ISEIS

Journal of Environmental Informatics 11(2) 131-145 (2008)

Journal of
Environmental
Informatics

www.iseis.org/jei

Estimating Woody Plant Density from Aerial Photographs in Communal and Leasehold Land Tenure Systems in Northwest Botswana

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Received 12 July 2006; revised 3 May 2007; accepted 12 December 2007; published online 30 May 2008

ABSTRACT. Information on woody plant density (WPD) is important for assessing impacts of land use, climate variability and climate change in semi-arid lands. Previous studies in Botswana have used visual methods with the aid of a portable microscope with 40× magnification to estimate WPD from counts of apices of shadows of woody plants on air photographs. This study investigated the reliability of quantitative woody plant data established using this procedure. The investigation focused on consistency of the visual derived data, relationship of the photo and field based WPD, effect of different photo scales and film types and reliability of the data in determining trends over time. Results showed that variations in woody plant counts (WPC) made at different periods by the same observer were not statistically significant at 95% probability level. Relatively strong relationships were established between ground and photo based WPD, $R^2 = 0.74$: $P < 0.05$ and $R^2 = 0.62$: $P < 0.05$ for predominantly tree and shrub layer sites, respectively. Different photo scales and film types resulted in statistically significant differences in WPC but these differences were minimized by standardizing the data to a single base scale and film type. The standardized multi-date WPD data from different scales and film types showed consistent trends with landscape and land use changes in the area. This study showed that calibrated low cost visual based geo-spatial data analysis methods could provide required information for detailed assessment of change in vegetation structure in semi-arid lands in response to land use and the indicated climate change.

Keywords: aerial photographs, canopy shadows, photo scale, photo film type, semi-arid lands, visual counts, woody plant density

1. Introduction

Information on woody plant density (WPD) is important in semi-arid lands of Southern Africa for assessing linkages between land use pressure, climate variability, fire and landscape (Justice et al., 1994; Walker, 1994; Dube and Kwerepe, 2000) and also for estimating changes in the aboveground carbon storage for climate change related studies (Asner et al., 2003; Bond et al., 2003). Climate change assessments show that a warmer and dryer climate will be experienced over the central land mass of Southern Africa covering most of Botswana and this coupled with an elevated CO_2 may favor woody plants in place of grasses (Hulme, 1996; Tyson et al., 2002; Bond et al., 2003; Dube, 2003; Scholes and Biggs, 2004). Past studies have noted an increase in WPD over the rangelands of Botswana and this has been attributed to land-use impacts (Campbell and Child, 1971; van Vegten, 1981; Perkins and Thomas, 1993; Moleele and Perkins, 1998; Dougill et al., 1999). However, recent results show that an increase in CO_2 since the industrial period could be a contributing factor (Bond et al., 2003). An increase in woody plants in place of the herbaceous layer has implications on the livelihoods of a large section of the population of southern Africa that is dependent on natural resources (Dube and Kwerepe, 2000; Dube, 2003).

Ground based data on WPD for assessing changes in vegetation structure over long periods in Botswana are scanty (Dahlberg, 1994; Hulme, 1996). Woody plants can be assessed using satellite data, which offer rapid, repetitive and wide coverage data (Harries et al., 2003). However, satellite data mostly provide information on woody plant cover and in semi-arid lands there are difficulties in separating woody plants from other cover types such as soil background (Graetz and Gentle, 1982; Dube, 2000; Dube and Pickup, 2001). This has made it necessary to calibrate satellite-based outputs using field surveys or high spatial resolution satellite products, which are not readily accessible in developing countries although major improvements have been made for instance in accessing Landsat data (Kleinn, 2000). Aerial photographs have a longer history than satellite data and require limited resources to interpret.

In Botswana, air photos date back from 1920s in some areas and have been flown every 10 years since 1940 at 1:40,000 to 1:50,000 and at larger scales for villages and towns, which provides an important multi-temporal data for assessing various land resources compared to satellite data. However, most forestry studies rely on large to very large-

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ISSN: 1726-2135 print/1684-8799 online
doi:10.3808/jei.200800117

scale photos, for example, 1:2,000 (Colwell, 1983; Harries, 2003). Apart from the limited availability of such large scale data in developing countries due to resource constraints, the vast and diverse nature of rangelands mean that such large scales may not provide representative information. The use of aerial photos at 1:30,000 to 1:50,000 for establishing quantitative data on WPD in natural rangeland conditions is rare.

Because manual interpretation of photos continues to be one of the readily available methods of extracting data for most parts of Africa, it is important to investigate ways of increasing the reliability of information generated using these methods (Czaplewski et al., 1989).

In Botswana woody biomass has been assessed using visual counts of woody plant canopy shadows on black and white photos of 1:30,000 or less with the aid of a microscope (Kgathi et al., 1994; Sekhwela, 1997). Using a three-dimensional stereo view model on a stereoscope, the relationship between terrain and woody plants was established. The outcome of these studies have played an important role in informing policy on the status of fuelwood energy supply around villages and are important for assessing land degradation and general change in the vegetation structure due to a combination of human and climate related factors (Dube and Kwerepe, 2000). However, there has been limited focus on investigating the reliability of the WPD estimates made from photos using these visual methods.

This study investigated the reliability of quantitative WPD data produced from conventional aerial photos using visual based methods. The objective was to assess potential sources of errors and establish ways of increasing the reliability of use of visual counts of apices of woody plant canopy shadows on conventional aerial photos for estimating WPD. The study investigated hypotheses that visual counts of apices of woody plant shadows on photos: i) yield consistent and repeatable WPD measurements; ii) produce results that are a true representation of woody plants on the ground; iii) is not influenced by photo film type; iv) is independent of scale; and v) can be used to assess the spatial distribution and trends in WPD under different landscape types. Areas of potential error in the process of establishing woody plant data using visual counts of canopy shadows on photos were reviewed and guidelines for conducting woody plant counts were devised to provide the bases for testing the hypotheses.

1.1. Background

The introduction of digital aerial photography, videography and other high spatial resolution satellite data with pixel size of 1 m or less has helped to provide data with comparable spatial resolution to conventional photos that can be rapidly analysed digitally (McGraw et al., 1998; Kleinn, 2000). Differences in intensity values between canopy shadows and surrounding areas has been used in automated methods to delineate individual trees (Strand et al., 2006). Warner et al. (2000) relied on shadow centres to develop an algorithm for identifying individual trees in a deciduous forest using imagery from the Automatic Data Acquisition and Registration sensors (ADAR). Narciso et al. (2000) used airborne imagery of about 1-m spatial resolution taken using the Digital MultiSpectral Video to determine the number of citrus trees. Such data are limited for historical trend analysis and are not easily accessible for operational purposes (Kleinn, 2000).

