

Southern Africa as a remote sensing test bed: the SAFARI 2000 Special Issue overview

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NASA's flagship Earth Observing System (EOS) Terra satellite was launched in 1999 and began sensing in March 2000 coincident with the first major field campaign of the Southern Africa Regional Science Initiative (SAFARI 2000). Terra's five sensors were used to support SAFARI 2000 studies on the southern African environment, and SAFARI 2000's ground, aircraft and independent satellite data sets were used in turn to validate and improve the remote sensing products derived from Terra. In this article, we review southern Africa's natural and cultural features that we believe formed an optimal environment in which to test the EOS program (including new sensors, products, validation, scientific research, education and outreach). Through the course of the text, we reference and summarize the articles in the SAFARI 2000 Special Issue to highlight the natural links between remote sensing science and the subcontinent's characteristics. We also note contemporary forces of change in the southern Africa landscape whose impacts will challenge the remote monitoring capabilities of future sensors and scientists. The article concludes with a brief description of SAFARI 2000 data resources and access provisions.

1. Introduction

Africa is experiencing rapid and substantial social, economic, and environmental change (UNEP 2002). Some studies suggest that this pattern will continue or intensify. For example, recent climate predictions suggest Africa could be 2–6°C warmer in 100 years' time; rainfall changes are more uncertain (Hulme *et al.* 2001). It is unclear how Africa's ecosystems will respond to such changes. Southern Africa may be especially vulnerable due to the dynamics of its climate, human demographics and disturbance regimes, such as herbivory and fire. Some models of the region suggest ecosystem instability could occur, particularly in the extensive semi-arid areas (e.g. Joubert *et al.* 1996). The instability may be compounded by the strategies that inhabitants use to adapt to environmental and socio-economic changes (IPCC 2001). The perceived threats to the regional ecology and climate have led the World Meteorological Organization (WMO; Easterling *et al.* 2003), the Intergovernmental Panel on Climate Change (IPCC 2001), and the International Geosphere Biosphere Programme (IGBP; Scholes and Parsons 1997) to prioritize southern Africa as a focus for scientific assessment (e.g. Schulze *et al.* 1993).

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To help address the uncertainty, researchers from southern Africa collaborated with the wider international science community to organize and conduct the Southern Africa Regional Science Initiative (SAFARI 2000). The aims of SAFARI 2000 were to identify and understand the linkages between land–atmosphere processes in southern Africa, and in particular to study the relationship of biogenic, pyrogenic and anthropogenic emissions and the consequences of their deposition to the functioning of the region’s biogeophysical and biogeochemical systems (Swap *et al.* 2002a). SAFARI 2000 was developed around existing activities and was designed to pool resources and exploit modern field, aircraft and space-based instrumentation. The Initiative emphasized new space-borne observatories, interdisciplinary teamwork and cross-border studies. Its implementation provided measurements at different scales over 4 years (1999–2002) with intensive campaigns held during the 2000–2001 wet and dry seasons. The 2000 wet season campaign (Otter *et al.* 2002) was timed to assess land and atmospheric properties during peak green biomass conditions, and the dry season campaign (Swap *et al.* 2002b) was timed to coincide with the subsequent peak biomass burning period.

With the operations of NASA’s flagship Earth Observing System (EOS) Terra satellite commencing in early 2000, SAFARI 2000 also provided the first comprehensive test of NASA’s EOS. EOS is the implementation arm of the Mission to Planet Earth Program (MTPE), conceived in the 1980s, later renamed the Earth Sciences Enterprise (ESE) program (NASA 1999) and now part of the Earth–Sun System Division. The ESE program mission was to integrate the Earth and environmental sciences into an interdisciplinary study of earth system science (NASA 1996). This necessitated advances in earth process modelling and data assimilation, satellite observation technology, remote sensor instrument design and calibration, systematic generation and distribution of high volume satellite products, and quality assessment and validation of the products (NASA 1999).

Many recognize EOS by its three largest satellites: (1) Terra, launched in 1999 and emphasizing systematic land, atmospheric and ocean measurements; (2) Aqua, launched in 2002 and emphasizing water cycle measurements; and (3) Aura, launched in 2004 and focused largely on atmospheric chemistry measurements. NASA systematically processes data from these satellites to derive high-level products. The products are archived in near-real time and available at no cost to the worldwide community. In addition to satellites and products, the EOS program also emphasizes science education, international cooperation and scientist-to-layperson interactions to benefit public policy and knowledge (NASA 1996). As a comprehensive integrated system, EOS offers an opportunity to change the technical content of earth science research in the US and, through international partnerships and free data product access, the world (NASA 1996). Against this background, SAFARI 2000 was more than an opportunity to use and regionally validate Terra satellite products: it was an early chance to link all of the EOS subcomponents (satellites, algorithms, data systems, integrated science, policy and societal outreach) and thus provide the first end-to-end assessment of the EOS program’s premise.

