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The Southern Africa Fire Network (SAFNet) regional burned-area product-validation protocol

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The development of appropriate validation techniques is critical to assess uncertainties associated with satellite-data-based products, to identify needed product improvements and to allow products to be used appropriately. At regional to global scales, there are several outstanding issues in the development of robust validation methodologies, including the need to increase the quality and economy of product validation by developing and promoting international validation standards and protocols. This paper describes a protocol developed to validate a regional southern Africa burned-area product derived from Moderate Resolution Imaging Spectroradiometer (MODIS) 500 m time series data. The protocol is based upon interpretations by members of the Southern Africa Fire Network (SAFNet) of multitemporal Landsat Enhanced Thematic Mapper plus (ETM+) data to derive maps of the location and approximate date of burning. The validation data are derived using Landsat ETM+ scenes distributed to

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encompass representative regional variation in the conditions for which the MODIS burned-area product was generated and to capture the more important factors that influence product performance. The protocol was developed by consensus to ensure inter-comparison of the independent data derived by the different SAFNet members and to allow these data to be scaled up to provide regional validation of the MODIS burned-area product. Biomass burning in southern Africa, the ETM+ sampling rationale, the interpretation and mapping approach, SAFNet member fire activities, and illustrative 2001 results and difficulties encountered with the protocol are described.

1. Introduction

Although southern Africa has some of the most extensive biomass burning in the world (Dwyer *et al.* 2000), there are no adequate data on the regional occurrence, size distributions, or trends in fire numbers or areas burned annually that meet the information needs of policy and decision-makers (Frost 1999). Resource managers need such information to identify areas that are most under threat of too-frequent burning, the likely points of origin of such fires, and what management strategies and operations would best enable more effective control of fire. Scientists require this information to investigate the impact of fire on plant and animal species, ecosystems, soils and biogeochemical cycles, and to estimate trace gas and particulate emissions and their associated radiative forcing and the forcing of surface albedo change on the climate (Crutzen and Andreae 1990, Crutzen and Goldammer 1993, Levine 1996, Ehrlich *et al.* 1997, Boucher and Haywood 2001, Hulme *et al.* 2001). Local fire information exists for some national parks, forests, and conservation areas, but are not representative of the region as a whole because these lands are subjected to specific fire management policies and are largely protected from the influence of people.

Satellite remote sensing provides the only practical means to monitor biomass burning over areas as extensive as southern Africa. Active fire locations have been derived systematically by hotspot detection algorithms applied to orbital satellite data. However, these data do not provide reliable information on the spatial extent and timing of burning, as clouds may preclude hotspot detection and because the satellite may not overpass when burning occurs (Justice *et al.* 2002). Algorithms that use multi-temporal satellite data to map the areas affected by the passage of fire, often called burn scars or burned areas, are less subject to these constraints and have received considerable attention for regional to continental scale mapping. Recently, regional southern Africa burned-area products have been produced using 5 km Advanced Very High Resolution Radiometer (AVHRR) (Barbosa *et al.* 1999), 1 km SPOT VEGETATION (Silva *et al.* 2003) and 500 m Moderate Resolution Imaging Spectroradiometer (MODIS) (Roy *et al.* 2002a) time-series data. No rigorous assessment of the accuracy of these regional products, or development of systematic methodologies to evaluate their accuracy, has yet been undertaken, though the potential research, policy and management applications of these and future regional burned-area products place a high priority on providing statements about their accuracy. Validation is the term used here, and more generally, to refer to the process of assessing satellite product accuracy by comparison with independent reference data (Justice *et al.* 2000, Morisette *et al.* 2002).

This paper describes a protocol developed to validate a regional MODIS burned-area product for southern Africa that maps the location at 500 m resolution and the approximate day of burning (Roy *et al.* 2002a). Some illustrative results are also presented. The protocol was developed in the context of the 2000 Southern Africa Regional Science Initiative (Swap *et al.* 2002) by members of the Southern African Fire Network (SAFNet). The overarching goal of the SAFNet is to achieve more effective and appropriate fire-management policies and practices in southern Africa through the use of remote sensing and other geospatial information technology. The SAFNet members have strong interests in long-term satellite fire information to support their research and operational agendas in resource management, environmental assessment and global-change research. SAFNet is a contributing network to the Global Observations of Forest Cover/Global Observation of Landcover Dynamics (GOFC/GOLD)-Fire initiative (Justice *et al.* 2003). A guiding principle of GOFC/GOLD-Fire is that the user community plays an active role in defining satellite fire-product requirements and in undertaking product assessment and testing of pre-operational algorithms. A number of international meetings, including the International Geosphere-Biosphere Programme Data and Information Services working group meeting on remote sensing of fires, Toulouse, France, 19–20 March 1998 (Ahern *et al.* 2001), and the GOFC-Fire Satellite Product Validation Workshop, Lisbon, Portugal, 9–11 July 2001, have highlighted the need for long-term fire-product validation sites and a network of researchers at these sites (Rasmussen *et al.* 2001). The protocol described in this paper fulfils this need in southern Africa and may be applicable to other regions pending further research. This wider applicability is relevant because of the international need to increase the quality and economy of validating global satellite products by developing and promoting the use of international standards and protocols for field sampling, scaling, error budgeting, data exchange, and product evaluation (Justice *et al.* 2000).

There is little heritage for fire-product validation. Previous approaches have used independent reference data from aircraft observations of prescribed fires and wildfires (Kaufman *et al.* 1998). However, aircraft campaigns are expensive to undertake in a regionally representative manner and are difficult to coordinate with cloud-free conditions. Burned areas identified in high-spatial-resolution satellite data have been used to validate low-spatial-resolution active fire products but do not provide a reliable validation if the fires are inactive or cloud covered at the time of satellite overpass (Pereira and Setzer 1996). More recently, high-spatial-resolution data collected simultaneously with low-resolution data have been used to validate active fire products (Justice *et al.* 2002). Since the surface effects of fire are persistent, the simultaneous collection of independent reference data with burning is not critical for burned-area product validation. Consequently, independent data derived from high-spatial-resolution satellite data have been used to validate lower-spatial-resolution burned-area products (e.g. Barbosa *et al.* 1999, Fraser *et al.* 2000). A number of high-spatial-resolution sensing systems offer potential for mapping the spatial distribution of burning across southern Africa. The wide spectral range of the Landsat Enhanced Thematic Mapper plus (ETM+) and, in particular, the availability of high-spatial-resolution 30 m mid-infrared and 60 m thermal wavelengths, make it well suited for this application. We adopted this approach and attempted to address several important requirements. These are that the independent reference data should be collected (1) to provide an unbiased and accurate estimate of the remotely sensed product, preferably with errors considerably smaller than the product; (2) with a distribution that is representative of the conditions over which the product was made; (3) to encompass a range of the more important conditions and factors that influence product performance; and, where possible, (4) to describe these conditions and factors.

The majority of the co-authors participated in a SAFNet field trip in July 2000 which aimed to develop the validation protocol, and to discuss southern African fire-information needs and how these could be met through the use of satellite products. Seven days were spent travelling through Zimbabwe and Zambia examining fire-affected areas on the ground and comparing these with satellite data acquired in the preceding months and previous year. The protocol was developed by consensus and subsequently refined through lessons learned from its application by SAFNet collaborators in 2000 and 2001. It is based upon local interpretation of multitemporal Landsat ETM+ data to derive high-spatial-resolution maps of the spatial distribution and approximate date of burning. In this paper, biomass burning in southern Africa is first described, followed by a description of the ETM+ sampling rationale, the interpretation and mapping approach, and then the description of the ETM+ scenes, related SAFNet member fire activities, and illustrative 2001 results and difficulties encountered with the protocol at these scenes.

2. Biomass burning and the spatial, spectral, and temporal characteristics of burned areas in southern Africa

Fire is prevalent throughout southern Africa, although it is less common in arid regions in the west and south-western interior where there is often insufficient biomass fuel (the part of the biomass that normally burns, i.e. dead wood, grass, shrubs and litter). In arid regions, several years of fuel accumulation, or a preceding exceptionally wet growing season, are required to generate sufficient fuel to support a widespreading fire. The availability of fuel is primarily controlled by annual precipitation and soil fertility, and is reduced by herbivory (e.g. cattle grazing, grasshoppers) and by people (e.g. fuel collected for domestic energy) (van Wiglen and Scholes 1997, Frost 1999). Most fires in southern Africa occur in the dry season, from approximately May to October, when herbaceous vegetation is either dead (annual grasslands) or dormant, and when deciduous trees have shed their leaves, thereby contributing to an accumulation of dry and fine fuels that are easily combustible (Scholes 1997, Frost 1999). Satellite observations indicate that burning accompanies the seasonal pattern of drying out of vegetation following the end of annual rains, moving approximately north-west to south-east throughout the dry season (Kendall *et al*. 1997, Barbosa *et al*. 1999, Dwyer *et al*. 2000). This is illustrated in figure 1, which shows the 1 km locations of active fires detected by the day and night overpasses of MODIS (Justice *et al*. 2002). Fires detected from March to July (excluding 4 June to 10 July when MODIS was non-functioning) and fires detected in August, September, October, and November 2001 are shown as red, yellow, green, blue and magenta, respectively. The percentage of MODIS observations labelled as cloudy by the MODIS active fire product over this 9 month period is also shown. Parts of eastern South Africa were observed to be 11–20% cloud covered, and the equatorial parts of Gabon, Congo, and the Democratic Republic of Congo were as much as 41–50% cloud-covered. Active fires and burned areas are less likely to be detected in these persistently cloudy regions.

