**CSIRO** PUBLISHING

www.publish.csiro.au/journals/ijwf *International Journal of Wildland Fire* **2010**, *19*, 861–878

# Southern African fire regimes as revealed by remote sensing

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**Abstract.** Here we integrate spatial information on annual burnt area, fire frequency, fire seasonality, fire radiative power and fire size distributions to produce an integrated picture of fire regimes in southern Africa. The regional patterns are related to gradients of environmental and human controls of fire, and compared with findings from other grass-fuelled fire systems on the globe. The fire regime differs across a gradient of human land use intensity, and can be explained by the differential effect of humans on ignition frequencies and fire spread. Contrary to findings in the savannas of Australia, there is no obvious increase in fire size or fire intensity from the early to the late fire season in southern Africa, presumably because patterns of fire ignition are very different. Similarly, the importance of very large fires in driving the total annual area burnt is not obvious in southern Africa. These results point to the substantial effect that human activities can have on fire in a system with high rural population densities and active fire management. Not all aspects of a fire regime are equally impacted by people: fire-return time and fire radiative power show less response to human activities than fire size and annual burned area.

**Additional keywords:** burnt area, fire frequency, fire radiative power, fire size, human land use, ignition frequency, vegetation type.

## Introduction

When the first satellite-derived information on fires became available in the 1990s, one of the most striking features was the sheer number of fires in Africa. Global maps of fire occurrence were dominated by a mass of burn points centred on Africa, which caused it to be dubbed 'The Fire Continent' (Goldammer 2001). Of course, these data only confirmed the observations of ecologists and African pastoralists that fire was an important part of these ecosystems. Savanna and grassland environments produce fine fuels that dry out rapidly when there is no rain. The seasonal rainfall over much of the region means that fuels can develop and cure over just 1 year, resulting in some of the most frequent fire-return intervals on Earth. Moreover, human ignition and fire management are pervasive throughout Africa, where much of the population is not yet urbanised, and communal land management is common.

Africa has been a source of seminal research into the ecological effects of fire intensity, frequency and season in savanna, grassland and fynbos systems (Phillips 1930; Pellew 1983; Trollope and Tainton 1986; Belsky 1992; Gignoux *et al.* 1997; Bond *et al.* 2003), and the continent boasts a suite of long-term fire exclusion and fire application experiments (see Brookman-Amissah *et al.* 1980; Swaine *et al.* 1992 for West African examples and Booysen and Tainton 1984; Abbadie *et al.* 2006; Govender *et al.* 2006; Higgins *et al.* 2007 for Southern African examples).

What the satellite data provide, which had not been available before, is a spatially explicit and comprehensive view of fire in Africa. Thus, for the first time, it is possible to describe fire regimes not only at localities, but across the whole continent. This makes it easier to expand our view of fire from a disturbance acting almost randomly on the system, to a process that is affected by the climate, topography, vegetation and social context in which it occurs. At the same time, the need to characterise and quantify patterns of fire has increased, prompted by greenhouse gas accounting efforts and climate change research (Scholes *et al.* 1996; Schultz *et al.* 2008), as well as by the desire of conservation managers to provide a more natural fire regime (Brockett *et al.* 2001).

The frequency, seasonality, intensity, severity, fuel consumption and spread patterns of fires that prevail at a certain location are referred to as the fire regime (Gill 1975; Bond and

 10.1071/WF10008 1049-8001/10/070861

Keeley 2005). How fire regimes will change as human populations, their land-use practices and the climate change is unclear (Bowman *et al.* 2009; Flannigan *et al.* 2009). Good descriptions of fire regimes at regional scales are needed to better understand these feedbacks. In the past, fire regime data have only been available for relatively small areas in Africa, almost all of which were protected areas where the fire regime was substantially different from the general, inhabited landscape. Furthermore, the samples did not include the full range of climate and vegetation on the subcontinent.

The available remotely sensed data on fire in Africa have improved substantially in the last few decades. The first satellite-derived fire products identified the date and location of actively burning fires ('hot spots'), but only fires burning at the time of satellite overpass could be recorded, which introduced a temporal bias (Giglio 2007). The radiometer sensors that provide these data are now more sensitive and resolved, and can also be used to provide an indication of the rate of energy release of the fires – Fire Radiative Power (FRP) (Wooster *et al.* 2003; Giglio 2007). Fire radiative power is measured in megawatts per pixel and gives an indication both of the biomass consumption rate and the fireline intensity (Roberts *et al.* 2005, 2009; Smith and Wooster 2005). These data are available over nearly a decade – sampled four times daily at 1-km resolution (from the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor on the Terra and Aqua polar-orbiting platforms), and every 15 min at 5-km resolution (from the Spinning Enhanced Visible and Infrared Imager (SEVIRI) sensor on the Meteosat geostationary satellite). Thus it is possible to characterise the daily and seasonal patterns of burning. Moreover, several algorithms to identify and map burned areas have been developed (Barbosa *et al.* 1999; Tansey *et al.* 2004; Roy *et al.* 2005*a*; Plummer *et al.* 2006; Giglio *et al.* 2009), which give an indication of the total area burned by fire, and can be used to derive the season and frequency of fire. The most complete of these burnt area data span nearly a decade, and can therefore give reliable estimates of fire frequency in places where the average return time is only a few years (see van Wilgen and Scholes (1997) for estimates of current fire-return periods in the region). Finally, because the burned area data provide information on the spatial extent of burning, they can be used to identify individual fires. This provides a route to elusive fire regime information such as ignition frequency and fire size distributions.

The wide range of data sources now available allows for a more nuanced view of fire regimes in Africa. The initial assessment of Africa as the fire hot-spot of the globe was based only on active fire data, i.e. the number of actively burning pixels recorded at certain times of day. If these fires were all very small – for example, crop fires or small management burns – then initial estimations of the extent and importance of African wildfires might be inflated. In fact, recent models suggest that the fires in grassy (C4) systems and in Africa contribute much less to global emissions of greenhouse gases and aerosols than initially expected (Randerson *et al.* 2005).

By combining all sources of remotely sensed information, it should now be possible to provide a description of the fire regime of any location on the continent. How will these data be useful? For land managers and policy-makers, it provides information on which to base regulatory decisions. Fire has always been an important focus of national land strategies in southern Africa and the control and management of fire will receive more attention as countries attempt to understand and reduce vulnerability to climatic change, and as incentives to manipulate fire regimes to store carbon increase. Baseline data on the extent, season and intensity of fire are required before decisions can be made on what fire regimes are appropriate, and whether management interventions are effective. For scientists who aim to understand the role of humans in the fire–vegetation–climate system (Archibald *et al.* 2009) and the importance of fire in determining biome distributions (Bond 2005), these remotely sensed data products provide the data to test their theories. Correlative studies at regional scales can now be used to supplement experimental and plot-level data.

This paper provides quantitative data on annual burnt area, fire frequency, fire season, fire intensity and fire size distributions derived from remotely sensed data sources for southern Africa. Data are summarised by country, by vegetation type and by land use. They are mapped at 0.25° and 1° resolution to demonstrate regional patterns and the limits of fire on the subcontinent. The data are available continent-wide but in order to focus on regions with which we had more detailed ecological experience, this study is limited to southern Africa. We were restricted by the temporal scale of the available data (maximum 8 years at the time of writing), so we only describe the current patterns of fire. This paper is a summary of our current knowledge, and a springboard for future research: it aims to expand fire research out of the national parks and protected areas of the region and to highlight the importance of humans in affecting fire in Africa.

## Methods

### Data

#### Satellite fire data

The various satellite data products and methods used to extract different fire regime characteristics are described below.

*Burnt area.* Eight years of burnt area data from the MODIS (MCD45A1) product were used. They covered the period April 2001 to March 2008. These data are produced at 500-m resolution using a view-direction-corrected change detection procedure to identify pixels that burned and the approximate day of burning (accurate to within 8 days) (Roy *et al.* 2005*a*). When insufficient input data are available to run the algorithm owing to excessive cloud cover or sensor problems, pixels are flagged as 'no data'. A southern African accuracy assessment indicates that the product can identify ~75% of the burnt area (Roy and Boschetti 2009). This accuracy is expected to decrease with increasing tree cover (Roy *et al.* 2008). Improved spatial resolution (500 m instead of 1 km) and the availability of quality flag information are a major improvement over previous burnt area products.

*Annual burnt area.* The monthly burned area data were summarised annually to produce a burnt or unburnt layer for each fire year (January to December). Boschetti and Roy (2008) suggest summarising the data using a fire year from April to March for southern African savannas. However, it is more common to use a calendar year, and very little ($<0.6\%$) of the burning occurs from January to March. Owing to technical problems on the MODIS satellite, there were no burnt area data for June 2001. In order to calculate an annual sum for 2001, the following method was used to fill in these missing data: for each year, the area burnt in June and the area burnt in the rest of the year were calculated. The 2001 burnt area (no June) was divided by the average burnt area (no June) over all other years to give a ratio indicating the degree to which the 2001 burn year was above or below the mean. The average area burnt in June in all other years was then multiplied by this ratio to give an estimation of the 2001 June burnt area. This filling algorithm was computed separately for each geographic unit used in the analysis (country, vegetation, land-use category and 1° grid) to accommodate differences in patterns of variability in different parts of the subcontinent. To test the effect of this filling algorithm, the July data were systematically removed from each of the remaining years (2002–07), and filled using the same methods. The results of this test showed the filling algorithm to be very accurate (all 6 years had $r^2$ values $>0.96$ and mean absolute errors $<1\%$).

*Fire frequency.* Monthly burned area data layers were combined to calculate the number of times a pixel burned in 8 years (fire frequency). Because we were more interested in accuracy than comprehensiveness, we were conservative in our approach to invalid data: we excluded all pixels that had invalid data more than two times a year on average (14% of the dataset). Savanna fires are grass-fuelled, with average return periods ranging from 2 to 6 years (van Wilgen and Scholes 1997), so the 8-year MODIS dataset can capture a great deal of the variation in fire frequency on the subcontinent. The result was a map at 500-m resolution of the number of burns a pixel experienced in 8 years.

*Fire-return period.* Calculating fire-return period from fire occurrence data involves fitting a distribution (usually the Weibull distribution) to a set of individual fire-return records, and accounting for the censoring that occurs at the beginning and end of the record period (Polakow and Dunne 1999; McCarthy *et al.* 2001; Moritz *et al.* 2009). Although methods for estimating fire return from fire count data are well developed, they require an *a priori* identification of landscape units within which to estimate parameters, and they make the assumption that the landscape being considered has a uniform fire regime (Polakow and Dunne 1999). This is likely to be problematic at different spatial scales and particularly in mixed forest–grassland systems, or landscapes of mixed cropland and natural vegetation where different parts of the landscape burn at different frequencies.

Despite this caveat, we used the Weibull distribution to estimate a fire-return period for different geographic units (country, land-use and vegetation classes). This was performed with R statistical computing software using the 'survival' package. The fire-return period was estimated by randomly selecting 100 500-m pixels in each class and fitting a Weibull distribution to the return periods (right-censored data were included, following Moritz *et al.* (2009) and Polakow and Dunne (1999)). The Weibull shape and scale parameters and their confidence intervals were estimated using all data, and also using only data from pixels that burnt at least once in the 8-year period. The difference between these two distributions provides an indication of the impact of having patches that never burn within a fire landscape. The median fire interval (*MEI*) was then estimated from these parameters following Moritz *et al.* (2009):

$$MEI = b(\ln 2)^{(1/c)}$$

where $b$ is the scale parameter and $c$ is the shape parameter.