In this overview of the SAFARI 2000 Special Issue of the *International Journal of Remote Sensing*, we outline the rationale for making southern Africa the early test bed for EOS. Specifically, we consider SAFARI 2000 from a remote sensing perspective. We do this by reviewing important features of the environment, climate, and cultural regimes as appropriate for a reader unfamiliar with the region. At relevant points in the text, we summarize Special Issue articles that used remote

sensing to address or exploit the environmental features. Together with companion special issues in *South African Journal of Science* (Otter *et al.* 2002), *Journal of Geographical Research* (Swap *et al.* 2003), *Journal of Arid Environments* (Totolo and Chanda 2003), and *Global Change Biology* (Shugart *et al.* 2004), this issue highlights some of the returns on SAFARI 2000.

2. Background

2.1 Satellite sensors in SAFARI 2000

Appreciating the fit of SAFARI 2000 to the EOS program requires some background on the capabilities afforded by EOS satellites. Technically, only two EOS platforms, Terra and Landsat 7, were available during SAFARI 2000. However, we use 'EOS' loosely here to refer to all platforms supported under NASA's ESE program, including the New Millennium Program, Earth System Science Pathfinders, and commercial and government agency partnerships; see table 1. Non-NASA platforms, particularly Europe's METEOSAT, were also employed and are included in table 1. For brevity, we only note significant features relative to earlier remote sensing systems.

The most notable remote sensing advancement during SAFARI 2000 was the EOS Terra satellite and its derived earth science products (NASA 1999). SAFARI 2000 investigators particularly used the land and atmosphere products (summarized in table 2) derived from the MODIS sensor on Terra. Although initial Terra product generation in 2000 lagged the observations by up to 50 days, product latency was reduced to just 2–3 days by 2001. Upon generation, the MODIS products became accessible online through the EOS Data Active Archive Centers (DAACs)—the Land Process (LP) DAAC for land products, and the GSFC Earth Sciences (GES) DAAC for atmospheric products.

The Landsat 7 Enhanced Thematic Mapper Plus (ETM+) sensor was also used extensively in SAFARI 2000, with more than 50 scenes acquired per Landsat path/row in southern Africa between 2000 and mid-2003 (figure 1). Many of these scenes were acquired automatically via the Landsat Long Term Acquisition Plan (LTAP; Arvidson *et al.* 2003). SAFARI 2000 collaborators submitted requests to the Landsat 7 team to increase LTAP acquisition priority for designated path/rows during field campaigns or when time series acquisitions were needed (e.g. Roy *et al.*, 2005). The ETM+ data proved especially helpful for mapping land cover and burned areas, as well as scaling up biophysical field measurements. Through a partnership with the Tropical Rain Forest Information Center (TRFIC; <http://www.landsat.org/dataservices/SAFARI2000>), the requested scenes are accessible online to the scientific community.

High-resolution data from the New Millennium Program (NMP) Earth Observing-1 (EO-1) satellite complemented the ETM+ acquisitions. EO-1 was launched in November 2000 and trails Landsat 7 on orbit by 1 min, facilitating synergistic data use. The EO-1 carries three technology demonstration sensors (table 1), including the hyperspectral imager Hyperion and Advanced Landsat Imager (ALI). Hyperion's 220 spectral bands provide the potential to deconvolve mixed land, atmosphere, and subpixel signals better than heritage systems. ALI's superior spectral coverage and higher signal-to-noise measurements, relative to Landsat ETM+, allow more accurate landcover mapping (Neuenschwander and Crawford 2005).

Table 1. Characteristics of the primary satellite sensors used in SAFARI 2000.

Satellite	Sensor	Nadir Pixel Size (m)	Frequency	Characteristics
EOS Terra	MODIS	250, 500 and 1000	Every other day (below $\sim 30^\circ$ latitude); Every day (above $\sim 30^\circ$ latitude), 1/16 days (repeat)	36 bands; systematically derived terrestrial, atmospheric, and oceanic products*
	MISR	275, 1100	1/9 days (repeat)	Four spectral bands, nine view angles
	ASTER	15, 30, 90	1/16 days (repeat; requested/approved scenes only)	15 spectral bands
EOS Landsat 7	ETM+	15, 30, 60	1/16 days (repeat; requested/approved scenes only)	Eight spectral bands
New Millennium Program NMP Earth Observing 1	ALI	30	Variable, but nominally 1/16 days (requested/approved scenes only)	10 spectral bands, including Panchromatic
	Hyperion	30		220 spectral bands
	LEISA AC	250		256 spectral bands
IKONOS	IKONOS	1, 4	Variable depending on view angle limits (requested/approved scenes only)	Five spectral bands, including Panchromatic
OrbView-2	SeaWiFS	1100	Daily	Eight spectral bands
Earth Probe	TOMS	>50 000	Daily	Six spectral bands
NOAA-14	AVHRR	1100	Daily	Five spectral bands; custom SAFARI 2000 products generated
METEOSAT-7	VISSR	2500, 5000	Every 30 min	Three spectral bands

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

Table 2. MODIS land and atmospheric products used in SAFARI 2000.