Fires in southern Africa are ignited by people, primarily for land management, and by lightning. In the absence of humans, fires are thought to have been most frequent at the onset of the wet season when fuel remains sufficiently dry for ignition

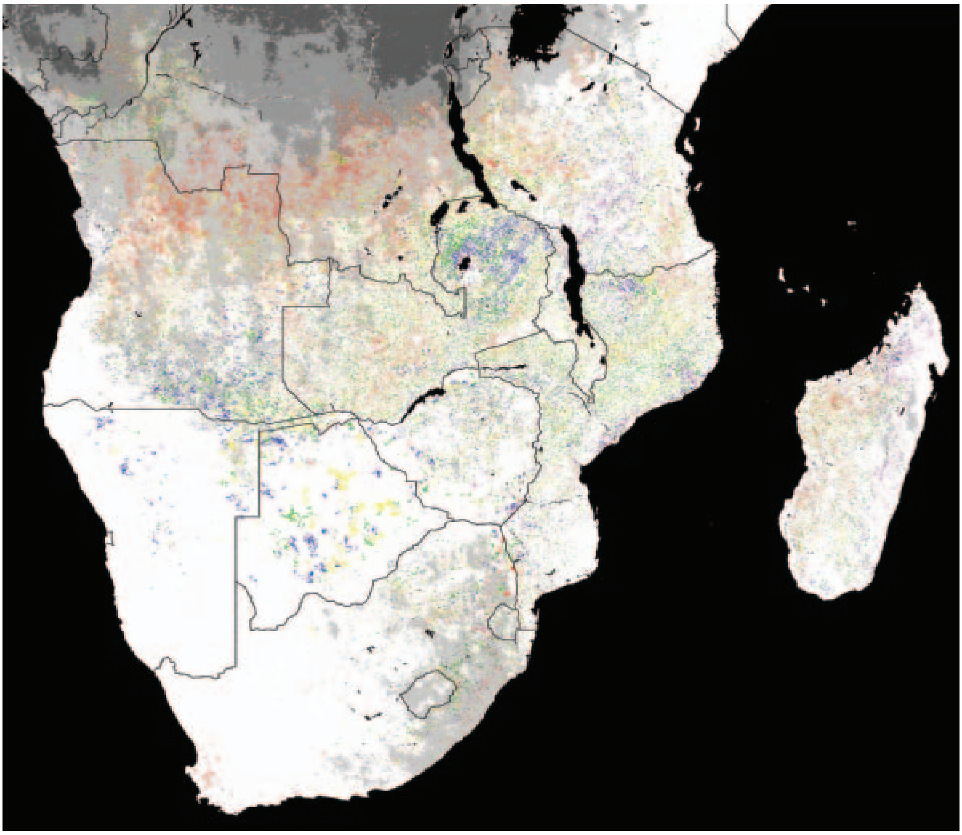

Figure 1. Temporal composite of the MODIS-Terra 1 km day and night active fire product over southern Africa, 1 March to 30 November (not including 10 June to 3 July) 2001. Fires occurring from March to the end of July (red), August (yellow), September (green), October (blue) and November (magenta). Black indicates water bodies. White and grey shades illustrate locations where no fires were detected and show the percentage of MODIS day and night 1 km observations labelled as cloudy by the MODIS active fire product over the 9 month period (white=0–10%, light grey=11–20%, grey=21–30%, dark grey=31–40%, some isolated pixels 41–50%). Country boundaries are shown (black lines).

by lightning associated with convective thunderstorms (van Wiglen and Scholes 1997). Fires started by people earlier in the dry season are likely to pre-empt many potential lightning fires from igniting or spreading later on (Frost 1999). Arguably, the incidence of fires is expected to be earlier and higher in settled areas. Late dry-season fires are likely to be larger and more intense than in the wet or early dry season, as more dry fuel load is available, and because the often hot and windy conditions cause fires to spread more easily and make them difficult to control. Fragmentation of the landscape, for example by the construction of roads, field boundaries and fire breaks, and because of lower fuel load, due to grazing and the collection of firewood, for example, generally results in smaller burned areas, regardless of whether the fires are controlled or not. The size distribution of burned areas varies between semi-arid and wet regions (Korontzi *et al.* 2003). In wetter regions, above about 1000–1200 mm per year, where there is sufficient rainfall to support closed-canopy woodlands and forests, prolonged moist conditions and heterogeneous vegetation structure constrain the spread of fires, even if the fuel load is high (Van Wilgen and Scholes 1997). As a result, the burned areas are generally small and spatially fragmented. The impact of fire is greatest in the grasslands and open savannah woodlands at intermediate rainfall amounts (about 550–750 mm per year) where there is sufficient grass production to produce hot fires that can damage trees, but not enough rainfall to allow their rapid regeneration and closure of their canopies, which would otherwise restrict grass production (Scholes *et al*. 2002). The burned areas are consequently larger and more contiguous. Below about 550 mm annual rainfall, where the vegetation is predominantly shrubby grassland, and grass production is strongly linked to annual rainfall, fire is intermittent and generally follows periods of well-above average rainfall. In these circumstances, the fires spread readily and burn large areas. Interannual variability in rainfall in Southern Africa is high and linked to a strong El Niño signal. Fuel production thus varies from year to year and, with it, fire timing and spatial distribution (Anyamba *et al*. 2003).

Burned areas are characterized by deposits of charcoal and ash, by the removal of vegetation cover and fuel, and by the exposure of underlying soil. These changes are amenable to remote sensing and field measurement, but they vary spatially. The type of vegetation that burns (or remains unburned), the fire behaviour and completeness of burn, the post-fire regrowth of the vegetation, and the rate of charcoal and ash dissipation by wind and water all vary as a function of several biophysical and anthropogenic factors. The magnitude and direction of spectral changes caused by charcoal and ash deposition depend on the type and condition of the vegetation prior to burning and the degree of combustion (Pereira *et al*. 1997, 1999, Roy and Landmann this issue). In general, charcoal and ash have low reflectances, typically 0.05 (400 nm) to 0.10 (2500 nm), although certain high temperature fires may deposit highly reflective white ash, e.g. 0.40 (400 nm) to 0.60 (2500 nm) (Roy and Landmann this issue). In ecosystems dominated by herbaceous vegetation, the above-ground plant material exposed to fire is typically non-photosynthetic (dead or dormant) and dry at the time fires occur. The major change at reflective wavelengths is a decrease in reflectance, i.e. from dry grass to ash and charcoal. In certain forests and shrub lands, the above-ground vegetation may be photosynthetically active when fire occurs, and so spectral changes may be less distinct. For example, dense green vegetation has a low reflectance at visible and shortwave infrared wavelengths, and deposits of charcoal and ash may not reduce the observed reflectance much further. Exposure of underlying soil by the action of fire may have variable effects depending on factors including the soil colour and wetness. For example, when a bright soil is exposed, the surface reflectance may increase. In contrast, exposed soil or the presence of a surface fire may be obscured by unburned overstorey vegetation and may not be detectable by remote sensing at optical wavelengths.

Fire behaviour controls the degree of burning and the parts of the vegetation that burn. Apparent surface temperature may increase, because of less evaporative cooling (Asrar *et al*. 1988), because a larger proportion of the incoming solar radiation is absorbed by low-reflectance charcoal and ash, and because of the lower heat capacity and thermal inertia of vegetation compared with that of soil and dried vegetation (Goward *et al*. 1985). Changes in the vegetation structure may alter the distribution of shadows and change the way light is reflected, absorbed and transmitted within and between plants and the surface. Much of the variation in observed reflectance of burned areas may be due to directional effects in wide field-of-view satellite data (Roy *et al*. 2002a, Stroppiana *et al*. 2002). The remotely sensed signatures of burned areas also change temporally as the vegetation regrows, and the charcoal and ash are dispersed by wind and water. Field radiometer measurements (Trigg and Flasse 2000) and satellite observations of southern Africa suggest that the remotely sensed signal can return to pre-burn levels in as little as 1–2 weeks.

3. Regional Landsat ETM+ spatial and temporal sampling

Definition of statistically rigorous sampling strategies for independent data collection at the regional scale remains a research issue, especially when using high-spatial-resolution satellite data in the sampling framework. Landsat ETM+ data are defined in a Worldwide Reference System composed of geolocated scenes each covering approximately 185×170 km (Arvidson *et al.* 2001), equivalent to about 5000 low-altitude aerial photographs (Jensen 1996). The Landsat ETM+ senses the Earth in a near-polar, sun-synchronous orbit, imaging the same point on the surface every 16 days (Goward *et al.* 2001). Consequently, the date of burning may be interpreted to within 16 days if consecutive ETM+ data sets are compared. There are approximately 430 Landsat ETM+ scenes that cover the land surface of southern Africa (including approximately 33 scenes over Madagascar). A simple random sample of these would necessitate acquiring a prohibitively large number of ETM+ data sets to adequately characterize the region's burning and to capture fire events under cloud-free conditions. Furthermore, reliable fire regime information, necessary to support a more efficient stratified sampling scheme, is not available. For these reasons, our sampling design was not statistically based.