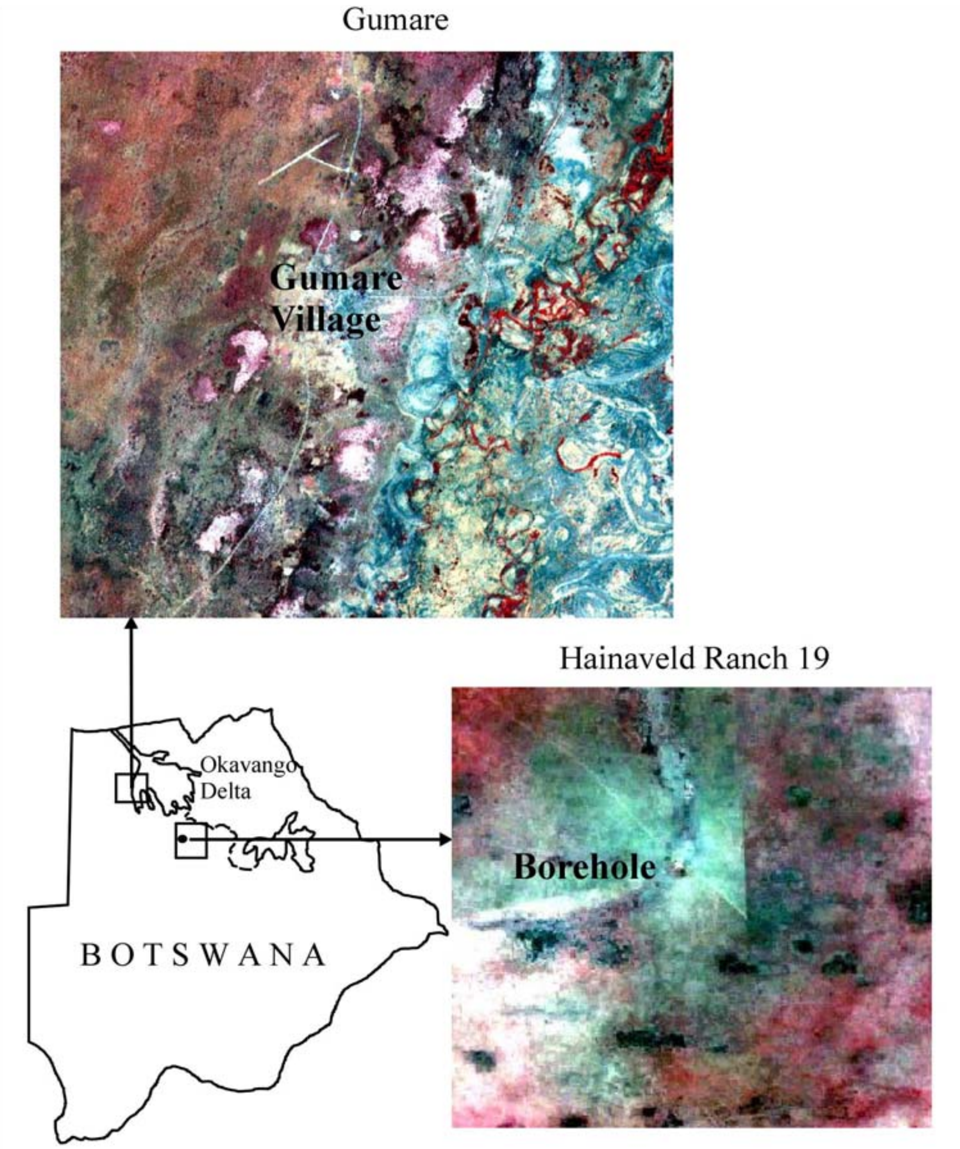
Ability to convert hardcopy photos into a digital format has made it possible to apply automated image analysis methods on conventional photos (Duhaime et al., 1997; Strand et al., 2006). Hudak and Wessman (1998) and Kadmon and Harari-Kremer (1999) used texture analysis to demonstrate the potential of digital methods in assessing woody plants using conventional photos. Kay et al. (1998) developed a semi-automated method known as OLICOUNT for recognizing and counting olive trees on scanned panchromatic aerial photos. Converting historical photos into a digital format increases prospects for integrated analysis incorporating for instance, information from satellite data (Holopainen and Wang, 1998; van Wyk and Brockett, 2000). However, this requires resources and skills for instance, to first rectify the data and then perform appropriate digital analysis (Wijayratne and Maclean, 1992; Kleinn, 2000).

It has been noted that digitally produced results are not necessarily more accurate than results from manual approaches (Kadmon and Harari-Kremer, 1999; van Wyk and Brockett, 2000). Others have used visual methods to establish information on woody plants on digital photos (Harries et al., 2003). Blazquez (1989) concluded that the amount of time required to preprocess the digital photos and perform tree counts digitally was comparable to the time taken using visual counts. These limitations minimise prospects for adopting automated approaches for regions with limited capacity in geospatial information technologies.

1.2. Study Area

The study was conducted in the north-western part of Botswana in two sites representing different land uses, landforms and vegetation types (Figure 1). One site was in the communal area of Gumare village on the western floodplains of the Okavango Delta at latitudes 19º - 20º S and longitudes 21º45’ - 22º40’ E. The second site was in the Hainaveld leasehold grazing area found on the Kalahari sands, south east of the Okavango Delta, at latitudes 20º50’ - 20º55’ S and longitudes 23º20’ - 23º55’ E, focused on Ranch 19. Mean annual rainfall in these sites is 400 mm with 35% variability and most of it occurs between October and April which is also the period when warm temperatures are experienced.

On the Gumare site the eastern part is the Okavango Delta Taoge River flooplain, which used to support aquatic vegetation but is now under grasslands because of the recession of Delta floodwaters on this western zone over the past decades (Shaw, 1984). On the western part, Gumare area is covered by fluvial sands supporting *Terminalia sericea* and *Acacia erioloba* woodland. But this gradually changes with distance from the Delta into the Kalahari wind deposited *Arenosols* soils which support shrubland. Cattle keeping has dominated the area since 1980s. Before then, communities relied



Notes: Gumare and Hainaveld Ranch 19 wet season, 1996, SPOT multispectral images at 20 m × 20 m spatial resolution - dark brown represents dense tree cover; brown areas cover mostly the Kalahari sands dominated by moderately dense shrub vegetation; red areas are actively growing vegetation; in general light tones are exposed areas - light pink and light green are bright and reddish sands respectively, covered by very sparse vegetation and light grey to light blue on the east in Gumare are exposed grey soils in the Okavango Delta floodplain with a dense network of old channels.

Figure 1. Location of the study site within Botswana.

on shifting cultivation in drier areas and floodplain cultivation on the wet eastern part where they also practised fishing. Gumare was used in this study because it was one of the areas considered severely degraded in Botswana after the 1980’s drought (SMEC, 1989; Sekhwela and Dube, 1991).

Hainaveld is formed by typical Kalahari landscape with longitudinal dunes and paleo drainage valleys supporting shruland vegetation. On sand dunes broadleaved shrubs, such as *Grewia flavescens*, *Terminalia sericea*, *Combretum gratissismus* and *Boscia* species, are dominant. In depressions and fossil valleys, thorny species such as *Dichrostychis cinerea* and *Acacia mellifera*, *tortilis*, *erioloba* and *hebeclada* occur. Surface water is limited in the Hainaveld and this constrained human activity in the past. However, in 1978 the area was zoned into private leasehold cattle ranches of 8 km × 8 km each serviced by a borehole. Studies have reported an increase in WPD in the vicinity of boreholes due to intensive cattle activity (Skarpe, 1983; Tsimako, 1991; Moleele and Perkins, 1998). Ranch 19 provided a typical Hainaveld landscape type and management practice common to most ranches in the country, where the borehole is the focal point and there is limited rotation grazing.

2. Data and Methodology

2.1. Data Sources

Historical black and white photos from 1950's were obtained from the Department of Surveys and Lands in Botswana (Table 1). The choice of dates and scale was limited by availability; for instance there were no photos for 1960s. Gumare photos showed greater contrast and this made it possible to enlarge them from 1:50,000 to 1:30,000 to improve identification of woody plants (Gerrard, 1969). In Hainaveld original scales were retained because of the generally low contrast mostly due to the homogenous shrub vegetation type.

