

Fig. 4. The average change (mean + s.e.) in woody (black), grass (grey) and forbes (white) cover at four sites along the Kalahari Transect.

between light and moisture availability along the transect.

The density of woody plants varied from over 950 stems/ha in Mongu to 181 stems/ha at Tshane, but neither stand basal area nor stem density varied linearly with mean annual rainfall (Table 4). Woody species richness declined southwards across the moisture gradient from 38 species/10 ha at Pandamatenga to 17 species/10 ha at Tshane. Grass and forb cover was highly variable along the transect (Fig. 4), suggesting that local conditions, especially relative intensities of livestock grazing and trampling, determine the patterns.

Canopy structure

Leaf area profiles derived from stem map data collected at four sites along the gradient (Fig. 5) show marked changes in the both the height and distribution of

leaves in the vegetation canopy. Patterns are typical for the range of vegetation types observed, with a distribution characteristic of woodland vegetation types in the north, and a typical savanna-shrub profile in the southern site.

General trends in the structure of the woody vegetation, as determined from Tracing Radiation and Architecture of Canopies (TRAC instrument; 3rd Wave Engineering, Ontario) data are shown in Fig. 6. TRAC measures the frequency and size of sun flecks along a grid line.¹⁹ The data allow accurate estimation of Plant Area Index [PAI (m²/m²), one-half the sum of the area of all plant material] by compensating for canopy clumping (non-randomness). Results show that the overstorey PAI decreased by about 1.5 units (from 2.2 to 0.6) along the rainfall gradient. Likewise, the Mean Contact Number (Ω), which indicates the effective

number of contacts with plant material made by photons travelling along the solar beam, decreased by about 50% along the transect as canopy cover decreased. The clumping parameter, a metric indicating the deviation in the spatial distribution of the canopy from a random distribution (<1 = fully clumped, 1 = perfectly random, >1 = regularly spaced), was fairly consistent (0.7 < Ω < 0.76 except for Okwa). This quantifies the overstorey discretization characteristic of savanna systems. The Okwa site was a consistent outlier in these results, but the shrubby structure of the vegetation at the site was not well suited to TRAC sampling at waist level.

The structural data collected during the March 2000 campaign is the most comprehensive near-synoptic data archive yet collected over the KT. Extensive comparative and correlative analyses are under way, as are scaling and validation studies involving satellite products. These studies should provide further insight into canopy resource allocation in a largely water-limited environment, vegetation succession, and relationships between structure and canopy spectral reflectance as measured by satellite.

Carbon and nitrogen cycling

Soil carbon and the C:N ratio decreased from north to south as the environment became drier. Soil ammonium and nitrate concentrations were highest at the Kataba forest site in Mongu and beneath tree canopies, while concentrations at the four other sites did not differ significantly²⁰ (Fig. 7). Symbiotic N fixation is almost absent in arid areas, even though the dominant woody species are in the potentially N-fixing subfamily Mimosoideae, and a shortage of available phosphorus may be the limiting factor. Soil NO emissions increased with temperature and soil moisture, although the response differed across the five sites. There did not appear to be a clear trend in estimated NO fluxes from north to south as daytime fluxes were highest at Pandamatenga. When the daily fluxes were plotted against the actual soil moisture at the time of the campaign, however, the NO fluxes were shown to decrease with soil moisture.²¹ Nitrogen is more ¹⁵N enriched in arid than in humid areas, indicating higher losses or lower inputs, relative to turnover as precipitation decreases.²¹ The lower organic matter and N fixation in arid areas can explain the high $\delta^{15}N$, and seem to have a stronger effect than NO emissions, although other soil N emissions could also affect the isotopic signatures.

