Southern African fire regimes as revealed by remote sensing

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Running head: Fire regimes in southern Africa

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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. The pattern can be explained by the differential effect of humans on ignition frequencies and fire spread: ignition frequency shows a unimodal distribution against population density, peaking at around 10-20 people per km^2. The mean size of the fires declines steeply as human densities increase above 1 person per km^2.

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 - fire density is a better predictor of burnt area than fire size.

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. The diversifying and improving set of remotely-sensed data on fire is invaluable in providing a comprehensive view of the patterns of fire ignition and spread in different southern African landscapes.

50 word summary: This paper provides baseline information for managers and scientists hoping to understand fire in southern Africa. It also highlights instances where findings from this region both conform to and challenge current global theories on fire.

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 which 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 one year, resulting in some of the most frequent fire return intervals on Earth. Moreover, human ignition and fire management is 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 & 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 Menaut (1977); Brookman-Amissah *et al.* (1980); Swaine *et al.* (1992) for West African examples and Booysen & Tainton (1984); 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 which 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 & 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; Smith & Wooster, 2005; Roberts *et al.*, 2009). These data are available over nearly a decade - sampled four times daily at 1 km resolution (from the MODIS sensor on the Terra and Aqua polar-orbiting platforms), and every 15 minutes at 5 km resolution (from the SEVERI 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.*, 2005a; 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 & 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 from 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 quarter degree and 1-degree resolution to demonstrate regional patterns and the limits of fire on the sub-continent. 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 500m 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.*, 2005a). When insufficient input data are available to run the algorithm due to excessive cloud cover or sensor problems pixels are flagged as 'no data'. A southern African accuracy assessment indicates that the product can identify about 75% of the burnt area (Roy & 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/unburnt layer for each fire year (January to December). Boschetti & 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.

Due 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 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 degree grid) to accommodate differences in patterns of variability in different parts of the sub-continent. To test the effect of this filling algorithm the July data were systematically removed from each of the remaining years (2002:2007), and filled using the same methods. The results of this test showed the filling algorithm to be very accurate (all six 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 eight 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 which 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 two to six years (Van Wilgen & Scholes, 1997), so the eight year MODIS dataset can capture a great deal of the variation in fire frequency on the subcontinent. The result was a map at 500m resolution of the number of burns a pixel experienced in eight 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 which occurs at the beginning and end of the record period (Polakow & 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 & 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 500m 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 & 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):

$$MEI = b(ln2)^{(1/c)}$$

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

Due 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 & Roy (2009). This produces a list of points with the size, location of the centroid, the 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. A number of different methods were used to create summary statistics from these data. Firstly, the number of fires in each 1-degree grid point was calculated and converted to a fire density (# of fires per km^2). 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 a number of 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-degree grid. We also calculated the 95th percentile of fire size for each 1 degree grid cell as a measure of the size of the largest fires experienced in different parts of the sub-continent.

Fire Radiative Power (FRP) 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/s). 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 which 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). Given that the energy content of grass fuels is fairly constant (around 18 000 Jg^{-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 & Wooster, 2005).

The SEVIRI sensor provides fire radiative power measurements every 15 minutes. It is placed on the Meteosat platform, which flies in a geostationary orbit about 36 000 km above the earth centred on the equator. The pixel sizes are of the order of 4.8 x 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 one 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 vs back fires) (Smith & 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 & Tainton, 2007). 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) because the length of the flame front is not known. There is ambiguity introduced since 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-degree 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 DRC and 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 one degree 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 7 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) were classed as 'other' and not included in the analysis as their geographic extent was very limited.

Land Use The land use categories were identified by lumping the 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, 2006) 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-degree 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 (http://www.r-project.org/ v2.10.1).

The environmental characteristics of pixels which burnt at least once in the 8 year data period were used to characterise the environmental limits of fire on the sub-continent. 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 fire radiative power data were summarised by country, land use and vegetation type, as well as by 1-degree 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 a number of ways. First the size of the 95th quantile of all fires in a 1-degree 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 % (sd 0.81) of southern Africa was identified as burned each year by the MODIS burned area product, which is thought to detect about 75% of the burned area mapped using high-resolution images in southern Africa (Roy & Boschetti, 2009). Therefore the mean percentage burned area could be as high as 15%. Invalid pixels (usually due to cloud cover) made up about 3% of the landmass and this area was not included in the calculation.