3.1 *Spatial sampling*

Eleven Landsat scenes, covering approximately 3% of the surface of southern Africa, were selected with a regional distribution designed to be representative of the conditions covered by the MODIS burned-area product and of the factors that influence product performance. The major factors that influence the accuracy of burned-area products are the degree of spectral change from unburned to burned vegetation, the spatial characteristics of the burned areas, and spectral changes of a similar direction and magnitude not caused by burning (e.g. cloud shadows) (Eva and Lambin 1998, Roy *et al.* 2002a). Spectral changes depend on the pre-fire fuel vegetation reflectance and the combustion completeness (Roy and Landmann 2005). As combustion completeness depends on the local behaviour of the fire (Shea *et al.* 1996, Ward *et al.* 1996), and because only anecdotal information on combustion completeness exists for the region, we selected the 11 Landsat scenes to capture regional variations in the vegetation and the spatial characteristics of burned areas. Vegetation in each scene typically burns every year. Figures 2 and 3 show the locations of the scenes in Namibia, Botswana, Zimbabwe, Malawi, South Africa, and Mozambique. The scene outlines have been superimposed on a MODIS 1 km land cover map (Friedl *et al.* 2002) (figure 2) and upon 1° Tropical Rainfall Measuring Mission precipitation estimates for 1999 and 2000 (Huffman *et al.* 1995) (figure 3). Substantial differences in annual precipitation between 2000 (a year of above average rainfall at many locations) and 1999 influenced the amount of available fuel and consequently the spatial extent and timing of burning in the subsequent dry seasons. Figure 4 illustrates the scenes in 'meteorological space',

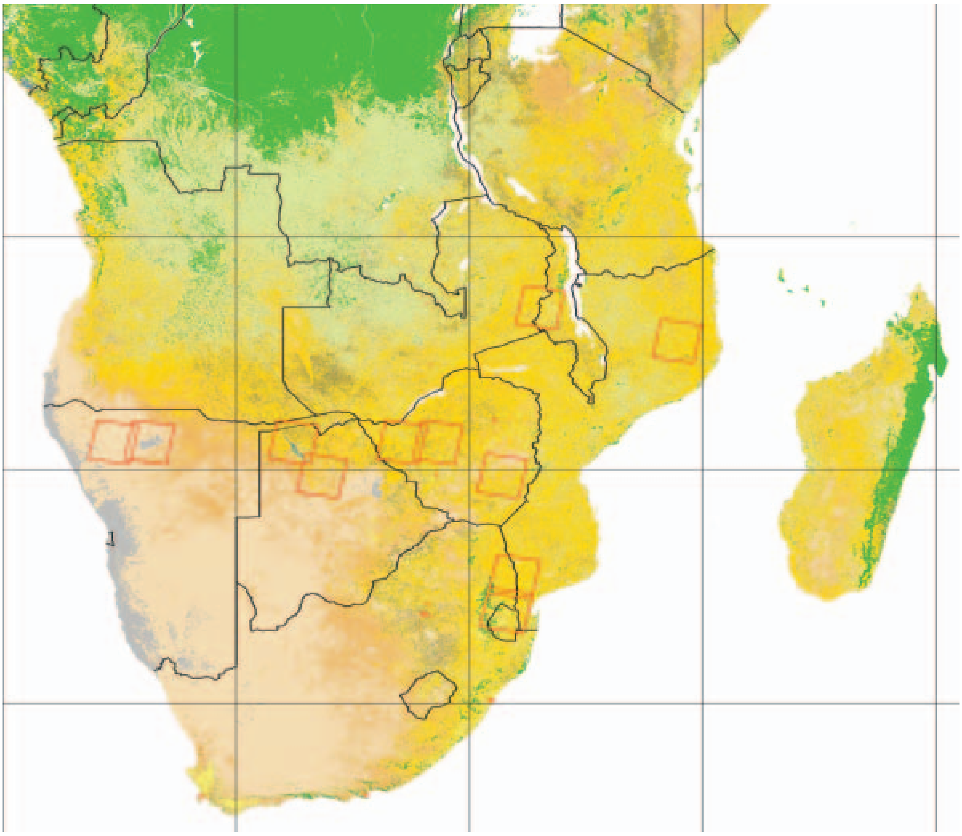

Figure 2. Eleven Landsat ETM+ validation scenes (red squares) superimposed upon MODIS 1 km land cover map (Friedl *et al.* 2002). Of the 17 MODIS land cover classes, predominant classes illustrated include: evergreen broadleaf forest (dark green), barren or sparsely vegetated (gray), woody savannas (light green), open shrublands (cream), grasslands (light brown), savannas (orange), croplands (yellow), cropland/natural vegetation mosaic (olive brown), urban (red). Country boundaries and meridians (10°, 20°, 30°, 40°, 50° East) and parallels (10°, 20°, 30° South) are shown (black lines).

showing their mean 1999 and 2000 annual precipitation amounts and mean annual air temperature (derived from mean monthly air temperature climatology data: Leemans and Kramer 1990). The figure 4 margins show probability densities (Venables and Ripley 1997) of the mean annual temperature and mean 1999 and 2000 annual precipitation for all of southern Africa—indicating that the scenes encompass a wide range of the regional variation of these variables. The scenes are geographically distributed approximately west to east from, hot arid, savannah (Namibia) to hotter, moister, woodland (Mozambique). This distribution corresponds approximately to increasing plant water availability, which is a regionally controlling factor on the type of vegetation, and so indirectly on human population density and land use, which together influence the frequency, timing, size and spatial distribution of burned areas. At each scene, SAFNet collaborators have existing operational and research fire activities and the contextual and geographic knowledge required to reliably interpret Landsat ETM+ data acquired there. These activities and the scenes are described further in section 6.

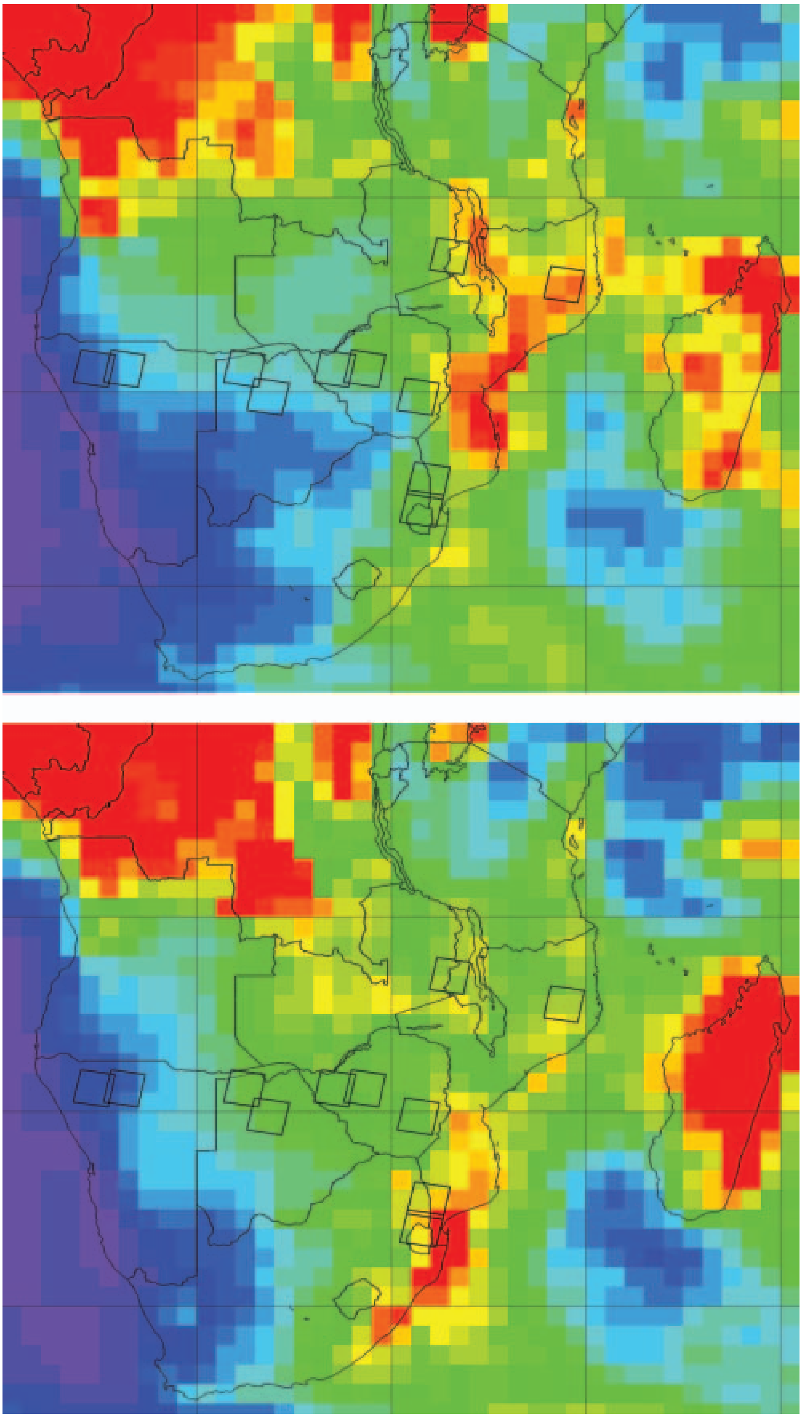

Figure 3. Eleven Landsat ETM+ validation scenes (black squares) superimposed upon annual precipitation estimates for 1999 (top) and 2000 (bottom). The annual precipitation estimates derived from the monthly 1° Tropical Rainfall Measuring Mission best-estimate precipitation rate product (Huffman *et al.* 1995) (blue <300 mm, yellow >1000 mm, red >1500 mm). Country boundaries and meridians (10°, 20°, 30°, 40°, 50° E) and parallels (10°, 20°, 30° S) are shown (black lines).