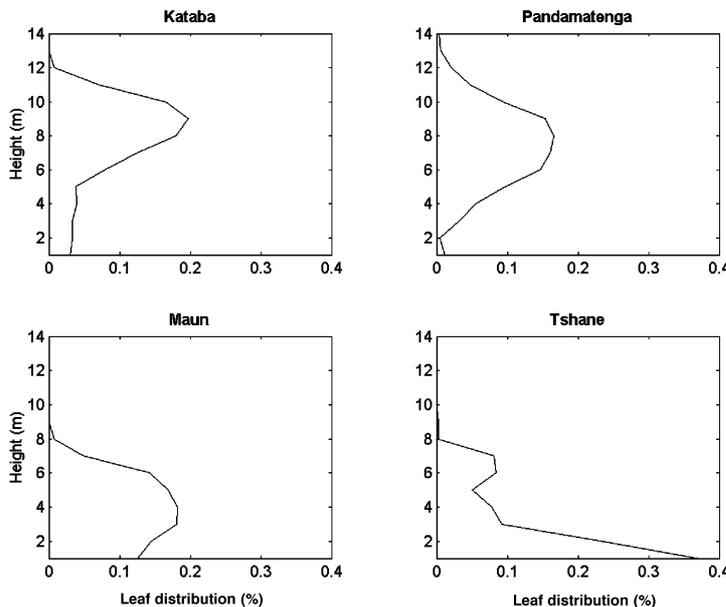


Fig. 5. Distribution of leaves in the canopy at four sites along the Kalahari Transect.

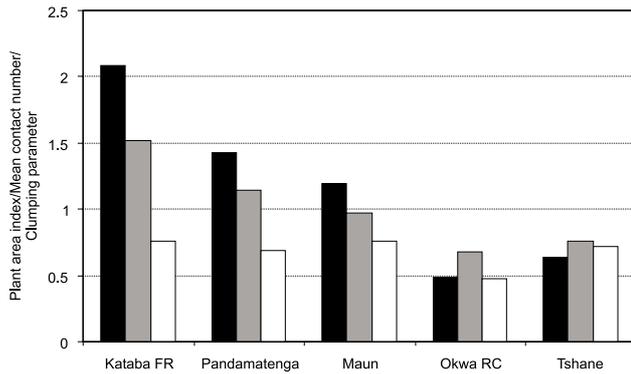


Fig. 6. Plant area index (black), mean contact number (grey) and the clumping parameter (white) for the vegetation along the Kalahari Transect.

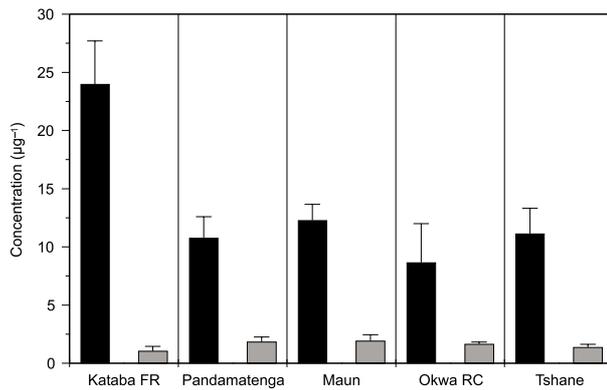


Fig. 7. Mean (\pm s.e.) soil ammonium (black) and nitrate (grey) concentrations along the Kalahari Transect (taken from Feral *et al.*²⁰).

Aerosol optical thickness

Figure 8 shows a time series of instantaneous measurements of aerosol optical thickness (AOT) at 340, 440, 675 and 870 nm in Maun during the KT wet season campaign. The measurements were taken with a Microtop II hand-held sun-photometer at intervals of 30 min between 06:00 and 15:30 GMT for three days (7–9 March 2000). The measurements show the spectral AOT of the total air column of the atmosphere, which in turn indicates the aerosol loadings in the air column. The data for the Maun site show relatively

high AOT on 7 and 8 March but lower values on 9 March, possibly because of a change in atmospheric circulation. These data are being used to correct the remote sensing data atmospherically, as well as to understand the magnitude and angular distribution of spectral irradiance.