Owing to the relatively short (8 years) data record, the algorithm did not always converge in landscapes with infrequent fire. These fire-return data allowed for an initial comparison of return periods across geographic units, but a rigorous assessment of fire-return periods across Africa is beyond the scope of this paper.

*Fire size and fire number.* Individual fires were identified from the MODIS burnt area data using the algorithm described in Archibald and Roy (2009). This produces a list of points with the size, location of the centroid, start date, mid-date and end date of each fire across southern Africa. As the resolution of the input data is 0.25 $km^2$ (a 500-m MODIS pixel) any fires smaller than 0.25 $km^2$ would not be identified or included in the final count. Several different methods were used to create summary statistics from these data. First, the number of fires in each 1° grid point was calculated and converted to a fire density (fires per square kilometre). Then the fires were divided into 12 size classes: $<0.25$ $km^2$ (the resolution of the original data), 1, 2.5, 5 10, 25, 50, 100, 250, 500, 1000 and 2500 $km^2$. It has been shown in many systems that the majority of the area is burned by the very largest fires: the top 1% of fires burn 99% of the area (Strauss *et al.* 1989), but there are several reasons why this rule might not apply to southern Africa. To test this, we calculated both the number of fires and the area burned by fires in each size class for each 1° grid. We also calculated the 95th percentile of fire size for each 1° grid cell as a measure of the size of the largest fires experienced in different parts of the subcontinent.

*Fire Radiative Power as an index of fireline intensity.* Fireline intensity is a measure of the rate of energy released from a fire per unit length of the burning front (measured in $kW\,m^{-1}\,s^{-1}$). It has traditionally been calculated as the product of the dry weight of biomass burned, the energy content of the fuel and the rate of spread of the fire (Byram 1959). Fireline intensity is a good predictor of the effort required to control a fire. Ecologically, fireline intensity is related to flame length and has effects on the size class of trees that are top-killed (Williams *et al.* 1999) and on the patchiness of a burn (Hely *et al.* (2003), but see Keeley (2009) for a discussion of the limitations of using fire intensity as an index of ecosystem response to fire). Fires with higher fireline intensities might also burn for longer, and burn larger parts of the landscape, as they are less likely to be extinguished by night-time weather conditions, moist fuels, or topographic barriers.

Satellite middle-infrared wavelength measurements sensed over actively burning fires can be used to calculate the rate of radiant energy release: the Fire Radiative Power (Kaufman *et al.* 1996). This is measured in units of megawatts per pixel ($mW\,pixel^{-1}$). Given that the energy content of grass fuels is fairly constant ($\sim 18\,000\,J\,g^{-1}$: Stocks *et al.* 1996), it can also be used to quantify the amount of biomass burned by fires in Africa (Wooster *et al.* 2003; Roberts *et al.* 2005). It could also theoretically be used as a spatially and temporally continuous measure of the fireline intensity (Smith and Wooster 2005).

The SEVIRI sensor provides FRP measurements every 15 min. It is placed on the Meteosat platform, which flies in a geostationary orbit ~36 000 km above the earth centred on the equator. The pixel sizes are of the order of 4.8 × 4.8 km at nadir, and somewhat larger in southern Africa. SEVIRI data were processed to FRP using the algorithm of Roberts *et al.* (2005) and used to identify high-intensity fire pixels in a 1-year period from February 2004 to January 2005. The energy released by individual fires varies greatly over the duration of the fire: for example, grassland fire FRP has been observed to change by an order of magnitude with the wind direction relative to the unburned fuel bed (head *v.* back fires) (Smith and Wooster 2005), and at night, the fire intensity is typically much lower. In our case, we were most interested in the maximum fireline intensity – as this affects vegetation processes like grass and tree response to fires (Trollope and Tainton 1986). Therefore, the maximum FRP recorded in each SEVIRI pixel was isolated as an indication of the maximum rate of energy release. At present, this index cannot be directly related to the conventional measure of fireline intensity (kW $m^{-1}$) because the length of the flame front is not known. There is ambiguity introduced because a very small, very intense fire could have the same FRP value as a very large, less intense fire.

*Seasonal patterns of fire.* The average and standard deviation in area burnt each month was quantified by country, vegetation type, land use and 1° grid. The month of peak fire activity, as well as the 'seasonality' of fire (how long the fire season is) was calculated for each geographic unit. The median and 95th quantiles of fire size and FRP were also plotted over time to test whether fire size and fireline intensity increase over the dry season.

### Geographic stratification and environmental explanatory data

*Country boundaries.* The current geographic boundaries of the 16 countries south of the Equator (including Madagascar) were used to quantify fire regimes for politically distinct regions. The Democratic Republic of Congo and the Republic of the Congo straddle the Equator but were included in the analysis as the majority of their landmasses are within the study region. In these instances, statistics were calculated only for the southern-hemisphere portion. A 1° grid square was also used to summarise and map data.

*Vegetation classes.* The 19 major vegetation classes in White's vegetation map of Africa (White 1983) were reclassified into seven classes: forest, forest transitions, thicket, savanna (including woodland), grassland, arid shrubland (including desert), and fynbos. Edaphic grassland mosaics were included in the grassland category, woodland mosaics were included in savannas, but forest transitions were maintained as a separate class. These are generally grassy systems with clumps of forest trees. The grass component burns extensively and this vegetation class can be seen to represent the edge of the forest–savanna boundary. All other vegetation (altimontaine, azonal, anthropic) was classed as 'other' and not included in the analysis as its geographic extent was very limited.

*Land use.* The land-use categories were identified by lumping the Global Land Cover 2000 (GLC2000) land-cover map (Mayaux *et al.* 2004) into three broad classes: settlements, cultivated land and uncultivated land (mostly used for grazing). The World Protected Areas (UNEP-WCMC world database on protected areas, see http://www.wdpa.org/, accessed 20 September 2010) map was overlaid on this to produce a map with four categories: settlements, cultivated, uncultivated and protected areas, which represent a gradient of decreasing intensity of human impact.

*Other data.* Spatial information on human population density (CIESIN 2005) was also used to investigate the effect of people on fire in southern Africa. These data were summarised (using the median) by 1° grid cell. Spatially explicit datasets on tree cover (Hansen *et al.* 2003), rainfall (Huffman *et al.* 2007), grazing density (FAO 2005) and soil texture (IGBP 2000) were also used to explore the environmental limits of fire (see Archibald *et al.* (2009) for detailed information on these data).

## Analysis

Spatial data manipulation was performed with *ERDAS Imagine 9.3* spatial analysis software and all analyses were performed using the open-source R statistical computing software (v2.10.1, see http://www.r-project.org/, accessed in September 2009).

The environmental characteristics of pixels that burnt at least once in the 8-year data period were used to characterise the environmental limits of fire on the subcontinent. Archibald *et al.* (2009) identified rainfall, tree cover, length of the dry season, grazing density, population density and soil fertility as potential drivers of burnt area. The median, 75th, 95th, and 99th quantiles of these variables were calculated for burnt pixels and for all pixels in the region and compared.

Annual burnt area, monthly burnt area, fire frequency, and FRP data were summarised by country, land use and vegetation type, as well as by 1° grid cell. These data were used to describe fire regimes across environmental, geographic, and human impact gradients in the region.

The proportion and probability of extremely large fires were summarised in several ways. First, the size of the 95th quantile of all fires in a 1° grid was calculated, and these data were mapped and plotted against information on fire number and burnt area to explore how important large fires are in determining annual area burned. Then, the median and 95th quantiles of fire size and FRP were plotted over time to test whether fire size and fireline intensity increase over the dry season, as has been shown in northern Australia. Finally, human population density was plotted against fire size and fire number to test theories of how human patterns of ignition and land use alter fire-size distributions.

## Results

### The environmental limits of fire

On average, 11.2% (s.d. 0.81) of southern Africa was identified as burned each year by the MODIS burned area product, which is thought to detect ~75% of the burned area mapped using high-resolution images in southern Africa (Roy and Boschetti 2009). Therefore, the mean % burned area could be as high as 15%.

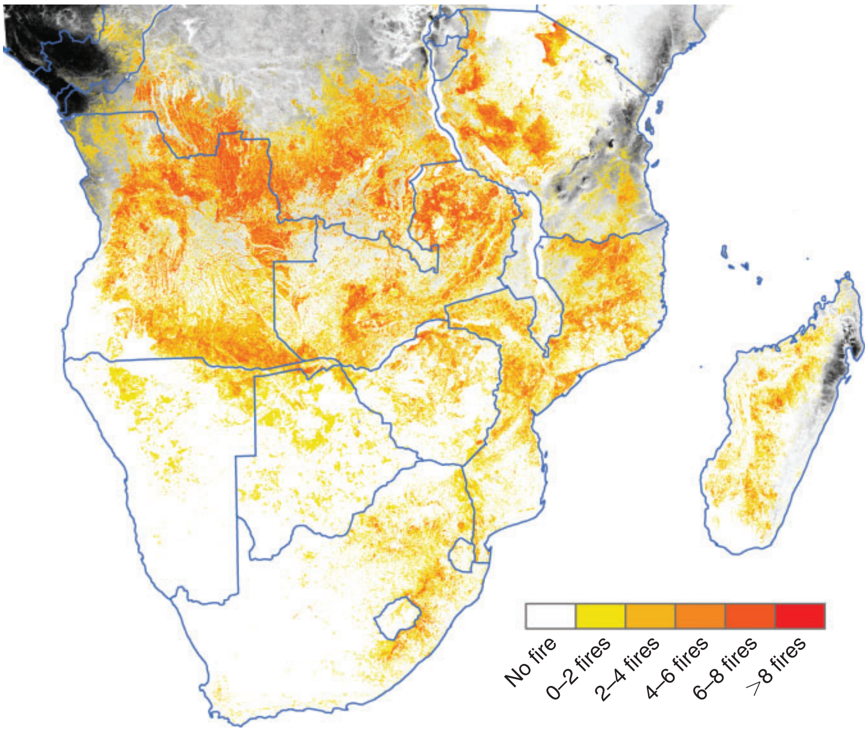


**Fig. 1.** The area affected by fire determined from an 8-year satellite burnt area product. Colours indicate the number of times pixels were classified as burned. Grey areas represent pixels that were classified as invalid over the time period; darker grey, less valid data.

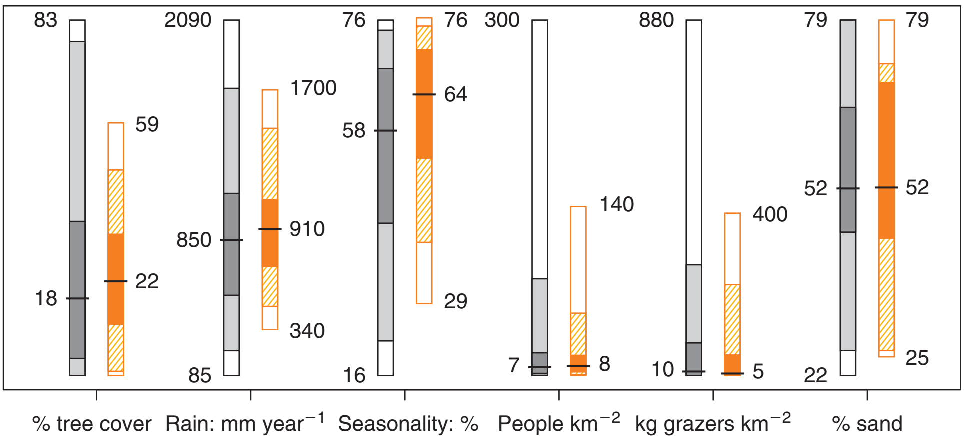


**Fig. 2.** The environmental limits of areas that burn in southern Africa (orange) compared with the environmental limits of the entire region (grey). The horizontal line represents the median (50th quantile), dark bars represent the 25th and 75th quantiles, light bars represent the 5th and 95th quantiles, and open boxes represent the 1st and 99th quantiles. Fire-affected areas have higher mean rainfall and tree cover than the entire region, but are also limited in the upper values of rainfall and tree covers in which fire occurs. Fire also occurs more in areas with strongly seasonal rainfall. Fire appears to be limited by very high human densities and grazer numbers.

