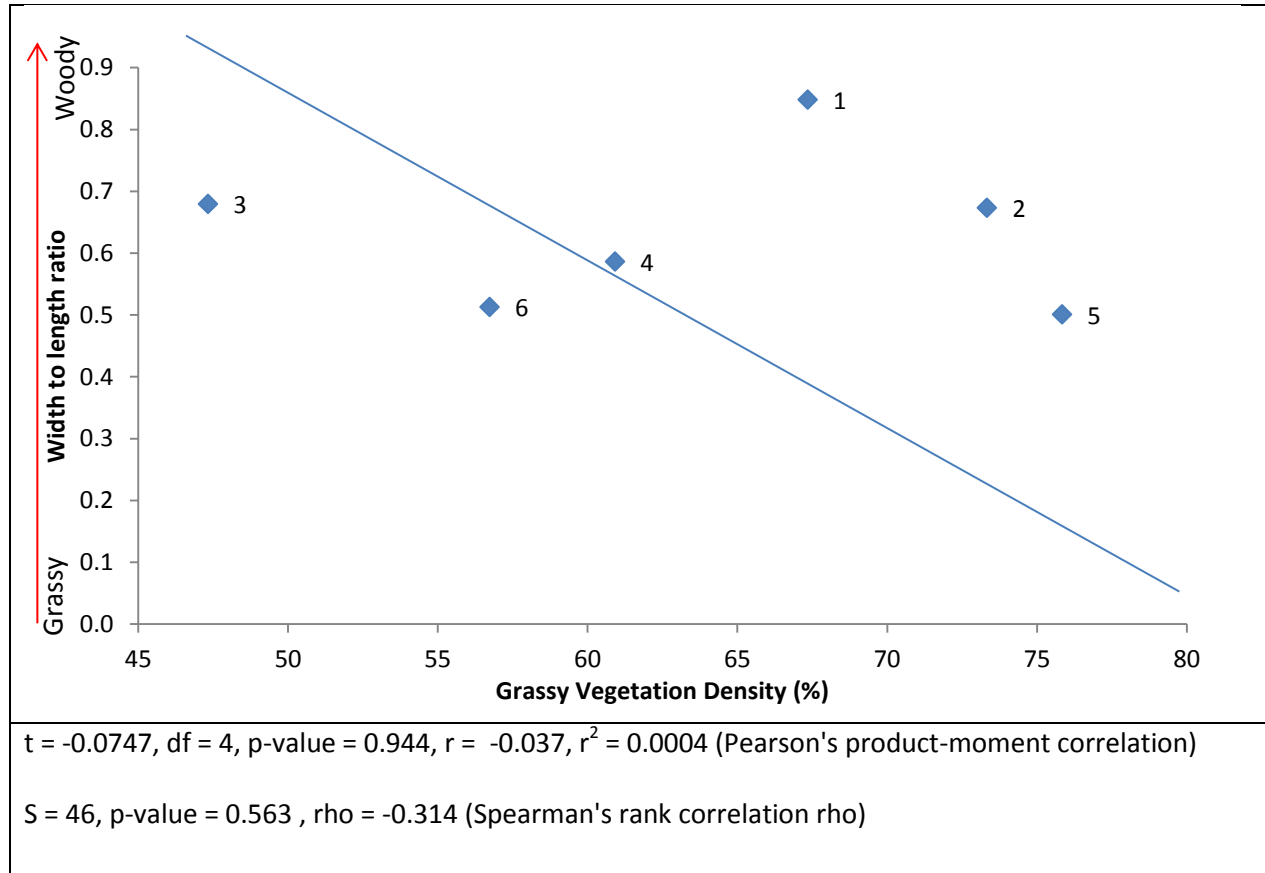


Figure 11. The relationship between woody vegetation density and morphology. The distance at which the relationship is strongest (as depicted) is at 800 meters from the center. The trend line depicts the **expected** relationship.