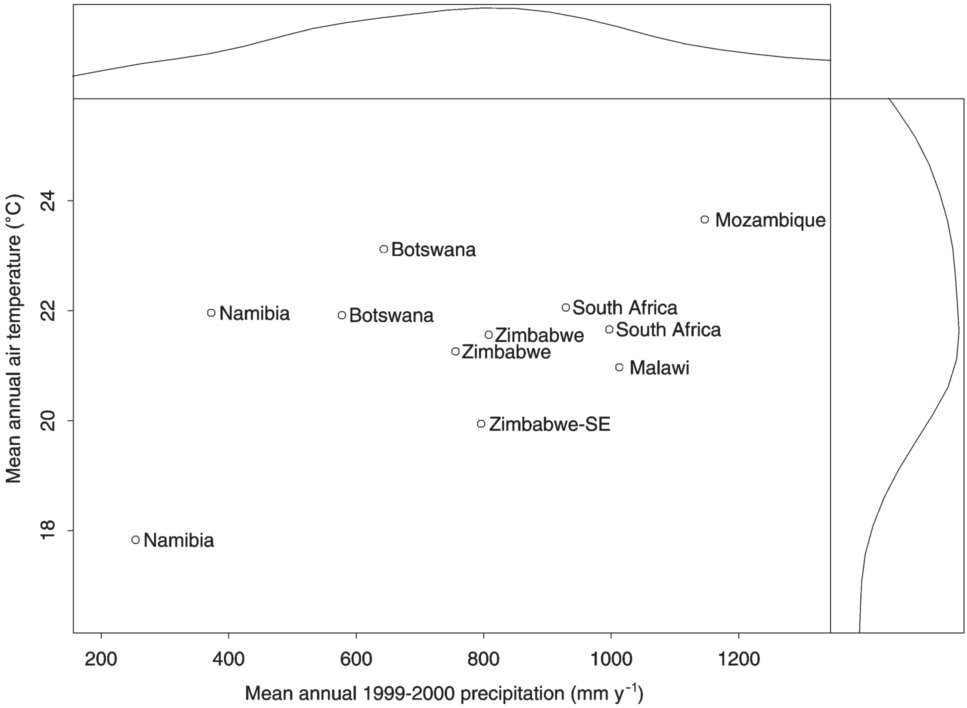

Figure 4. Mean annual air temperature (derived from 0.5° mean monthly 2 m air-temperature climatology data; Leemans and Kramer 1990) plotted against mean 1999 and 2000 annual precipitation (derived from the monthly 1° Tropical Rainfall Measuring Mission best-estimate precipitation rate product; Huffman *et al.* 1995) at the geographic centres of the 11 Landsat ETM+ scenes illustrated in figures 2 and 3. Probability densities of the mean annual temperature and mean 1999 and 2000 annual precipitation for all of southern Africa (including Madagascar) are shown in the plot margins.

3.2 *Temporal sampling strategy*

At least two Landsat ETM+ data sets were obtained for each of the 11 scenes in 2000 and again in 2001. The Landsat ETM+ does not acquire every scene globally because of mission resource constraints. The Landsat Long Term Acquisition Plan (LTAP) is used to operationally determine which scenes are acquired with the goal of building a global archive of sunlit, substantially cloud-free land observations (Arvidson *et al.* 2001). To specifically support this validation work, the 11 scenes were designated a priority, overriding the LTAP, guaranteeing their acquisition following a schedule driven by when the SAFNet collaborators expected burning would occur during the dry season. To facilitate rapid ETM+ data provision, an agreement was made with the Landsat mission operations center (NASA Goddard Space Flight Center) and with the primary US ground receiving station and data processing system (US Geological Survey EROS Data Center) to generate a daily notification e-mail describing the ETM+ acquisition date, granule identifier, cloud cover, and quality score for the 11 prioritized scenes. These e-mails, followed by an examination of ETM+ quick-look images, were used to identify cloud-free acquisitions sensed before and after significant biomass burning events. Whenever possible, consecutive ETM+ acquisitions were ordered to allow the most precise definition of the date of burning. A total of 28 and 30 Landsat ETM+ data sets were ordered in this way in 2000 and 2001, respectively. Of these ETM+ scenes, 20 in 2000 and 23 in 2001 were mapped following the protocol (table 1). Some scenes were not used after they had been ordered because of cloud cover not evident in the quick-looks, and because later ETM+ acquisitions were used that captured more comprehensive burning. In both 2000 and 2001, cloud cover increased the time period between Landsat ETM+ data that were useful for mapping. In 2000, MODIS data were unavailable during 11–17 July and 5–19 August (Roy *et al.* 2002b), and so attempts were made to not use ETM+ data acquired in this period. This, combined with the timing of burning and cloud cover, resulted in particularly long time periods between acquisitions at the Namibian and one of the Zimbabwean scenes in 2000 (table 1).

The Landsat ETM+ data were sent soon after they were acquired by express parcel delivery to southern Africa. It typically took no less than 3 days for an ETM+ acquisition to be delivered within the US (depending on which Landsat ground station was used), 1 day to prepare the data, and 7 days for the data to reach the appropriate SAFNet collaborator. Radiometrically and geometrically corrected (Level-1G) Landsat ETM+ data (Goward *et al.* 2001), defined in the Universal Transverse Mercator (UTM) projection, were provided in GeoTiff format on CD-ROM. For many scenes it was necessary to manually coregister the different ETM+ acquisitions to achieve coregistration within one 30 m pixel. For 2000, false-colour prints were also provided, using ETM+ band combinations and contrast stretches selected to provide good visual discrimination of burned areas. The prints were on 36×36 inch map sheets (approximately 1 : 250 000 scale), near-photographic quality (600 dots per inch), with scale bars, latitude, longitude, and UTM graticules

Table 1. Landsat ETM+ acquisitions used to produce validation data sets following the protocol (listed geographically from west to east).

Country ETM+ path/row	Dates of 2000 mapped ETM+ acquisitions	Dates of 2001 mapped ETM+ acquisitions
Namibia	2 July	6 August
180/073	22 October	23 September
Namibia	22 April	15 August
179/073	13 September	2 October
Botswana	25 August	9 September
174/074	10 September	15 October
Botswana		19 August
175/073		4 September
		6 October
Zimbabwe	1 June	23 August
171/073	21 September	24 September
Zimbabwe	27 August	14 August
172/073	28 September	1 October
Zimbabwe	22 August	10 September
169/074	7 September	12 October
Malawi	7 September	25 August
169/069	9 October	26 September
South Africa	31 August	18 August
168/077	18 October	3 September
South Africa	15 August	18 August
168/078	31 August	3 September
Mozambique	10 August	14 September
165/070	27 September	30 September

superimposed. By 2001, the SAFNet collaborators had laptop personal computers with image-processing software. Consequently, the use of prints was abandoned in favour of digital mapping, which allowed a number of advantageous interactive image-processing options. After the ETM+ data were interpreted, the results were e-mailed by each SAFNet member to the US in vector format.

4. SAFNet Landsat ETM+ data interpretation

To maximize accuracy of interpretation, it was recognized that SAFNet members with expert knowledge of the geographic region and the local drivers of and constraints on biomass burning should interpret the ETM+ images. In addition, they were able to undertake limited fieldwork as part of their existing fire work. Although automated Landsat classification and thresholding techniques provide useful information on the spatial extent and characteristics of burning, they cannot be relied upon to provide consistently accurate results. For example, automated techniques may not be able to differentiate between old and new burns, reliably detect small, spatially fragmented, low combustion completeness burns, accommodate the gross errors that may occur in satellite data, or differentiate between burned and spectrally similar unburned features. In general, the Landsat near-infrared and middle-infrared bands provide stronger burned-area discrimination than the visible bands (Pereira *et al.* 1999) and are less sensitive to smoke aerosols (Kaufman and Remer 1994). Our interpretation approach was based upon multitemporal visual comparison of ETM+ near-infrared and middle infrared bands, augmented by the ETM+ thermal band and a spectral index that is sensitive to burned vegetation.

Multitemporal satellite data provide several interpretative advantages over single date data for mapping burned areas (Pereira *et al.* 1997, 1999, Eva and Lambin 1998). These include a reduction in the likelihood of spectral confusion with spectrally similar static land cover types, the option to use relative rather than absolute changes in spectral values to account for spectral differences between pixels and dates, and the opportunity to define the date of burning more precisely. These advantages are illustrated in figure 5, which shows two false-colour Landsat ETM+ data sets acquired a month apart (bands 5 (1550–1750 nm), 4 (750–900 nm), and 3 (630–690 nm) are shown as red, green, and blue, respectively). The burned areas have a low reflectance in all these bands and so appear dark. The spatial and spectral appearances of the burned areas vary within and between the two dates. The decreasing burned-area reflectance over the month is apparent. Burned areas that were not observed in the earlier ETM+ September acquisition but are observed in the later October acquisition must have occurred between the acquisition dates or at the time the October data were captured. These are the burned areas that we were interested in mapping, as their approximate date can be inferred and because they are considerably easier to identify than the older burns evident in the September acquisition. Static features that are spectrally similar to burned areas, such as the central water body, do not change between the two dates and so are not mapped. Discrimination between burned areas and shadows required considerable interpretation skill, as shadows are transient and spectrally similar to burned areas. In figure 5, the cloud shadows evident in the October data may be identified as such because they are geometrically offset from clouds in consistently the same direction relative to the Sun. We used the 60 m Landsat ETM+ thermal band to provide additional information to differentiate between burned areas and shadows. This is