Invalid pixels (usually due to cloud cover) made up ~3% of the landmass and this area was not included in the calculation.

Fire-affected pixels were considered pixels that burned at least once in the 8-year period for which there were data, and 35% of the landmass is classified as fire-affected (Fig. 1). Most of this area burnt only once or twice, but almost 4% of it burnt every year over the 8 years.

The environmental characteristics of 'fire-affected' pixels give an indication of the environmental limits of fire in southern African savannas (Fig. 2). Fire does not occur in pixels with tree cover greater than ~59%, human population densities greater than 140 people per square kilometre, or grazing densities higher than 400 kg km$^{-2}$. Fire also does not occur in regions with rainfall less than 340 mm or seasonality less than ~29%

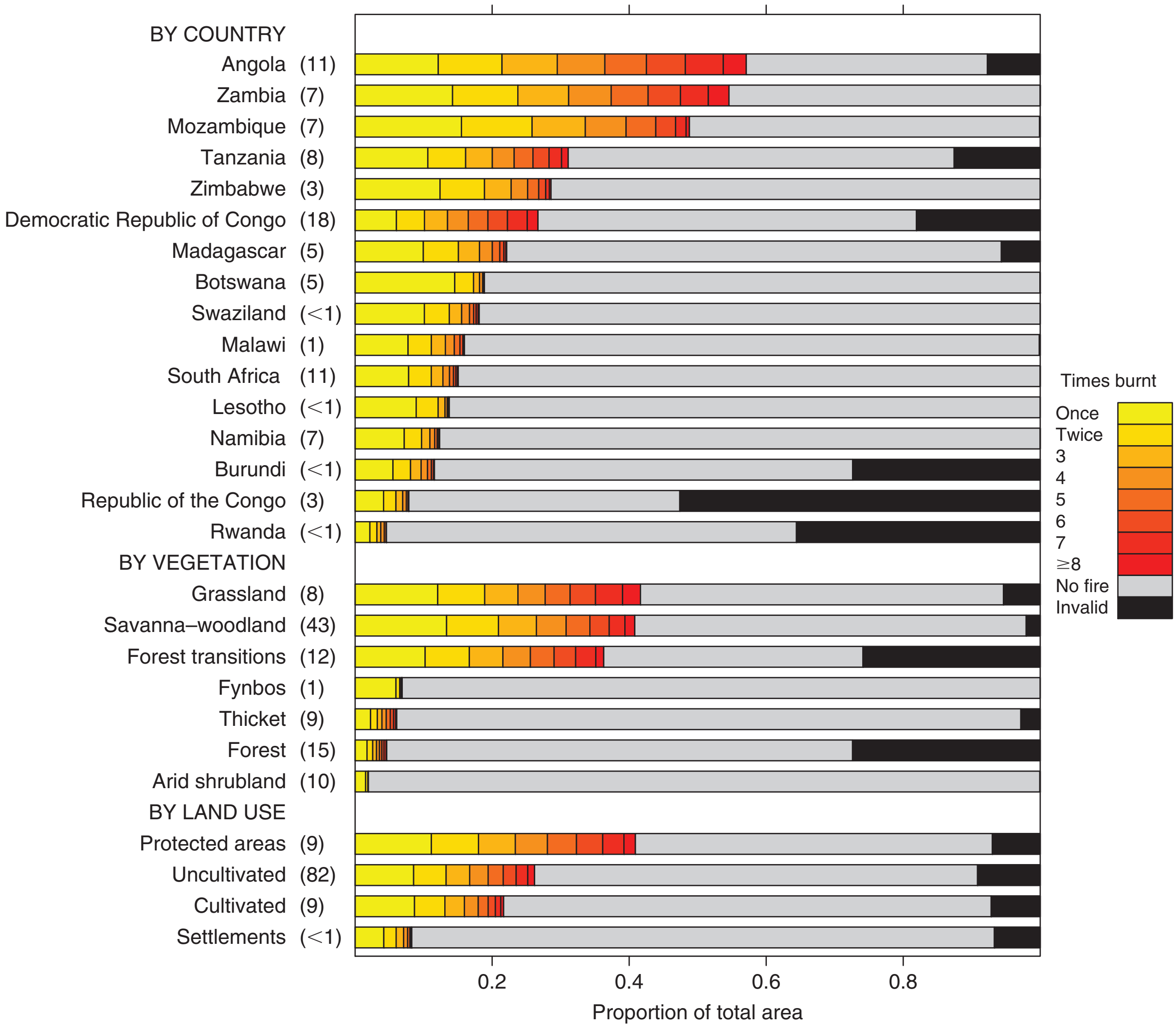


**Fig. 3.** The frequency of fire (expressed as the proportion of the total area that burned 0–8 times over 8 years). Data are summarised by country, vegetation type and land-use category in southern Africa and values in brackets represent the percentage of the landmass covered by each class. Grassy systems (grasslands, savanna–woodland and forest transitions) have substantially more fire than non-grassy systems, and the area affected by fire decreases as human land use intensifies (from grazing, to cultivation, to settlements).

(a seasonality score of 0% would occur if an equal amount of rainfall fell in each month of the year; if all the rainfall fell in 1 month the seasonality would be 100%). See Markham (1970) and Archibald *et al.* (2010) for a complete definition of rainfall seasonality. Soil texture does not appear to be related to fire occurrence at this scale.

### *Fire regimes by country, vegetation, and land use*

The countries that show the most fire activity are Angola, Zambia and Mozambique (Fig. 3). Over 50% of the land area of these countries is affected by fire, and much of this area burned more than four times in the 8-year period (return period of approximately 2 years). Except for the fynbos region in the Western Cape, fires in southern Africa are largely grass-fuelled surface fires, so it is not surprising that vegetation types with a dominant grass layer (savannas, grassland and forest transitions) burned more extensively, and more frequently, than vegetation types with little grass, such as forest, arid shrubland and thicket (Fig. 3). Fires in the fynbos are crown fires, consuming dense sclerophyllous shrubs and small trees, with fire-return periods on the order of 10–30 years. This 8-year dataset is unlikely to characterise their fire frequency accurately (median fire intervals fitted using the Weibull distribution either didn't converge or gave unrealistically high values, Table 1).

Median fire-return intervals (*MFI*) for grassland and savanna systems in the region range from 1.7 to ~10 years, depending on the rainfall and degree of human impact (Table 1). In Malawi, for example, which has a very high human population density, very little (<5%) of the landscape outside protected areas burns, which means that estimated *MFI*s are over 100 years. Those parts of the landscape that do burn, however, burn with characteristic return periods of 3–10 years (Table 1). A similar

**Table 1. Fire statistics of different vegetation types and land-use categories for each country in southern Africa**

Columns represent: the total area evaluated, median % burnt area ('% burnt'); 25% confidence intervals (CI); the median fire-return interval (*MEI*) calculated (CI, 25%) for all pixels ('*MEI* all') and only burnt pixels ('*MEI* burnt'); the month of peak fire; and the seasonality of fire (ranging from 0, fire all year round; to 1, all fire occurred in 1 month). The tilde (~) indicates that the Wiebull parameterisation did not converge, so median fire return could not be calculated

