# The Southern African Regional Science Initiative (SAFARI 2000): wet season campaigns

L.B. Otter[a*], R.J. Scholes[b], P. Dowty[c], J. Privette[d], K. Caylor[c], S. Ringrose[e], M. Mukelabai[f], P. Frost[g], N. Hanan[h], O. Totolo[i] and E.M. Veenendaal[e]

**The Southern African Regional Science Initiative (SAFARI 2000) involved two wet season and one dry season field campaigns. This paper reports on the wet season campaigns. The first was conducted at five sites along the Kalahari Transect in Zambia (Kataba Forest) and Botswana (Pandamatenga, Maun, Okwa River Crossing, Tshane) during February 2000 and concentrated primarily on characterizing the land surface with respect to exchanges of matter and energy with the atmosphere. The second, conducted in February 2001, focused on fluxes of water, gases and energy between the canopy and the atmosphere at Maun, Botswana, and at Skukuza in the Kruger National Park, South Africa. Eddy covariance measurements at Skukuza and Maun were designed to collect a near-continuous record of the seasonality and inter-annual variability in savanna carbon, water and energy exchanges in representative savanna ecosystems. This paper gives brief descriptions of the sites, the measurements made, and the methods used. It highlights some preliminary results, particularly from the first campaign, and outlines the next stages of the SAFARI 2000 project.**

## Introduction

The Southern African Regional Science Initiative (SAFARI 2000) is an experiment involving atmospheric chemists, plant physiologists, ecologists and meteorologists from 18 countries, with measurements taken during the period from 1999 to 2001.[1] It uses the presence of a semi-closed atmospheric circulation pattern over southern Africa to organize a series of mass-balance studies on the exchange of trace gases and aerosols between the land and the atmosphere across the subcontinent. Its predecessor, SAFARI-92,[2] focused almost exclusively on trace gases resulting from the burning of biomass in wildfires, and showed that other trace gas sources, notably from the soil,[3] plants,[4] industries and domestic fires,[5] contributed substantially to the atmospheric load.[6] One of its hypotheses was that the conspicuous build-up of tropospheric ozone over southern Africa during the spring is a consequence of an interaction between atmospheric constituents derived from dry season fires and dust, with constituents produced by soils and plants following the first rains. SAFARI 2000 aims to improve our understanding of these other sources of trace gases and aerosols, their chemical transformation in the atmosphere, and their transboundary transport in southern Africa.[1]

SAFARI 2000 was designed as an integrated experiment, covering all the major sources and sinks of the reactive substances. This required significant observational effort both in the dry season, with the emphasis on fires and dust, and in the wet season, focused on biogenic processes. Observations were made at various spatial scales, and measurements were taken at ground (up to 1 km$^2$) and tower (21–30 m high, <20 km$^2$) levels, from aircraft (local to regional scale), and from satellites (1000s of km$^2$ to global scale). There were numerous field studies of short duration, and investigations where data were collected continuously or at regular intervals over several years, but most activities occurred during three major field campaigns: wet season campaigns during February/March 2000 and 2001 and the September 2000 dry season campaign.[7] This paper outlines the wet season campaigns and discusses some of the preliminary data, showing overall patterns or trends (a complete analysis of the data is beyond the scope of this article).

[a]Climatology Research Group, University of the Witwatersrand, Private Bag 3, WITS, 2050 South Africa
[b]Division of Water, Environment and Forestry Technology, CSIR, Pretoria, South Africa.
[c]Global Environmental Change Program, University of Virginia, Charlottesville, VA, U.S.A.
[d]NASA Goddard Space Flight Center, Greenbelt, MD, U.S.A.
[e]Harry Oppenheimer Okavango Research Centre, University of Botswana, Maun, Botswana.
[f]Zambian Meteorology Department, Mongu, Zambia.
[g]Institute for Environmental Studies, University of Zimbabwe, Harare, Zimbabwe.
[h]Natural Resource Ecology Laboratory, Colorado State University, Fort Collins, CO, U.S.A.
[i]Department of Environmental Sciences, University of Botswana, Gaborone, Botswana.
*Author for correspondence:
E-mail: luanne@crg.bpb.wits.ac.za