Table 1. Scale, Photo Film Type and Date of Aerial Photographs Used

Gumare		Hainaveld	
Date	Scale	Date	Scale
May 1996	1:10 000**	April 1996	1:10 000**
August 1991	1:30 000*	August 1991	1:30 000
May 1983	1:30 000*	May 1983	1:50 000
April 1973	1:30 000*	July 1973	1:40 000
May 1951	1:3 000 000	May 1957	1:40 000

* Enlarged from 1: 50,000; ** True colour photos

True colour photos were produced from an aerial survey carried out by Poseidon Geophysics (PTY) LTD Company in Gaborone for the period of April to May 1996. These photos were originally acquired to use for verification of satellite images in a different study. The aerial survey used a camera with a focal length of 152 mm to produc true colour 1:10,000 film positives at 23 cm × 23 cm format with 60% forward overlap and 20% sidelap from which hardcopy pho- tos were made. In Gumare these true colour photos were avai- lable over an east-west strip extending 25 km and 10 km from the village, respectively. In Ranch 19 the true colour photos were from two orthogonal flight lines extending 10 km from the borehole in a northeast-southwest and northwest-southeast direction.

2.2. Visual Counts of Woody Plants

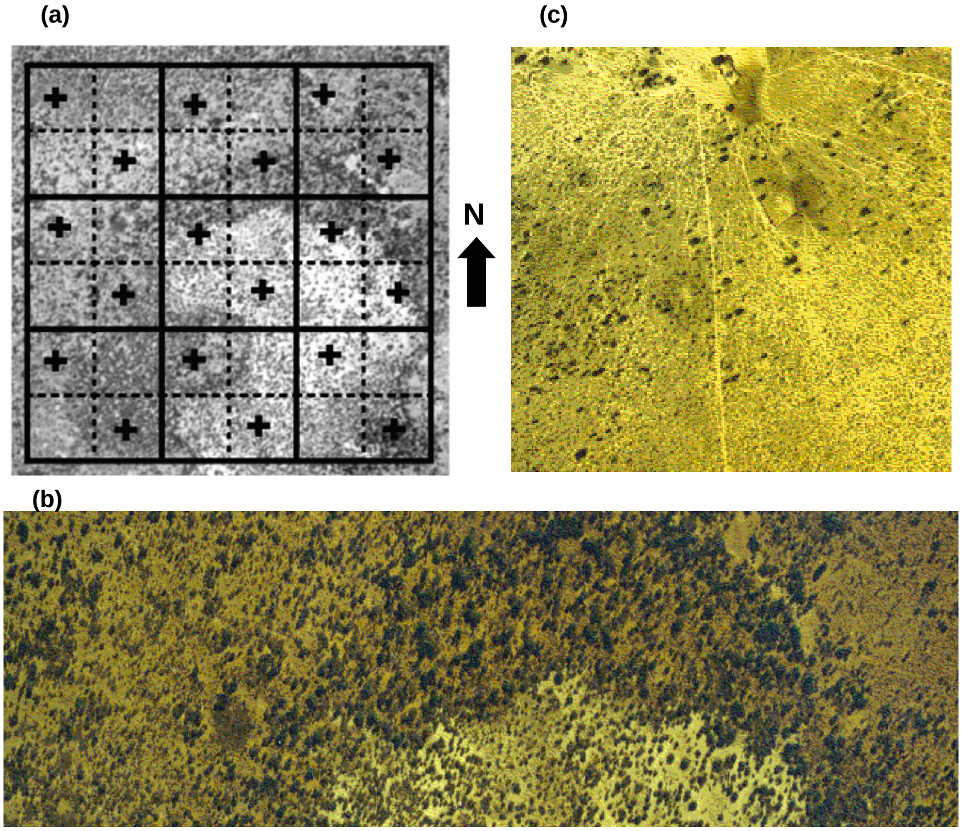
Woody plant data were derived from counts of apices of woody plant canopy shadows from black and white and true colour photos. A single eye piece microscope, model P854 with a 40× magnification, 2 mm × 2 mm field of view and with a superimposed 10 × 10 microgrid was used to identify and count woody plants (Kgathi et al., 1994; Sekhwela, 1997). The microscope is portable and has magnification greater than the conventional stereoscopes which are normally 8×. This makes it possible to detect shrubs with a diameter less than half a metre at the 1:10,000 photo scale. Although the microscope lacks the stereo-view it has the advantage of channelling ones view to a defined area and the 10 μm × 10 μm grid in the eye piece facilitates systematic counting. The disadvantage of using the microscope is that the magnification, the field of view and the microgrid are not adjustable to different scales. Since plants have to be identified by eye the method is liable to subjectivity and it is time consuming.

Woody plants were recognized on the black and white photos by their discontinuous dark tones, granular coarse texture and lack of a defined shape, although they appeared more or less as dots at smaller scales or where shrubs dominated, for example in Hainaveld (Figure 2a). This was in contrast to grasslands, fields, burnt areas or swampy flooded zones, which tend to have a smooth texture and a generally continuous coverage. On true colour photos, woody canopy had dark green or dark to light brown tone depending on whether plants were green, flowering or towards senescence (Figures 2b and 2c). On true colour photos grasses were distinguished from woody plants by a continuous smooth texture with light brown or light gray colour depending on the soil background and the condition of grasses. Counts were made with the microscope field of view centered on the identified plot on the photo. A single tree/shrub was defined by the apex of the shadow identified as a single entity by tone, usually darker relative to surroundings and assuming near circular to various irregular shapes. This entity defining an individual tree/shrub, covered part or the whole of a single square of the micrgrid in the field of view of the microscope.

2.2.1. Potential Sources of Variation

There are several potential sources of error in the visual approach of determining WPD from conventional photos using the hand held singe eye piece microscope. Deciding on what constitutes a single plant on a photo incorporates a degree of subjectivity each time counts are made, even where scale and the observer remain constant (Kay et al., 1998; Wyk and Brockett, 2000). On a constant scale identifying a single plant is strongly influenced by tone which is affected by the quality of photos, season, vegetation structure and density and landscape. In areas of bright sands or on dry season photos, when plants have shed leaves, chances of under-estimating woody plants are increased. Dark soil results in dark tones, which gives rise to blurred boundaries between canopies and increased chances of over-estimation. Blurring or shallow shadows make it difficult to differentiate grasses from woody plants on true colour photos. As a result tone was influential within a single photo, between photos of different dates and scale and between true colour and black and white photos.

With a fixed magnification and field of view on the microscope, scale influenced plot size and the ability to detect and distinguish canopies of individual plants. Plot sizes, defined by the field of view of the microscope varied from 400 m^2 on the 1:10,000 photos to one hectare on the 1:50,000 scale. As a result plots on large-scale photos were nested inside the smaller scale photo plots for the same plot centre. The difference in plot size has a potential to influence comparison of WPD from different scales considering the diversity of plant distribution in semi-arid lands. For instance, it was possible to identify on 1:10,000 photos, shrubs with a canopy



Notes: (a) Black and white 1:30 000 aerial photograph showing part of the area west of Gumares; Overlaid on the photo is a grid showing the 300 m × 300 m ground plots subdivided into 150 m × 150 m and with centres of the opposite squares marked with a plus symbol; (b) True colour 1:10 000 photo showing different tree/shrub canopy sizes over part of the area shown in (a) above; (c) True colour 1:10 000 photo showing a section of the Hainaveld Ranch 19 from the borehole located at the extreme north – scattered big trees occur in the middle of shrubs.