| Vegetation | Land use | km$^2$ ($\times 10^3$) | % burnt | CI | *MEI* all | CI | *MEI* burnt | CI | Peak month | Seasonality |
|---|---|---|---|---|---|---|---|---|---|---|
| Angola | | | | | | | | | | |
| Arid shrubland | Protected areas | 21 | 0 | (0–0) | ~ | ~ | ~ | ~ | Aug | 0.5 |
| Arid shrubland | Uncultivated | 43 | 0 | (0–0) | 99 | (0.2–>5000) | 0.5 | (0.3–0.8) | Aug | 0.6 |
| Arid shrubland | Cultivated | 1 | 0 | (0–0) | 2.7 | (2.5–3) | ~ | ~ | Aug | 0.8 |
| Forest | Uncultivated | 7 | 33 | (31–36) | 2.9 | (2.4–3.5) | 1.7 | (1.5–2) | Jun | 0.9 |
| Forest | Cultivated | 1 | 5 | (0–10) | ~ | ~ | ~ | ~ | May | 1 |
| Forest transitions | Uncultivated | 220 | 33 | (30–37) | 1.8 | (1.6–2.1) | 1.2 | (1.1–1.3) | Jun | 0.9 |
| Forest transitions | Cultivated | 2 | 51 | (45–58) | 0.9 | (0.8–1) | 0.8 | (0.8–0.9) | May | 0.9 |
| Grassland | Protected areas | 16 | 67 | (65–67) | 1.1 | (1–1.2) | 1 | (0.9–1) | Jun | 0.9 |
| Grassland | Uncultivated | 79 | 51 | (50–52) | 1.5 | (1.3–1.6) | 1.1 | (1–1.2) | Jun | 0.9 |
| Grassland | Cultivated | 1 | 61 | (52–63) | 1.6 | (1.4–1.7) | 1.1 | (1–1.2) | Jun | 0.9 |
| Savanna–woodland | Protected areas | 47 | 34 | (30–36) | 2.3 | (2–2.6) | 1.5 | (1.4–1.7) | Aug | 0.9 |
| Savanna–woodland | Uncultivated | 767 | 26 | (24–27) | 3.3 | (2.8–3.9) | 1.4 | (1.3–1.6) | Aug | 0.8 |
| Savanna–woodland | Cultivated | 41 | 17 | (15–19) | 7.3 | (5.4–9.9) | 2.1 | (1.8–2.6) | Aug | 0.8 |
| Savanna–woodland | Settlements | 1 | 0 | (0–0) | ~ | ~ | ~ | ~ | ~ | ~ |
| Botswana | | | | | | | | | | |
| Arid shrubland | Protected areas | 14 | 0 | (0–0) | ~ | ~ | ~ | ~ | ~ | ~ |
| Arid shrubland | Uncultivated | 9 | 0 | (0–0) | ~ | ~ | ~ | ~ | ~ | ~ |
| Savanna–woodland | Protected areas | 83 | 1 | (1–5) | 4.6 | (1.7–12) | 0.4 | (0.3–0.5) | Aug | 0.8 |
| Savanna–woodland | Uncultivated | 389 | 2 | (1–5) | 2.3 | (2.1–2.5) | ~ | ~ | Aug | 0.7 |
| Savanna–woodland | Cultivated | 38 | 3 | (0–4) | 70 | (4.9–986) | 6.5 | (2.7–16) | Aug | 0.7 |
| Savanna–woodland | Settlements | 1 | 0 | (0–1) | ~ | ~ | ~ | ~ | Aug | 0.5 |
| Burundi | | | | | | | | | | |
| Forest | Uncultivated | 1 | 1 | (0–1) | ~ | ~ | ~ | ~ | Aug | 0.8 |
| Grassland | Protected areas | 1 | 0 | (0–0) | ~ | ~ | ~ | ~ | ~ | ~ |
| Grassland | Uncultivated | 6 | 1 | (0–2) | ~ | ~ | ~ | ~ | Aug | 0.9 |
| Grassland | Cultivated | 4 | 0 | (0–1) | ~ | ~ | ~ | ~ | Aug | 0.9 |
| Savanna–woodland | Protected areas | 1 | 30 | (22–33) | 4.8 | (3.8–6) | 2.6 | (2.2–3) | Jun | 0.9 |
| Savanna–woodland | Uncultivated | 9 | 4 | (2–6) | 33 | (10–106) | 2.9 | (1.9–4.4) | Aug | 0.9 |
| Savanna–woodland | Cultivated | 5 | 3 | (1–5) | 53 | (13–221) | 3.3 | (2.1–5.2) | Aug | 0.9 |
| Democratic Republic of Congo | | | | | | | | | | |
| Forest | Protected areas | 56 | 3 | (2–3) | 134 | (13–1360) | 2.9 | (1.5–5.7) | Jun | 0.9 |
| Forest | Uncultivated | 943 | 2 | (2–2) | 57 | (13–252) | 1.2 | (0.9–1.7) | Jun | 0.9 |
| Forest | Cultivated | 65 | 0 | (0–0) | ~ | ~ | ~ | ~ | Jun | 0.9 |
| Forest | Settlements | 1 | 0 | (0–0) | ~ | ~ | ~ | ~ | ~ | ~ |
| Forest transitions | Protected areas | 20 | 29 | (25–33) | 2.1 | (1.8–2.4) | 1.6 | (1.4–1.8) | Jun | 0.8 |
| Forest transitions | Uncultivated | 362 | 21 | (18–24) | 2.5 | (2–3.1) | 1.2 | (1.1–1.4) | Jun | 0.9 |
| Forest transitions | Cultivated | 12 | 2 | (2–2) | 1042 | (0.6–>5000) | 5.3 | (1–27) | Jun | 0.9 |
| Grassland | Protected areas | 10 | 37 | (31–37) | 1.6 | (1.4–1.8) | 0.8 | (0.7–0.8) | May | 0.8 |
| Grassland | Uncultivated | 91 | 34 | (31–36) | 1.7 | (1.5–1.9) | 1.1 | (1–1.2) | Jun | 0.8 |
| Grassland | Cultivated | 8 | 4 | (3–5) | 41 | (11–151) | 1.3 | (1–1.8) | Jun | 0.8 |
| Savanna–woodland | Protected areas | 21 | 32 | (28–34) | 2.9 | (2.5–3.4) | 1.6 | (1.4–1.8) | Jun | 0.8 |
| Savanna–woodland | Uncultivated | 374 | 32 | (28–34) | 2.4 | (2.1–2.8) | 1.2 | (1.1–1.3) | Jun | 0.8 |
| Savanna–woodland | Cultivated | 3 | 18 | (16–20) | 4.5 | (3.6–5.8) | 1.9 | (1.6–2.3) | Jun | 0.7 |
| Thicket | Uncultivated | 1 | 58 | (51–63) | 1.5 | (1.3–1.6) | 1.2 | (1.1–1.2) | Aug | 0.9 |
| Lesotho | | | | | | | | | | |
| Grassland | Uncultivated | 21 | 2 | (1–4) | 5.5 | (4.7–6.3) | ~ | ~ | Aug | 0.9 |
| Grassland | Cultivated | 4 | 1 | (1–2) | 203 | (5.3–>5000) | 4.1 | (2–8.3) | Aug | 0.9 |
| Madagascar | | | | | | | | | | |
| Forest | Protected areas | 13 | 2 | (2–2) | 72 | (12–451) | 3 | (1.9–4.8) | Aug | 0.6 |
| Forest | Uncultivated | 99 | 3 | (3–4) | 279 | (16–4970) | 6.4 | (2.6–16) | Aug | 0.6 |
| Forest | Cultivated | 47 | 1 | (1–1) | 496 | (5.4–>5000) | 3.7 | (1.5–9.6) | Sep | 0.8 |
| Forest transitions | Protected areas | 1 | 0 | (0–4) | 106 | (0.2–>5000) | 8.5 | (1.3–54) | Oct | 0.9 |
| Forest transitions | Uncultivated | 12 | 1 | (1–2) | 3465 | (2.2–>5000) | 16 | (1.9–133) | Oct | 0.8 |
| Forest transitions | Cultivated | 9 | 0 | (0–0) | 24 | (15–39) | 3.3 | (1.1–10) | Oct | 0.9 |
| Grassland | Protected areas | 1 | 6 | (5–8) | 38 | (14–105) | 5.9 | (3.7–9.3) | Sep | 0.7 |
| Grassland | Uncultivated | 126 | 11 | (8–15) | 8.2 | (6–11) | 2.3 | (2–2.8) | Aug | 0.8 |

(*Continued*)

**Table 1. (Continued)**

| Vegetation | Land use | km$^2$ ($\times 10^3$) | % burnt | CI | *MEI* all | CI | *MEI* burnt | CI | Peak month | Seasonality |
|---|---|---|---|---|---|---|---|---|---|---|
| Grassland | Cultivated | 2 | 8 | (6–8) | 21 | (11–38) | 3 | (2.2–3.9) | Sep | 0.8 |
| Savanna–woodland | Protected areas | 6 | 6 | (5–7) | 36 | (14–98) | 4.1 | (2.8–5.8) | Aug | 0.7 |
| Savanna–woodland | Uncultivated | 210 | 8 | (7–10) | 21 | (12–39) | 2.9 | (2.3–3.7) | Aug | 0.6 |
| Savanna–woodland | Cultivated | 8 | 4 | (3–6) | 111 | (19–656) | 10 | (4.6–23) | Sep | 0.8 |
| Thicket | Protected areas | 1 | 1 | (0–3) | 117 | (15–952) | 2.1 | (1.5–3) | Oct | 0.9 |
| Thicket | Uncultivated | 54 | 2 | (1–2) | 1783 | (5.6–>5000) | 9.6 | (2.1–44) | Sep | 0.7 |
| Malawi | | | | | | | | | | |
| Grassland | Protected areas | 3 | 31 | (26–34) | 3.1 | (2.6–3.6) | 1.8 | (1.6–2) | Aug | 0.7 |
| Grassland | Uncultivated | 7 | 4 | (4–4) | 147 | (11–1877) | 11 | (3.9–31) | Sep | 0.8 |
| Grassland | Cultivated | 3 | 2 | (1–2) | 139 | (18–1055) | 3 | (1.9–4.8) | Sep | 0.8 |
| Savanna–woodland | Protected areas | 8 | 13 | (12–14) | 12 | (7.8–17) | 3.6 | (2.9–4.6) | Aug | 0.8 |
| Savanna–woodland | Uncultivated | 43 | 5 | (5–6) | 109 | (11–1111) | 5.9 | (2.9–12) | Aug | 0.7 |
| Savanna–woodland | Cultivated | 28 | 2 | (2–2) | 200 | (10–3929) | 8.2 | (3.1–21) | Aug | 0.8 |
| Mozambique | | | | | | | | | | |
| Forest transitions | Protected areas | 6 | 32 | (27–40) | 3.4 | (2.9–4) | 2 | (1.7–2.2) | Sep | 0.8 |
| Forest transitions | Uncultivated | 213 | 17 | (16–18) | 6.6 | (5.1–8.6) | 2 | (1.7–2.3) | Aug | 0.8 |
| Forest transitions | Cultivated | 9 | 16 | (13–19) | 5.5 | (4.4–6.9) | 2 | (1.7–2.3) | Aug | 0.8 |
| Grassland | Uncultivated | 2 | 13 | (11–14) | 15 | (9.5–25) | 3 | (2.3–3.9) | Aug | 0.8 |
| Grassland | Cultivated | 1 | 3 | (3–4) | 138 | (9.4–2024) | 7.4 | (3.1–18) | Aug | 0.8 |
| Savanna–woodland | Protected areas | 38 | 17 | (15–22) | 5.6 | (4.5–7.1) | 2.7 | (2.3–3.2) | Aug | 0.8 |
| Savanna–woodland | Uncultivated | 433 | 20 | (19–21) | 3.2 | (2.8–3.8) | 1.9 | (1.7–2.1) | Aug | 0.8 |
| Savanna–woodland | Cultivated | 54 | 15 | (14–17) | 7.5 | (5.7–10) | 3.2 | (2.7–3.8) | Aug | 0.8 |
| Namibia | | | | | | | | | | |
| Arid shrubland | Protected areas | 82 | 0 | (0–1) | 8 | (6.5–9.7) | 2.9 | (1.2–7.2) | Aug | 0.9 |
| Arid shrubland | Uncultivated | 364 | 0 | (0–1) | 1.9 | (1.7–2) | ~ | ~ | Aug | 0.8 |
| Arid shrubland | Cultivated | 2 | 1 | (0–1) | 0.4 | (0.4–0.5) | ~ | ~ | Sep | 0.6 |
| Grassland | Uncultivated | 1 | 5 | (4–13) | 16 | (9.3–26) | 4.4 | (3.3–5.8) | Oct | 0.6 |
| Savanna–woodland | Protected areas | 26 | 15 | (12–18) | 6.7 | (5.1–8.9) | 2.8 | (2.3–3.4) | Aug | 0.9 |
| Savanna–woodland | Uncultivated | 323 | 5 | (4–5) | 57 | (13–257) | 4.9 | (3–8) | Aug | 0.9 |
| Savanna–woodland | Cultivated | 16 | 0 | (0–1) | 124 | (1.3–>5000) | 3.6 | (1.7–7.8) | Aug | 0.8 |
| Savanna–woodland | Settlements | 1 | 2 | (2–5) | 34 | (13–86) | 2.8 | (2.1–3.7) | Jun | 0.7 |
| Republic of the Congo | | | | | | | | | | |
| Forest | Protected areas | 14 | 0 | (0–0) | ~ | ~ | ~ | ~ | ~ | ~ |
| Forest | Uncultivated | 178 | 0 | (0–0) | ~ | ~ | ~ | ~ | Aug | 0.9 |
| Forest | Cultivated | 14 | 1 | (0–1) | ~ | ~ | ~ | ~ | Aug | 0.9 |
| Forest transitions | Protected areas | 8 | 11 | (7–13) | ~ | ~ | ~ | ~ | Jun | 0.9 |
| Forest transitions | Uncultivated | 83 | 9 | (8–9) | ~ | ~ | ~ | ~ | Jun | 0.9 |
| Forest transitions | Cultivated | 3 | 9 | (7–13) | ~ | ~ | ~ | ~ | Jun | 0.9 |
| Rwanda | | | | | | | | | | |
| Grassland | Protected areas | 2 | 0 | (0–0) | ~ | ~ | ~ | ~ | Aug | 1 |
| Grassland | Uncultivated | 3 | 0 | (0–0) | ~ | ~ | ~ | ~ | Aug | 0.9 |
| Grassland | Cultivated | 5 | 0 | (0–0) | ~ | ~ | ~ | ~ | Aug | 0.8 |
| Savanna–woodland | Protected areas | 2 | 23 | (9–30) | 3.9 | (3.2–4.7) | 2.1 | (1.9–2.4) | Aug | 0.9 |
| Savanna–woodland | Uncultivated | 7 | 0 | (0–1) | ~ | ~ | ~ | ~ | Aug | 0.8 |
| Savanna–woodland | Cultivated | 8 | 0 | (0–0) | 1340 | (0–>5000) | 3.6 | (0.8–17) | Aug | 0.9 |
| South Africa | | | | | | | | | | |
| Arid shrubland | Protected areas | 19 | 0 | (0–0) | ~ | ~ | ~ | ~ | Nov | 0.6 |
| Arid shrubland | Uncultivated | 444 | 0 | (0–0) | ~ | ~ | ~ | ~ | Sep | 0.4 |
| Arid shrubland | Cultivated | 3 | 5 | (2–5) | 73 | (20–262) | 2.8 | (1.9–4.1) | Jun | 0.6 |
| Forest transitions | Protected areas | 3 | 5 | (4–5) | 55 | (15–201) | 5.6 | (3.4–9.3) | Aug | 0.7 |
| Forest transitions | Uncultivated | 35 | 4 | (3–5) | 118 | (13–1103) | 7.6 | (3.5–16) | Aug | 0.8 |
| Forest transitions | Cultivated | 15 | 3 | (2–4) | 64 | (10–396) | 4.2 | (2.6–6.8) | Aug | 0.8 |
| Forest transitions | Settlements | 1 | 1 | (0–1) | 809 | (9.4–>5000) | 5.2 | (2–14) | Jun | 0.9 |
| Fynbos | Protected areas | 9 | 2 | (1–2) | ~ | ~ | ~ | ~ | Nov | 0.7 |
| Fynbos | Uncultivated | 53 | 1 | (0–1) | ~ | ~ | ~ | ~ | Jan | 0.5 |
| Fynbos | Cultivated | 10 | 3 | (2–3) | 189 | (19–1898) | 10 | (4.2–26) | Feb | 0.6 |
| Fynbos | Settlements | 1 | 0 | (0–0) | ~ | ~ | ~ | ~ | Dec | 0.3 |
| Grassland | Protected areas | 8 | 17 | (16–18) | 8.3 | (6.1–11) | 3.2 | (2.6–3.8) | Aug | 0.7 |
| Grassland | Uncultivated | 187 | 9 | (8–9) | 14 | (8.8–21) | 2.5 | (2–3.1) | Aug | 0.8 |
| Grassland | Cultivated | 63 | 11 | (9–12) | 23 | (11–47) | 6.4 | (4.2–9.5) | Aug | 0.8 |