## March 2000 Kalahari Transect campaign

The deep, aeolian sands of the Kalahari Basin cover about a third of southern Africa. The substrate is relatively uniform, but occurs over a wide rainfall gradient (200–1000 mm/yr mean annual rainfall), providing an excellent natural experiment for examining climate–vegetation–soil interactions. This potential led the International Geosphere–Biosphere Programme (IGBP) to designate the 'Kalahari Transect' (KT) as one of several terrestrial transects along which global change phenomena could be studied.[8–12] These transects are sets of field sites covering large areas (in the order of 1000 m across) and spanning significant variation in major environmental or land-use factors. While some homogeneity is acknowledged, the Botswana portion of the transect is known to be heterogeneous in terms of climate and cover density.[13,14] Conceptually, the KT extends from equatorial forest in Congo-Brazzaville to the subtropical, arid shrubland of the Kalahari desert in South Africa.

In February 2000, approximately 40 researchers (the number varied from site to site) travelled from Mongu, Zambia, to Tshane in Botswana, spending an average of four days at each of five sites (Table 1) en route.[18] All five sites are on the southern African plateau, with elevations between 929 and 1115 m (Table 1) (Fig. 1), and were selected to span a significant portion of the rainfall gradient in the region. Immediately before the campaign, the field sites in Botswana had received above-average rainfall, associated with tropical cyclone Eline, an Indian Ocean storm, which led to flooding in the eastern part of the region. By contrast, the Mongu site had received slightly below-normal rainfall at the time of the campaign.

The main objective was to collect accurate data relating to vegetation structure and composition, partitioning of solar radiation, soil nitrogen turnover, ex-

**Table 1**. The five sites visited during the February/March 2000 campaign. They are listed from north to south.

| Site | GPS location | Elevation (m a.s.l.) | Mean annual rainfall (mm) | Vegetation | Additional site information |
|---|---|---|---|---|---|
| Kataba Forest Reserve | 15.44°S, 23.25°E | 1084 | 950 | Kalahari woodland dominated by *Brachystegia spiciformis* with sparse woody understorey | EOS validation core site; 30-m tower |
| Pandamatenga Agricultural Research Station | 18.66°S, 25.5°E | 1065 | 630 | Open woodland dominated by *Ricenodendron* rautanenii, *Baikiaea plurijuga* and *Burkea africana* | Adjacent to large agricultural areas that are subject to light grazing |
| Harry Oppenheimer Okavango Research Centre | 19.92°S, 23.59°E | 929 | 460 | *Colophospermum mopane* woodland | Focus area was 3 km away from a walk-up flux tower and here tree height was lower with patches of *Terminalia sericea* |
| Okwa River Crossing | 22.41°S, 21.71°E | 1089 | 407 | Open Kalahari shrubland dominated by *Acacia mellifera, Terminalia sericea* and *Grewia flava* | Somewhat anomalous site on Pleistocene drainage line |
| Tshane | 24.16°S, 21.89°E | 1115 | 365 | Open savanna dominated by *Acacia leuderitzii* and *Acacia mellifera* | Land-use gradient: away from the site in the direction of Tshane, the grazing intensity increased |

change of $CO_2$, volatile organic carbons (VOCs) and water between vegetation and the atmosphere for the sites along the transect. Table 2 summarizes the measurements made and the techniques used during this experiment. Further details are given in the Earth Observer report[16] and forthcoming individual journal articles. The effects of land use on vegetation and soils at Tshane were also investigated, since grazing pressures increase as one moves away from Tshane towards the village of Hukuntsi.

The campaign coincided with the first remotely sensed measurements of Earth from the Terra satellite, launched by NASA in December 1999.[17] Detailed vegetation measurements are being used to help validate products from the MODIS, ASTER and MISR sensors on the satellite, so the five sites were among the first areas specifically targeted by these instruments (Table 3). Data and products from Landsat 7, NOAA-AVHRR, SPOT, TOMS, Meteosat and SeaWiFS satellites, and fine-resolution (1 m) images from the IKONOS satellite, were also acquired.

