



Textural analysis of high resolution imagery to quantify bush encroachment in Madikwe Game Reserve, South Africa, 1955–1996

A. T. HUDAK* and C. A. WESSMAN

Center for the Study of Earth from Space / Cooperative Institute for Research in Environmental Sciences, and Department of Environmental, Population, and Organismic Biology, University of Colorado, Boulder, CO 80309, USA

(Received 19 October 1999; in final form 20 January 2000)

Abstract. Fire suppression associated with decades of cattle grazing can result in bush encroachment in savannas. Textural analyses of historical, high resolution images was used to characterize bush densities across a South African study landscape. A control site, where vegetation was assumed to have changed minimally for the duration of the image record (1955–1996), was used to standardize textural values between multirate images. Standardized textural values were then converted to estimates of percent woody canopy cover using a simple linear regression model. Results indicate a 30% relative increase in percent woody cover between 1955 and 1996.

1. Introduction

Woody plant encroachment is the slow proliferation of woody plants at the expense of grasses in savannas, which are by definition composed of both plant functional types. Encroaching woody species may be trees or shrubs, which are collectively referred to as 'bush' in the South African savanna region targeted in this study. Causes of bush encroachment have been widely debated but are most strongly associated with chronic cattle grazing and fire suppression (Archer *et al.* 1995, Hudak 1999b). Bush encroachment reduces the grazing capacity of savanna rangelands and is therefore widely regarded as undesirable. A method to quantify bush encroachment is desirable not only to assess obvious changes in ecosystem structure but also associated, potential long-term changes in ecosystem function, carbon storage, and biodiversity (Hudak 1999a). Moreover, bush encroachment has pervaded not only South African rangelands but also many other savanna regions around the world (Archer 1995), giving global implications to the potential ecological effects of bush encroachment.

Hudak and Wessman (1998) demonstrated a technique for mapping bush densities across a savanna landscape using historical aerial photographs from 1955, 1970 and 1984. They did so by scanning the photos to produce images of 10 m resolution, mosaicking these images to produce large image composites, and then applying a

*Current Address: USDA Forest Service, Pacific Northwest Research Station, Forestry Sciences Laboratory, 3200 SW Jefferson Way, Corvallis, OR 97331; e-mail: ahudak@fs.fed.us

textural index to the composites to indicate bush density. This approach was successful for two primary reasons. First, a spatial resolution of 10 m was sufficiently high to capture the spatial variability in savanna canopy structure, which at this scale was primarily determined by the woody overstory component. Second, the radiometric properties of the aerial photos from each year were sufficiently uniform to allow spatial mosaicking. However, radiometric similarity did not exist between aerial photos acquired in different years, which precluded absolute quantification of bush encroachment. Different environmental (light, atmosphere, surface) conditions, as well as different photo acquisition equipment and development procedures, confound quantitative comparisons between multitemporal photos.

The approach used by Hudak and Wessman (1998) to map historic patterns in bush density should be applicable to many other savanna regions, given the widespread availability of sequential aerial photos. This paper builds upon that earlier study by introducing a simple strategy for overcoming the problem of dissimilar contrast in multitemporal aerial photos. We hypothesized that the incongruent radiometries of multirate images can be standardized, given a site where vegetation cover has not markedly changed over the duration of the image record.

2. Approach

Assessing human influences on ecosystems in South Africa can be difficult due to the paucity of experimental control areas—natural ecosystems unaffected by humans—with which to objectively compare (Macdonald 1989). Indeed, the lack of any livestock exclosures in the study region at first seemed to preclude any means to quantify historic bush encroachment. However, textural images are sensitive to bush density, not grazing *per se*. Therefore, a control site need not satisfy the requirement of no grazing but only the requirement of no bush density change. By this criterion, a potential control site in the Madikwe landscape did exist: a heavily encroached, 350 ha area on a farm situated just east of Madikwe Game Reserve (MGR). The resident farmer there, and his father before him, had maintained cattle on the farm at a constant stocking density of 8 ha/head since 1936. Furthermore, this farmer stated the only fire to have occurred anywhere on his farm since then was in 1960, but this fire occurred away from the area chosen as a control site. Hence, we assumed that the vegetation within the control site had been subjected to a constant disturbance regime for sixty years.