(*Continued*)

**Table 1. (Continued)**

| Vegetation | Land use | km$^2$ ($\times 10^3$) | % burnt | CI | *MEI* all | CI | *MEI* burnt | CI | Peak month | Seasonality |
|---|---|---|---|---|---|---|---|---|---|---|
| Grassland | Settlements | 4 | 4 | (3–5) | 113 | (20–626) | 5.6 | (3.1–10) | Jun | 0.8 |
| Savanna–woodland | Protected areas | 33 | 16 | (12–16) | 7.6 | (5.7–10) | 3.8 | (3.1–4.6) | Aug | 0.7 |
| Savanna–woodland | Uncultivated | 234 | 5 | (3–5) | 60 | (18–201) | 3.4 | (2.3–4.9) | Aug | 0.7 |
| Savanna–woodland | Cultivated | 66 | 6 | (4–8) | 62 | (17–224) | 3.8 | (2.5–5.6) | Aug | 0.8 |
| Savanna–woodland | Settlements | 2 | 3 | (2–3) | 109 | (3.1–3807) | 4.9 | (2.2–11) | Jun | 0.8 |
| Thicket | Protected areas | 2 | 0 | (0–1) | 3.9 | (3.5–4.3) | ~ | ~ | Jan | 0.5 |
| Thicket | Uncultivated | 24 | 1 | (1–2) | 3.7 | (3.3–4.1) | 0 | (0–>5000) | Aug | 0.8 |
| Thicket | Cultivated | 2 | 2 | (2–3) | 94 | (5.1–1733) | 11 | (3.4–33) | Aug | 0.8 |
| Swaziland | | | | | | | | | | |
| Grassland | Protected areas | 1 | 36 | (33–38) | 2.2 | (2–2.5) | 1.9 | (1.7–2.1) | Aug | 0.8 |
| Grassland | Uncultivated | 2 | 11 | (9–12) | 18 | (11–32) | 3.7 | (2.8–4.8) | Aug | 0.9 |
| Savanna–woodland | Protected areas | 1 | 8 | (6–9) | 153 | (17–1366) | 10 | (4.2–25) | Aug | 0.7 |
| Savanna–woodland | Uncultivated | 15 | 3 | (2–5) | 130 | (16–1025) | 6 | (3.1–11) | Aug | 0.8 |
| Tanzania | | | | | | | | | | |
| Arid shrubland | Uncultivated | 1 | 0 | (0–0) | ~ | ~ | ~ | ~ | Aug | 0.8 |
| Forest | Uncultivated | 1 | 10 | (3–17) | ~ | ~ | ~ | ~ | Aug | 0.9 |
| Forest transitions | Protected areas | 11 | 13 | (4–17) | ~ | ~ | ~ | ~ | Jun | 0.9 |
| Forest transitions | Uncultivated | 84 | 4 | (4–4) | 26 | (8.4–80) | 3.4 | (2.1–5.4) | Aug | 0.8 |
| Forest transitions | Cultivated | 9 | 9 | (7–9) | 19 | (8.6–42) | 2.6 | (1.9–3.5) | Aug | 0.8 |
| Grassland | Protected areas | 14 | 39 | (36–41) | 1.9 | (1.7–2.1) | 1.4 | (1.2–1.5) | Aug | 0.8 |
| Grassland | Uncultivated | 64 | 9 | (8–10) | 20 | (10–41) | 2.1 | (1.6–2.9) | Aug | 0.7 |
| Grassland | Cultivated | 11 | 9 | (8–10) | 15 | (9.1–25) | 2.7 | (2.1–3.5) | Aug | 0.8 |
| Savanna–woodland | Protected areas | 82 | 30 | (25–31) | 1.6 | (1.4–1.8) | 1.2 | (1.1–1.4) | Aug | 0.8 |
| Savanna–woodland | Uncultivated | 291 | 12 | (11–14) | 9.9 | (6.3–15) | 2.6 | (2–3.3) | Aug | 0.8 |
| Savanna–woodland | Cultivated | 95 | 18 | (17–19) | 4.9 | (3.9–6.3) | 1.9 | (1.6–2.2) | Jun | 0.8 |
| Thicket | Protected areas | 33 | 42 | (33–45) | 2.1 | (1.9–2.4) | 1.3 | (1.2–1.4) | Jun | 0.7 |
| Thicket | Uncultivated | 111 | 3 | (3–4) | 151 | (23–991) | 5.9 | (3.1–11) | Aug | 0.7 |
| Thicket | Cultivated | 68 | 5 | (4–6) | 168 | (20–1433) | 7.6 | (3.5–16) | Aug | 0.7 |
| Zambia | | | | | | | | | | |
| Forest | Protected areas | 6 | 7 | (7–8) | 12 | (7.7–17) | 2.4 | (2–3) | Jun | 0.8 |
| Forest | Uncultivated | 31 | 8 | (7–9) | 26 | (12–56) | 3.8 | (2.8–5.1) | Aug | 0.8 |
| Grassland | Protected areas | 46 | 31 | (30–35) | 3.8 | (3.1–4.5) | 1.7 | (1.5–1.9) | Aug | 0.8 |
| Grassland | Uncultivated | 39 | 26 | (24–26) | 4 | (3.3–4.8) | 1.8 | (1.6–2) | Aug | 0.8 |
| Grassland | Cultivated | 6 | 53 | (51–55) | 1.7 | (1.5–1.8) | 1.2 | (1.1–1.3) | Aug | 0.8 |
| Savanna–woodland | Protected areas | 143 | 33 | (32–34) | 2.6 | (2.3–3) | 1.8 | (1.6–2.1) | Aug | 0.8 |
| Savanna–woodland | Uncultivated | 408 | 22 | (21–23) | 7 | (5.2–9.3) | 2.2 | (1.9–2.7) | Aug | 0.8 |
| Savanna–woodland | Cultivated | 43 | 20 | (18–21) | 5.5 | (4.4–7) | 2.1 | (1.8–2.4) | Aug | 0.8 |
| Savanna–woodland | Settlements | 1 | 0 | (0–1) | ~ | ~ | ~ | ~ | Aug | 0.7 |
| Thicket | Protected areas | 4 | 37 | (33–44) | 2.3 | (2–2.6) | 1.8 | (1.6–2) | Jun | 0.8 |
| Thicket | Uncultivated | 1 | 44 | (43–57) | 1.5 | (1.4–1.6) | 1.3 | (1.2–1.4) | Aug | 0.9 |
| Zimbabwe | | | | | | | | | | |
| Forest transitions | Uncultivated | 2 | 2 | (2–3) | 76 | (15–375) | 3.3 | (2.1–5.1) | Aug | 0.8 |
| Grassland | Protected areas | 1 | 18 | (13–25) | 4.4 | (3.6–5.3) | 2.1 | (1.9–2.4) | Aug | 0.8 |
| Grassland | Uncultivated | 6 | 4 | (3–5) | 63 | (16–245) | 4.6 | (2.9–7.2) | Aug | 0.9 |
| Grassland | Cultivated | 1 | 0 | (0–1) | 2.8 | (2.5–3) | ~ | ~ | Aug | 0.8 |
| Savanna–woodland | Protected areas | 48 | 16 | (15–17) | 13 | (8.2–20) | 2.4 | (2–3) | Aug | 0.8 |
| Savanna–woodland | Uncultivated | 228 | 10 | (7–10) | 21 | (12–39) | 4.3 | (3.2–5.8) | Aug | 0.8 |
| Savanna–woodland | Cultivated | 102 | 4 | (4–5) | 36 | (16–82) | 2.8 | (2–3.8) | Aug | 0.8 |
| Savanna–woodland | Settlements | 2 | 1 | (1–1) | >5000 | (0–>5000) | 49 | (0.2–>5000) | Aug | 0.8 |

pattern is seen in most cultivated areas, where very small percentages of the area burn frequently (Table 1). This highlights the importance of choosing the correct landscape units to calculate fire-return intervals.