Fire affected pixels were considered pixels which burned at least once in the 8 year period for which there were data, and 35% of the landmass is classified as fire-affected (Figure 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 (Figure 2). Fire does not occur in pixels with tree cover greater than about 59%, human population densities greater than 140 people per km^2, 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 about 29% (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 one month the seasonality would be 100%). See Markham (1970) and Archibald *et al.* (in press) 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 (Figure 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 eight year period (return period of approximately two 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 (Figure 3). Fires in the fynbos are crown fires, consuming dense sclerophyllous shrubs and small trees, with fire return periods in the order of 10-30 years. This eight 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 (MEI) for grassland and savanna systems in the region range from 1.7 to about 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 MEI'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 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 (Figure 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 southern-most countries show much burning into October. This supports previous satellite-based studies which noted a progression of fire from northwest to southeast through the dry season (Cahoon *et al.*, 1992; Kendall *et al.*, 1997; Dwyer *et al.*, 2000; Roy *et al.*, 2005b). 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 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 (Figure 5). Annual burned area is greatly reduced outside protected areas in areas which 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 fire radiative power, all vegetation types display variations on a grass-fuelled fire regime (Figure 5). This is because areas classified as forest, thicket or arid shrubland inevitably contain some grassy vegetation and it is this which generally burns.

Regional and seasonal patterns

Areas that burn the most tend to have many fires, but not necessarily the largest fires (Figure 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 km^2 and on the size of individual fires. The number of ignitions increases with human population density, (Figure 7A) but there is a simultaneous reduction in mean and maximum fire size (Figure 7B) 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 be both larger and have a higher intensity than early-season burns (Frost, 1999; Roy *et al.*, 2005b). 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 fire radiative power later in the dry season (Figure 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 (Figure 8).

Discussion

Frequent fires in southern Africa occur within clearly defined environmental limits (Figure 2) and different parts of the sub-region 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). While annual mean burnt area fraction (Figure 5A), maximum fire size (Figure 5D), Fire Radiative Power (Figure 5E), and cumulative fire-affected area (Figure 3) decrease as human impact increases, the effect on the seasonality of fire (Figures 4 & 5F), number of individual fires (Figure 5C), and the frequency of fire in the places that do burn (Figure 5B) 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 while 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 which 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.

Since 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 (Figure 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 (c.i. 2.9-11.8) which is a more reasonable estimate for this system (Table 1). Similarly, Figure 5A 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: Figure 5B). A space for time substitution 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 homogenous areas are selected on which to perform space-for-time substitution, but when summarising by quarter-degree 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 which occur late in the dry season. A southern African analysis does not support this pattern (Figure 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 (eg, 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 & Potgieter, 1985; Stambaugh & 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 (Figure 6) also suggests that barriers to fire spread are limiting the maximum fire size in many parts of the sub-continent.

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, Richard & Bradstock, 2008)

The fire-size distributions in southern Africa break some of these rules (Figure 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 regressed 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, etc km^2). 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 were counted, and then decreases (Figure 9). There appears to be a trade-off between fire size and fire number in controlling total burned area which 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 & 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 (Laris, 2006; Kull, 2004; Frost, 1999), and is often cited as explanations for why Africa is such a "fiery continent" (Crutzen & 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; Figure 7A) but this does not completely compensate for the simultaneous reduction in mean and maximum fire size (Figure 7B). 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 is found in less-impacted areas.

There is no evidence that any parts of southern Africa are following a lightning-driven ignition regime (Figure 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 are 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 systems such as boreal forests - where large fires dominate the area burned, and climatic factors control the probability of these large fires (Fauria *et al.*, 2008; Balshi *et al.*, 2009). This hypothesis is confirmed by research into the inter-annual variability of fire in southern Africa (van der Werf *et al.*, 2004; Archibald *et al.*, in press): 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 (Figure 3) supports the theory that fire is involved in creating and maintaining these vegetation types and their distribution on the sub-continent (Bond, 2005). C4 grasses promote frequent fire, which prevents recruitment of forest species (Hoffmann, 1999). Low-light forested environments on the other hand prevent the development of a flammable grassy understory (Hennenberg *et al.*, 2006).

Figure 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 inter-annual variability in fire (Archibald *et al.*, in press). This 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 inter-annual patterns emerge.

Acknowledgments

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 would like to acknowledge the contributions of Winston Trollope, Patience Zisadza, Peter Frost, Brian van Wilgen, Navashni Govender, and the members of the GOFC-GOLD 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, NERC Grant NE/F001584/1, and NASA Earth System Science grant NNG04HZ18C.

Figure headings

Figure 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 which were classified as invalid over the time period: darker grey = more invalid data.