Figure 2. Aerial photographs showing part of Gumare and Hainaveld Range 19.

diameter of 20 cm on the ground and therefore 0.8 mm diameter under the 40× magnification. But this was not the case on 1:50,000 photos where, 0.8 mm diameter relates to shrubs of one metre diameter on the ground (Figures 2a and 2b).

Intercepting canopies are likely to be identified as a single canopy at 1:50,000, separate canopies at 1:30,000 and as part of a multi-stem single plant at 1:10 000. Further, on the 1:10,000 scale, plant canopies with over 2-m diameter completely cover the micrometer squares and this increases the potential to be counted as more than one plant. In cases where a single plant entity covered more than one square, each square was counted as a single tree as long as more than half of its area was covered. This increased the possibility of overestimation at large scale. However, consideration was made to the fact that the method does not cater for understorey canopy and the error could eventually cancel out when it comes to estimating the total number of plants in an area.

Other potential sources of error result from the fact that photos are normally not co-registered due to limited resources, as was the case in this study. As a result problems of mismatch in establishing centres of plots on different photo scale were likely to occur. However, both study sites have a flat relief and as a result photos show low geometric distortion when compared to available topographic maps (Lillesand and Kiefer, 1994). In addition, there was always a potential to introduce noise in the data while performing practical tasks such as maintaining the position of the microscope centred on the plot each time counts were made.

There is a need to establish measures to minimise the potential incidences of errors, calibrate and test the reliability of the woody plants information before using the data to assess WPD in an area. Measures that were applied to improve the quality of the data in this study include designing guidelines for counting plants, estimating the level of consistency in counts made at different periods by the same observer, validating photo counts using ground based counts, establishing and correcting for the effect of differences in scale and testing the effect of using black and white photos as opposed to true colour photos. In addition a detailed sampling scheme that allowed for smoothing the data without major loss of detail was applied for the production of multi-date woody plant counts.

Table 2. Guidelines Used to Minimize Inconsistencies in Performing Counts of Apices of Shadows of Woody Canopy Plants Using a Hand Held Microscope with 40× Magnification and a Fixed Field of View of 2 mm × 2 mm Overlaid with a 10 × 10 Microgrid

Part I	Counting began on the right and two columns were considered simultaneously.
	Plants with over half of their canopy inside the boundary column located on the right were counted.
	Within the two columns overlaps were considered on the right and the left side ignored till the next two columns are taken.
	Overlaps on the last left column were ignored for each plot count
	Plants that clearly occurred as a single entity but were straddled between columns such that their canopies were less than half the coverage of the squares they straddled were ignored on the right but counted on the left column.
Part II	To further minimise errors two counts were made on each plot.
	When the second count was made on the same plot counting began on the left and the opposite rules applied for dealing with overlaps.
	These counts were accepted when the differences between them were within the region of 8 plants or less.*

* A threshold of 8 plants was considered an acceptable error for the different scales after a series of counts were made and found to vary within the region of 0 - 8 plants.

Table 3. Photo Scales, Size of Sample Data used and Tests that were Conducted to Determine the Reliability of the WPD Produced from Photos

Test	Photo type	Scale	Plots
Consistency	Black and White	1: 30 000	116
	True Colour	1: 10 000	116
Photo film type	Black and White; True Colour	1: 30 000	74
Field and Photo data	True Colour	1: 10 000	50
Scale effects	Black and White: True Colour	1:30 000; 1:40 000; 1:50 000; 1:10 000	21
Multi-temporal data (5 dates)	Black and White; True Colour	1: 10 000; 1:30 000	83

Note: Photos were produced from the 1996 1:10,000 true colour positive transparencies.

2.2.2. Guidelines for Visual Counts

To minimize inconsistencies, structured procedures for counting plants on the 10 × 10 microgrid overlying the field of view of the microscope were devised (Table 2). For example, to deal with overlaps between columns, where canopy covered over half the square it was counted as a single plant. However, judgement of this using a visual approach is likely to be inconsistent at different times. Counting guidelines given in Table 2 were devised to reduce such subjectivity. The counting guidelines were applied to produce data for the different tests conducted to evaluate and standardize WPD data produced from visual counts of canopy shadows (Table 3).

2.3. Reliability of Woody Plant Data

2.3.1. Consistency

The production of woody plant data from photos using a portable microscope was based on the hypothesis that visual counts of apices of woody plant shadows of individual plants on aerial photos yield consistent and repeatable WPD measurements. The hypothesis was addressed by testing a null hypothesis to the effect that, the means of paired plant counts performed at different times will be equal or less than 8 plants at $P = 95\%$ (Tables 2 and 3). This probability was selected to provide an allowance for potential errors inherent in the visual approach. An area extending west and east of Gumare village with a range of soils and vegetation types was used to incorporate likely effect of different landscape types (Figure 1, Table 3). Soil ranged from bright sands to dark silty-clay soils, which supported a variety of woody plants in terms of canopy density and structure.

Systematic random sampling was applied with the photos divided into plots equivalent to 300 m × 300 m on the ground, excluding the edges where photo distortions are generally high (Figure 2a), (Howard, 1970). Each plot was subdivided into 150 m × 150 m quarter squares which amounted to 20 m × 20 m on the 1:10,000 scale and 60 m × 60 m on 1:30,000 photos relative to the ground. These subdivisions were considered adequate to produce a sample large enough to carry out the required statistical test at a reasonable time and cost. The centres of the opposite quarter squares within each 300 m × 300 m square were fixed. The same position of plots and centres were maintained for the two different photo scales for counts that were to be performed at different periods in each case. This was made possible by the use of larger scales, 1:10,000 and 1:30,000. However, the potential for mis-location could not be eliminated given that this was achieved manually. A set of woody plant data referred to as Count 1 was produced for each scale. Counts were made again after a month on the same plots by the same observer to produce Count 2 data set. More plants were recorded on the 1:30,000 60 m × 60 m plots than on the smaller 20 m × 20 m plots of the 1:10,000 photos as would be expected.

To assess the degree of similarity between Counts 1 and 2 data sets, descriptive statistics, variance and a paired student *t*-test were used on MINITAB statistical package. To compare the means of Counts 1 and 2 in each scale the F-ratio, which is the product of the larger variance divided by the smaller one was first calculated. The variance ratio was used as an indicator of the level of deviation from the homogeneity of variances in the two data sets for the following hypothesis and decision rule:

$\mathbf{H_0}$: $\sigma_1^{\ 2} = \sigma_2^2$ vs. $\mathbf{H_1}$: $\sigma_1^2 \neq \sigma_2^2$

$\alpha = 0.1$ and $n_1 - 1$ and $n_2 - 1$ degrees of freedom

where H_0 and H_1 = null and alternative hypotheses, σ_1^2 and σ_2^2 = population variances, α = significance level and n = number of samples in Counts 1 and 2. Heterogeneity in variances has a tendency to increase the probability of Type I error when the *t*-test is applied that is, rejecting the null hypothesis even when the populations have the same means (Underwood, 1997). The black and white Counts 1 and 2 data were skewed towards large values with a peaked distribution. As a result the square roots of the squared differences were transformed to logarithm base 10 scale to approximate a normal distribution. Areas of no difference were replaced by a log of one. A paired *t*-test was run to test that:

$\mathbf{H_0}$: $\mu \leq log\ 8$ vs $\mathbf{H_1}$: $\mu > log\ 8$

$\alpha = 0.5$ and n - 1 degrees of freedom

where μ = the log mean difference between Counts 1 and 2, 8 = threshold acceptable error difference between two consecutive counts on the same plot, α = level of significance, and n = number of samples.