Vegetation condition at the control site (observed in 1996) supported our assumption. The woody overstory was overwhelmingly dominated by the principal encroaching species in the area, *Dichrostachys cinerea* subsp. *africana*. This leguminous woody weed is closely related to trees of the genus *Acacia* and produces nutritious seed pods that cattle seek out and eat, thereby facilitating seed dispersal and germination (Brown and Archer 1987, 1989; Scholte 1992, Schultka and Cornelius 1997). Most importantly, the *D. cinerea* at this site were in all stages of development, from seedlings to large (sometimes fallen) individuals dying of old age, suggesting that woody cover had reached a stable equilibrium.

3. Study area description

Madikwe Game Reserve (MGR) is located in a semi-arid savanna region on the northern border of South Africa (centered at 25.0° S, 26.2° E), as illustrated in figure 1. The landscape is generally flat except for some scattered rocky ridges and outcroppings. The long dry season and generally infertile soils limit cropping to <5% of

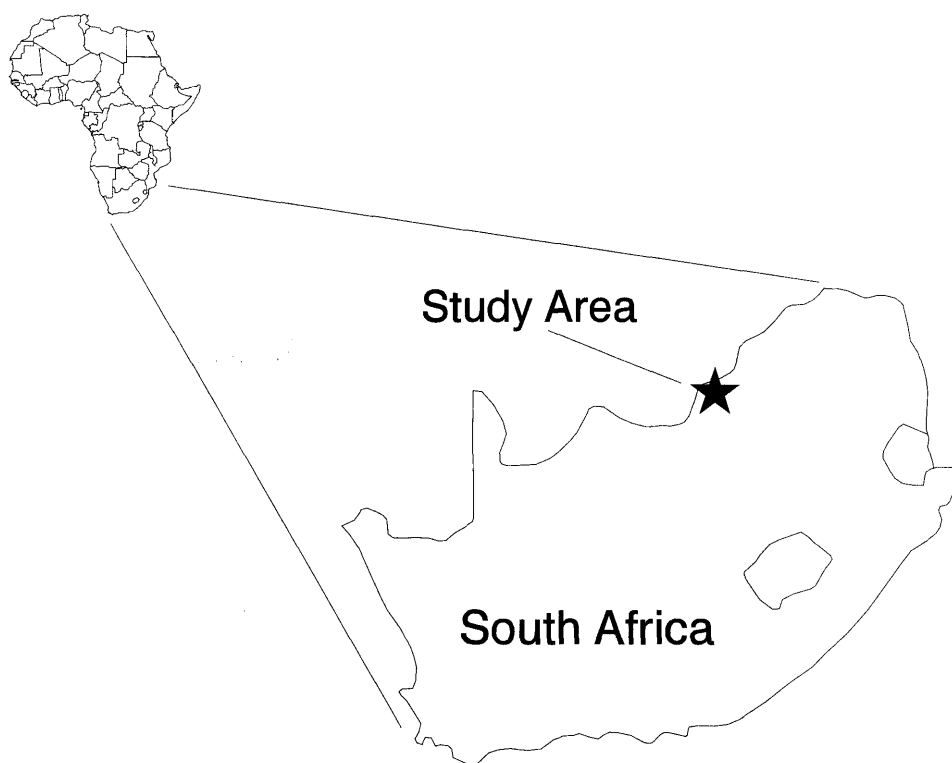


Figure 1. Study area location.

the land area, making cattle grazing the overwhelming land use in this sparsely populated region. Soils vary from red clay loams prone to bush encroachment to rocky soils of dolomitic origin that support a more open canopy structure. A legacy of chronic grazing and fire suppression over many decades depleted the grazing potential of the land (Hudak 1999b). In 1991, the government concluded tourism would be a more profitable land use, resulting in the establishment of MGR (Madikwe Development Task Team 1994). The photographs from the Madikwe landscape in figure 2 illustrate typical canopy structure, as it appears at three successive stages in the bush encroachment process.