MODIS product identifier	Product family
<i>Atmosphere</i>	
MOD 04	Aerosol products
MOD 05	Total precipitable water (water vapour)
MOD 06	Cloud products
MOD 07	Atmospheric profiles
MOD 08	Atmospheric products (level 3 gridded statistics)
MOD 35	Cloud mask
<i>Land</i>	
MOD 09	Land surface reflectance
MOD 11	Land surface temperature and emissivity
MOD 12	Land cover
MOD 13	Vegetation indices
MOD 14	Thermal anomalies (active fire detection)
MOD 15	Leaf area index and FPAR†
MOD 17	Net photosynthesis and primary productivity
MOD 43	Albedo and BRDF* characterization
MOD 44	Vegetation continuous fields

Each product may contain multiple parameters and be available in gridded and ungridded formats.

†FPAR: fraction of absorbed photosynthetically active radiation.

*BRDF: bidirectional reflectance distribution function.

Other satellites were employed less frequently in SAFARI 2000. Twenty-eight IKONOS scenes, coordinated and purchased through NASA's Data Buy program and hosted online through TRFIC, brought fine spatial resolution (~1–4 m) capabilities to the Initiative. IKONOS data were primarily used for remotely assessing the fraction of woody vegetation cover at field sites and for scaling field measurements to coarser resolutions for EOS validation. The TIROS-N series of polar orbiters carry the multisensor TIROS Operational Vertical Sounder (TOVS) and AVHRR, a five-band moderate resolution imager, among other sensors. TOVS provided atmospheric profiles of meteorological fields for assimilation into weather forecast and climate models and for studies of inter-annual and long-term climate variability. AVHRR images were used to map daily aircraft flight plans (e.g. to assess cloudiness and smoke densities) during the 2000 dry-season campaign. Given its nearly 20-year multimission span, AVHRR also provided a historical record that revealed environmental and climatological trends and cycles in the region (Scanlon *et al.* 2002, Anyamba *et al.* 2003, Pinheiro *et al.* 2004). The eight-band SeaWiFS sensor, onboard OrbView 2, provides similar moderate-resolution imagery, but was designed for ocean colour monitoring. Eckardt and Kuring (2005) also found SeaWiFS to be well suited for detecting dust aerosols over water. SeaWiFS and AVHRR also provide benchmarks upon which to assess EOS. The Earth Probe's Total Ozone Mapping Spectrometer (EP-TOMS) provided observations over the region in six ultraviolet spectral bands, from which SAFARI 2000 investigators generated Daily Aerosol Index and Tropical Tropospheric Ozone maps in near-real time during the dry season campaigns. High-frequency imagery from the geostationary Meteosat-7 was acquired at the South African Weather Bureau and used primarily to support aircraft deployments and to characterize weather events during the Initiative.

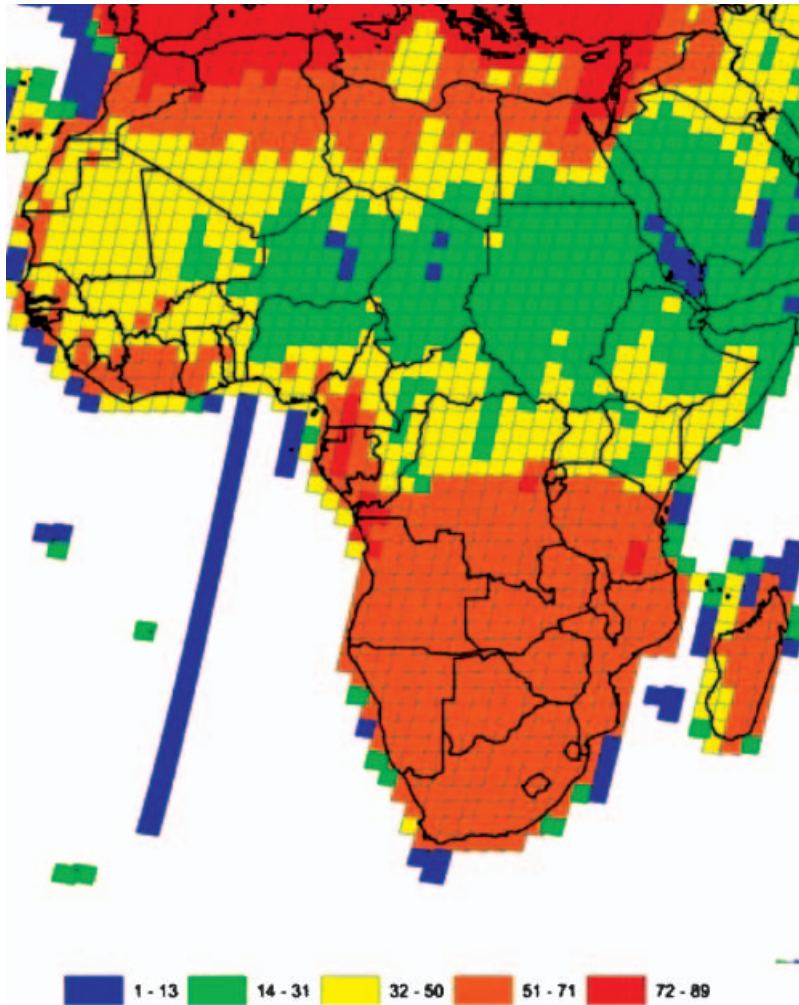


Figure 1. Colour-coded map indicating the number of Landsat 7 scenes acquired for each path/row sequence over Africa between 29 June 1999 and 31 May 2003. SAFARI 2000 requests for Landsat 7 data in part led to an acquisition rate of more than 50 scenes for locations south of the equator. That collection together with the Initiative's field, aircraft and other satellite data now provides a rich archive for further research.