Consistency is an important index for measuring data quality and in this case consistency is likely to vary with scale and characteristics of the vegetation canopy. Consistency in data made at smaller scale, 1:40,000 and 1:50,000 is important given the increasing difficulty to identity individual plant shadows at these scales. This is more so for the case of Hainaveld area which was dominated by shrubs than Gumare. It was therefore necessary to test consistency in both Hainaveld and Gumare area and in all scales used in the study (Table 1). But the consistency test required a repetition of the counting process on the same sample plots at different periods which is demanding in terms of time. Due to the strenuous and time consuming nature of the visual based woody plant count method particularly, in this case where a single eye piece microscope was used, this test was only applied in Gumare area and was limited to two scales, 1:10,000 and 1:30,000.

2.3.2. Black and White versus True Colour Photos

The hypothesis that there is no difference between true colour and black and white photo based counts of woody plants was addressed to assess the likely effect of the use of different photo film types. A null hypothesis to the effect that the difference between the mean of plant counts from the same plots on black and white and true colour photos is equal or different by 8 plants was tested at a probability level of 99% using a paired student *t*-test statistics (Table 3). For this test the most common scale in the study, 1:30,000 was used. It was easier to locate identical plots at this scale than on smaller scales (Tables 1 and 3). A sampling scheme and counting procedure similar to the one applied for the consistency test were applied and this resulted in woody plants data from black and white and true colour photos from the same locations. However, an F-ratio of 2.48 showed that the variance of black and white counts was significantly different from that of true colour photos ($P < 0.005$). A transformation of the data using a square root and a logarithm scale did not improve the results. As a result the student *t*-test was not performed.

2.3.3. Field and Photo Based Data

Field data was generated towards the end of the 1996 wet season, April to May within the period of the 1996 aerial survey. Woody plant counts were made at 300 m intervals along transects laid from Gumare village and from the borehole of Hainaveld Ranch 19 (Figure 1). This sampling scheme made it possible to sample different densities of WPD because WPD has been shown to change with distance from land-use focal points (Perkins and Moleele, 1998; Dube and Pickup, 2001). Counts of living and dead standing woody plants were made in 25 m × 25 m plots centred on the transect. A slightly larger plot size, in contrast to 20 m × 20 m on the 1:10,000 photos was used to take into consideration likely positioning errors of ground plots on the photos (Table 3). However, 6 plots from Ranch 19 were excluded because they could not be satisfactorily identified on the photos.

Woody plant counts from the field and from photos were converted to WPD. The strength of the relationship between the two data sets was established using a simple linear regression analysis, Model I was given as:

$$y = \beta_0 + \beta_1 x \tag{1}$$

where y and x are woody plants from the ground and from photos, respectively and β_0 and β_1 are the intercept and the slope of the regression line. Because both the ground and the photo WPD were subject to error, Model I results were likely to be biased (Sokal and Rohlf, 1995). As a result the slope and intercept from Model I results were compared with the slope and intercept derived using the Model II regression, the reduced major axis (RMA) determined from:

$$\beta_1 = \sigma_y / \sigma_x \text{ and } \beta_0 = Y - \beta_1 X \tag{2}$$

where Y and σ_y are mean and standard deviation for field based WPD and X and σ_x are the same parameters for photo based WPD. Model II has the advantage of minimising the sum of the cross products of the differences on both axes in contrast to the simple regression where only one dimension is considered (Curran and Hay, 1986).

2.3.4. Scale and Woody Plant Counts on Photos

The effect of scale was investigated using Hainaveld Ranch 19 where the data represented scales found in both study sites (Tables 1 to 3). One Way Analysis of Variance was used to assess the variance across data from different scales.

The result was an F-value 188.91 ($P < 0.001$), confirming the influence of scale in visual counts of woody plants on photos as was expected (Table 1). As a result there was need to standardise data from different scales. This was achieved by adjusting the data to a single base scale, the 1:10,000 true colour photos. True colour photos were used as a base scale because they were the most recent date and had the largest scale, although the potential for errors is also high in larger scales. But using 1:10,000 true colour photos as a reference scale also provided for standardising the data for differences that may arise from using different photo film types.

Standardisation was achieved by determining a scale factor that defined the relationship between WPD from each scale and the 1:10,000 reference scale given as an average ratio derived from:

$$\alpha_{(y,x)} = (\Sigma_{i-j} (P_{xi} / K_{yi})) / n \qquad (3)$$

where $i - j$ = plots on photos, x = 1996 1:10,000 true colour photo scale, y = black and white photo scale, P_{xi} = WPD at a plot location i from x scale (1996 true colour photo), K_{yi} = corresponding WPD at plot location i on y scale (black and white photo scale), n = number of pairs of plots from x and y photo scales and $\alpha_{(y,x)}$ = scale factor describing the relationship between WPD from y scale to x scale.

The data generated for comparisons between different photo scales was used to establish the average ratio in Hainaveld. In Gumare, woody plant counts from the consistency test were applied. One Way Analysis of Variance was applied to assess the variance across the standardised data from different scales used in the study (Table 1). The results of the variance analysis showed that in contrast to the original data variance across the standardised data was not significant (F-value 0.35, $P < 0.001$).

2.3.5 Multi-temporal Woody Plant Density Data

The reliability of visual based WPD from aerial photos was further investigated by assessing change in WPD from 1950s to 1996 over a 25 km long and 300 m wide belt transect drawn east from Gumare village (Tables 1 to 3). The transect extended from the Kalahari aeolian sands through the intensively used Taoge river floodplain to the Veterinary Fence (on fluvial sands) which separates communal grazing from wildlife areas in the Okavango Delta (Figure 1). The belt transect was fixed on the same location on each photo date and divided into 300 m × 300 m squares within which counts were conducted as noted for the consistency test above. The exception was the large scale 1:10,000 photos where the 300 m × 300 m squares were subdivided into 75 m × 75 m squares and three diagonal plots were counted. The belt transect was used to minimize effects of errors of location between different photos. On the 1:10,000 true colour photos, there was need to compensate for a combination of the small plot size relative to other scales and chances of over-estimating woody plant counts.

Counting rules were applied such that each count was an average of two counts taken in opposite directions (3 counts for 1: 10,000 photos) (Table 2). Total woody plant counts in each 300 m × 300 m plot was an average of the counts made in the sub-plots. This resulted in 83 average woody plant counts per date which were converted into WPD per hectare and standardised by adjusting to the 1:10,000 1996 WPD as follows:

$$K' = k_{y(t)} \times \alpha_{(y,x)} \qquad (4)$$

Table 4. The Distribution and Variances of Count 1 and Count 2 Woody Plant Counts Made at Different Periods by the Same Observer on 1:10,000 True Colour and 1:30,000 Black and White Photos

Parameter	True Colour 1:10,000			Black and White 1:30,000		
	Count 1	Count 2	Diff.	Count 1	Count 2	Diff.
Mean	48.68	59.74	12.84	75.07	87.52	15.70
SE	2.30	2.87	0.94	3.97	4.98	1.56
STD	24.81	30.91	10.21	42.76	53.72	16.82
Min	0.00	0.00	0.00	2.00	1.00	0.00
Max	94.00	102.50	40.40	161.50	207.00	88.00
K	-0.686	-1.033	-0.541	-1.11	-1.199	3.47
SK	-0.434	-0.523	0.669	-0.233	-0.184	1.738
F-value	1.553* (p = 0.0095)			1.578* (p = 0.0075)		

* Degrees of freedom = 115.