4. Image processing

Two Systeme Probatoire d'Observation de la Terre (SPOT) panchromatic images, acquired 27 July 1990 and 25 June 1996, were obtained for this analysis (Satellite Applications Centre, Pretoria, South Africa). Simulated SPOT images in 1955, 1970 and 1984 were created from 10 m images scanned from historical aerial photographs and subsequently mosaicked. Image brightness and contrast were optimized before scanning each photo, to minimize seams in the mosaic (details are described in Hudak and Wessman 1998). Histograms of these image mosaics were normally distributed across the full dynamic range (0–255). A linear stretch was applied to the two SPOT images to similarly span the full dynamic range, with 1–2% of the values in the lower and upper tails assigned to 0 and 255, respectively. This step negated rare, unusually high maximum or low minimum values, which would have



(a)



(b)



(c)

Figure 2. Vegetation cover at the Madikwe landscape as it typically appears late in the dry season (a) before, (b) during and (c) after bush encroachment. Pictured in each photo is game scout and field assistant Moses Moeti.

otherwise prevented a normal distribution across the full dynamic range. The linear stretch was also important for matching histograms between the SPOT images and the simulated SPOT images.

Pixel sizes after georectification varied slightly from 10 m, so each image was resampled to exactly 10 m resolution, using nearest neighbor resampling. Consistent image grain size and extent were required to insure precision, accuracy, and comparability in the textural values generated from the multirate images. Sizable portions of the landscape were outside the extent of the 1990 SPOT image and the 1955 SPOT simulation image. Hence, textural values were only compared between the portion of the landscape containing data from all 5 dates. Textural images were generated using a 3×3 standard deviation filter (Hudak and Wessman 1998). Spatial analysis was accomplished in a geographic information system (GIS) using Arc/Info software (ESRI, Redlands, CA).

5. Standardization of textural images

Mean texture at the control site in the simulated SPOT images was forced to match mean texture at the control site in the 1996 SPOT image. i.e. textural adjustment constants (K) were calculated at the control site (CS) according to equations 1–3:

$$K_{(96-55)} = \text{CS texture}_{96} - \text{CS texture}_{55} \quad (1)$$

$$K_{(96-70)} = \text{CS texture}_{96} - \text{CS texture}_{70} \quad (2)$$

$$K_{(96-84)} = \text{CS texture}_{96} - \text{CS texture}_{84} \quad (3)$$

Thus, $K_{(96-55)}$, $K_{(96-70)}$ and $K_{(96-84)}$, calculated as -7.916 , -5.737 and -1.661 , respectively, were added to the whole 1955, 1970 and 1984 textural images, respectively. (The 1990 SPOT image could not be standardized because the control site was situated outside the extent of this image.) If our assumption of negligible vegetation change at the control site was correct, then radiometric differences between images would be removed and remaining differences between the standardized textural images could be attributed to vegetation change alone.

6. Field validation

Hudak and Wessman (1998) determined that image texture correlates significantly to two canopy structural parameters measured in the field: woody stem count and percent woody canopy cover. While woody stem count proved the better correlate in that analysis, we used percent woody cover measurements to validate this analysis because percent woody cover can be measured much more quickly using the plotless Bitterlich technique (Mueller-Dombois and Ellenberg 1974, Friedel and Chewings 1988). Field sampling sites ($n=30$) were geolocated with a global positioning system (GPS) (Trimble Pathfinder BasicPlus) and differentially corrected to an accuracy of ± 2 m via postprocessing of concurrent base station files (provided courtesy of Telkom, Pretoria, South Africa). Mean textural values from the 25 June 1996 SPOT image were calculated within a 50 m radius of each corrected position (approximately 70 pixels) and compared to the field measurements.