2.7 Remoteness versus Burned Area

The relationship between remoteness and burnt area (Figure 12) is ambiguous because with all data points included (sites one to six), the relationship is weakly positive ($r^2=0.482$, $p = 0.944$, $n=6$). When the potential outlier (site 3) is removed, the relationship becomes negative and closer to being significant ($r^2=0.395$, $p = 0.256$, $n = 5$).

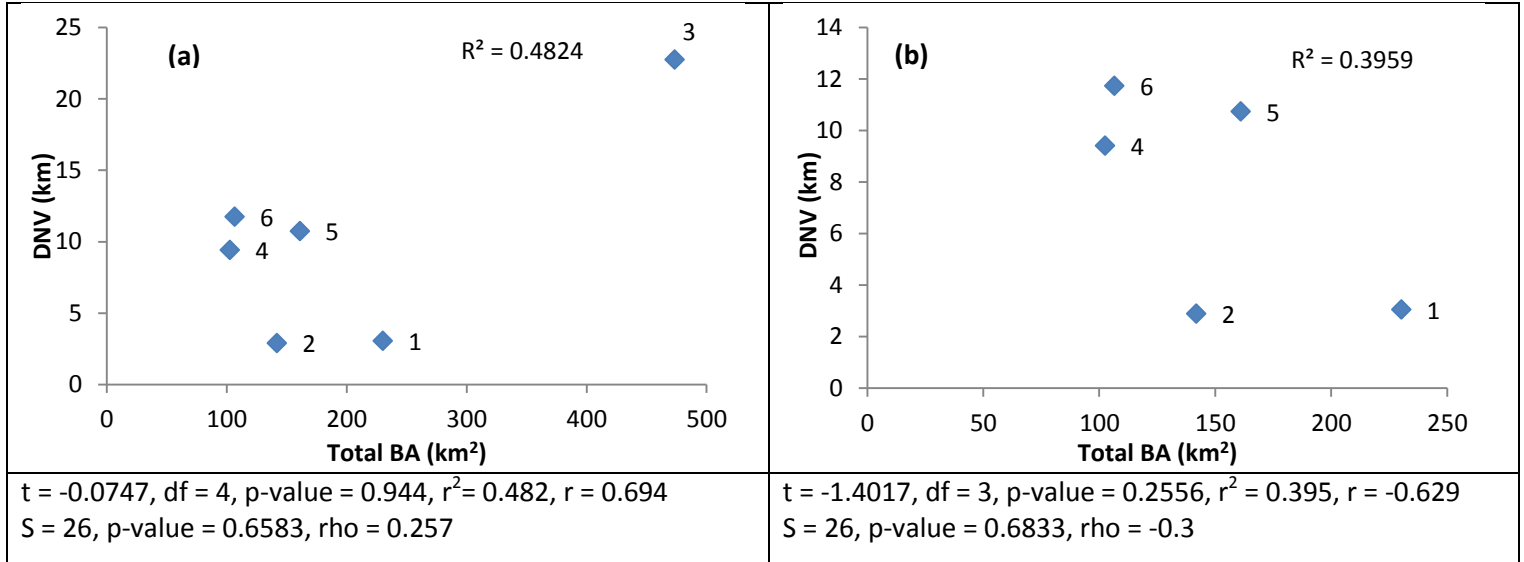


Figure 12. The relationship between remoteness (DNV) and total burnt area from 2009 to 2013. 9a includes all data points and 9b has the outlier from site three removed.

2.8 Remoteness versus charcoal concentration

At first glance the data (Figure 13) seems to indicate that the more remote the sampling point is, the less charcoal can be found there ($r^2 = 0.374$, $r = -0.611$, $p = 0.197$). However, the relationship may not be that straight forward. For instance, sites one and two have very similar remoteness values ($S1 = 2896$ m, $S2 = 3053$ m), but have very different charcoal signatures with site two having more than double the amount of charcoal than site one (74 versus 35 part per cc). Sites 4, 5 and 6 also all have a similar remoteness index but a lot of variability in their charcoal concentrations ($S4=41.5$, $S5=56$ and $S6=19.50$ parts per cc). Site 3 is the odd one out being more remote than the points and having a low concentration of charcoal (21 parts per cc and 22760 m).