The seasonal pattern of burning is remarkably similar across the region (Fig. 4). July, August and September are the dominant months for burning. Fires start slightly earlier in countries that are closer to the Equator, and only the southernmost countries show much burning into October. This supports previous satellite-based studies that noted a progression of fire from north-west to south-east through the dry season (Cahoon *et al.* 1992; Kendall *et al.* 1997; Dwyer *et al.* 2000; Roy *et al.* 2005*b*). The winter-rainfall fynbos region clearly has a different seasonal burning pattern. Arid shrubland vegetation in the south-western part of the subcontinent straddles both winter and summer rainfall regimes, and although it burns very little, it

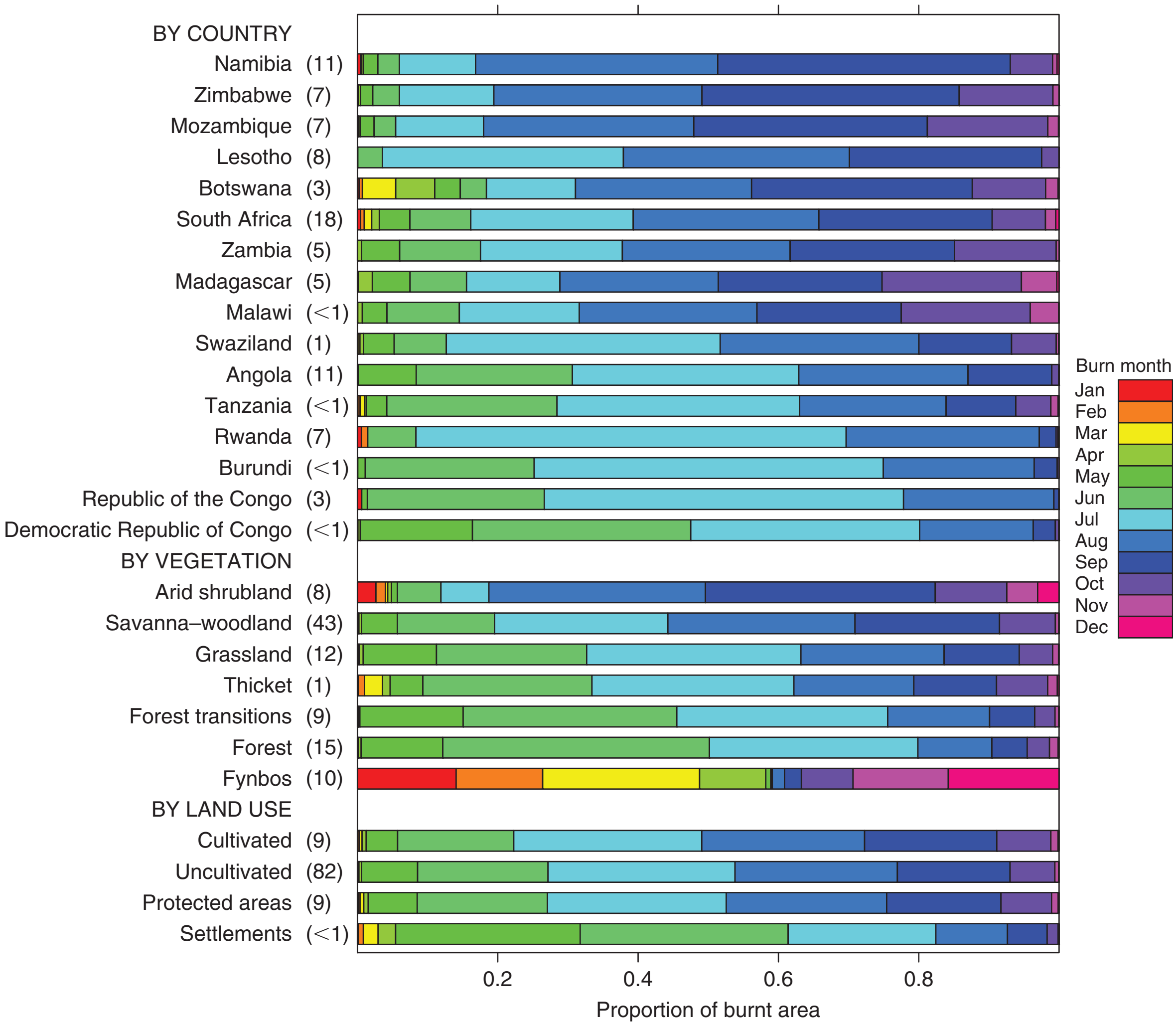


**Fig. 4.** Proportion of total area burned each month in the different countries, vegetation types and land-use categories in southern Africa. Values in brackets represent the percentage of the landmass covered by each class. Most areas have very similar seasonal fire patterns (burning from July to October), but the winter rainfall fynbos region burns from November to March, and settlement areas – with very high human densities – burn earlier in the season.

shows some fire throughout the year. Settled land has a markedly greater proportion of early-season burning than other land uses, and more than 80% of the area is burnt by the end of July.

When summarised by vegetation and by land use, it appears that certain fire characteristics are more easily influenced by human activities than others (Fig. 5). Annual burned area is greatly reduced outside protected areas in areas that are utilised by humans and their cattle, and further reduced in areas of cultivation and settlement. Maximum fire size shows the same pattern. In contrast, the season of burning does not change across land-use types, and nor does the mean fire-return time (except in settlements, which generally have much longer return times). Fire radiative power generally decreases as human land use increases, except for the arid shrublands where it is the cultivated areas that have high fire intensities (presumably because these areas are also irrigated), and in fynbos where FRP remains high across all land uses. Except for the fynbos, which has a markedly different season of burning, return time and FRP, all vegetation types display variations on a grass-fuelled fire regime (Fig. 5). This is because areas classified as forest, thicket or arid shrubland inevitably contain some grassy vegetation and it is this that generally burns.

### *Regional and seasonal patterns*

Areas that burn the most tend to have many fires, but not necessarily the largest fires (Fig. 6). Flat, arid systems such as the Kalahari can have very large fires, but the annual area burnt is often less than 10% of the landscape. In contrast, parts of central Zambia where over 50% of the area burns annually seldom have fires larger than 30 $km^2$ (3000 ha).

Increasing human densities have different effects on the number of fires per square kilometre and on the size of individual fires. The number of ignitions increases with human population density (Fig. 7*a*), but there is a simultaneous

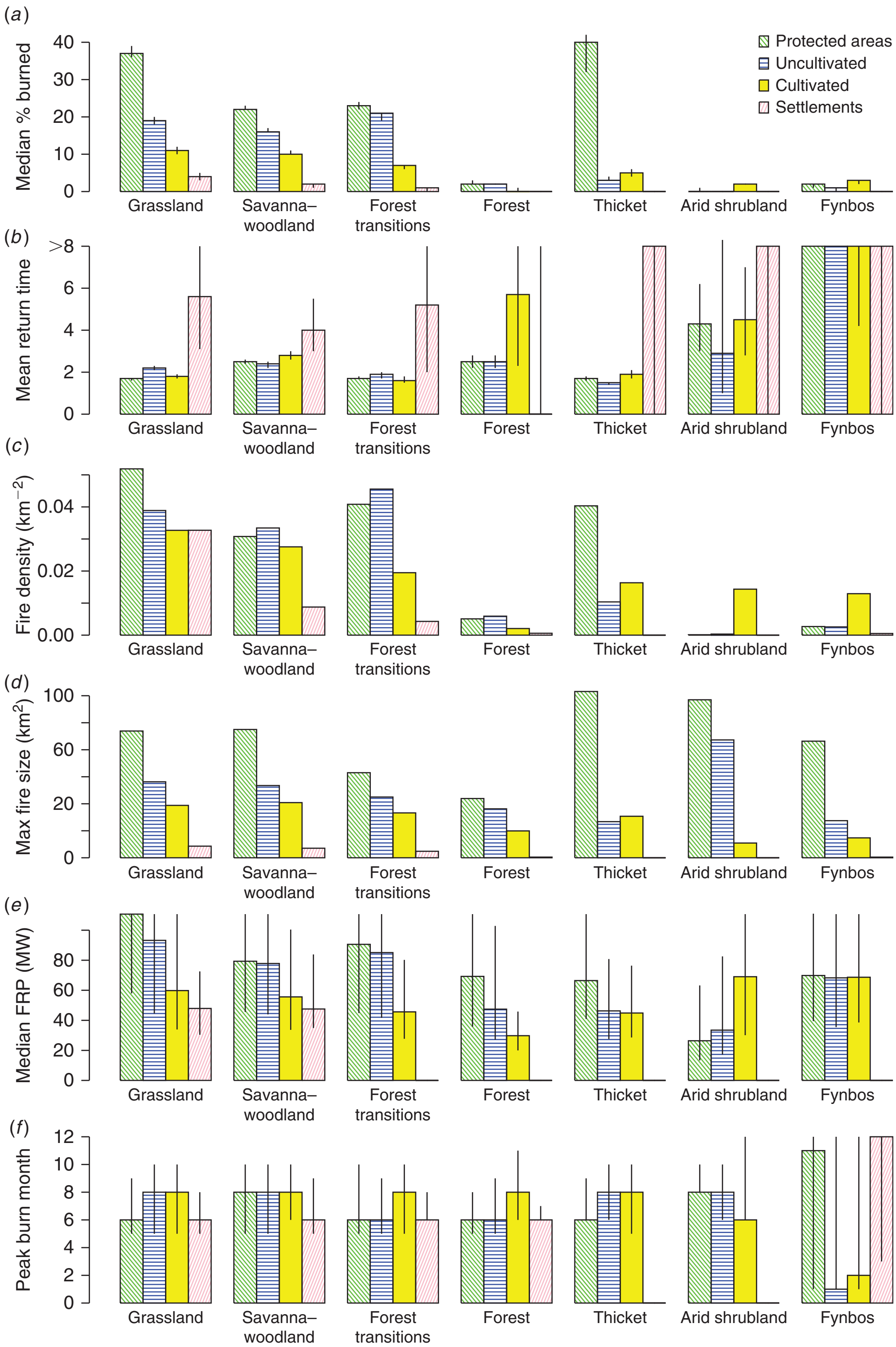


**Fig. 5.** Aspects of the fire regime stratified by vegetation types over a gradient of human land use. For more detailed, country-specific data, see Table 1. (*a*) Median % burned area (±25 quartiles) summarised over 8 years. (*b*) Mean fire-return periods (years with 25% confidence limits) calculated using only pixels that burned: >8 means that the Weibull estimation either did not converge or gave values greater than the length of the fire dataset. (*c*) Fire density: the number of fires per square kilometre per year. (*d*) The size of the top 1% of fires in each landscape type. (*e*) The median (±25 percentiles) Fire Radiative Power (FRP) (in MW per 5 × 5-km pixel). (*f*) The month when the greatest area burned (lines represent start and end of season calculated using a threshold of 5% of the total).