7. Results

The correlation between mean SPOT image texture and percent woody cover was weak yet significant, as shown in figure 3. A simple linear regression model of

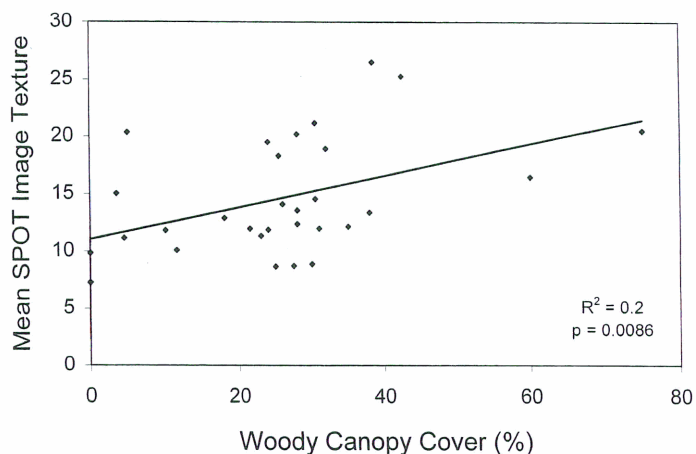


Figure 3. Correlation between SPOT image texture and field measurements of percent woody canopy cover ($n = 30$).

this relationship enabled prediction of percent woody cover from image textural values ($\% \text{ woody} = 1.4577 \times \text{texture} + 4.5518$). The map of predicted percent woody cover values is shown in figure 4.

Mean textural values from all five years, both before and after standardization of the 1955, 1970 and 1984 textural images, are graphed in figure 5. Estimates of percent woody canopy cover were also calculated from the standardized textural values using the same simple linear regression model; these estimates are listed in table 1. Absolute percent woody cover was 5.6% higher in 1996 than in 1955, which translates into a relative increase of 30% over 41 years.

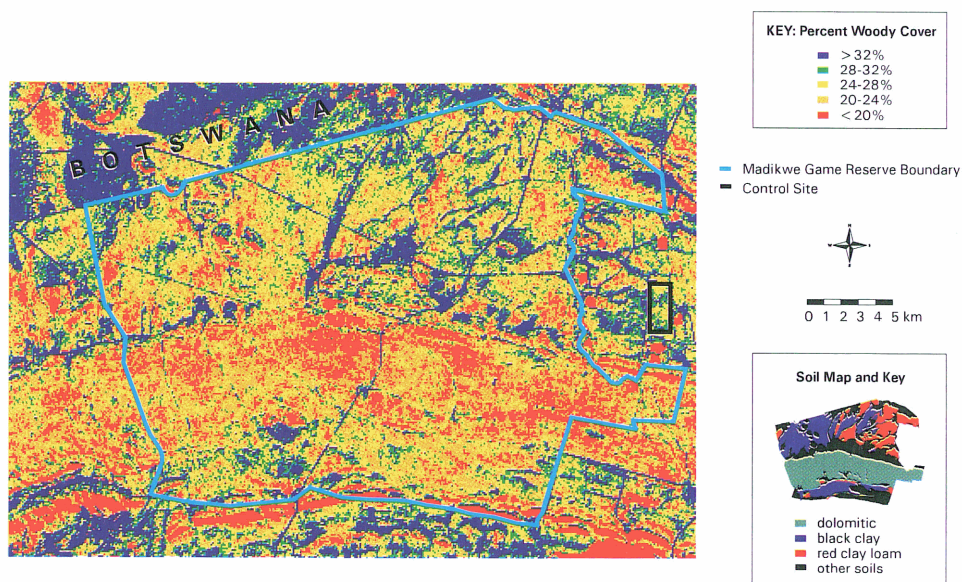


Figure 4. Percent woody cover in Madikwe Game Reserve and surrounding vicinity, 25 June 1996.