Note: SE = standard error of the mean; STD = standard deviation; Min. = Minimum value; Max. = Maximum value; K = kurtosis; SK = skewness; Diff. = mean difference between Count 1 and 2; n = 232 (Count 1 + Count 2 plots).

Table 5. Results of a Paired t-test for Plant Counts Carried out at Different Times on the Same Plots (Reconverted from Logarithm Base 10 to Original Values)

Photo type	Mean	SE	STD	t-value	95% CI
True colour (1:10 000)	7.701	1.124	3.55	-0.32 (p = 0.63)	6.09 to 9.72
Black & white (1:30 000)	7.98	1.134	3.88	-0.02 (p = 0.51)	6.22 to 10.24

Note: Mean = Mean of differences between Count 1 and Count 2; 95% CI = 95% confidence interval.

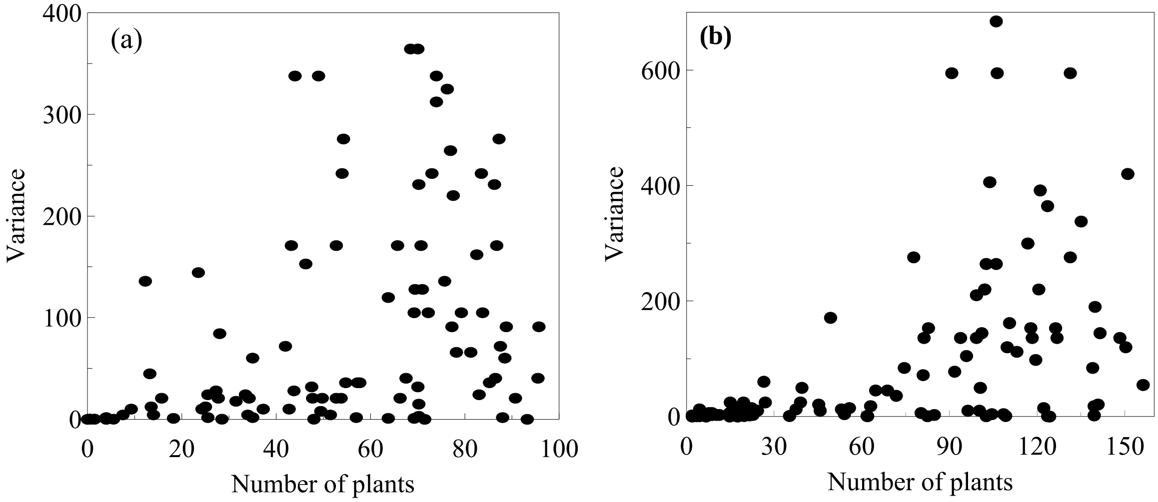


Figure 3. The distribution of variance with respect to density of plants in a plot using the average of Count 1 and 2 made at different times by the same observer in Gumare (a. True colour 1: 10,000 and b. Black and white 1: 30,000 1996 photographs).

Table 6. Summary Statistics of 1996 Ground and Air Photo Woody Plant Density per Hectare and the Results of the Regression Analysis of the Two Data Sets

	Gumare			Hainaveld – Ranch 19		
	Mean	SE$_n$	Range	Mean	SE$_n$	Range
Field	644.70	0.19	1440.00	753.45	0.1	928.00
MI	646.90	0.16	1272.37	753.45	0.1	686.75
MII	644.69	0.19	1478.56	750.59	0.1	879.46
Photo	803.18	0.17	1631.3	1194.7	0.1	1675.00
	R^2	SE	β_0: β_{0RMA}	β_1:β_{1RMA}	F-value	p-value
Gumare (DF = 16):						
	0.74	257.00	20.42:83.31	0.78:0.91	41.67	0.001
Hainaveld (DF = 31):						
	0.62	156	260.77:126.18	0.41:0.53	49.9	0.001

Note: Field = original raw data; MI and MII = model I and Model II regression; β_{0RMA} = Intercept for model II (reduce major axis); SE$_n$ = normalized standard error of the mean (SE/mean).

where K' = WPD adjusted to 1:10,000 scale, $k_{y(t)}$ = original WPD from photo scale y determined from plot size t and $\alpha_{(y,x)}$ = scale factor as noted above. To further minimise variability in data due to noise the data was smoothed along the transect using a three interval moving average for each date.

3. Result Analysis

3.1. Level of Consistency

The results of the consistency test showed that woody plant counts made at different periods on the same plots were highly correlated, r = 0.94 and 0.93 for 1:10,000 true colour and 1:30,000 black and white photos, respectively. The distribution of Counts 1 and 2 data was comparable in each scale, skewed towards smaller values and with flat distribution about the mean as shown by the negative coefficient of skewness and the kurtosis (Table 4). The F-values showed that heterogeneity of varances for Counts 1 and 2 was not substantial and that the variations in woody plant counts were comparable for the two scales used, a factor confirmed by results of a paired t-test at 95% level (Table 5).

However, in both cases Count 2 data sets had relatively higher numbers of plants and were more variable than Count 1 (Table 4). Variations were more likely where the density of woody plants was high in both scales that is, plots of more than 50 and 100 plants in 1:10,000 and 1:30,000, respectively (Figures 2a, 2b, 3a and 3b).

3.2. Relationship between Field and Photo Based Woody Plant Density

The degree of variability within the field data was comparable to the photo results with covariances of 75 and 67% for Gumare where a smaller sample was used and 33 and 39%

Table 7. The Distribution of Woody Plant Counts from Black and White (B&W) and True Colour (TC) Photos Taken from the Same Plots, Scale, Date and Time

Photo	Range	Mu:SE	SD	K	SK	F-value	DF
B & W	100	98:2.72	23.4	-0.259	0.35	2.480 (p=0.00)	73
TC	60.5	86:1.72	14.8	-0.688	-0.112		

Note: Mu and SE are the mean and standard error; K is the kurtosis; SK is the skewness indices.

Table 8. Scale Adjustment: WPD from the Same Date and Plot but on Photos with Different Scales

Scale	Plot size (m)	Average ratio (SD)	Mean (SE_n)	SD	Range
Gumare – 104 plots:					
1:10 000	20 × 20	1	1250 (0.05)	631	2350.00
1:30 000	60 × 60	5.5 (2.2)	226 (0.05)	111.83	443.00
Hainaveld – 21 plots:					
1:10 000	20 × 20	1	1493 (0.05)	330.37	1362.00
1:30 000	60 × 60	3.1 (1.0)	542 (0.08)	190.12	681.25
1:40 000	80 × 80	4.9 (1.3)	335 (0.07)	111.84	414.00
1:50 000	100 × 100	6.2 (1.7)	258 (0.06)	77.46	293.00

Note: SD = standard deviation; SE_n = normalized standard error of the mean.

for Hainaveld. In both sites, field derived WPD was consistently lower than photo based WPD. Differences between ground and photo based WPD is exaggerated in areas of higher WPD, which shows the potential to over-estimate the number of woody plants on the large scale, 1:10,000 photos in areas of high density. But in this case it may also indicate a potential for under-estimation in the field in areas of dense woody plants due, for example, to difficulties in maintaining the size of the plot and increased possibilities of overlooking smaller plants.