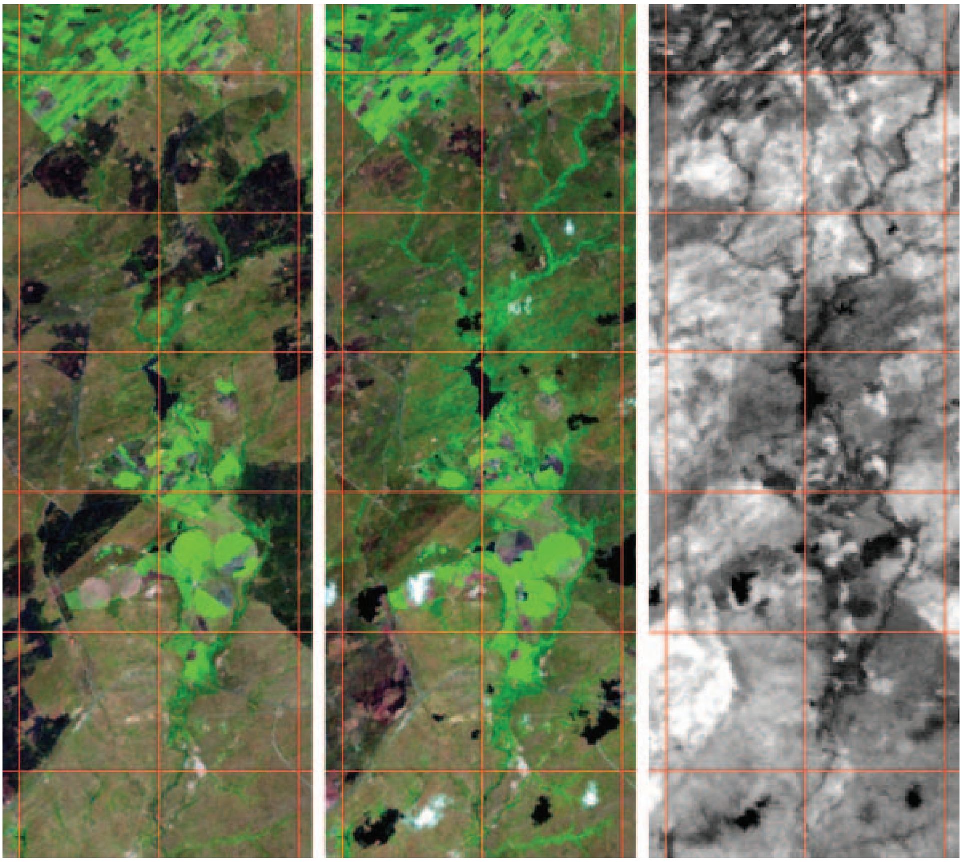

Figure 5. Landsat ETM+ 30 m reflective wavelength data acquired 10 September (left) and 12 October (middle), and 60 m thermal wavelength data acquired 12 October (right), 2001, near the Save Valley Conservancy, Zimbabwe (the south-east Zimbabwe Landsat scene illustrated in figures 2–4). Reflective 30 m data displayed as red: band 5 (1550–1750 nm), green: band 4 (750–900 nm), blue: band 3 (630–690 nm). Thermal 60 m band 6 (10.4–12.5 μm) data displayed as a greyscale (lighter tones are warmer). The red grid lines are spaced every 3 km. The water body in the image centre is located at 20° 55′ 15″ S, 31° 47′ 37″ E. Burned areas appear dark in the reflective wavelength data and light in the thermal data. Clouds and cloud shadows are evident across the 12 October data.

illustrated in the right image of figure 5 where the burns are significantly warmer than the shadows. Similarly, we found that wet and burned surfaces were often most easily differentiated using the thermal band.

Spectral indices based on band ratios of Landsat Thematic Mapper band 4 (760–900 nm) and band 7 (2080–2350 nm) have been shown to provide a good burned–unburned discrimination (Lopez Garcia and Caselles 1991, Koutsias and Karteris 2000, Miller and Yool 2002) and have attractive properties, such as normalizing certain illumination and topographic variations (Verstraete and Pinty 1996). We found from empirical examination of these and other Landsat indices (Pereira *et al.* 1997, 1999) that a spectral index computed as the difference between the Landsat ETM+ band 5 (1550–1750 nm) and band 7 (2090–2350 nm) divided by their sum provided useful interpretive information for the 11 Landsat scenes examined in this study, with similar results using ETM+ band 4 instead of band 5 (Lopez Garcia and

Caselles 1991). Our visual interpretation approach was based upon multitemporal comparison of the ETM+ near-infrared and middle-infrared bands, augmented by the ETM+ thermal band and this spectral index. Figure 6 illustrates the spectral index for the two Landsat acquisitions shown in figure 5. The burned–unburned contrast is more evident in the spectral index data than in the individual ETM+ reflectance bands. The temporal difference between the September and October spectral indices (figure 6, right image) highlights the areas that burned between the two dates. However, some changes due to non-burning events are also evident and need to be interpreted with care. For example, several of the October cloud shadows introduce temporal spectral index differences that are similar to those caused by burning. In addition, misregistration effects along high-contrast edges may obscure changes and introduce spurious changes (Roy 2000). Despite these limitations, the spectral indices and their temporal difference provided valuable additional information for our visual interpretation.

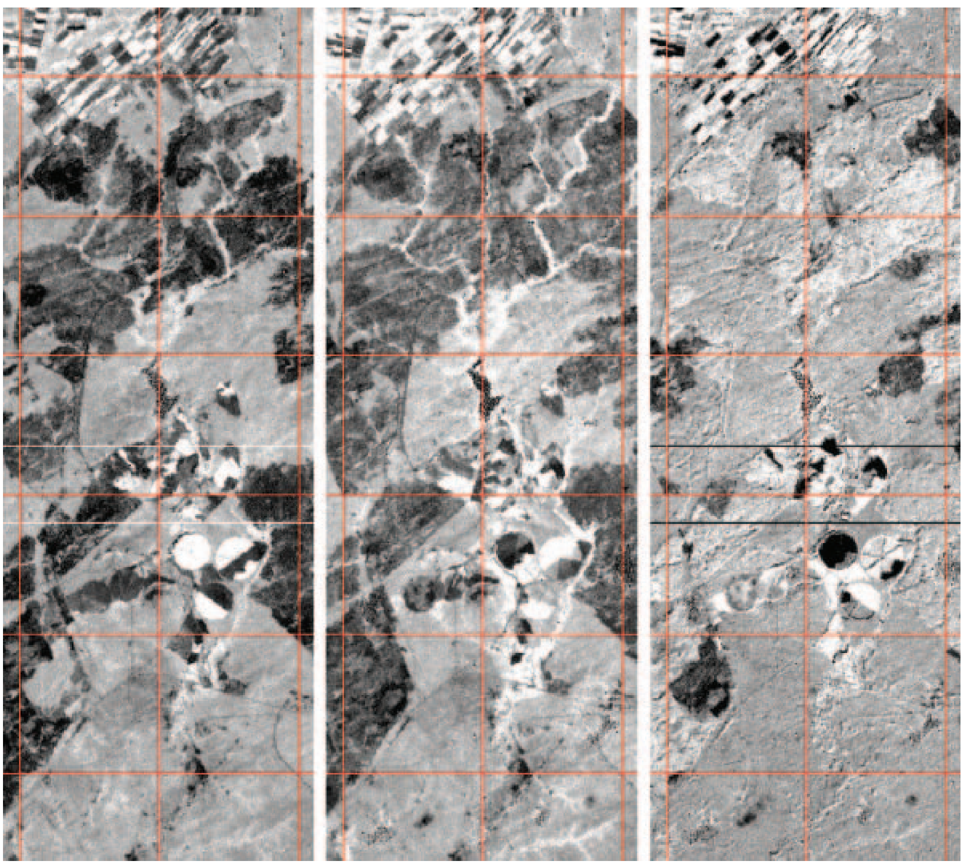

Figure 6. Spectral indices (band 5 – band 7)/(band 5 + band 7) computed for 10 September (left) and 12 October 2001 (middle) from the Landsat ETM+ data illustrated in figure 5. The right image shows the temporal difference of the spectral indices (12 October to 10 September).

5. SAFNet mapping convention and fieldwork

On receipt of the Landsat ETM+ data the SAFNet collaborators defined the boundaries of (1) the mapped region (i.e. falling within the geographic union of the two ETM+ acquisitions), (2) burned areas interpreted as having occurred between the two ETM+ acquisition dates, and (3) areas within the mapped region that could not be interpreted (e.g. because of cloud occurring in one or more ETM+ acquisitions). Only the interpreted land within the mapped region was considered when the Landsat ETM+ and MODIS derived burned-area data were subsequently compared. In this way regions that could not be interpreted would not be mistakenly considered unburned in the comparison process.

The boundaries of the data sets (1), (2) and (3) were digitized into a standard vector format using laptop computers and image-processing software that allowed zooming, local contrast stretching, and rapid comparison of ETM+ data from different acquisition dates. To reduce the mapping effort, particularly in scenes containing large numbers of small and spatially fragmented burns, a minimum mapping unit of 240 m was adopted whereby only burned areas with small axis dimensions of 240 m or greater were mapped. This dimension was selected as it is a multiple of the ETM+ 30 m reflective and 60 m thermal band pixel dimensions and is about one-quarter of a MODIS 500 m pixel.