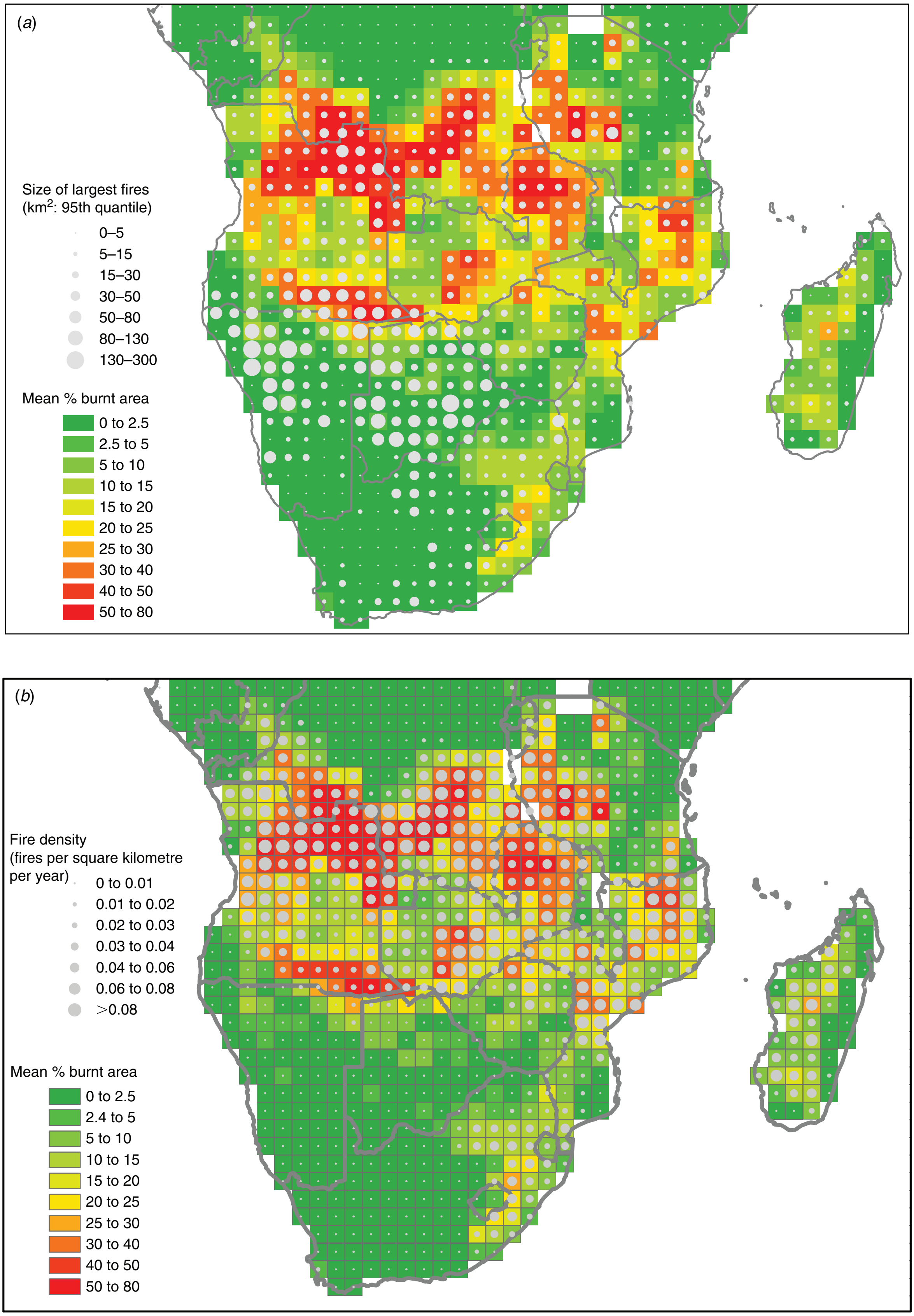


**Fig. 6.** Maximum fire size (*a*) and density of fires per square kilometre (*b*) – both plotted over the mean % burnt area for southern Africa. Areas that have the largest fires do not correspond to areas with higher total burned areas (*a*), but fire density and burned area seem to be related (*b*).

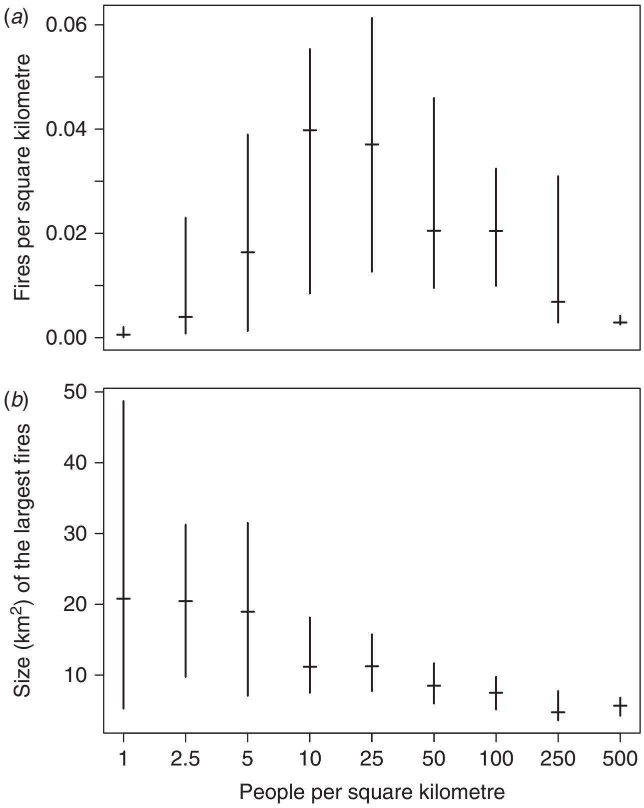


**Fig. 7.** Population density and its relationship with (*a*) the density of fires, and (*b*) the size of the largest fires. Large fires are defined as the 95th quantile of all sizes and the graph gives the median (horizontal line) and ±25th percentiles (box). The number of individual fires increases as population densities increase, peaking at ~25 people per square kilometre and then dropping off. However, the size of large fires decreases steadily with increasing human population densities, and areas with more than 10 people per square kilometre seldom have fires larger than 20 $km^2$ (2000 ha).

reduction in mean and maximum fire size (Fig. 7*b*), which explains why total area burned decreases with increasing human densities (Archibald *et al.* 2009).

Because more dry fuel is available at the end of the dry season, and because hot windy weather conditions are conducive to fire spread, it would be expected that fires at the end of the season would both be larger and have a higher intensity than early-season burns (Frost 1999; Roy *et al.* 2005*b*). This has certainly been found in savanna systems in northern Australia, and in protected areas in Africa (Govender *et al.* 2006; Russell-Smith *et al.* 2007; Yates *et al.* 2008). Regionally, however, only the thicket vegetation type shows a marked increase in FRP later in the dry season (Fig. 8). In most other vegetation types, fire size and intensity increase at the beginning of the season and stay high until the number of fires drops off again at the end of the season (Fig. 8).

## Discussion

Frequent fires in southern Africa occur within clearly defined environmental limits (Fig. 2) and different parts of the subregion show different characteristic fire regimes. We quantified some of this variability by classifying the landscape according to country, major vegetation type, and land use.

Most noticeable from this analysis is the way that the fire characteristics change across a gradient of intensity of human impact (which is assumed to increase from protected areas, uncultivated but grazed land, cultivated land, and settlements). Although annual mean burnt area fraction (Fig. 5*a*), maximum fire size (Fig. 5*d*), FRP (Fig. 5*e*), and cumulative fire-affected area (Fig. 3) decrease as human impact increases, the effect on the seasonality of fire (Figs 4, 5*f*), number of individual fires (Fig. 5*c*), and the frequency of fire in the places that do burn (Fig. 5*b*) is much less obvious. This implies that the ignition regimes in these different areas are quite similar, and that it is fire spread and fuel continuity that are most affected by intensifying human use of the landscape.

It is important to remember that although the four land-use classes represent a gradient of increasing human impact, there is no 'without humans' land-use category in this analysis. Many protected areas in southern Africa still have people living in them, and even in those like the Kruger National Park that do not have resident communities except for tourists and park staff, the overwhelming majority of fires are still lit by humans (whether by managers, poachers, tourists or cross-border migrants). What is different about the national parks is that they generally have fewer roads, less cultivation, and a lower biomass of grazing mammals than areas outside parks, and we suggest that this is what accounts for the differences in annual burnt area and fire size.

As people light most of the fires in all land-use and vegetation classes, it is not surprising that the seasonal pattern of fire is similar across categories (Fig. 4). Only the fynbos vegetation type associated with the small winter-rainfall region on the south-west coast of Africa has a different seasonal pattern of fire. In all other vegetation and land-use classes, the majority of fires occur in the middle of the dry season: in July, August and September. As there are very few lightning strikes in these months, a lightning-driven fire regime in southern Africa would probably show very different seasonal patterns. However, such a fire regime is unlikely to have existed in the region for at least the last 400 000 years (Karkanas *et al.* 2007).

Space-for-time substitution is often used to infer fire-return periods in instances where long-term data are not available (Scholes *et al.* 1996). Our results indicate that this could give a very skewed picture of fire patterns in Africa – or in any part of the globe where a relatively small percentage of the landscape burns with high frequency while other parts of the landscape do not burn. For example, 5.3% of the uncultivated savanna land in Malawi burns each year and a space-for-time substitution would suggest that the average fire-return time in this vegetation type is 19 years. In fact, the satellite data show that the patches of the landscape that do burn will burn frequently, and fitting the Weibull distribution to these patches gives a fire-return time of 5.9 years (confidence interval, CI 2.9–11.8), which is a more reasonable estimate for this system (Table 1). Similarly, Fig. 5*a* shows that the spatial extent of fire in forest vegetation is very low (less than 3%). These small areas, which are presumably patches of grassland within the forest, have fire-return periods very similar to the return times shown by grassy fuels in the region (3 to 4 years: Fig. 5*b*). A space-for-time substitution