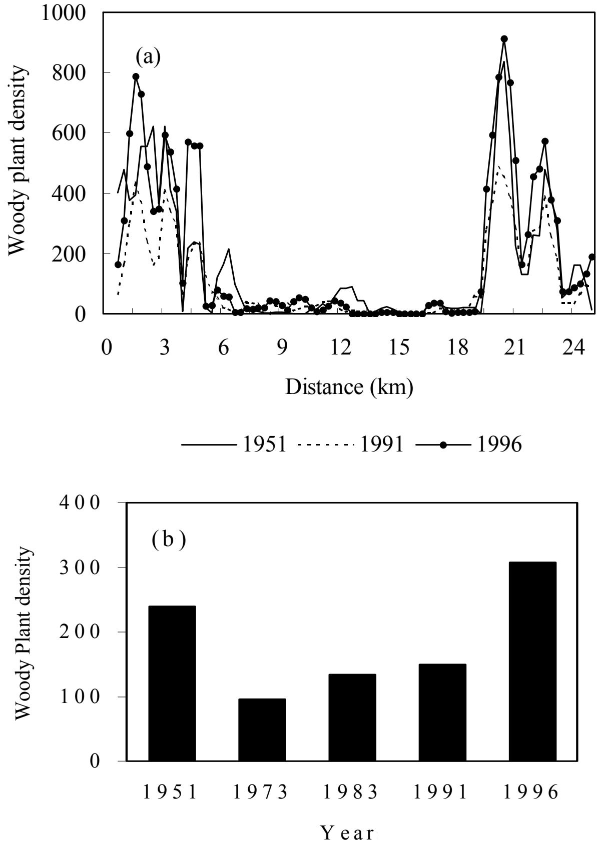
From Model I results, 74 and 62 % ($P < 0.01$) of the variation in the data were explained by the linear relationship between photo and ground based WPD for Gumare and Hainaveld, respectively (Table 6). The range from Model I was lower in both cases. While the slope and intercept from Models I and II were different, the means and the normalized standard errors of WPD were comparable and within the range of the mean of the raw data. The slope of both regression models was steeper in Gumare than in Hainaveld, indicating that change in the magnitude of WPD values derived from photos is more associated with change in the ground based WPD than in Hainaveld where shrub vegetation dominates. Although the Gumare model had a higher standard error of 257 compared to Hainaveld, the standard errors recorded in each case do not greatly deviate from the acceptable threshold error of 8 woody plants, which is 200 plants per hectare at 1:10,000.

The main source of differences between the photo and ground WPD resulted from difficulties encountered in locating sample plots on photos. Identifying field plots was particularly difficult in the Hainaveld and on the western part of Gumare, where the landscape is homogeneous. Partly because of this, establishing a relationship between field to photo counts could not be carried out at smaller scales. When taking into account these limitations the results of the regression model were considered a good indication that WPD from counts of canopy shadows at 1:10,000 were a good representation of WPD on the ground.

3.3 Photo Film Type, Scale and Standardisation

In terms of photo film type woody plant counts from black and white photos had a larger range and a slightly greater mean of 98 plants compared to 86 on the true colour photos (Table 7). From the description statistics woody plant counts from true colour photos had lower variability and deviation from the normal distribution but with a flatter distribution compared to the case of black and white photos (Table 7). These results, in addition to the variance ratio noted above show that photo film type influenced visual counts of woody plants on photos (Underwood, 1997).

From the analysis of the distribution of the variance, differences due to photo type were likely to be greater in areas of high density of woody plants as indicated in the results of the consistency test. However, as with other tests it was not possible to separate the effect of photo type from errors related to the location of plots and the processes of counting which are likely to have contributed to the variances observed in a way that could not be quantified in this study. The two data types had a moderate correlation coefficient of $r = 0.6$ ($P = 0.05$) indicating some degree of association which shows that despite the differences, it is likely that similar conclusions could be reached using one of these data sets, particularly where relative assessments are concerned. However, these results mean that there is need for caution in the interpretation of results of woody plant counts from different photo film types, unless where standardisation has been applied. The average ratios used to standardize the data from black and white smaller scales to the 1:10,000 therefore also standardized for differences in photo film type (Table 8). In Hainaveld where there were different scales, the average ratios increased with declining scale. This is related to the decline in the number of woody plants counted in smaller scale photos despite the larger plot size used. There were also differences between Gumare and Hainaveld results at the same scale for instance, 1:30,000, indicating the influence of different vegetation structure and density in these two areas. But this might also be influenced by the different plot size used relative to the photo scale. However, the standardisation was shown using ANOVA to be effective in reducing variations due to scale and photo film type.



Notes: (a) Woody plant density plotted with distance from Gumare village for 1951, 1991 and 1996 dates; (b) Trends in average woody plant density per date over a 25 km transect from Gumare village for 1951, 1973, 1983, 1991 and 1996.

Figure 4. Trends in woody plant density in Gumare standardized for scale differences (Based on black and white 1:30,000 and true colour 1:10,000 aerial photographs).

3.4. Trends in Woody Plant Density in Gumare

An analysis of the temporal data from Gumare showed that the data depicted correctly, changes in WPD in the area (Figures 4a and 4b). The distribution of WPD for the 1951, 1991 and 1996 dates where data was available for the whole transect clearly demonstrates consistency in the WPD data produced (Figure 4a). The distribution of WPD is defined by landform which is formed by grasslands in the floodplain with limited woody plants, flanked by fluvial and Aeolian sands on the east and western margins respectively which support higher WPD (Figures 1 and 4b) (Hudak and Wessman, 1998). Areas of low WPD within the sand zones coincide with minor channels of Taoge River although on the west, fluctuation is due to land-use disturbances from Gumare village. The observed invasion by woody plants in the floodplain on the 1991 and 1996 dates is a response to the recession of the Okavango Delta waters (Shaw, 1984).

Average WPD per date over 16.2 km from the village, where data was available for all dates, shows that 1973 recorded the lowest WPD. This resulted from extensive clearing of land for cultivation purposes, noted on the photos, in response to good rains, about 600 mm annual rainfall in contrast to the average, 400 mm. However, there has been a gradual rise in WPD since then, with a large increase between 1991 and 1996, where average WPD exceeded 1951 levels. This increase followed the decline of the Delta floodwaters and the 1980s drought, which significantly reduced cultivation but favoured livestock rearing. Several studies have linked drought and livestock activity with increase in woody plants (Walker et al., 1981; Skarpe, 1990; Perkins and Thomas, 1993).

4. Discussion

There is an increasing demand for reliable information on woody plant dynamics due to the indicated climate change. Woody plants are important in carbon sequestration and as a source of carbon for instance, through burning and deforestation. All parties to the United Nations Framework Convention for Climate Change (UNFCCC) have to submit national communications indication among others the status of forests as a carbon source and sink (Kleinn, 2002). For developing countries there is an opportunity to attract foreign investments into carbon mitigation projects through the Clean Development Mechanism (CDM) of the Kyoto Protocol (Schoene, 2002). Another important dimension of WPD is the indicated potential for woody plants in semi-arid areas to in- crease in response to elevated CO_2 in the atmosphere and a warm and drier climate in future (Dukes and Mooney, 1999; Lioubimtseva and Adams, 2004). As a result mechanisms for establishing reliable information on forest carbon stocks and their changes are increasingly becoming more pertinent than was the case before (Kleinn, 2002). This study helped shed light on procedures that can be applied to increase reliability of WPD data estimates in semi-arid environments where the data is generated using visual counts of apices of woody plant canopy shadows on small scale conventional aerial photos with the aid of a high magnification portable microscope. The validity of the visual photo based WPD was confirmed on the western part of the Okavango Delta in Botswana using a 5 date data from 1951 to 1996 over a 25 km transect. Changes that were observed from the multi-date data were consistent with landforms and changes in water availability, rainfall and land use activities.