2.2 Aircraft sensors in SAFARI 2000

The wide range of spatial scales encompassed in SAFARI 2000 investigations prompted the use of research aircraft during the intensive field campaigns. Aircraft activity peaked during the 2000 dry season campaign when five aircraft flew simultaneously: the University of Washington CV-580, two South African Weather Service Aerocommander 690As, the United Kingdom Meteorological Office C-130 and the NASA high-altitude ER-2 remote sensing aircraft. The aircraft were deployed to sites hosting field measurements, along land cover gradients, over large biomass fires and emission plumes, through vertical atmospheric strata, and over coastal waters. In some cases, the aircraft underflew the Terra satellite. Their onboard sensors ranged from *in situ* nephelometers to wide field-of-view imagers.

The imagers on the ER-2 included EOS Terra sensor simulators (e.g. AirMISR, MODIS Airborne Simulator). These sensors were used to collect EOS-quality measurements and test EOS product algorithms at finer spatial scales than afforded by their associated Terra-based sensors (King *et al.* 2003). Within this Special Issue, only one article (Hao *et al.* 2005) incorporated aircraft remote sensing data. We refer readers interested in additional aircraft-based studies to the Special Issue of the *Journal of Atmospheric Research* (Swap *et al.* 2003).

3. Southern African remote sensing test bed

The SAFARI 2000 study region encompassed Africa's land south of the equator, although the majority of land studies addressed locations from Zambia southward (latitude $>8^{\circ}$ S). Although it comprises less than half of the continent, southern Africa hosts a wide range of conditions. Climatologically, most of southern Africa experiences semi-arid subtropical weather characteristics, with hot rainy summers and warm dry winters. The great majority of rain falls in the austral summer (\sim November through April). Generally, annual precipitation is greatest in northern areas (>1200 mm per year) and decreases to the south and south-west (~ 150 mm per year). However, more extreme rainfall patterns exist near the subcontinent's perimeter, from continuously wet conditions in humid equatorial regimes on the western side of the continent and at high altitudes along parts of the east side (up to more than 3000 mm rain per year), to seasonally arid regimes (as little as 20 mm per year in parts of the Namib Desert) (Nicholson *et al.* 1988).

Approximately two-thirds of the subcontinent is covered by deep Aeolian sands (Kalahari Sands, covering ~ 2.5 million km^2), with the remaining soils largely composed of sedimentary material with basaltic intrusions (Scholes and Parsons 1997). Most of these soils are fairly old and depleted of key nutrients such as phosphorus. At the regional scale, soil fertility is negatively related to rainfall (Van Wilgen and Scholes 1997).

The climate and soil nutrient characteristics exert important regional controls on the type and amount of vegetation (Scholes *et al.* 2002, Shugart *et al.* 2004 and articles therein). The dominant biomes are savannah ecosystems and their variants including arid shrublands, lightly wooded grasslands, deciduous woodlands and dry forests. The savannahs are pervasive, such that 60% of those worldwide are in Africa, and 60% of African savannahs are in the SAFARI 2000 region (R.J. Scholes, personal communication 2001). The northern reaches of the savannahs transition to woodlands. The economically important Miombo woodlands, which extend north into Central Africa, comprise the largest continuous block (~ 2.7 million km^2) of dry deciduous woodlands in the world (Desanker *et al.* 1997). To the south of the savannah areas, vegetation becomes increasingly sparse, transitioning to shrublands and grassy deserts. We refer readers to Ringrose and Chanda (2000) for a fuller description of Kalahari vegetation and land issues.

The savannahs provide challenging remote sensing targets over which to test land algorithm physics due to the discontinuous canopy structure and associated crown shadowing. In SAFARI 2000, the extensive homogenous savannahs in regions of low topographic relief, relatively low population density, and fairly consistent soil background allowed scientists to focus on algorithms with less concern about precise geolocation or topographic correction. For example, Hansen *et al.* (2005) tested the ability of several MODIS-derived intermediate products (e.g. monthly composites and temporal metrics) to predict fractional overstory cover in western Zambian

woodlands and to validate the MODIS Vegetation Continuous Fields (VCF) product. They found that composites work nearly as well as single overpass swath imagery. Their VCF product was subsequently used by other SAFARI 2000 researchers, such as Pinheiro *et al.* (2004), who related continental canopy structure to directional thermal remote sensing effects.