Skukuza flux tower

Eddy covariance measurements of the fluxes of CO₂, water (LE) and energy (H) began at Skukuza in April 2000. With the exception of data breaks during periods of

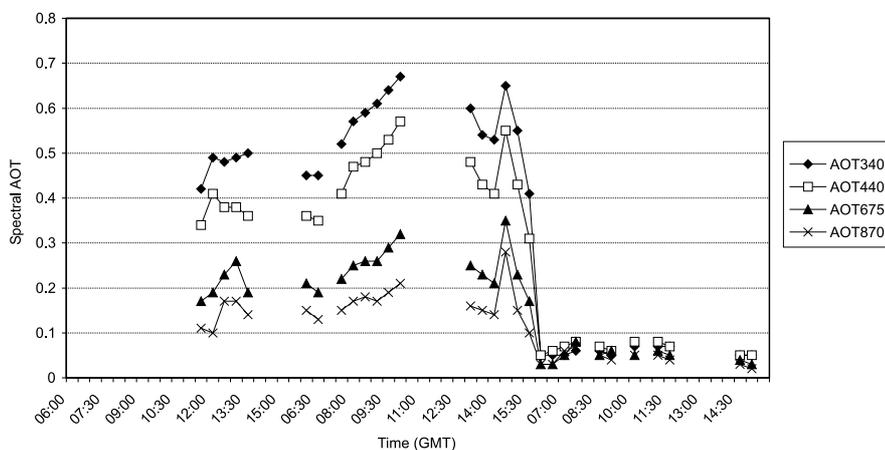


Fig. 8. Time series of instantaneous measurements of aerosol optical thickness (AOT) at 340, 440, 675 and 870 nm in Maun, Botswana, during the Kalahari Transect wet season campaign, from 7 to 9 March 2000.

power or instrument failure, fluxes and associated micrometeorological, soil and canopy profile measurements are continuous, with 30-min averaging. Rainfall in the 1999–2000 rainy season (1260 mm) was more than double the average for Skukuza (550 mm). As a result, the growing season was unusually extended and net primary production was high, particularly in the herbaceous layer. Flux measurements for three example days spanning the period from the end of the wet season to the beginning of the dry (April–June 2000) are shown in Fig. 9. As expected, the CO₂ and LE fluxes declined into the dry season while the Bowen ratio (H/LE) increased. Sensible heat flux remained relatively constant, however, because increased partition of available energy to H is offset by the reduction in available energy with the onset of the southern hemisphere winter.

Next steps

The KT campaign resulted in a rich data set for the relatively data-sparse Kalahari region. Some of the first leaf- and canopy-level flux and conductance measurements for the region were obtained. Information about canopy structure was rigorously measured at multiple spatial scales. The 2001 campaign provided further information on the Skukuza and Maun sites in terms of canopy fluxes, as well as a more complete and coherent understanding of biogenic VOC fluxes. The data from both campaigns will be used to calibrate and validate models of the structure and function of the land surface, and associated biogenic emissions, in southern Africa. These models, in turn, will form part of an integrated model of the land-human-atmosphere system in southern Africa. SAFARI 2000 data are also being used to validate the operational remote sensing algorithms and products, especially leaf area index, fractional photosynthetically active radiation, and net primary productivity, developed in the EOS programme. These are potentially useful results for measuring plant production on a landscape scale, and for assessing the extent to which production potential has been disturbed directly or indirectly by human activities. MODIS validation studies based on SAFARI 2000 data will be reported in a forthcoming special issue of *Remote Sensing of Environment*.²²

Data analysis is under way and will be reported in the scientific literature and through conference reports. A suite of papers, particularly on the Kalahari work, is being prepared for a special issue of