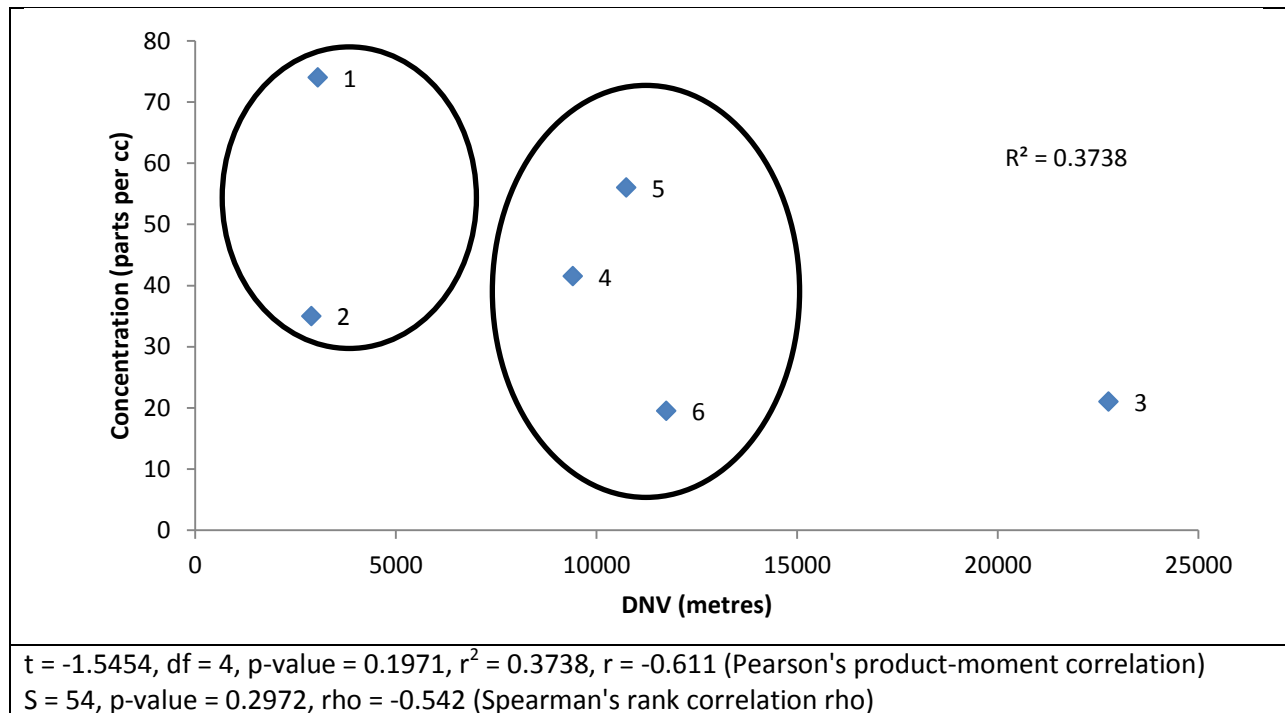


Figure 13. The relationship between remoteness (DNV) and charcoal concentration. The numbers signify the site number.

2.9 The relationship between rainfall and grassy vegetation density

Figure 14 shows the relationship between grassy vegetation density and Mean Annual Precipitation. According to the data, there is no strong relationship between the two variables ($r = -0.343$, $p > 0.05$). An interesting observation is the fact that there is considerable variability between sites with the same rainfall (e.g. site 6, 4 and 5). Site 5 receives the same amount of rainfall but is far more grassy relative to trees than sites 4 and 6.