As part of the MODIS validation, a 30-m flux tower was erected at the Mongu site (Fig. 2), and used for measuring radiation and gaseous fluxes in and above the Kalahari Woodland canopy. A tower (21 m) was also erected at the Skukuza site (Fig. 2). Located on the ecotone between two different vegetation types, it thus measures the exchanges between *Combretum* savanna and the atmosphere when the wind is from the northwest, and *Acacia* woodland when it blows from the southeast.[15] Following the Kalahari Transect campaign, some researchers visited the Skukuza site to measure soil moisture, canopy $CO_2$ and $H_2O$ fluxes, canopy structure (TRAC and LAI 2000), albedo and scene component spectra (for instance, of grass and shrubs) around the tower site. Soil samples were also collected from the burn trial plots for $^{15}N$ analysis.

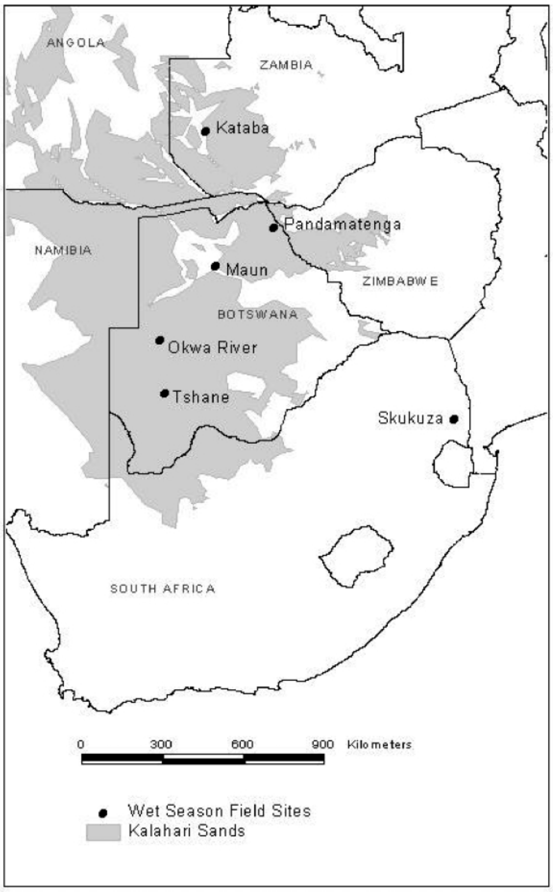



**Fig. 1**. Map of field sites and the extent of Kalahari sands as delineated in the FAO Soil Map of the World.

### February 2001 campaign

The February 2001 campaign focused on the areas around the towers at Maun and Skukuza. The main objective was to investigate and compare canopy fluxes of $CO_2$/$H_2O$ and VOCs at these two very different sites. Researchers at each location also had other objectives as discussed below.

#### Maun, February 2001

The team at Maun consisted of researchers from the Harry Oppenheimer Okavango Research Centre (HOORC, Botswana), CSIR (S.A.), University of Natal (S.A.), National Center for Atmospheric Research (NCAR) (U.S.A), and Lancaster University (U.K.). The tower at Maun is operated by HOORC in collaboration with the Max Planck Institute for Biogeochemistry in Jena. It is equipped with a sonic anemometer and a $CO_2$/$H_2O$ analyser, which have been recording canopy fluxes over the last two years. During this campaign, a second 3D sonic anemometer, linked to a Relaxed Eddy