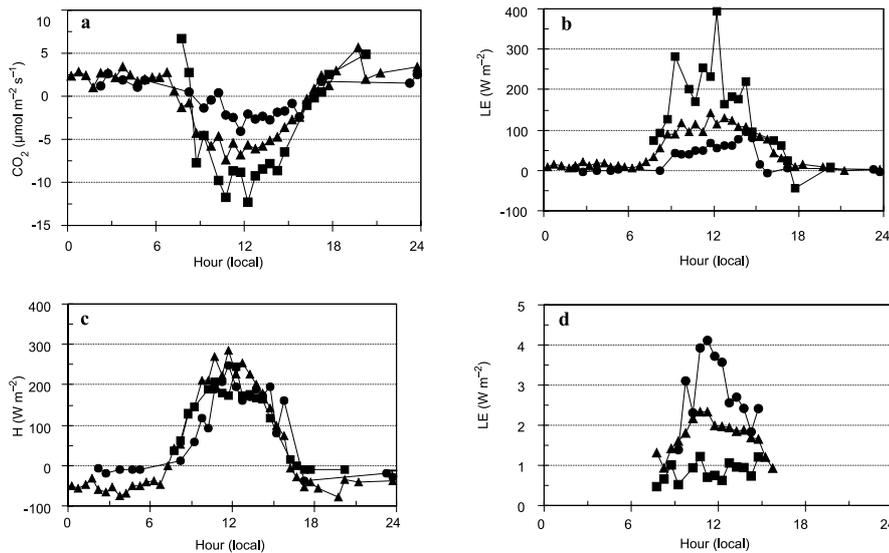


Fig. 9. CO₂ flux (a), latent heat flux (b), sensible heat flux (c) and daytime Bowen ratio (d) measured from the tower at Skukuza on 13 April (squares), 13 May (triangles) and 20 June 2000 (circles).

Global Change Biology. In July 2001, SAFARI 2000 scientists presented posters at the IGBP Open Science Conference in Amsterdam. The first SAFARI 2000 preliminary data workshop was held in Siavonga, Zambia, and the project had a special session at the Fall AGU meeting in December 2001 in San Francisco, where approximately 40 papers and posters on the first results were presented. A special issue of the *Journal of Geophysical Research* is expected by the end of 2002. (For updates, see SAFARI 2000 website <http://www.safari.gecp.virginia.edu> or <http://safari2000.org>.)

The data collected in these campaigns are being distributed through the SAFARI 2000 Regional Data Centre (<http://safari2000.org>) in cooperation with NASA. Associated satellite and ancillary data are available on the first SAFARI CD-ROM, released in August 2001. A second CD is being prepared. Data are available online to those who register with the Regional Data Centre and agree to the terms set out in the project's data policy.

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- Swap R.J., Annegarn H.J. and Otter L.B. (2002). Southern African Regional Science Initiative (SAFARI 2000): summary of Science Plan. *S. Afr. J. Sci.* **98**, 119–124 (available at <http://safari.gecp.virginia.edu>).
- Lindesay J.A., Andreae M.O., Goldammer J.G., Harris G., Annegarn H.J., Garstang M., Scholes R.J. and van Wilgen B. (1996). The IGBP/IGAC SAFARI-92 field experiment: Background and overview. *J. Geophys. Res.* **101**, 23521–23530.
- Parsons D.A.B., Scholes M.C., Scholes R.J. and Levine J.S. (1996). Biogenic NO emissions from savanna soils as a function of fire regime, soil type, soil nitrogen, and water status. *J. Geophys. Res.* **101**, 23683–23688.
- Guenther A., Otter L., Zimmerman P., Greenberg J., Scholes R. and Scholes M. (1996). Biogenic hydrocarbon emissions from southern African savannas. *J. Geophys. Res.* **101**, 25859–25865.
- Marufu L., Ludwig J., Andreae M.O., Lelieveld J. and Helas G. (1999). Spatial and temporal variation in domestic biofuel consumption rates and patterns in Zimbabwe: implications for atmospheric trace gas emissions. *Biomass Bioenergy* **16**, 311–332.
- Scholes R.J. and Scholes M.C. (1998). Natural and human-related sources of ozone-forming trace gases in southern Africa. *S. Afr. J. Sci.* **94**, 422–425.
- Swap R.J., Annegarn H.J., Suttles J.T., Haywood J., Helmlinger, M.C., Hely C., Hobbs P.V., Holben B.N., Ji J., King M., Landmann T., Maenhaut W., Pak B., Piketh S.J., Platnick S., Privette J., Roy D., Thompson A.M., Ward D. and Yokelson R. (2002). The Southern African Regional Science Initiative (SAFARI 2000): overview of the dry season field campaign. *S. Afr. J. Sci.* **98**, 125–130.
- Koch G.W., Scholes R.J., Steffen W.L., Vitousek P.M. and Walker B.H. (eds) (1995). *The IGBP Terrestrial Transects: Science Plan*. IGBP Report 36. IGBP Secretariat, Stockholm.