Limited field observations were made, focusing only on regions where there were difficulties interpreting the Landsat ETM+ data. Fieldwork was limited by restricted road access and, in Mozambique, by the possible presence of land mines. Even without these constraints, the large spatial extent of each Landsat scene limited the amount of fieldwork that could be performed within the scene. Spectrally and contextually similar ambiguous burns were identified from the ETM+ data, and only a subset of these was visited. A handheld Global Positioning System was used to locate field observations. While in the field, recent burns evident on the ground but not observable in the later Landsat ETM+ acquisition were assumed to have occurred after the Landsat data were acquired. In many cases, the SAFNet interpreters could confirm that recent burns occurred after the Landsat data were acquired using their contextual knowledge and by asking people in the local community. In these cases the recent burns were not mapped. If their burn date could not be confirmed, they were mapped as 'Not Interpreted'.

6. Landsat ETM+ scenes, SAFNet activities, mapping difficulties and illustrative results

The 11 Landsat scenes, the fire-related activities of the SAFNet members, and difficulties encountered in following the protocol at the scenes are described from west to east (figures 2 and 3). The independent burned-area data derived using the protocol during the 2001 dry season and the corresponding MODIS burned-area product are illustrated at three of the scenes.

6.1 *Namibia*

The two Landsat scenes lie in the north-west arid zone of Nambia and span an annual rainfall gradient of 300–350 mm in the west to 550–600 mm in the east (Mendelsohn *et al.* 2000). The scenes cover different land uses. The north-east is characterized by densely populated subsistence farming where the landscape is so fragmented by human activity that burned areas are relatively small and often fall below the 240 m minimum mapping unit. In the north-west, grass and scrubland is used for reserve cattle grazing by subsistence farmers. There are few permanent human settlements in this area, and as a consequence, fires cause extensive burns. This is illustrated in figure 7, which shows the 2001 dry season MODIS burned-area product (coloured pixels) and the ETM+ derived independent burned-area data (red vectors left image) for the western and parts of the eastern Namibian scene. The temporal progression of burning detected by MODIS over this period is clearly evident (figure 7, left). A strong correspondence is observed between the *locations* and approximate *dates* of the 500 m MODIS burned-area product and the independent ETM+ derived data (figure 7, right). The white pixels in the north-east scene corner correspond to 500 m locations where MODIS results could not be computed because of missing data and persistent cloud (Roy *et al.* 2002a).

The Etosha National Park lies across the centre of the two Landsat scenes. Since 1981, fires have been prescribed in the park to remove moribund grasses, control bush encroachment, recycle nutrients, and manipulate game movements in an attempt to maintain or improve biodiversity (Du Plessis 1997). The park is divided into 25 blocks that are burned at the start of the rainy season depending on the herbaceous fuel accumulation, mean seasonal rainfall, and the time since each block last burned (Du Plessis 1997). Non-prescribed fires (for example, caused by lightning) are extinguished by park staff unless they occur in blocks that have been selected for burning. To the south of the park, burned areas tend to be considerably smaller than those illustrated in figure 7 because of coordinated efforts to prevent, control, and extinguish fires on valuable grazing land used by commercial cattle farmers. NOAA AVHRR 1 km High Resolution Picture Transmission data are used

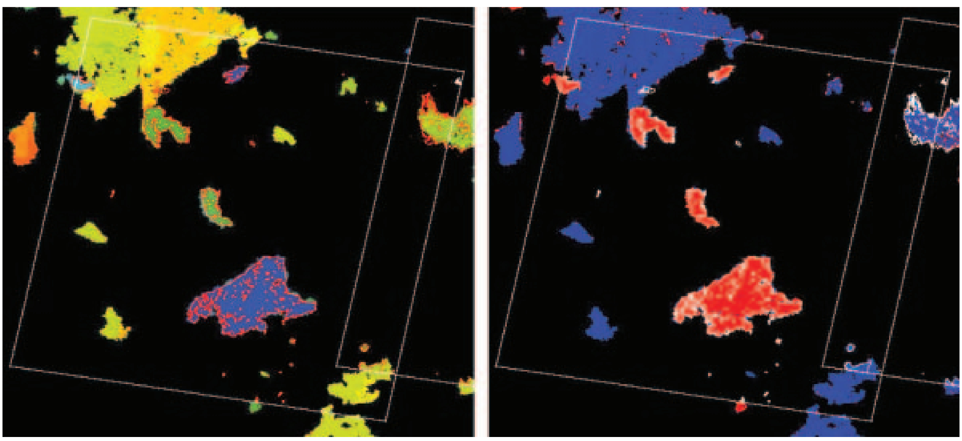

Figure 7. MODIS 500 m burned-area product coloured pixels and Landsat ETM+ independent burned-area validation data vectors, Namibia (Landsat Path 180, Row 73, the west Namibian Landsat scene in figures 2 and 3). The vectors show independent burned-area data mapped using the protocol from two ETM+ acquisitions sensed 6 August and 23 September 2001 (left: red vectors; right: white vectors). Vectors for parts of the adjacent scene are also shown. The coloured pixels show the burned areas detected by MODIS over 105 days from 20 July to 1 November 2001 (left: coloured with a rainbow scale to indicate the approximate day of burning; right: red to indicate burned areas detected within the Landsat ETM+ acquisition period, blue to indicate MODIS burned areas detected before or after the ETM+ acquisition period). Black indicates no burning detected by MODIS. White pixels show areas that could not be mapped due to missing MODIS data or persistent cloud. The 185×170 km Landsat ETM+ scene boundary is shown (white box).

by the Etosha Ecological Institute to produce burned-area maps in support of the Etosha National Park's fire and vegetation management program (Le Roux 2000, 2001). They are also supplied to the Natural Resource Information Service of the Ministry of Lands, Resettlement and Rehabilitation, who use them to monitor burning between Etosha and the Angolan border; the Directorate of Forestry's National Remote Sensing Centre for assessing the effectiveness of community fire management in the Caprivi; the Ministry of Agriculture who require burned-area estimates and fire origin information for damage assessment purposes; and the Directorate of Forestry for state forest management and reporting.

6.2 *Botswana*

The two Landsat scenes encompass the Okavango Delta and land to the south-east. The Okavango wetlands ecosystem supports approximately 140 000 residents in Ngamiland District, through different land use practices that include fishing, agriculture, hunting, and tourism. Fire is a form of disturbance that has been increasing in the Delta but has not been well studied. Anecdotal evidence suggests that changes in plant community structure are occurring which are reducing ecosystem functional capacity. Spatial and temporal assessments of the structure and composition after fire events are being undertaken for the seasonal floodplain communities. At least 10 years or more of fire history data may be required, however, to assess fire effects on plant species composition and biodiversity. There are significant challenges in mapping burned areas in wetlands due to spectral confusion with wet soil, the presence of spectrally ambiguous low-intensity smoldering surface fires, and small and spatially fragmented burns occurring on islands and along dryland–wetland interfaces. Subsurface fires that burn desiccated peat layers are prevalent but cannot easily be observed using ETM+ data (Gumbricht *et al.* 2002). Figure 8 illustrates the 2001 dry season MODIS

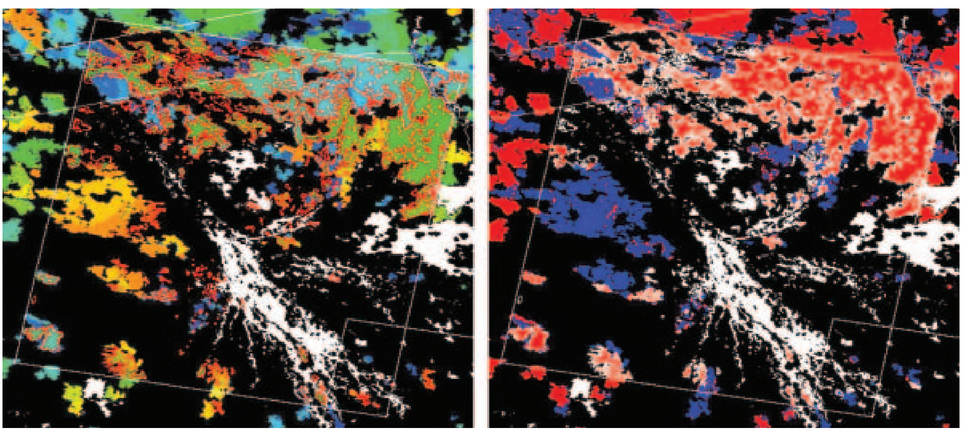

Figure 8. MODIS 500 m burned-area product and Landsat ETM+ independent burned area validation data, Okavango delta, Botswana (Landsat Path 175, Row 73, the north-west Botswana Landsat scene infigures 2 and 3). The vectors show independent burned area data mapped using the protocol from ETM+ acquisitions sensed 19 August, 4 September and 6 October 2001 (left: red vectors; right: white vectors). The MODIS burned areas are coloured in the same way as in figure 7. The 185 km × 170 km Landsat ETM+ scene boundary and the Botswana, Namibia (Caprivi Strip) and Angola boundaries are also shown (white vectors, left and right).

burned-area product and the independently derived ETM+ burned-area data. There is a high spatial and temporal correspondence between these data sets. Approximately 50% of the scene is burned, although much of the Delta is flagged by MODIS as unknown (white pixels). The land around the Delta, including the Hainaveld and Gumare regions in Ngamiland District, encompasses two different land tenure systems that are common over Southern Africa—communal grazing systems and private leasehold ranches. An assessment of change in woody plant density over a period of 45 years in these systems showed that, in addition to grazing pressure and rainfall, fire was instrumental in shaping vegetation structure (Dube 2000). The frequency and spatial patterns of fire are not documented, however. Botswana has adopted a policy of fire suppression through campaigns implemented under the mandate of the Ministry of Agriculture's Agricultural Resource Board, which emphasizes community involvement and use of firebreaks. Nevertheless, because of limited resources and the large areas that need to be covered, ground-based methods have been ineffectual in monitoring the effectiveness of this suppression policy. The Department of Meteorological Services has used a semi-automated burned-area detection algorithm based on AVHRR daytime 1 km data to produce burned-area maps (Flasse 1999). Satellite fire products, used in conjunction with information on vegetation, rainfall and land use, may allow fire managers to develop more effective fire-management systems in Botswana (Dube and Kwerepe 2000).