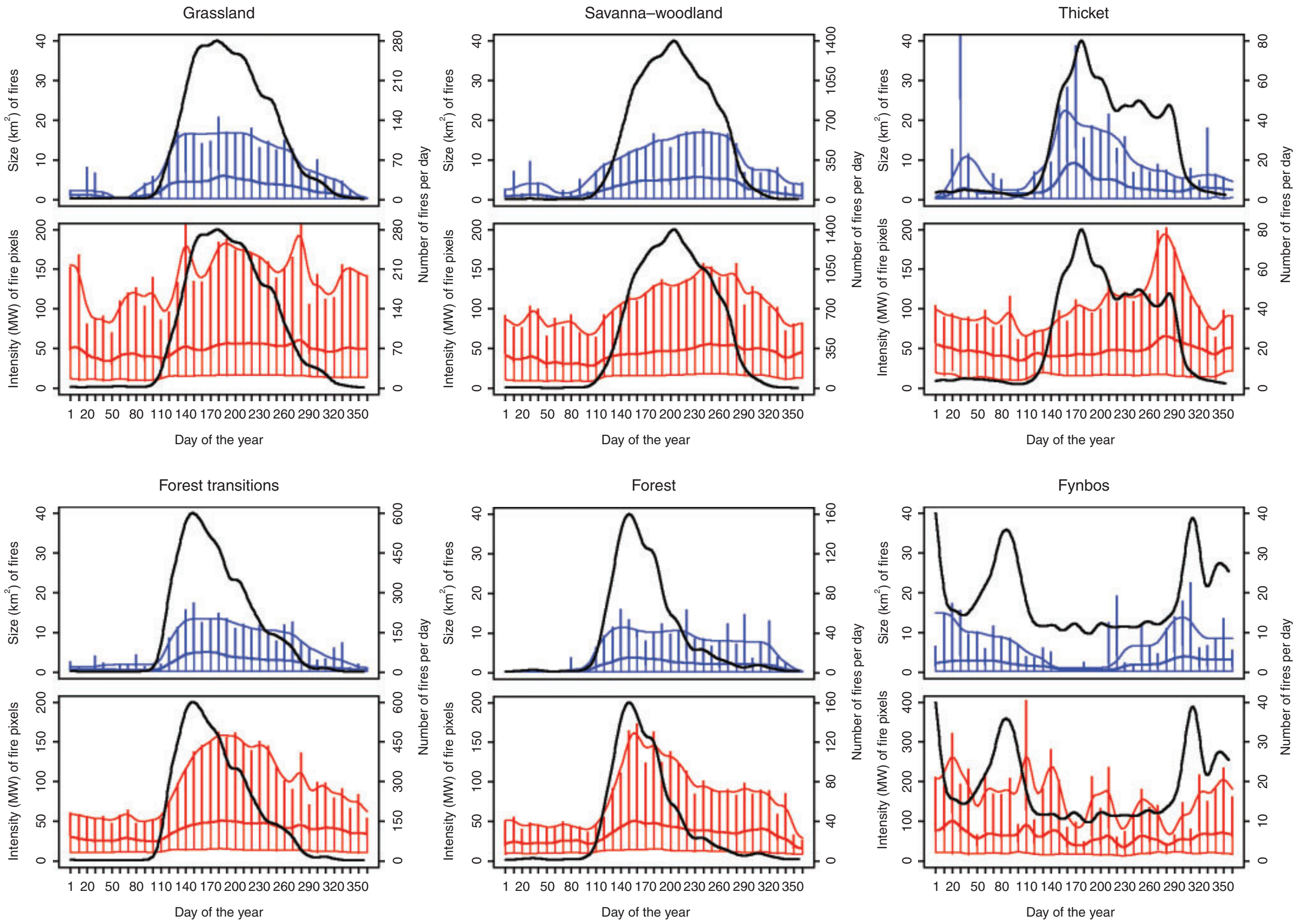


**Fig. 8.** Seasonal patterns of fire size and fire intensity (Fire Radiative Power, FRP) across six different vegetation types in southern Africa. Coloured bars represent the 5th, 50th and 95th percentiles of fire size (blue) and FRP (red) for each 10-day timestep in the year 2004. The black line represents the number of fires per day over the year and can be used to identify the start and end of the fire season. From Yates *et al.* (2008); Williams and Bradstock (2008), one would expect small fires early in the fire season, and larger, more intense fires later in the fire season. Savanna–woodlands show a slight increasing trend in fire size and fire radiative power over the fire season, forests show a slight decreasing trend. Grasslands have uniformly high FRP values throughout the year, and the thicket shows larger fires early in the season and more intense fires later in the season. The Fynbos region burns from October to March and at much higher FRPs (note the difference in scale).

would estimate a uniformly low fire-return time of 33 years for African tropical forests, whereas in fact there are small patches that burn frequently, and large areas that never burn. This problem can be accommodated by ensuring that homogeneous areas are selected on which to perform space-for-time substitution, but when summarising by 0.25° grid square for climate modelling, for example, this is not possible.

Yates *et al.* (2008) and Williams *et al.* (1998) have shown in northern Australia that fires lit in the early dry season are smaller and less intense than fires that occur late in the dry season. A southern African analysis does not support this pattern (Fig. 8). In most vegetation types, fire size distributions and fire intensities remain fairly stable throughout the fire season, and forests even show a decreasing trend in fire intensity. One explanation for this divergence is that these two savanna systems have very different seasonal patterns of burning. All of southern Africa is characterised by relatively early-season burning, and the 'Aboriginal burning regime' that is being promoted in Australia is already in operation in Africa. Therefore, except in the thicket vegetation type, there is no evidence of the large, late-season fires that so characterise the current fire patterns of the northern territories of Australia. A finer-scale analysis of the southern African data may reveal more intense and larger fires during the late dry season in some individual landscapes (e.g. Govender *et al.* 2006).

Fires can go out when there is not enough fuel to sustain them, when weather conditions are not appropriate for burning, or when they run into topographic or anthropogenic barriers or previously burned areas (Trollope and Potgieter 1985; Stambaugh and Guyette 2008). If fuel and weather conditions were the main factors driving the occurrence of large fires, then one would expect to see a stronger association between high-energy fires and large fires. Similarly, the fact that the largest fires appear to be in unpopulated areas, with very flat landscapes (Fig. 6), also suggests that barriers to fire spread are limiting the maximum fire size in many parts of the subcontinent.

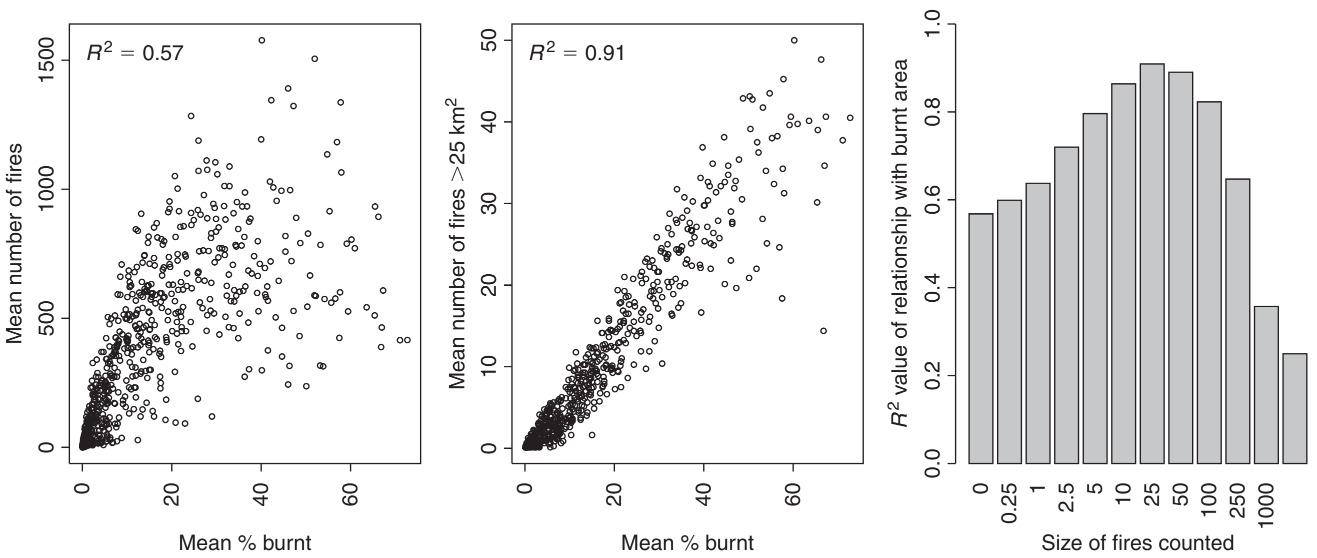


**Fig. 9.** The relationship between the number of fires and the area burned. Better relationships are found when one considers only the number of large fires (>25 km$^2$); this relationship worsens again when only very large >100 km$^2$ fires are included.

### *Fire size distributions*

The frequency distribution of fires of different sizes contains ecological information: it should change depending on the ignition rate and pattern, the rate of regrowth of fuels, and the density of barriers to fire spread in the landscape. It is a useful metric for protected area managers striving to optimise 'pyrodiversity', the variety of fire regimes (Brockett *et al.* 2001).

Like many other natural phenomena, fires have a skewed distribution, with a large majority of small fires and a few large fires. It has been shown in systems ranging from boreal forests (Strauss *et al.* 1989) to Australian savannas (Yates *et al.* 2008) that the few largest fires burn the majority of the area, and that the many small fires do not contribute significantly to burnt area. Thus, it is the probability of large infrequent fire events that has been the focus of much fire research (Williams and Bradstock 2008).

The fire-size distributions in southern Africa break some of these rules (Fig. 6). Here, it appears that it is the number of fires, rather than the area burned by large fires, that is a better indication of the annual area burned – i.e. most of the area burned in southern Africa is due to the accumulation of many small- to medium-sized fires, rather than to the occasional extreme fire event.

To test how different fire sizes contribute to the total burned area, we fitted a regression equation to mean annual burnt area against the average number of fires in different size classes (the number of fires greater than 0, 0.25, 1, 5 km$^2$, etc.). The explanatory power improves from an $r^2$ of 0.57 ($P < 0.001$) when all fires are included, to an $r^2$ of 0.91 ($P < 0.001$) when only fires bigger than 25 km$^2$ are counted, and then decreases (Fig. 9). There appears to be a trade-off between fire size and fire number in controlling total burned area that is related to the frequency distribution of fire sizes. It would be productive to compare fire size distributions between different savanna ecosystems, and across different biomes (see Archibald and Roy (2009) for some examples of this within African savannas).

## Conclusions

All of these lines of evidence point to a very strong human control on fire regimes in southern Africa. The frequency with which people in Africa light fires, and their proactive approach to using fire as a management tool is well known (Frost 1999; Kull 2004; Laris 2006), and is often cited as an explanation for why Africa is such a 'fiery continent' (Crutzen and Andreae 1990). Our research highlights other more complicated relationships between human land use and fire regimes. In particular, human activities appear to decrease the area burned by individual fires. The number of ignitions increases with human population density (up to a certain extent; Fig. 7*a*) but this does not completely compensate for the simultaneous reduction in mean and maximum fire size (Fig. 7*b*). Thus the total burned area fraction decreases in areas of high human-use intensity. However, because ignitions remain high, areas in human-impacted landscapes that *do* burn have a similar fire frequency, seasonality and intensity as found in less-impacted areas.

There is no evidence that any parts of southern Africa are following a lightning-driven ignition regime (Fig. 4). These results support previous assertions that people are the main causes of fire in the region, and they also suggest that paucity of ignitions is generally not a key factor limiting the area burned in southern Africa. Because very large fires contribute a relatively small fraction of the total burnt area in southern Africa, we would expect that area affected by fire would be less variable between years than in systems such as boreal forests – where large fires dominate the area burned, and climatic factors control the probability of these large fires (Fauria and Johnson 2008; Balshi *et al.* 2009). This hypothesis is confirmed by research into the interannual variability of fire in southern Africa (van der Werf *et al.* 2004; Archibald *et al.* 2010): burned area is not as strongly linked to climate variability in this region as it is in other parts of the globe.

The sharp disjunction between the extent of fire in the 'grassy' vegetation types of Africa and the 'non-grassy' vegetation types (Fig. 3) supports the theory that fire is involved in creating and maintaining these vegetation types and their distribution on the subcontinent (Bond 2005). C4 grasses promote frequent fire, which prevents recruitment of forest species (Hoffmann 1999). Low-light forested environments, however, prevent the development of a flammable grassy understorey (Hennenberg *et al.* 2006).

Fig. 5 shows that forest systems have very little fire but when fire does occur, it occurs with the same frequency, FRP and fire size as the grassy systems. This is most easily explained as fires occurring in patches of grassy vegetation within the forest matrix. Having said this, we did not specifically search for evidence of fire-induced transformation of forest, such as is prevalent in South America (Cochrane *et al.* 1999).

We have previously published findings (Archibald *et al.* 2009) that assess the relative importance of climate, vegetation and human drivers in affecting annual burned area. We have also shown that within one landscape, the presence and land-use activities of people can dampen patterns of interannual variability in fire (Archibald *et al.* 2010). The present paper complements these findings by using newly developed datasets on fire size, fire number and fire intensity to explore the mechanisms by which these regional and interannual patterns emerge.

## Acknowledgements

Regional-scale research is of little value without input from people with local knowledge and the authors thank all southern African fire ecologists who have contributed ideas and information to this study. In particular, we acknowledge the contributions of Winston Trollope, Patience Zisadza, Peter Frost, Brian van Wilgen, Navashni Govender, and the members of the Global Observation of Forest and Land Cover Dynamics Southern African Fire Network. The exemplary work on savanna fire regimes by Australian fire ecologists helped to contextualise and give meaning to the analyses presented here. This work was supported by CSIR Parliamentary Grant funding, Natural Environment Research Council Grant NE/F001584/1, and NASA Earth System Science grant NNG04HZ18C.

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Manuscript received 8 January 2010, accepted 21 April 2010