3.1 Disturbances

Although the southern African landscape is expansive and less developed relative to many regions, it is by no means stationary. Significant physical and biotic disturbances continuously impact southern African ecosystems (IPCC 2001). These forces are sometimes compounded by anthropogenic forces at different temporal and spatial scales, from local land use changes to globally elevated carbon dioxide levels. Below, we describe the major environmental forcings that were, or could be, addressed in SAFARI 2000 together with contemporary remote sensing systems like EOS.

3.1.1 Fire disturbanc. Fire is prevalent throughout Africa, with most fires in southern Africa ignited by people for land-management purposes (Frost 1999). The savannahs of Africa are thought to experience the most extensive biomass burning in the world (Scholes and Andreae 2000). For example, African fires have been shown to have a measurable effect on the seasonal cycle of atmospheric CO₂ recorded at Ascension Island in the Atlantic (Wittenberg *et al.* 1998). Here, we discuss the savannah and dambo landcover systems that contribute substantively to the subcontinent's burning regime.

The series of events comprising the savannah fire regime suggests the complexity of the land-atmosphere interactions in the region. Savannah fire characteristics depend significantly on the soil type: eroded, acidic, nutrient-poor soils tend to have larger, hotter fires, while nutrient-rich soils tend to have smaller, cooler fires (Scholes and Walker 1993). Vegetation on fertile soils is generally nutritious and palatable to herbivores, which graze and reduce the herbaceous biomass. Soil microbes similarly consume dead matter. These biomass consumers significantly reduce the fuel load available for fires. In contrast, the predominate granitic soils in the region are relatively infertile, such that the vegetation (typically broad-leafed savannah) is unable to fix nitrogen adequately after the initial spring green-up. By summer, this results in nutrient-poor grasses which are largely non-palatable to both herbivores and microbes. When these grasses senesce in the Austral Autumn, they create a mat of combustible dry material that is susceptible to fire. While pervasive and frequent, savannah fires tend to remain confined to the grassy understories; tree crowns rarely ignite (Frost 1996).

Dambos also burn frequently but provide a more limited fire hazard. Dambos are large, flat shallow depressions in the ground characterized by seasonal flooding. They typically form atop a clayey-sandy-loamy soil in south Central Africa (Democratic Republic of Congo, Zimbabwe, Zambia, Angola, Tanzania and Mozambique). Their fertile soils are covered with grasses but little woody material, and are used extensively for grazing and agriculture. By burning dambos, local inhabitants can remove dead debris such that the next season's crop or fodder is more robust (Raussen *et al.* 1996).

Six studies in this Special Issue address fire characteristics in the dambos and savannahs of southern Africa. Roy and Landmann (2005) studied savannah fires,

and described the changes in surface spectral reflectance as a function of burned area fraction and combustion completeness. Their approach is based on linear mixture modelling of reflectance spectra collected over prescribed burns South Africa. They demonstrate that burned-area fraction and combustion completeness cannot be spectrally deconvolved in the absence of additional information. Similarly, Sá *et al.* (2005) considered the relationship of burn spectral reflectance to combustion completeness over dambos. They found significant non-linear relationships between combustion completeness and simulated Landsat ETM+ visible band responses derived from ground-based spectrometer data. These articles suggest that remote detection of combustion completeness may be possible but only in a site-specific manner.

The various efforts to understand the reflectance spectrum of savannah fires will likely lead to more accurate satellite remote sensing products. Roy *et al.* (2005) devised a protocol for assessing the accuracy (validation) of the MODIS burned area product based on estimating the fractional cover of burn areas using multi-temporal Landsat ETM+ data. Their approach was implemented under the auspices of the Southern Africa Fire Network (SAFNet), a regional component of the Global Observation for Forest and Land Cover Dynamics (GOFD/GOLD; <http://www.fao.org/gtos/gofc-gold/>) programme. The SAFNet continues to serve the region (<http://safnet.umd.edu/>). Similarly, Morissette *et al.* (2005) developed an approach to validate the moderate-resolution active fire-detection product from MODIS using high-resolution ASTER data. By analysing 18 different scenes with statistical models, they characterized the probability of detecting fires (binary: 'fire' or 'no fire') with MODIS as a function of the spatial heterogeneity detected with ASTER. They conclude that a logistical regression model, refined with a random 'mixed effect' model, provides a robust estimator. They recommend this for future MODIS fire validation studies.

The frequency of fires in the southern Africa dry season leads to significant regional atmospheric pollution (both gases and particulates). Earlier studies (e.g. Garstang *et al.* 1996) determined that a semi-persistent high-atmospheric-pressure gyre often recirculates fire emissions around the region. Aerosol deposition within the gyre leads to fertilization, potentially offsetting the surface nutrient losses to fire emissions (Garstang *et al.* 1998). Eventually, however, easterly winds sweep most remaining particulates out over the Atlantic and Indian Oceans. SAFARI-2000 scientists (Annegarn *et al.* 2002, Swap *et al.* 2003) also observed an abrupt 'River of Smoke' that marked a regional-scale purge of smoke-laden air off the south-eastern coast (over the Indian Ocean). The factors controlling the relative dominance and frequency of these two large exit streams are not fully understood, although recent work has begun to describe the process (Kanyanga *et al.* submitted).