**Table 2**. Activities and measurement techniques used during the February/March 2000 Kalahari Transect campaign.

| Activity grouping | Measurement interval or sample collection procedure | Parameter or process | Instrument or technique |
|---|---|---|---|
| Meteorology | 30-min intervals<br>30-min averages | Temperature, humidity, wind speed and direction | Wet and dry bulb temperatures; mercury thermometer<br>Weather station on portable tower |
| Leaf and canopy radiation | 3 parallel transects extending 750 m, separated by 250 m and marked at 25-m intervals | Canopy properties<br>(canopy transmission, leaf area, leaf orientation and clumping, % cover) | Licor plant canopy analyser LAI-2000<br>TRAC<br>Decagon Accupar ceptometer<br>Nikon digital hemispherical camera<br>ASD field spectrometer<br>Kipp and Zonen albedometer (near-infrared, shortwave)<br>Kipp and Zonen net radiometer (tower mount) |
| | | Component spectra (e.g. leaves, soil), canopy transmission spectra | ASD field spectrometer, Licor 1800 spectrometer |
| Vegetation structure and composition | | Tree/shrub cover/basal area and composition | Stem map<br>Line transects<br>Circular sample plots<br>Spherical densiometer |
| | | Landscape-scale composition/structure | Line transects |
| | | Grass composition | Line transects<br>Circular sample plots |
| | | Grass biomass | Quadrat clipping |
| | | Root distribution | Soil pit profile/root excavation |
| | | Tree age structure | Tree cores |
| Leaf processes | Measurements made on dominant tree species at the various sites | $CO_2$ and light response curves of photosynthesis and dark respiration at 3 temperatures | Licor 6400 portable photosynthetic system |
| | | Leaf-specific area and mass | Calipers, balance, leaf area meter |
| | | VOC emissions | Samples from leaf enclosures collected on absorbent cartridges and analysed by GC-FID and mass spectrometry |
| Canopy fluxes | Measurements made from flux towers | Canopy energy, water and carbon fluxes | Open path $CO_2$/$H_2O$ analyser, hygrometer, 3D sonic anemometer, net radiometer, air temperature/humidity probe, pyrgeometer |
| Nitrogen cycling | Analyses done on soil samples and leaves of dominant trees and grasses from the various sites; additional samples along a land-use gradient at HOORC and Tshane sites were also collected and analysed | N mineralization | *In situ* isotope dilution method: soil extracts analysed in the laboratory |
| | | Nitrification | *In situ* isotope dilution method: soil extracts analysed in the laboratory |
| | | Nitrogen fixation by soil microorganisms-soil crusts | *In situ* acetylene reduction assay: gas samples analysed the laboratory |
| | | Nitrogen content of leaves, twigs, roots, and soil | Combustion technique using a gas chromatograph |
| | | Soil $NO_3^-$ and $NH_4^+$ | KCl extraction and colorimetry |
| | | NO fluxes from soils | Dynamic laboratory soil incubation chamber technique linked to a chemiluminescence NO/$NO_2$ analyser |
| Atmospheric aerosols | 30-min intervals<br>8–12 h TSP samples | Aerosol characterization and optical thickness<br>Total suspended particulate (TSP) matter | Handheld multispectral sun photometer<br>High volume pump and glass-fibre filters |
| Soil moisture and heat flux | 30-min averages – at portable tower | Soil temperature | Soil heat flux plates (5 cm) and thermocouples (2.5 and 7.5 cm) |
| | | Soil moisture | TDR soil moisture probes (0–30 cm) |
| | 30-min averages – at Kataba Forest Reserve flux tower | Soil moisture<br>Soil temperature | TDR soil moisture probes (5, 15, 30, 60, 125 cm)<br>Thermisters (5, 15, 30, 60, 125 cm); soil heat flux plate (10 cm) |
| | Surface (0–30 cm) measurements over a 1-hectare plot at Kataba Forest Reserve, Pandamatenga, Okwa River Crossing | Spatial variability in soil moisture | Handheld TDR probe |
| Soil characterization | | Texture and particle size distribution<br>Bulk density | Hydrometer<br>Gravimetric methods |

**Table 3**. Characteristics of the various satellite sensors and the data collected during the Kalahari campaign. Satellite data are being collected throughout the SAFARI 2000 campaign.

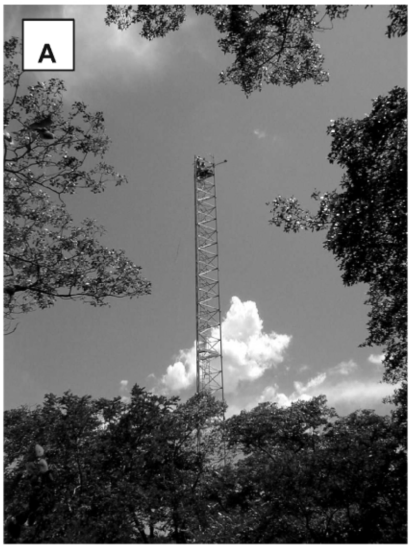
| Sensor | Pixel size (m) | Frequency | Characteristic* |
|---|---|---|---|
| MODIS | 250, 500 and 1000 | Daily | 36 bands, wide range of land products including LAI, FPAR, albedo, surface type, vegetation indices, surface temperature, fire detection |
| MISR | 275, 1100 | 1/9 days (repeat) | 4 spectral bands, 9 view angles, various radiation products |
| ASTER | 15, 30, 90 | 1/16 days (repeat; requested/approved scenes only) | 15 spectral bands, including multispectral thermal infrared |
| Landsat 7 ETM+ | 15, 30, 60 | 1/16 days (repeat, requested/approved scenes only) | 8 spectral bands |
| AVHRR | 1100 | Daily | 5 spectral bands, unique SAFARI products |
| SeaWiFS | 1100 | Daily | 8 spectral bands |
| IKONOS | 1 (pan), 4 (spectral) | Variable depending on view angle limits (requested/approved scenes only) | 4 spectral bands |