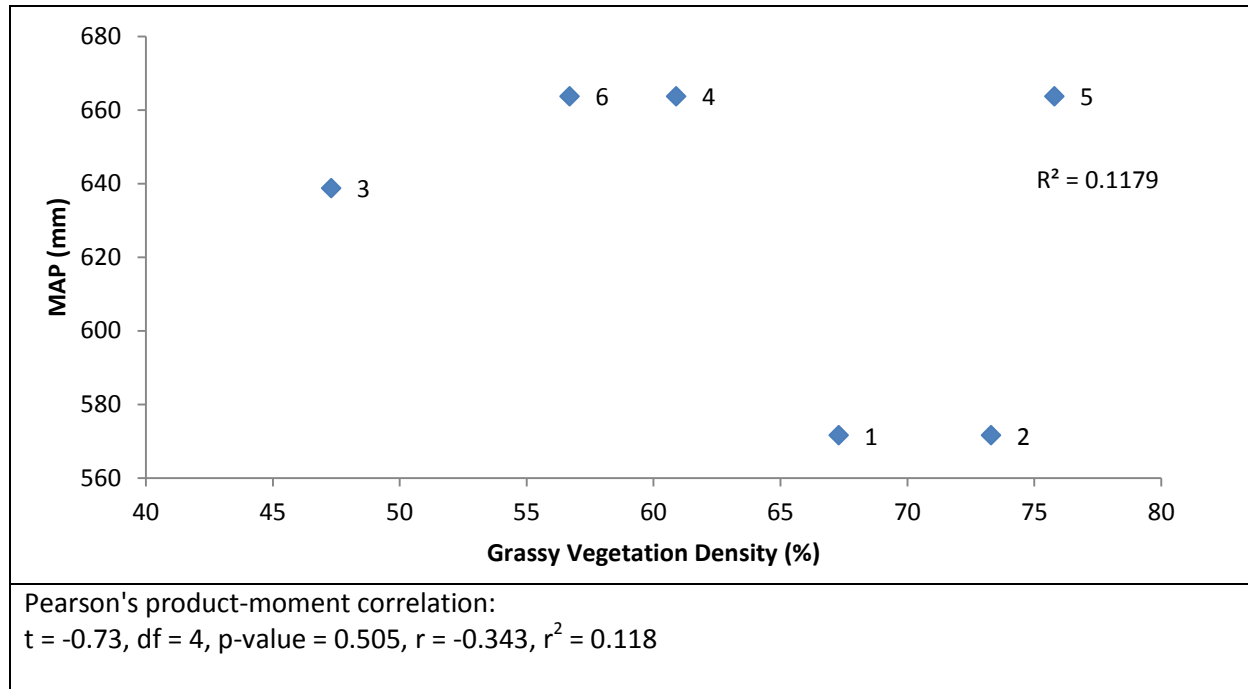


Figure 14. The relationship between grassy vegetation density (%) and Mean Annual Precipitation.

Discussion

Understanding past changes in the savanna ecosystem requires that we calibrate palaeo-proxies with present day environmental conditions shaping the vegetation. This is the aim of this study, to establish links between charcoal found in surface sediments in BNP, Kavango East and Zambezi regions, Namibia and various environmental features, which include fire, rainfall, vegetation density and settlement density. I hypothesized the following:

H₁: Charcoal abundance will reflect area burned over the past five years.

H₂: The area burned and charcoal abundance will increase with increasing distance to nearest villages.

H₃: Charcoal morphology (length:width ratio) will reflect the proportion of trees and grasses in the landscape.

H₄: The grass: tree ratio and hence charcoal morphology will be affected by rainfall. I expect a higher proportion of grasses in high areas with more rainfall, and therefore a higher length:width ratio.

Charcoal Abundance/Concentration and Area Burned H₁

A significant finding was that charcoal abundance reflects burned area (Figure 7, $r^2 = 0.78$, $p < 0.05$) given that site 3 was discarded as an outlier (see Figure 6). Therefore we have shown that there is a strong relationship between burned area and macro-charcoal abundance found in surface sediments. This means that burned area can be inferred quite accurately from long-term macro-charcoal sequence data given that the relationship holds. This is a weighty finding since the knowledge of burned area in the past, perhaps before the arrival of humans, can inform modern fire management policy (see Trollope & Trollope 1999).