The ability to track and quantify these emission aerosols was significantly advanced with EOS Terra in SAFARI 2000. Data from both MODIS and MISR are used to operationally generate aerosol optical thickness (AOT) products. Hao *et al.* (2005) investigated the accuracy of the MODIS AOT product (10 km × 10 km resolution; daily) using sun photometers, including stationary units from the Aerosol Robotic Network (AERONET), handheld units from the US Forest Service, and a mobile unit flown on the CV-580 aircraft. They found that in areas of intense biomass burning, the MODIS AOT values at 470, 550 and 660 nm were consistently 40–50% lower than ground- and aircraft-based measurements. The accuracy varied with view direction and land cover, suggesting that the MODIS

algorithm's surface reflectance anisotropy and the aerosol scattering phase function differences need further attention. Their study ultimately helped motivate improvements in the MODIS AOT algorithm (Y. Kaufman, personal communication 2004).

An end-to-end (fuel to fire to emissions) investigation of a savannah wildfire near Etosha National Park (Namibia) was conducted by Alleaume *et al.* (2005). By extrapolating field biophysical measurements with local vegetation maps and correlating the results with the MODIS vegetation index, they developed a 500 m resolution map of fractional tree cover. They also measured fire fuels (e.g. woody debris, litter grass) in plots within and alongside a large prescribed burn. By relating the field-measured fuels to their fractional cover product, they created maps of the fire's fuel load and combustion completeness. This allowed estimation of the fire's total emission of various gases and particulates. Their results suggest that the case study fire may have emitted up to 1.5% of the total CO₂ emitted in the region during the August–September peak fire period of other recent years. They too caution that combustion completeness can vary significantly within a pixel, and that a common satellite-derived fire severity index proved ineffective.

3.1.2 Hydrological disturbance. Interspersed with the normal wet/dry seasonality and north–south rainfall gradient in the region (see §3) are a series of strong episodic rainfall phenomena. The areas of low rainfall in many cases overlap areas of high evaporation potential, and variability in rainfall can result in periodic episodes of severe and prolonged drought (UNEP 2002). Tyson (1986) hypothesized an 18-year rainfall oscillation (successive spells of nine 'wet' and nine 'dry' years) in southern Africa; more recent work finds additional variability at a higher frequency, such as 2.3, 3.5, 5 and 6 years (Nicholson 2000). The entire region is subject to extremes in interannual climate variability associated with the El Niño/Southern Oscillation (ENSO) phenomenon (Janowiak 1988, Lindsey 1988). This is exemplified by a biennial tendency in rainfall fluctuations over the region (Ropelewski and Halpert 1996).

Under low rainfall conditions, Aeolian processes primarily cause soil erosion and may produce significant mineral aerosol loadings that are transported and later deposited to provide nutrients. South-western Africa provides an excellent target for detecting erosion and assessing mineral dust aerosols due to the abutment of extensive desert against the clear upwelling waters of the south-eastern Atlantic Ocean. The prevailing easterly winds often carry sand well out over the ocean. Eckardt and Kuring (2005) used SeaWiFS data to observe approximately 150 dust plumes over three years and demonstrate the persistence of mineral dust production point sources. The dust source is maintained by fluvial landforms and associated hydrology at either saltpans or dry river beds in the Namib Desert. Eckardt and Kuring (2005) suggest that recharge of dust sources in the Namib Desert is likely to occur on shorter timescales than the accumulations that fuel the world's more important source regions.

While much of southern Africa is susceptible to water stress and heightened Aeolian processes, the significantly above average precipitation in the 1999–2000 wet seasons, associated with a cold ENSO event (La Niña), brought the opposite disturbance—flooding—to eastern areas. The period was punctuated in January by Tropical Cyclone *Eline*, which made landfall near Maputo, Mozambique before travelling north and heading east over the Indian Ocean. The impacts of *Eline* were severe and widespread. Most rivers in the eastern part of the region flooded, many

lives were lost, and many landscapes were altered through destruction of riparian habitat. A particularly dense grass layer developed in response to the above-average rainfall, and the subsequent 2000 dry season biomass burning was particularly robust (Hély *et al.* 2003).

In contrast to such large episodic events, regular flooding events are sometimes critical to sustaining some of the wetland systems in the region. For example, the Okavango Delta in north-west Botswana is the largest inland delta in the world. Its source is the Okavango River, whose headwaters drain Angola's western highlands. Instead of flowing into the sea, the annual winter flood (June–August) of fresh water flows inland, spreading over more than 15 000 km² of Kalahari sand in a mosaic of lagoons and channels. This highly fractured landscape provided an excellent target for analyses of fine-resolution sensors such as EO-1, Landsat and ASTER.