*A complete list of EOS products by sensor is available online (http://spsosun.gsfc.nasa.gov/download.html).

Accumulation (REA) system, was set up for sampling canopy VOC emissions, whose concentrations were determined by gas chromatography and a flame ionization detector. An aerosol sampling head containing quartz-fibre filters was also installed on the tower (as well as one at the research station) for collecting atmospheric aerosols. At ground level the branch enclosure technique[4] was used to collect VOC samples in absorbent cartridges from dominant woody species in the area. Physiological variables (such as leaf temperature, photosynthetic rates, stomatal conductance and photosynthetically active radiation), measured with a Licor 6200 instrument, and water stress data were also collected.

### Skukuza, February 2001

An eddy covariance system linked to a closed-path $CO_2$/$H_2O$ analyser, jointly run by the CSIR and Colorado State University, was installed on the tower in April 2000 to measure the canopy fluxes. A REA system, similar to that at Maun, was temporarily installed by the researchers from NCAR for the 2001 campaign period to collect canopy VOC samples. Approximately 150 woody species were screened for isoprene emissions using a Licor 6400 leaf cuvette system linked to a portable gas chromatograph. Samples from dominant species and from species that showed some emissions in the screening phase were collected on cartridges that will be analysed at NCAR for the concentration of all VOCs. At the tower site, physiological measurements (photosynthetic and transpiration rates, light intensity, stomatal conductance) on plants were made by the National Botanical Institute, South Africa, with a Licor 6400.



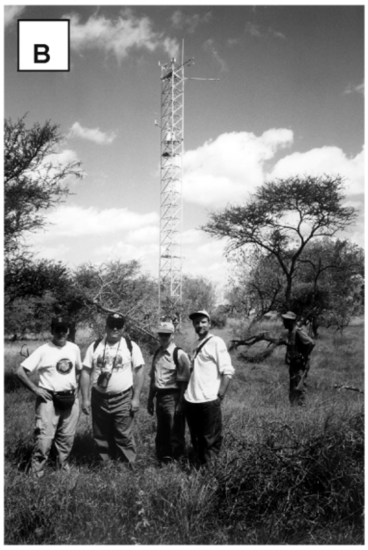




**Fig. 2**. The 30-m and 21-m walk-up towers in Kataba Forest Reserve, Mongu, Zambia (**A**) and Skukuza, Kruger National Park, South Africa (**B**), respectively. From the left, Phil Russell (NASA-Ames), Mark Helmlinger (NASA-Jet Propulsion Laboratory), Tim Suttles (Raytheon), Niall Hanan (Colorado State University) and a game guard further back are seen here standing in front of the Skukuza tower.