This study showed that the reliability of visual based approaches can be improved by first setting up clear guidelines for generating woody plant data from photographs (Table 2). Applying a systematic procedure reduces subjectivity that may arise when counts are made at different periods or by different observers. Guidelines for conducting plant counts on photos have a potential to upgrade visual qualitative approaches to approximate requirements of quantitative methods because they increase consistency in the data extraction process. In this study the portable microscope used to count plants had the advantage of providing a channeled view and the overlaid microgrid made it possible to systematically apply the established guidelines for counting plants. The instrument had a 40× magnification as opposed to the 8× provided in a normal stereoscope and this increased the ability to identify plants at small scales of 1:40,000 and 1:50,000.

The study did not test differences in counts made by different people, an important factor in comparing results from different studies (Czaplewski et al., 1989). Accuracy is also related to conditions under which counts are made, for instance photo interpreter fatigue may reduce accuracy (Blazquez, 1989). The consistency test conducted was also limited to the larger scales due to time constraints. There is also a need to compare the level of accuracy between different film types; the black and white and true colour photos, relative to field data (Levine, 1969). Further, this study was limited to visible radiation based photos, which are common in Africa.

Despite the noted limitations external factors such as the generally clear skies characteristic of semi-arid areas and the fact that for Botswana, aerial surveys are made over the dry season, result in the production of high quality photos which is an added advantage in plant identification. Photo reproduction processes may however, reduce quality (Gerrard, 1969; Luman et al., 1997). Over-estimation was more likely on photos taken during the wet season when canopy shadows are deep and larger resulting in an increased probability of counting areas of canopy overlaps as individual plants (Czaplewski et al., 1989). This partly accounts for the noted large differences between WPD from field plots and from wet season photos where despite the smaller plot size, 20 m × 20 m in contrast to 25 m × 25 m on the ground, higher WPD were recorded on the photos.

Semi-arid lands generally support open canopies and this increases ability to identify individual woody plant crowns. The results of this study showed that where dense woody plants were supported there was a higher chance to over-estimate WPD. But this was scale depended, for instance overestimation was more likely on large scale photos, 1:10,000 than at 1:30,000, a factor which also had a role in the discrepancy between the field and the photo counts at 1:10,000 as noted above. The use of a microscope with a field of view and level of magnification which could not be adjusted relative to the photo scale was another contributing factor in increasing the potential for over-estimation on large scales. The effects of seasons and different photo film types are scale depended. The results obtained here with respect to the test on effect of photo film type are specific to the scale used.

However, it was shown that variations due to photo film type and scale can be significantly reduced by standardising the data to one base scale and photo film type, thereby increasing the reliability of the data. There was an increase in the average ratios used for standardizing for scale differences with declining photo scale despite the increase in plot size which reflected the level of generalization at smaller scales, for instance, higher chances of counting adjacent canopies as single plants (Table 8) (Czaplewski et al., 1989). As a result it is likely that scale had a role in the observed large increase in WPD between 1991 based on 1:30,000 and the 1996 1:10,000 results in Gumare. Further, at small scales in contrast to large scales, emerging shrubs are likely to be missed despite the large magnification used. This discussion also shows the limitations of the standardisation process applied. While standarddisation to 1:10,000 true colour photos helped reduce diverse errors unique to each scale, errors characteristic to the wet season photo features, the large 1:10,000 scale and the film type were inevitably carried through to the black and white small-scale photo data. This study did not quantify how these errors were distributed over the different data sets.

There were also differences in the standardizing average ratios at the same scale between sites; Gumare and Hainaveld, which shows the influence of different landscape types on the results of woody plant counts (Thorley, 1975). Large tree canopies found in Gumare increased the possibility of over-estimating numbers of plants particularly at larger scales while in Hainaveld, where shrubs dominate, there was a higher chance for under-estimation for instance, clumps of shrubs counted as single plants, particularly under smaller scales (Kay et al., 1998; Warner et al., 2000). These landscape effects indicate the need to stratify the landscape prior to conducting woody plant counts. Stratification will help to extrapolate results over larger areas with reasonable accuracy where adequate samples have been made, which will reduce the limitation of coverage inherent in this visual approach (Colwell, 1983; Kleinn, 2002).

The study showed that the use of a very high magnification, 40×, instrument makes it possible to utilize small scale photography which is commonly available in developing countries to establish WPD. Larger scales are recommended for identifying and counting woody plants in rangelands but these are not readily available (Tueller, 1987). Smaller scales have the advantage of larger coverage. In this case using small scale photos, combined with the generally flat terrain of the area helped to minimize the effect of relief distortions and made it possible to produce consistent results using photos that were not co-registered or rectified to a map projection (Lillesand and Kiefer, 1994). But small scales made it difficult to differentiate shrubs from trees which is important because shrub density is associated with land degradation and it is growing to be linked to rising CO_2 in the atmosphere as noted above (Hoffman and Cowling, 1990; Skarpe, 1990).

This study points to a need to determine the optimum scale to use to produce the most reliable WPD data from aerial photos using visual counts of apices of woody plant shadows under different vegetation types and density. The optimum scale should be the scale where photo based counts is consistent with field based counts. In addition, in order to provide data for monitoring woody vegetation over time both photo and field data need to be geo-referenced for instance using a Global Positioning System (GPS) which is now readily available. Geo-referenced data provides for continuous monitoring of the same sites and to link the data to other data bases for example, forest inventories based on earth resource satellites such as Landsat Enhanced Thematic Mapper Plus (ETM+) conducted under international initiatives such as the Global Observation of Forestry Cover and Global Observation of Land cover Dynamics (GOFC-GOLD). Improvements in woody plant estimates are required to meet the growing demand on forestry information globally for land use planning, climate change and biodiversity related requirements.

5. Conclusions

While the method of establishing WPD from the visual counts of apices of shadows of woody plants on photos using a high magnification portable microscope has several potential errors and is time consuming it is possible to produce consistent results where careful procedures have been laid out in advance. In this study the reliability of the data was enhanced by applying consistent procedures of extracting the data, standardizing data to a single base photo scale and film type and carrying out measurements in such a way that data can be smoothed to reduce noise without overgeneralization. The relationship between photo and ground based counts resulted in $R^2 = 0.74$ and 0.62 ($P < 0.05$) in Gumare and Hainaveld Ranch 19, respectively indicating that air photo based WPD can be used as surrogate data for assessing woody plant distribution on the ground. Quantitative information on WPD can be produced from visual based methods for detailed case studies required to assess various environmental and land use factors influencing vegetation structure.

The study showed that scale is a cross-cutting factor influencing the reliability of WPD derived from counts of apices of woody plant shadows on aerial photographs. Where possible a single scale should be used across dates, film types and observers. Stratification in terms of vegetation type and density and application of the most appropriate scale will reduce errors in the visual based approaches. While this is so, rapid and more objective computer based approaches which are cost effective need to be investigated and applied for long term monitoring of woody plants to meet land use, climate change and biodiversity assessment needs in semi-arid lands. Semi-automated methods make it possible to take advantage of developments in high spatial resolution digital data and to produce information that will facilitate comparative studies in similar regions (Held and Billlings, 1998).

Acknowledgments. I am greatly indebted to Mark Stafford Smith CSIRO, Alice Springs and Geoff McDonald, University of Queensland for their valuable input in the earlier drafts of this study. MBM Sekhwela, University of Botswana motivated me to take up this study and provided some of the materials used. Financial support was from the European Union University of Botswana Manpower Development Fund and the Australian Centre for International Agricultural Research.

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