- Scholes R.J. and Parsons D.A.B. (eds) (1997). *The Kalahari Transect: Research on Global Change and Sustainable Development in Southern Africa*. IGBP Report 42. IGBP Secretariat, Stockholm.
- Chanda R., Ringrose S. and Magole L. (eds) (1998). *Towards Sustainable Natural Resource Management in the Kalahari Region, Abstracts and Report from the Kalahari Transect Regional Scientific Workshop*. START Report No. 2.
- Ringrose S. and Chanda R. (eds) (2000). *Towards Sustainable Management in the Kalahari Region: Some Essential Background and Critical Issues*, Directorate of Research and Development, University of Botswana, Gaborone.
- Steffen W. (2000). The IGBP terrestrial transects: tools for resource management and global change research at the regional scale. In *Towards Sustainable Management in the Kalahari Region: Some Essential Background and Critical Issues*, eds S. Ringrose and R. Chandra, pp. 1–12. Directorate of Research and Development, University of Botswana, Gaborone.
- Ringrose S., Vanderpost C. and Matheson W. (1998). Analysis of soil organic carbon and vegetation cover trends along the Botswana Kalahari Transect. *J. Arid Environ.* **38**, 379–396.
- Ringrose S., Lesolle D., Botshoma T., Gopolang B., Vanderpost C. and Matheson W. (1999). An analysis of vegetation cover components in relation to climatic trends along the Botswana Kalahari Transect. *Botswana Notes and Records* **31** and **33**.
- Scholes R.J., Dowty P.R., Caylor K., Parsons D.A.B. and Shugart H.H. (in press) Trends in savanna structure and composition on an aridity gradient in the Kalahari. *J. Veg. Sci.*
- Dowty P., Frost P., Lesolle D., Midgley G., Mukelabai M., Otter L., Privette J., Ramontsho J., Scholes R., Ringrose S. and Wang G. (2000). Summary of the SAFARI 2000 wet season field campaign along the Kalahari Transect. *NASA Earth Observer*
- Privette J.L. (2000). *Southern Africa Validation of NASA's Earth Observing System (SAVE EOS)*. Proc. *IJPRS Remote Sensing 2000*, Cape Town.
- Scholes R.J., Greja N., Giannechinni M., Dovie D., Wilson B., Davidson N., Piggot K., McLoughlin C., van der Velde K., Freeman A., Bradley S., Smart R. and Ndala S. (2001). The environment and vegetation of the flux measurement site near Skukuza, Kruger National Park. *Koedoe* **44**, 73–83. The researchers at the five sites came from Botswana (University of Botswana, Botswana Meteorological Services, Botswana Ministry of Agriculture), Namibia (Etosha Ecological Institute), South Africa (CSIR, University of Natal, University of Venda, National Botanical Institute), Zambia (Zambian Meteorological Department), Zimbabwe (University of Zimbabwe), Australia (Northern Territory University), the U.K. (University College London), and U.S.A. (NASA-GSFC, Boston University, University of Virginia).
- Chen J.M. and Cihlar J. (1995). Plant canopy gap size analysis theory for improving optical measurements of leaf area index. *Appl. Optics* **34**, 6211–6222.
- Feral C.J.W., Epstein H.E., Otter L.B., Aranibar J.N., Shugart H.H., Macko S.A., and Ramontsho J. (in press). Carbon and nitrogen in the soil-plant system along rainfall and land-use gradients in southern Africa. *J. Arid Environ.*
- Aranibar J.N., Otter L.B., Macko S.A., Feral C.J., Dowty P., Epstein H.E., Shugart H.H. and Swap R.J. (submitted) Nitrogen cycling along a precipitation gradient in southern Africa. *Global Change Biology*.
- Privette J.L., Myneni R.B., Knyazikhin Y., Mukelabai M., Tian Y., Wang Y., Roberts G. and Leblanc S. (in press). Early spatial and temporal validation of MODIS LAI in Africa. *Remote Sensing of the Environment*.
- Goodman P.S. (1990). *Soil, vegetation and large herbivore relations in Mkuzi Game Reserve, Natal*. Ph.D. thesis, University of the Witwatersrand, Johannesburg.