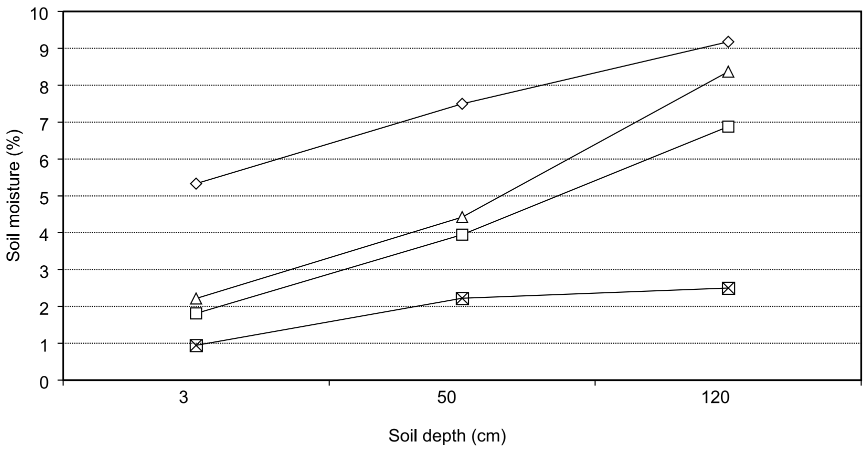



**Fig. 3**. Change in average soil moisture with depth at Pandamatenga (diamonds), Maun (squares), Okwa River Crossing (triangles) and Tshane (stars).

## Preliminary results

### KT campaign

This section shows some of the preliminary results from the Kalahari Transect campaign, whose analysis is continuing. Further information will be presented in more detail in the future.

#### *Soil moisture*

There was a significant decline in soil moisture between Pandamatenga and Tshane at the time of the campaign (with slightly higher values at Okwa River Crossing than at Maun (Fig. 3)). At all sites soil moisture increased with depth.

#### *Vegetation structure and composition*

Spatial analysis indicates significant aggregation across all individuals in the vegetation communities at moister northern sites, and random spatial distributions at southern arid sites. Understorey individuals were more highly aggregated than overstorey individuals. In addition, the spatial pattern of understorey trees in relation to canopy dominants shows a marked transition along the moisture gradient, indicating changing tradeoffs

**Table 4**. Site and plot-level characteristics of woody vegetation at the sampling locations along the Kalahari Transect. Leaf area values are derived from allometric leaf biomass relationship found in Goodman.[23]

| Site | Site-level characteristics[a] | | | | Plot-level characteristics[b] | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Basal area ($m^2$/ha) | Biomass (kg/ha) | Leaf area ($m^2/m^2$) | Stem density (stems/ha) | Plot size ($m^2$) | Basal area ($m^2$/ha) | Biomass (kg/ha) | Leaf area ($m^2/m^2$) | Average no. stems per individual |
| Kataba | 8.47 | 42 064 | 1.703 | 336 | 2 500 | 10.5 | 57 650 | 2.79 | 1.7 |
| Pandamatenga | 15.24 | 49 766 | 1.675 | 432 | 5 000 | 11.9 | 62 180 | 2.02 | 1.2 |
| Maun | 8.65 | 22 105 | 0.738 | 2 622 | 2 500 | 10.1 | 36 200 | 1.86 | 3.6 |
| Okwa | 1.93 | 2 822 | 0.190 | 7 000 | | | | | |
| Tshane | 5.32 | 15 175 | 0.509 | 4 547 | 10 000 | 3.0 | 13 000 | 0.51 | 6.1 |

[a]Characteristics determined from a 300 x 350 m area, with vegetation sampled in 42 circular plots of radius 5 m.
[b]Characteristics of woody vegetation derived from detailed stem-map data of overstorey and understorey vegetation for a smaller area within the larger 300 x 350-m grid.

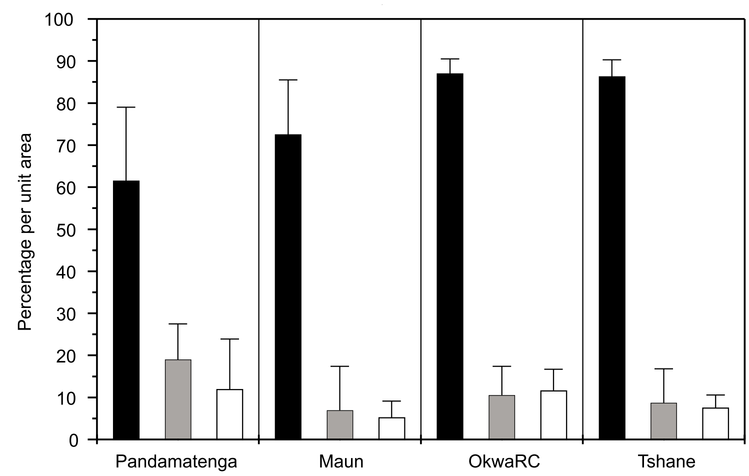



**Fig. 4**. The average change (mean + s.e.) in woody (black), grass (grey) and forbes (white) cover at four sites along the Kalahari Transect.