I justified the exclusion of site 3 on the basis of it visually being out of place in Figure 6 and because it is geographically quite unique (see Figure 1). All other sites are close to river banks (Kavango and Kwando Rivers) and therefore also close to human settlements which are located along the rivers (Mendelsohn and Roberts, 1997a). Site 3 is 15 km away from the river and is the only site which is located in an area where the vegetation is not directly impacted by the river by flooding and by humans which burn the area. Thus, I would argue that the charcoal found in site 3 falls under a fire regime less impacted by humans and I would argue that all the other sites belong to a system where the effect of humans and the rivers over-ride a natural fire regime. The relationship between area burned and charcoal abundance might differ between riverine and non-riverine areas, a factor that might be related to both vegetation type and density of human settlement. Site 3's total burned area for the years 2009 to 2013 is the highest of all sites (473 km²) and yet has about the same amount of charcoal as site 6 whose surrounding vegetation burnt is a quarter of that of site 3 (107 km²). What this means is that the area of vegetation burned at site 3 does not register as strongly in the charcoal record, as in all the other sites. A possible reason could be that the biomass per area is less in site 3 and thus less ends up in the sediments. I have no *post hoc* means of testing this though. Ideally, one would have to measure the standing crop biomass *in situ*.

Charcoal Abundance and % grass cover (H₃)

Charcoal abundance is also strongly positively correlated with % grassy vegetation cover (Figure 8). This suggests that grasses are the main fire fuel type, confirming past findings in the literature (e.g. Higgins et al. 2000). The more important aspect of this result is that macrocharcoal fragments in the sedimentary record reveal the vegetation composition of the savanna ecosystem in the past. If the assumption holds that the relationship between charcoal abundance and proportion grasses is permanent, then one can infer how the vegetation has changed over time by looking at long-term charcoal data derived from sediment cores. This has conservation implications as one can assess the natural variability of the savanna ecosystem in the past, as a consequence of other variables such as rainfall, herbivory and fire. This has been done (see Gillson & Duffin 2007), but using fossil pollen and not to my knowledge fossil charcoal. Using charcoal would add another proxy to further validate (or challenge) inferences about past vegetation changes.

A further point of discussion for the charcoal concentration (see Figure 2) for the sites is that one has to consider the area burned. The reason why sites 4 and 6 have a low amount of charcoal is simply because the area adjacent to them cannot burn (see Figure 1 for map). The Kwando River flows right next to these sites which means that their source area for charcoal effectively halves. This shows the importance of considering the surrounding area of the point of sampling, as this has a major effect on the charcoal signature.

The relationship between settlement Density/Remoteness, Burned Area and Charcoal Concentration (H₂)

There are three main groups based on visual inspection: Sites 1 and 2 belong into a group, site 3 is on its own, and sites 4 to 6 are one group. This means that site 3 is the most remote site and site 1 and 2 the least rural. This makes sense, since most of the settlements are concentrated along the banks of the rivers Kavango (west) and Zambezi (east) (Mendelsohn and Roberts, 1997a). The closest settlements to sites 1 and 2 are Mwitjiku (310 m) and Bagani (850 m).

Figure 13 suggest that the concentration of charcoal decreases with increasing distance from settlements. This falsifies my hypothesis (H₄) where I proposed that a higher settlement density will increase burning and therefore bolster the charcoal deposited in the sediments. However, with as few as six samples, one needs to be cautious in reaching premature conclusions, particularly because the relationship is not statistically significant ($p=0.197$). Furthermore, some authors have noted that the relationship between settlement density and charcoal deposition is not linear (Bistinas et al., 2013). They suggest that the burned area increases with population density and then decreases as the population density exceeds a threshold. Because this threshold is unique for each region, the relationship has to be investigated for that region. Furthermore, Archibald et al. (2008) have highlighted the complexity of the human-fire relationship, noting for example (p.614) that “areas of high population density have been shown to be associated with an increase in the number of fires (Keeley et al., 1999), but increased population densities also result in more intensive land use, reduced fuel loads, and fragmentation of landscapes, which act to reduce the spread of fire (Frost, 1999).” So the fuzzy result

between charcoal abundance and distance to settlements is not surprising and it is clear that further research in this area is needed, but is beyond the scope of this study.