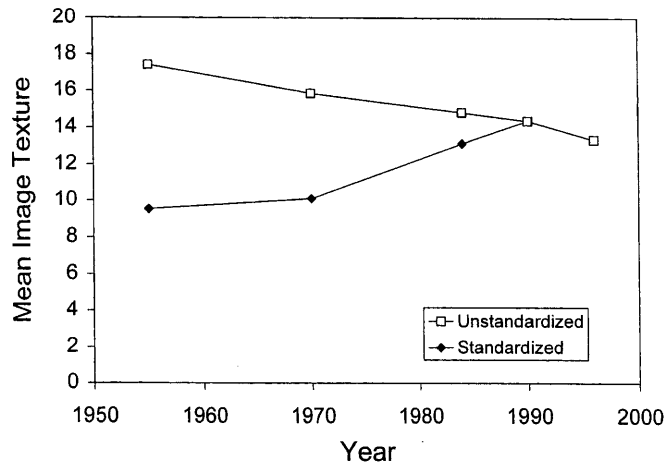


Figure 5. Textural change trajectories, 1955–1996, before and after standardization of the 1955, 1970 and 1984 textural images. Mean textures were calculated from the portion of Madikwe Game Reserve common to all five images (32 621 ha). Standard error bars are smaller than the plot symbols.

Table 1. Percent woody cover estimates, based on a 32 621 ha area in Madikwe Game Reserve common to all five images. (The apparent peak in 1990 is not a standardized value, because the control site lies outside the extent of the 1990 SPOT image.)

Image year	Texture mean	Standard deviation	Standard error	% Woody cover
1955	9.520	5.826	0.032	18.4
1970	10.092	5.973	0.033	19.3
1984	13.117	4.547	0.025	23.7
1990	14.321	4.078	0.023	25.4
1996	13.310	4.164	0.023	24.0

The 1955, 1970 and 1984 SPOT simulation images were assembled only for the area within or in the immediate vicinity of MGR (including the nearby control site), while the 1990 and 1996 SPOT images included nearly as much land outside of MGR as inside. Therefore, we compared 1990 and 1996 textural values inside vs. outside MGR. Because the radiometry of each SPOT image is uniform, a difference in the degree of textural change inside vs. outside MGR should only be due to differential vegetation change. Results in table 2 show lower texture overall in 1990 than in 1996, but a greater decline inside MGR than outside.

Table 2. Difference in image texture and percent woody canopy cover, inside vs. outside Madikwe Game Reserve (MGR), 1990–1996.

Landscape portion	Area (ha)	Change in mean texture, 1990–1996	Change in woody cover (%), 1990–1996
Inside MGR	36 575	–1.047	–1.53%
Outside MGR	29 564	–0.535	–0.78%
Total	66 139	–0.818	–1.19%

8. Discussion

We caution that several potential sources of uncertainty exist in this analysis: a nonuniform atmosphere, variable sun/target/sensor geometry, and temporal dynamics in land cover properties themselves (McGwire *et al.* 1993). The unquantified uncertainty underlying our assumption of minimal vegetation change at the control site is most problematic, but the use of a control site is not entirely unprecedented. Hall *et al.* (1991) used 'control sets', or landscape elements having a mean reflectance expected to change little over time, to radiometrically standardize multi-date, multisensor images. In another study, Hudak and Wessman (2000) used a control site to standardize vegetation indices between multitemporal Landsat satellite images, and obtained reasonable estimates of woody cover change. However, further tests clearly are still needed to assess the broader applicability of this technique.