6.3 *Zimbabwe*

The two Landsat scenes in north-west Zimbabwe cover demarcated indigenous forests in Matebeleland North province, parts of Hwange National Park, commercial cattle ranches, and communal land. The demarcated forests are managed by the Forestry Commission under multiple-use principles including wildlife management, consumptive and non-consumptive safaris, timber harvesting, lease grazing, sale of firewood, and the collection of non-timber forest products. Although these activities reduce the fuel load, a fire-protection program is followed from August to November, emphasizing the early detection and suppression of fires through manning fire lookout towers and fire line clearing. Fire-management decisions are made from post-fire assessments. Burned areas are mapped at a 1 : 100 000 scale by forest officers after fires are extinguished. At the end of each year, these maps are synthesized into a single 1 : 250 000 scale map, and statistics are prepared by cause and hectarage. An analysis of fire reports compiled between 1985 and 1989 indicated that approximately 10% of the demarcated indigenous forests burn every year. The collection of primary fire data is limited in scope because of difficulties of access to remote areas and economic constraints. Currently, remotely sensed data are not used. Figure 9 illustrates the 2001 dry season MODIS burned-area product and the burned-area data independently derived from the west Zimbabwe ETM+ scene. The small and highly fragmented burns in the north-east of the scene occur over the communal lands and, in many cases, were not detected by the 500 m MODIS product. The extensive burns to the south-east lie in the Hwange National Park and were detected by MODIS except for some highly elongated burned areas with small axis dimensions close to the minimum mapping unit of 240 m. The information illustrated in figure 9 may significantly improve post-fire mapping capabilities and contribute to programs aimed at increasing the awareness of communities surrounding the demarcated forests. Fires frequently

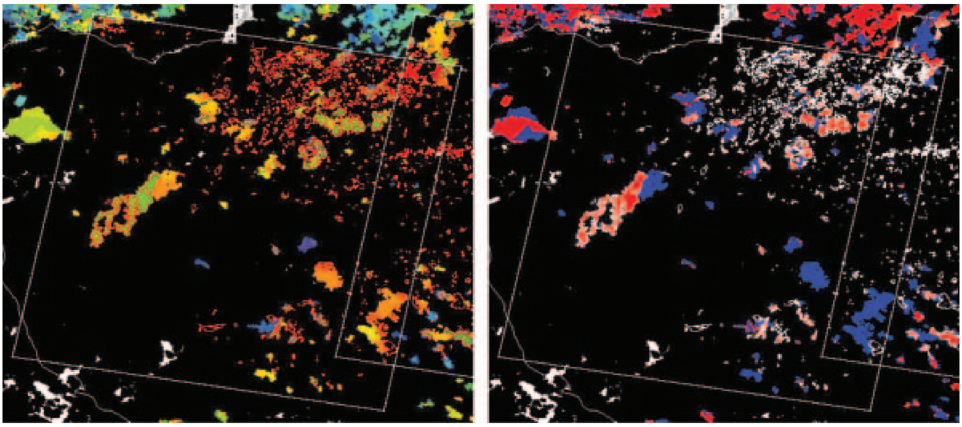

Figure 9. MODIS 500 m burned area product and Landsat ETM+ independent burned-area validation data, Matabeleland, Zimbabawe (Landsat Path 171, Row 73, the west Zimbabwe Landsat scene in figures 2 and 3). The vectors show independent burned-area data mapped using the protocol from two ETM+ acquisitions sensed 14 August and 1 October 2001 (left: red vectors; right: white vectors). Vectors for parts of the adjacent scene are also shown. The MODIS burned areas are coloured in the same way as figure 7. The 185×170 km Landsat ETM+ scene boundary and the Botswana and Zambian boundaries are also shown (white vectors, left and right).

originate from within these communities. An annual time series of these data may allow priority areas for fire protection to be defined more accurately, thereby allowing limited resources to be used more efficiently.

The third Landsat scene, in south-east Zimbabwe, covers the Save Valley Conservancy (SVC), a 3400 km^2 private wildlife reserve. The SVC was formed from an amalgamation of 20 former cattle ranches that ceased ranching in 1992 in favour of co-managed wildlife operations with safari hunting and game-viewing tourism as the principal sources of income (Du Toit 1994). After the SVC was formed, several ranch managers began to rethink the existing fire-exclusion policy, practised since at least the early 1970s, although most continue to fight wildfires. Some managers now try to estimate the probability of below-average rainfall during the coming wet season, before they choose an appropriate fire-management plan for the current dry season, preferring not to burn if a drought is anticipated. The World Wildlife Fund (WWF) is providing technical guidance for wildlife restocking of the Conservancy over the next 5–10 years. Patterns of wildlife distribution are strongly related to burning patterns and are taken into account in the interpretation of wildlife population counts, for the setting of hunting and culling quotas, and for making decisions on further stocking of particular species. Some ranch managers expect that the reintroduction of elephants will destroy shrubs, while others anticipate that canopy trees will be destroyed first. If woodland does disappear as a result of elephant activity, fire may be the crucial factor in determining whether the vegetation structure becomes bush land, scrubland or thicket (when fire is absent), or wooded grassland (if severe fires are frequent) (Dunham 2002). Given the size of the SVC, the large-scale nature of the ecological processes within its habitats, and the constraints on detailed fieldwork, the use of satellite data combined with strategic fieldwork is considered a crucial part of the WWF's program in the SVC. The MODIS burned-area product detected the majority of the ETM+ mapped burned areas in 2001, including an escaped prescribed fire that burned for 3 days with an ETM+ sensed area of 185 km^2. The MODIS product failed to detect suspected arson fires and low-intensity prescribed fires lit around buildings and safari camps with areas smaller than approximately 1 km^2 that had been mapped following the protocol.

6.4 *Malawi*

The Landsat scene covers the Chimaliro Forest Reserve, 160 km^2 of Miombo woodland created originally in 1924 to protect upper river catchments. A total ban on the removal of natural forest products existed until 1996 when the Reserve was selected for a community co-management plan by the Forestry Research Institute of Malawi (FRIM). Complete protection from anthropogenic fires is thought to be the best policy to ensure natural forest regeneration in the Reserve. However, this policy is impossible to implement in practice. Consequently, a controlled early burning policy is followed to reduce understorey fuel load in the early dry season and the possibility of intense wildfires occurring later on. The controlled fires are ignited by fire guards after grasses suitable for thatching have been removed. Community members may unofficially burn areas if these are considered to need clearing to encourage the growth of green palatable shoots for livestock grazing in the dry season. Research on alternatives to imposing forester-devised fire-control methods have been undertaken by the FRIM through a study of the knowledge, attitudes and practices of the rural communities surrounding the Reserve. The immediate goals of this research are to establish whether community land-use practices can be modified to reduce the incidence and impacts of anthropogenic fires on the regenerative ability and productivity of the forest. The satellite data may help in establishing the link between rural people's activities and the timing, occurrence, frequency, and spread of fire in and around the Reserve. Mapping burned areas from Landsat ETM+ has been a challenge because of topographic shadows occurring across the Reserve and the complex burned-area spatial distribution. This is illustrated in the top images of figure 10 which show topographic shadows across the Reserve in the August ETM+ acquisition where there is burning in the September acquisition. The MODIS 500 m burned-area product failed to detect many of the burns over the Reserve, although the reasons for this have yet to be investigated at the time of writing.