Because the Okavango floods during the dry season, remote sensing research on flood evolution and associated land change can be conducted with comparatively little hindrance from clouds. Specifically, high-resolution 'tasked acquisition' (non-continuous imaging) systems (e.g. Landsat, EO-1) can acquire clear scenes on consecutive targeting opportunities for assessing temporal trends. McCarthy *et al.* (2005) exploited this in developing a new Okavango Delta land cover map that evolved from a novel two-step classification approach. Prior studies had suggested that landcover patterns are correlated with the flooding processes. McCarthy *et al.* (2005) therefore developed flooding metrics from a time series of moderate resolution AVHRR data. To classify the region, they first used traditional statistical methods, then exploited the inundation metrics in tandem with Landsat vegetation indices. They found the two-step approach improved mapping accuracy.

Neuenschwander *et al.* (2005) used a recently developed supervised classification technique to help assess the validity of the EO-1 technology demonstration sensors over the Delta. They used a time series of Advanced Landsat Imager (ALI) and ETM+ scenes to discriminate 23 landcover classes in the eastern Okavango Delta and linked these classes to the inundation frequency and duration. They observed that the amount of water was similar between 2001 and 2002, however the spatial distribution and flooding patterns differed. They achieved consistently higher classification accuracy with ALI compared with ETM+, which they attribute to the ALI's higher signal-to-noise ratios and greater radiometric dynamic ranges.

Despite these and many prior studies, the evolution and fate of the Delta are not clear. The Delta ecosystem itself is nutrient-limited, since the Okavango River water is relatively clean. However, as fresh water becomes increasingly scarce, proposals to divert water from the Okavango River before it reaches the Delta have been presented. A shrinking Delta would likely induce salinization and drying effects (desertification) on local ecosystems. Ringrose *et al.* (2005) consider the ability to detect drying gradients in the Delta using aircraft and satellite imagery. They postulate that islands grew from former floodplains colonized by riparian vegetation and created encircled areas that became more densely treed. Their evidence suggests that after long-term exposure to drying, soil humic content becomes negligible. They support their theory with field measurements.

3.1.3 Contemporary anthropogenic disturbance. The advantages of testing EOS in southern Africa are largely a consequence of the unique climatic and land cover disturbances described above. However, the present outline of regional forcings would be incomplete without mention of major contemporary anthropogenic

factors—political instability, population changes, and disease—that were not addressed directly by SAFARI 2000 studies.

Parts of southern Africa have suffered from armed conflict or political instability almost continuously for the past three decades. In January 2002, more than 6 million people in sub-Saharan Africa fell under the mandate of the United Nations High Commission on Refugees (Buvé *et al.* 2002). The consequent socio-economic, security and environmental issues have prompted significant settlement and land use shifts. For example, urbanization in Angola and Mozambique has been driven largely by civil conflict, which forced many rural residents to flee to relatively safer urban areas (UNEP 2002). Other land and demographics changes are driven by explicit changes in government policy, such as the recent rapid reallocation of commercial farm ownership and the initiation of a fast-track resettlement plan in Zimbabwe (Waeterloos and Rutherford 2004).

On a larger scale, southern Africa has one of the world's highest rates of natural population increase: approximately 2.1% per year (Cohen 2004). The challenge of feeding the growing population has in some cases led to overexploitation of resources and land degradation (UNEP 1999). Rapid urbanization has heightened environmental pressures in many countries, leading to unprecedented levels of localized natural resource depletion and pollution (UNEP 2002). Increasingly, however, population predictions must consider the impacts of disease in the region. Africa is the continent most severely affected by HIV/AIDS, and southern Africa is particularly strongly affected (Buvé *et al.* 2002). HIV-1 prevalence in adults in many countries is estimated to exceed 20% (UNAIDS/WHO 2004). Other diseases, such as insect-vector diseases (e.g. malaria and trypanosomiasis), water-borne diseases (e.g. typhoid, cholera, and schistosomiasis), and poverty-related diseases (e.g. tuberculosis) remain prevalent in Africa (IPCC 2001). In some cases, responses to disease eradication have prompted large-scale land use changes. For example, the tsetse fly population has traditionally prevented extensive human and cattle presence in parts of the continent's mid-latitudes. Since the eradication efforts of the 1970s, there has been increasing settlement into areas formerly devoid of cattle (Myslik *et al.* 1997, Reid *et al.* 2000).

In sum, the population and land use changes in response to these forces are difficult to predict. Although contemporary anthropogenic forces were not explored in the present set of SAFARI 2000 articles, they undoubtedly will contribute to environmental and land use changes in the region. EOS and its successor satellite systems surely will be tasked to detect and monitor the impacts of these changes.

4. Discussion

Planning for SAFARI 2000 began in 1997, and formal workshops commenced in 1998. By the end of 2001, most of the data had been collected, and participants were focusing on data reduction and analysis. The studies described in this and the companion special issues suggest that the Initiative achieved the goal of providing a thorough test of EOS systems and science. For MODIS land products alone, SAFARI 2000 helped validate approximately seven of the nine product types. These results were conveyed back to the algorithm developers, and product improvements were made. At the time of writing, the complete mission archive of MODIS Terra data has been reprocessed three times using improved algorithms.