Univariate linear relationships between field and remotely sensed data are often the most practical validation method. The slope in the relationship between image texture and percent woody canopy cover was quite weak in this study (see figure 3); consequently, the range in predicted percent woody cover values is unrealistically narrow (see figure 4). On the other hand, the bush density patterns indicated in figure 4 reflect the distribution of soil types in MGR, which are the major determinant of vegetation composition across this landscape. These same patterns were evident in the 1955, 1970 and 1984 textural images—serving as a form of replication that strengthens our confidence in image texture as a good indicator of relative bush densities across a landscape (Hudak and Wessman 1998).

Raw textural values were lower in the SPOT images than in the SPOT simulation images mosaicked from aerial photos scanned at the same 10 m resolution (see figure 5). Greater atmospheric scattering effects on SPOT imagery probably explain this reduced contrast in SPOT data relative to aerial photos. Hudak and Wessman (1998) concluded that the radiometry of multitemporal SPOT panchromatic images should be approximately equivalent and should therefore allow monitoring of canopy structure. Indeed, raw textural values from the 1990 and 1996 SPOT images used in this analysis proved very similar (see figure 5 and tables 1 and 2). In fact, these images were acquired by the same satellite (SPOT 2).

The greater decline in texture inside MGR than outside from 1990 to 1996 (see table 2) suggests differential change in vegetation cover, which may relate to extensive management fires set in MGR in 1992, 1993 and 1994 to control bush encroachment (Hudak 1999a). If one assumes that canopy structure outside MGR has changed little between 1990 and 1996, then the larger decrease in texture inside MGR translates into an absolute loss in percent woody cover of 0.75%. Although far too minor to consider definitive, this is a reasonable figure given that the average woody plant fire mortality rate is 1.3% (Bruce Brockett, MGR fire ecologist, *personal communication*).

If the bush encroachment rate suggested in table 1 is assumed to be linear and extrapolated back one hundred years, when white settlers arrived and current grazing practices are believed to have commenced (Hoffman 1997), then it appears that bush densities have approximately doubled during the past century. However, we have no evidence that bush encroachment is a linear or nonlinear process. Two earlier studies in neighboring Botswana demonstrated the potential for higher initial rates of bush encroachment: Skarpe (1990) conducted an overgrazing experiment on a 10 × 10 m plot and induced a doubling in percent woody cover in only five years. Van Vegten (1983) estimated a tripling in woody biomass from 1950 to 1975 over a 108 km² area, beginning in a savanna with very little woody cover.

Our bush encroachment estimates seem reasonable given the widespread consensus among regional farmers that significant bush encroachment has occurred (Hudak 1999b). In another study most relevant to our own, Caylor *et al.* (1999) used declassified Corona satellite photography to quantify bush encroachment in Botswana. They estimated that percent woody cover increased from 25.6% in 1967 to 32.5% in 1996; this relative increase of 27% over 29 years agrees remarkably well with our own estimate of 30% over 41 years.

9. Conclusion

Image texture is a good indicator of woody plant density in savannas. Multitemporal textural images can be standardized to account for differential radiometric contrast, and reasonable estimates of woody canopy cover change obtained, provided a control site exists where one may assume minimal vegetation change for the duration of the image record. We recommend further testing of this technique in other ecosystems, using other image sources, to evaluate its broader utility for quantifying long-term changes in savanna vegetation cover.

Acknowledgments

This research was funded primarily by an EPA STAR Graduate Fellowship. At the University of Colorado, CIRES and the Department of EPO Biology provided additional support. We thank North West Parks Board for the opportunity to work in Madikwe Game Reserve, Eugene Breytenbach for the 1990 SPOT image, and Bruce Brockett, Markus Hofmeyr, Greg Stuart-Hill, Bob and Mary Scholes, and Dean Fairbanks for their assistance in South Africa.