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 ($m^2/m^2$), 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 ($0.7 < \Omega < 0.76$ 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 significantly[20] (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 $^{15}N$ 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.

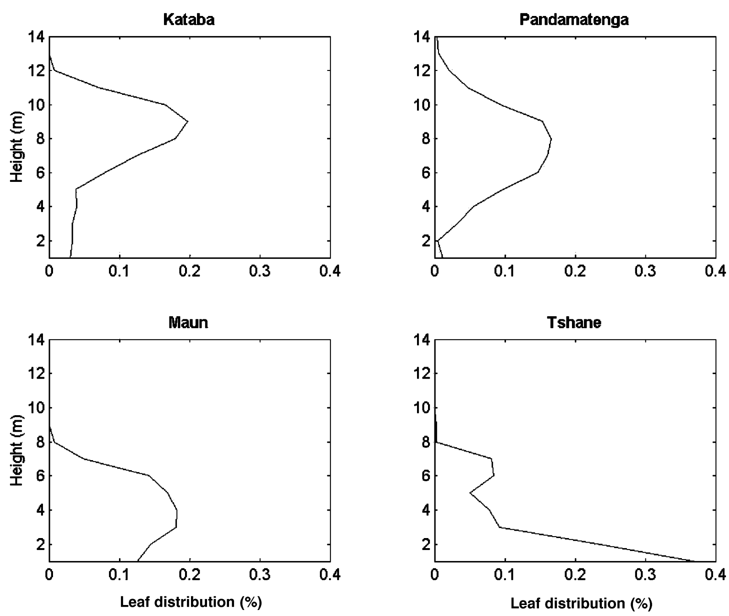



**Fig. 5**. Distribution of leaves in the canopy at four sites along the Kalahari Transect.

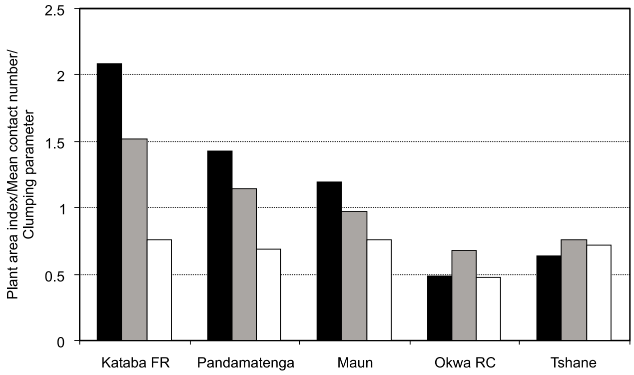



**Fig. 6**. Plant area index (black), mean contact number (grey) and the clumping parameter (white) for the vegetation along the Kalahari Transect.

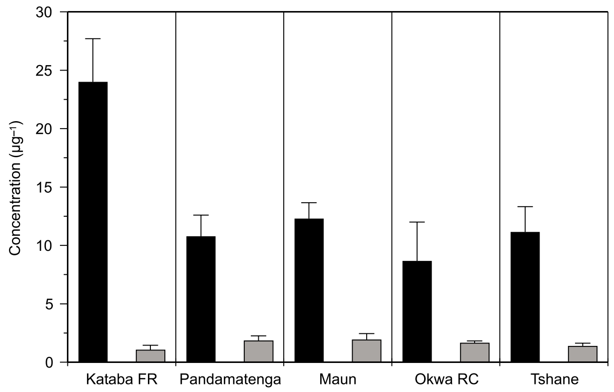



**Fig. 7**. Mean (± s.e.) soil ammonium (black) and nitrate (grey) concentrations along the Kalahari Transect (taken from Feral *et al.*[20]).