Another reason why I would be cautious in interpreting this data is the high degree of variability for sites close to another (less than 1km distance). Sites 1 and 2 are 800 meters apart from one another yet site 1 has double the amount of charcoal (74 parts per cm³). Figure 13 displays this point quite clearly where the two groups (circled) take on a vertical orientation which means that they are about equally 'remote' but vary in their charcoal signature.

Site 3 is the most remote sample and thus is probably least impacted by humans particularly because the site is in the middle of a protected area. If that is true then the data suggests that humans increase burning as reflected by a more charcoal at the sites, at least in this region.

The data suggests that there is no strong relationship between burned area (BA) and remoteness (Figure 12). However, site 3 does lend insight since it is the most remote sample and thus the relationship between BA and remoteness is probably least impeded by other factors. This would mean that BA is highest the further away from the influence of humans. This would make sense since humans are known to fragment the landscape (Archibald et al., 2012) and thus decrease the degree to which the fire can spread. However, humans intentionally burn and thus could potentially increase the BA. The question is, do natural (i.e. lightning induced) fires which are unobstructed by roads etc. have a greater BA than human-controlled fires? I think humans dramatically alter the fire regime and over-ride the natural fire regime as seen in Figure 10b.

The relationship between macro-charcoal morphology and vegetation composition (H₃)

If charcoal concentration is indeed a reflection of the frequency of burning and particularly fuel type, then we should expect a high L: W ratio or a low W:L to match a high charcoal concentration in grass-dominated landscapes. This hypothesized relationship hinges on the assumption that fuel type does in fact reflect in the charcoal morphology as approximated by the dimensions and their ratios (Ward & Hardy (1991) as cited in Umbanhowar Jr. & McGrath, 1998). We find that the relationship between morphology and charcoal concentration is quite the contrary to what we expected (Figure 5). The relationship between L:W ratio and concentration is negative, which means that the sites with a lot of charcoal have very woody-like charcoal fragments suggesting more woody surroundings. A tentative conclusion is to falsify hypothesis H₂ which proposes that more grassy savannas will leave a charcoal signature with charcoal particle size ratios deviating from a 1:1 relationship.

One way it could be altered is by variable burning temperature. For instance, Enache and Cumming (2006) noted that burning temperature has a major effect on charcoal morphology which in turn depends on the vegetation. In the context of my study, I would propose that the temperatures of the fires would be lower in the sites bordering the Kavango river (S1 and S2) and higher in the sites bordering the Kwando river (S4 and S6). Kwando river sites, especially site 4 and 6 experience the build-up of high fuel loads (grassy) as a result of the moisture supplied by the river through flooding (Brown and Jones, 1994). The sites close to the Kavango River would experience lower temperatures because

the fuel loads are kept low as humans regularly burn the area. Therefore, fuel load could account for an altered morphology in the charcoal record.

However, there **seems** to be no relationship between morphology and vegetation density in our study area (Figure 11). If fuel type left a signature in the charcoal record, one would expect a more grassy savanna vegetation to a higher the L:W ratio. Based on the findings of Ward and Hardy (1991), I predicted that the sample sites which have a high proportion of grasses would have greater L:W ratios than those sites with less proportion of grasses. However, there is a flaw, not with the argument but with a particular presupposition. One cannot assume that all grasses have the same height and/or has the same biomass. It is possible that L:W ratio is adjusted not primarily by the proportion of grasses to trees, but by grass biomass per area. Thus, two sites might have the same proportion of grass to trees but might differ in absolute biomass of grass per given area. To rectify this problem one would have to measure the standing crop for each study site to check whether the length and/or above ground biomass affects the morphology significantly. This is particularly important in light of the fact that the vegetation in the study area is quite heterogeneous (Brown and Jones, 1994). The floodplains especially of sites 4 and 6 are a patch-mosaic vegetation type, consisting of mostly grassland varying considerably in their species composition depending on inundation levels and compaction by regular game (Brown and Jones, 1994). So one would expect the macro-charcoal morphology to reflect the local vegetation types which makes the interpretation of the data difficult since each site falls within a different vegetation type. Given that the sites bordering the Kwando river (S4, S5 and S6), which are dominated by grasses (Brown and Jones, 1994), I would expect a high L:W ratio or a low W:L ratio. This is exactly what one finds (see Figure 5).