6.5 *South Africa*

The two Landsat scenes in South Africa cover the Kruger National Park (KNP). The greater part of the KNP is characterized by fine-leaved savannah with precipitation ranging from approximately 500 to 900 mm per year (Kruger *et al.* 2002). Fire is a key management issue, and its importance in shaping the vegetation structure and associated faunal diversity has long been recognized (National Parks Board 1954, Biggs and Potgieter 1999). Burning activity peaks in the park in September, while in the surrounding communal areas, burning is distributed more evenly throughout the year. KNP fire-management policy is evolving along with changing attitudes towards ecosystem management. An integrated fire policy was initiated in 2002 that recognizes the reality of arson fire (Biggs 2002). The park is divided into large and small fire-management units (FMUs) and smaller pristine wilderness areas. Prescribed patch burns are applied randomly in all the FMUs until

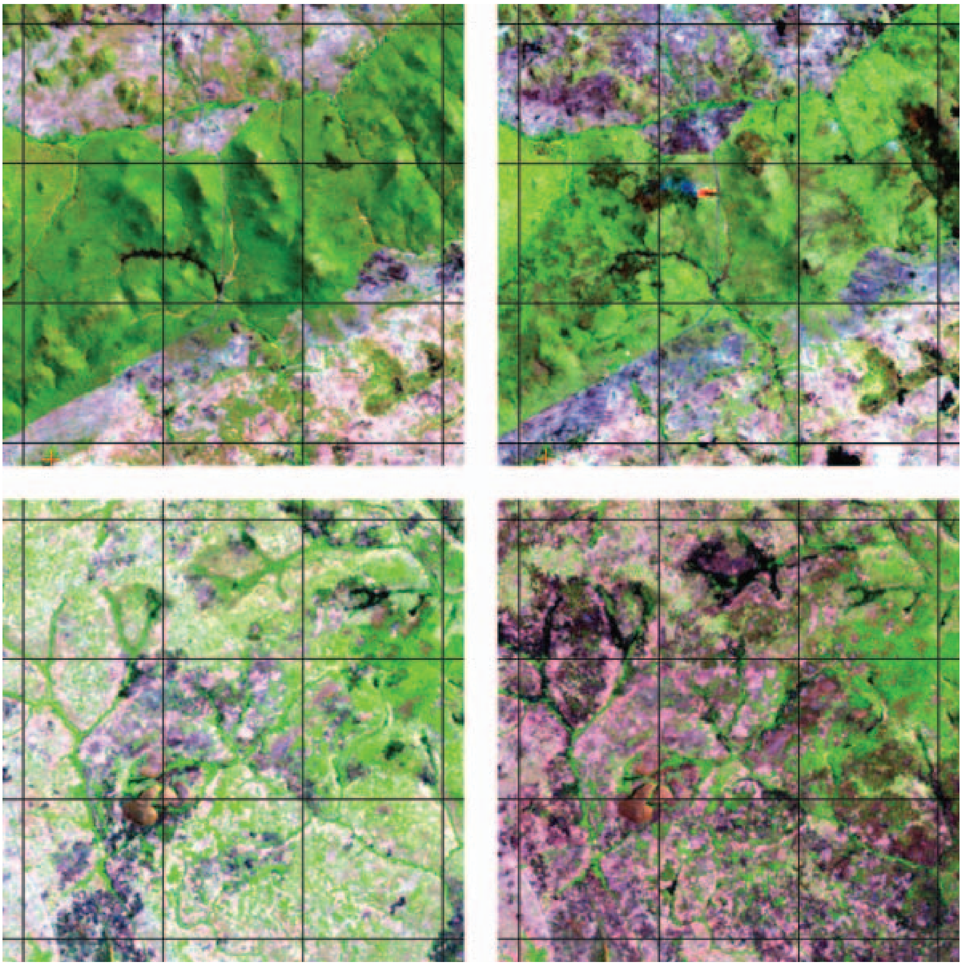

Figure 10. Landsat ETM+ subsets to illustrate regions that are difficult to map burned areas. Landsat ETM+ 30 m reflective wavelength data displayed as Red: band 5 (1550–1750 nm), Green: band 4 (750–900 nm), Blue: band 3 (630–690 nm). The top two images show spatial subsets over Chimaliro Forest Reserve, Malawi (left: 25 August; right: 26 September 2001). The bottom two images show spatial subsets over Mecuburi Forest Reserve, Mozambique (left: 14 September; right: 30 September 2001). The black grid lines are spaced every 3 km.

a 50% burned-area target is reached in September. Lightning and unplanned fires are left to burn no more than the target area set for an individual FMU from September onwards. The targets are based on vegetation biomass and species composition goals derived in accordance with the park policy to 'maintain biodiversity in all its facets and fluxes' (Braack 1997). Both fire-suppression activities, and management objectives to monitor and modify fire-management programs require accurate and timely information on the location, spatial distribution, and timing of fire. The primary problem experienced in mapping burned areas from Landsat ETM+ data, and with MODIS, in both 2000 and 2001 was the high cloud cover occurring during much of the dry season. This is evident in figure 1. The cloud cover reduced the mapped region to a fraction of the ETM+ scene, and in one case resulted in an ETM+ acquisition period of 48 days (table 1) and consequently weaker burned-area discrimination because of charcoal and ash dissipation by the elements.

6.6 *Mozambique*

The Landsat scene covers the Mecuburi Forest Reserve, the largest forest reserve in Mozambique. The Reserve covered 230 000 ha at the time of its proclamation in 1950, but today no more than 80 000 ha is in a state that justifies continued management as a forest reserve. The reserve is predominantly wet Miombo woodland (south-eastern and eastern areas receive 1000–2000 mm of rainfall with the northern areas receiving 500–1000 mm per year). As many as 20 tribal groups claim resource rights to the region. These occupying and surrounding people practice slash-and-burn agriculture, growing cassava as the staple crop, with maize, sorghum and some millets as secondary crops. The timing and spatial extent of burning are related to human activity. Illegal hunters cause most forest fires between May and October. During October and November, most burning probably results from fires that burn out of control while farmers are preparing their fields. Government statistics indicate that about 50% of northern Mozambique burns every year (DNFFB 1996). Currently, there is no enforced legislation on the use of fire; nor is there any fire management in the Reserve. Community-based natural resource management is one of the strategies being adopted by the Mozambican government to promote the sustainable use and conservation of the country's natural resources. A UN Food and Agriculture Organization (FAO) project, established in 1997, is an integral part of this program. The FAO project is proposing a number of co-management initiatives to develop local bylaws for forest management in the Reserve. Satellite-derived fire information on burn timing and spatial extent will be used to aid this effort and to monitor the impacts thereafter. Mapping burned areas from Landsat ETM+ and MODIS has proven to be a challenge because of the extensive and fragmented nature of the burned areas. This is illustrated in the bottom images of figure 10. In addition, topographic shadows and wet soils made the ETM+ interpretation complex and time-consuming.

7. Discussion and future work

The validation protocol follows a consensus approach to map the location and approximate date of burning by visual interpretation, augmented by limited fieldwork, of multitemporal Landsat ETM+ data. The protocol was implemented by members of the Southern Africa Fire Network (SAFNet) in 2000 and 2001 in Namibia, Botswana, Zimbabwe, Malawi, South Africa, and Mozambique at 11 Landsat ETM+ scenes. The scenes were selected to be representative of the conditions covered by the MODIS burned-area product and of the factors that influence product performance. They capture regional variation in the vegetation and the spatial characteristics of burned areas, and were located where SAFNet members have existing fire projects. Definition of statistically rigorous sampling strategies for independent data collection at the regional scale remains an open research issue. The development of statistically based sampling strategies could be undertaken by consideration of several years of burned-area data that do not have systematic or gross errors and that capture inter annual and seasonal fire variability. At the time of writing, these data do not exist. The experience of this work is that the development of such a strategy should also consider the considerable financial and human resources required to undertake a substantive validation.

The success of the validation protocol was contingent on the Landsat ETM + data being acquired before and after significant biomass burning events and then being sent to southern Africa within weeks of the post-fire ETM + acquisition. Agreements made with the US Landsat mission operations center and the primary US ground receiving station were necessary to guarantee ETM + acquisition and to expedite the identification process. At least two ETM + data sets were obtained for each scene in the 2000 and 2001 dry seasons. Persistent cloud meant that the period between ETM + acquisitions was as great as 48 days, reducing the ability to map burned areas and precisely define the date of burning. To reduce the mapping effort, a minimum mapping unit of 240 m was adopted whereby only burned areas with small axis dimensions of 240 m or greater were mapped. Despite this, the protocol was time-consuming to implement in the Malawi and Mozambique scenes because of the large number of small and spatially fragmented burned areas. Shadows cast by clouds and surface relief variations reduced mapping reliability and made the interpretative process more time-consuming. Clouds and spectral confusion with unknown features that were inaccessible to fieldwork precluded mapping in certain areas. Several outstanding issues remain. It is unknown to what degree burns produced by low-combustion completeness fires, burns with small and/or spatially fragmented dimensions relative to the ETM + pixel dimension, and burns with spectral persistence less than the 16 day ETM + acquisition period, were mapped using the ETM + data. Similarly, it is unknown if burned areas produced by surface fires and concealed by unburned overstorey vegetation were mapped. Further research is required in these respects, as this lack of information constrains our ability to define precisely the limits of MODIS burned-area detection.

Preliminary statistical comparisons between the Landsat ETM + derived independent burned-area data and the 500 m MODIS burned-area product have been presented recently (Roy *et al*. 2003) and will be described in a separate peer-reviewed publication in preparation. These and select qualitative results illustrated in this paper indicate a high accuracy in mapping the location and approximate day of burning, although burns with small axis dimensions and areas smaller than approximately 500 m and 1 km^2, respectively, are not detected reliably.

The SAFNet resource management and environmental assessment activities described in this paper, and other SAFNet activities, are being used to identify regional needs for information on fire location, extent, and time of occurrence. These activities include geographically the 11 Landsat ETM + scenes. We expect that our validation results and satellite data acquired at these scenes will be useful for validation of future MODIS fire products and products derived from other current and planned remote sensing systems. At the time of writing, it is planned to repeat the validation approach in 2002 to provide a multi-annual MODIS burned-area product validation. A long-term goal of SAFNet is to identify how best to incorporate these and other satellite products into an operational fire monitoring system that meets the information needs of policy-makers, natural resource managers, and the scientific community. Conventional methodologies to quantify satellite product accuracy provide useful information (Foody 2002) but may not be comprehensible or relevant to all product users. The development of validation reporting metrics specific to the information needs of different users in southern Africa will be investigated. This work will be linked to ongoing research to obtain a better understanding of the factors that influence the accuracy of the MODIS burned-area product.

Acknowledgements

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