References

- ARCHER, S., 1995, Tree-grass dynamics in a *Prosopis*-thornscrub savanna parkland: reconstructing the past and predicting the future. *Ecoscience*, **2**, 83–99.
- ARCHER, S., SCHIMEL, D. S., and HOLLAND, E. A., 1995, Mechanisms of shrubland expansion: land use, climate or CO₂? *Climatic Change*, **29**, 91–99.
- BROWN, J. R., and ARCHER, S., 1987, Woody plant seed dispersal and gap formation in a North American subtropical savanna woodland: the role of domestic herbivores. *Vegetatio*, **73**, 73–80.
- BROWN, J. R., and ARCHER, S., 1989, Woody plant invasion of grasslands: establishment of honey mesquite (*Prosopis glandulosa* var. *glandulosa*) on sites differing in herbaceous biomass and grazing history. *Oecologia*, **80**, 19–26.
- CAYLOR, K. K., LE, L., and SHUGART, H. H., 1999, Structural dynamics in southern African savannas: detecting change through declassified satellite photography. Presented at the Ecological Society of America Conference, Spokane, Washington.
- FRIEDEL, M. H., and CHEWINGS, V. H., 1988, Comparison of crown cover estimates for woody vegetation in arid rangelands. *Journal of Ecology*, **13**, 463–468.
- HALL, F. G., STREBEL, D. E., NICKESON, J. E., and GOETZ, S. J., 1991, Radiometric rectification: toward a common radiometric response among multirate, multisensor images. *Remote Sensing of Environment*, **35**, 11–27.
- HOFFMAN, M. T., 1997, Human impacts on vegetation. In *Vegetation of Southern Africa*, edited by R. M. Cowling, D. M. Richardson, and S. M. Pierce (Cambridge: Cambridge University Press), pp. 507–534.
- HUDAK, A. T., 1999a, Ecological causes and effects of bush encroachment in South African savanna. Ph.D Dissertation (Boulder: University of Colorado).
- HUDAK, A. T., 1999b, Rangeland mismanagement in South Africa: failure to apply ecological knowledge. *Human Ecology*, **27**, 55–78.

- HUDAK, A. T., and WESSMAN, C. A., 2000, Deforestation in Mwanza District, Malawi, Africa from 1981 to 1992 as determined from Landsat MSS imagery. *Applied Geography*, **22**, 155–175.
- HUDAK, A. T., and WESSMAN, C. A., 1998, Textural analysis of historical aerial photography to characterize woody plant encroachment in South African savanna. *Remote Sensing of Environment*, **66**, 317–330.
- MACDONALD, I. A. W., 1989, Man's role in changing the face of southern Africa. In *Biotic Diversity in Southern Africa: Concepts and Conservation*, edited by B. J. Huntley (Cape Town, South Africa: Oxford University Press), pp. 51–77.
- MADIKWE DEVELOPMENT TASK TEAM, 1994, Madikwe Game Reserve Management Plan (Rustenburg: South Africa).
- MCGWIRE, K., FRIEDL, M., and ESTES, J. E., 1993, Spatial structure, sampling design and scale in remotely-sensed imagery of a California savanna woodland. *International Journal of Remote Sensing*, **14**, 2137–2164.
- MUELLER-DOMBOIS, D., and ELLENBERG, V., 1974, The count-plot method and plotless sampling techniques. In *Aims and Methods of Vegetation Ecology* (New York: John Wiley & Sons), pp. 96–108.
- SCHOLTE, P. T., 1992, Leaf litter and *Acacia* pods as feed for livestock during dry season in *Acacia-Commiphora* bushland, Kenya. *Journal of Arid Environments*, **22**, 271–276.
- SCHULTKA, W., and CORNELIUS, R., 1997, Vegetation structure of a heavily grazed range in northern Kenya: tree and shrub canopy. *Journal of Arid Environments*, **36**, 291–306.
- SKARPE, C., 1990, Shrub layer dynamics under different herbivore densities in an arid savanna, Botswana. *Journal of Applied Ecology*, **27**, 873–885.
- VAN VEGTEN, J. A., 1983, Thornbush invasion in a savanna ecosystem in eastern Botswana. *Vegetatio*, **56**, 3–7.