Another possible reason why the data does not reveal a clear relationship between macro-charcoal morphology and vegetation type could be due to the fact that charcoal is altered. Thus, depending on the processes of transportation and deposition to the pans from which the charcoal was extracted, the charcoal could be variably broken up and its morphology modified (Scott, 2010).

The relationship between rainfall and charcoal morphology (H₄)

The rainfall for the study region reveals two things: Firstly, the area is wet when compared with the rest of Namibia. Secondly, there is an increasing rainfall gradient going from the west to east (see Figure 5). This means that sample site 1 and 2 receive about 100 mm less rainfall per year (ca. 570 mm/yr) than do sites 4, 5 and 6 (ca. 670 mm/yr). Based on the findings of previous findings where rainfall was the most important predictor of grassy vegetation. Site 3 is intermediate which receives about 640 mm per year. This means that parallels can be drawn to study of Ekblom and Gillson (2010) conducted in the Kruger National Park where rainfall is the major determinant of available biomass and thus as a driver of fire. However, once the critical threshold of 650 mm rainfall is exceeded, as is the case here, then woody biomass is no longer controlled by rainfall but by other factors such as humans, fire and herbivores (Sankaran et al., 2005). Therefore, I reject my hypothesis that tree density will vary with rainfall on the grounds that fire and humans are controlling the vegetation rather than rainfall. To continue this line of argument, all study sites apart from site 3 are uniquely positioned in the landscape, being either on floodplains (S4 and S6), on a drainage line (S5), or close to human settlements within a fragmented

landscape impacted by agriculture and/or animal husbandry (S1 and S2)(Mendelsohn and Roberts, 1997b). Although parallels can be drawn to KNP, as in Ekblom and Gillson's study, the comparison falls apart because proximate drivers such as seasonal flooding (Brown and Jones, 1994) and anthropogenic practises are more important in shaping the vegetation and thus the macro-charcoal signature.

Conclusions

Four main conclusions can be made in reference to the four hypotheses posed:

- (1) We have shown that there is a strong relationship between burned area and macro-charcoal abundance found in surface sediments. This means that burned area can be inferred quite accurately from long-term macro-charcoal sequence data given that the relationship holds. This is a weighty finding since the knowledge of burned area in the past, perhaps before the arrival of humans, can inform modern fire management policy (see Trollope & Trollope 1999). Therefore, I accept H_1 which states that charcoal abundance will reflect the area burned over the past five years.
- (2) No distinctive pattern emerged when correlating burned area and charcoal abundance with distance to nearest villages (Figures 9 and 10). However, with the removal of outlier site 3, the data suggests that relationship is negative in both instances. This would suggest that humans increase the burned area through active ignition. This is only a tentative conclusion since we did not directly test this explanation. I reject H_2 which states that burned area and charcoal abundance will increase with increasing distance to nearest villages.
- (3) The data revealed no conclusive relationship between macro-charcoal morphology and proportion trees and grasses (H_3). I concluded that although the idea is promising, other factors such as sedimentation processes and fire temperature alter the charcoal morphology. Further research is needed to ascertain what impacts charcoal morphology.
- (4) Rainfall in the Kavango East is a poor predictor of grassy vegetation density. This is because other local factors such as river inundation, human-induced fires and landscape fragmentation over-ride the influence of rainfall. This is in line with previous findings (e.g. (Sankaran et al., 2005) where it was found that water limits the maximum amount of woody cover, but "disturbance dynamics control" (p. 848) the savanna vegetation structure when the MAP exceeds 650 mm.

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