Many algorithm improvements were a direct result of SAFARI 2000 remote sensing studies. However, as noted in the Introduction, a full test of EOS requires

communication of distilled science results back to regional policy-makers and the broader community. Although this goal has not been adequately achieved, participants at the SAFARI 2000 Synthesis Workshop (Charlottesville, VA, October 2002) agreed to summarize key SAFARI findings in a book, written in language accessible to the educated lay reader. This may be one of the more important contributions of the Initiative. A regional network of scientists, policy-makers and non-governmental organizations, known as the Air Pollution Information Network for Africa (APINA), has already made extensive use of SAFARI 2000 results (Cumbane *et al.* 2003). Additionally, the Initiative led to many opportunities for societal outreach. For example, SAFARI 2000-based efforts in public education (e.g. Internet-based 'distance learning' courses between the University of Virginia, Eduardo Mondlane University, and University of Witwatersrand; Macko *et al.* 2004) and governmental outreach (e.g. participation by government ministers at annual SAFARI 2000 workshops) helped make EOS goals tangible to the public.

Finally, the resources and experience gained in SAFARI 2000 were valuable assets for many participant organizations, both in Africa and abroad. More precisely, resources may leave or deteriorate in the region if an operational long-term observing network is not developed in the wake of the Initiative (AAAS 1999). Such observing networks have been called for by several international organizations (e.g. IPCC and WMO). More recently, the Global Earth Observations System of Systems (GEOSS), emanating from the Earth Observation Summits of 2003 and 2004, may provide support for sustaining regional resources (Cheves 2003).

Further, the need for globally distributed field data resources is critical for validation of future remote sensing systems. For example, the National Polar Orbiting Environmental Satellite Suite (NPOESS), and its initial EOS 'bridging' satellite, NPOESS Preparatory Project (NPP), will begin replacing EOS and NOAA polar orbiting satellites in about 2011 (2008 for NPP; Murphy *et al.* 2001). These systems, like EOS, have a large suite of global satellite products. However, where EOS products were developed by NASA-funded scientists over many years, the NPP and NPOESS systems—including algorithms and products—are contractually purchased from private industry. Frequent updates and algorithm improvements, as practised under EOS, may not occur. Although evaluations of the products against independent measurements will be a shared government and industry activity, responsibility for collecting field validation data rests primarily with NASA and its NPOESS program partners (NOAA and the Department of Defense). Through their own science programs and in cooperation with the Committee of Earth Observation Systems (CEOS) Working Group for Calibration and Validation (WGCV), these agencies will depend heavily on existing field networks and prior EOS infrastructure (Morissette *et al.* 2002). Already, SAFARI 2000 data sets are being used in pre-launch NPP algorithm testing and evaluation. Developing skilled field personnel and leaving a long-term observing network in the region for NPP/NPOESS-era validation (2008–2020) will be an important legacy for SAFARI 2000.

4.1 Data availability

The Initiative operated under the SAFARI 2000 Data Policy, which stipulated that participants must publicly release all data within 3 years of collection. Although individual institutions and circumstances may override that condition, most data sets are indeed in the public domain. The majority of SAFARI 2000 data sets are

available via a three-volume SAFARI 2000 CDROM Series (12 disks in total) developed at NASA's Goddard Space Flight Center (Privette *et al.* 2001, Nickeson *et al.* 2002, 2003). These volumes are available at no cost from the Oak Ridge National Laboratory (ORNL) Distributed Active Archive System (DAAC) <http://www.daac.ornl.gov>. Scientists in southern Africa may request these volumes through the University of the Witwatersrand. Most of the satellite data sets may be ordered online from the EOS DAACs through the EOS Data Gateway (<http://edcimswww.cr.usgs.gov/pub/imswelcome/>) and other portals.

5. Conclusions

Southern Africa landscapes span the range from stable to fluctuating, fertile to barren, parched to flooded, and economically developed to underdeveloped. Although the region sometimes presented logistical challenges to field investigators, it compensated by providing a rich set of remote sensing targets and test opportunities due to its unique features, including (1) a vigorous biomass burning regime and resultant atmospheric loading seasonality, (2) extensive undeveloped shrublands, savannahs and woodlands overlaying consistent sandy soils (Kalahari sandsheet), (3) low topographic relief, (4) a 4 month 'dry season' of low cloudiness, (5) an extensive inland river delta (Botswana's Okavango Delta) subject to seasonal flooding, and (6) climatic, landform, and biotic gradients. The SAFARI 2000 studies comprising this and the companion Special Issues led to numerous modifications to EOS algorithms, validation protocols, and data handling, as well as EOS-based scientific discoveries. SAFARI 2000 efforts in public outreach—particularly to regional educational institutions and governments—helped make EOS goals tangible to the public. In sum, the execution of the SAFARI 2000 science initiative amid a natural remote sensing test bed led to a comprehensive and effective evaluation of the EOS system. The region's environment and sustained field observation capability can benefit the validation programs for other remote sensing systems.

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