### *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 $CO_2$, water (LE) and energy ($H$) began at Skukuza in April 2000. With the exception of data breaks during periods of 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 $CO_2$ 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

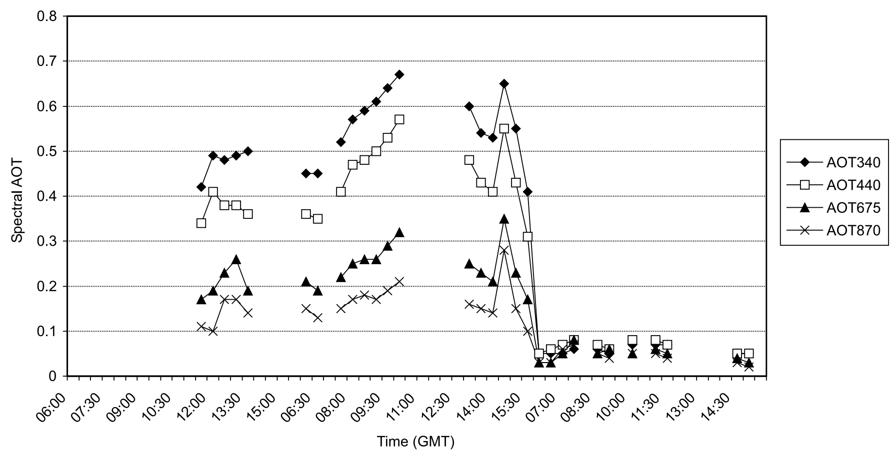



**Fig. 8**. Time series of instantaneous measurements of aerosol optical thickness (AOT) at 340, 440, 675 and 870 nm in Maun, Botswana, during the Kalahari Transect wet season campaign, from 7 to 9 March 2000.

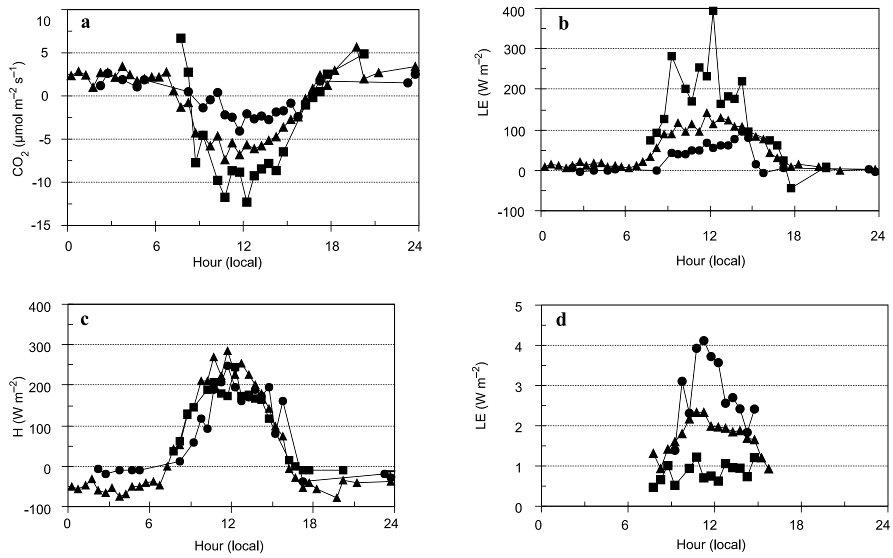



**Fig. 9**. $CO_2$ flux (**a**), latent heat flux (**b**), sensible heat flux (**c**) and daytime Bowen ratio (**d**) measured from the tower at Skukuza on 13 April (squares), 13 May (triangles) and 20 June 2000 (circles).

*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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1. 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).
2. Lindesay J.A., Andreae M.O., Goldhammer 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.
3. 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.
4. 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.
5. 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.
6. 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.
7. 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.
8. 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.
9. 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.
10. 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.
11. 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.
12. 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.
13. 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.
14. 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**.
15. 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.*
16. Dowty P., Frost P., Lesolle D., Midgly 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*
17. Privette J.L. (2000). *Southern Africa Validation of NASA's Earth Observing System (SAVE EOS). Proc. IJPRS Remote Sensing 2000,* Cape Town.
18. Scholes R.J , Greja N., Giannecchinni 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).
19. 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.
20. 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.*
21. 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.*
22. 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.*
23. Goodman P.S. (1990). *Soil, vegetation and large herbivore relations in Mkuzi Game Reserve, Natal.* Ph.D. thesis, University of the Witwatersrand, Johannesburg.