Figure 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 25 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.

Figure 3: The frequency of fire (expressed as the proportion of the total area which 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).

Figure 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.

Figure 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 which 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 km^2 per year. D) The size of the top 1% of fires in each landscape type. E) the median (+- 25 percentiles) Fire Radiative Power (in MW per 5 km x 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)

Figure 6: Maximum fire size (A) and density of fires per km^2 (B) - both plotted over the mean percentage 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).

Figure 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 ±25 percentiles (box). The number of individual fires increases as population densities increase, peaking at around 25 people per km^2 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 km^2 seldom have fires larger than 20 km^2 (2000 ha).

Figure 8: Seasonal patterns of fire size and fire intensity (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, Richard & 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 FRP's (note the difference in scale).

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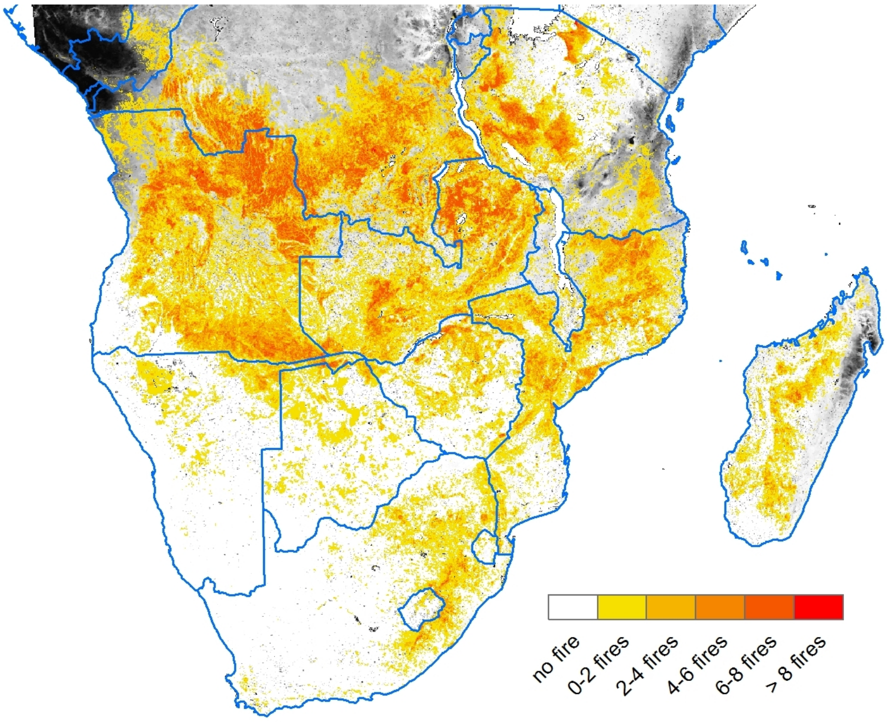
Figures



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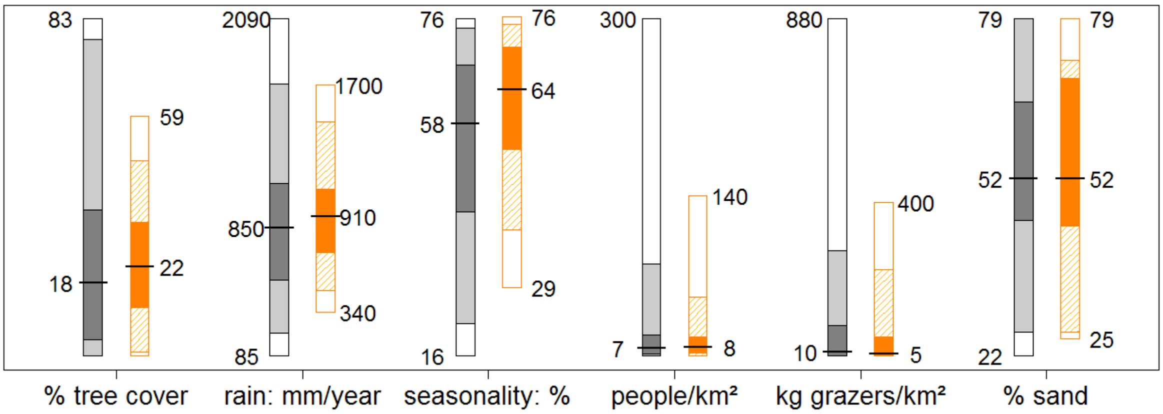

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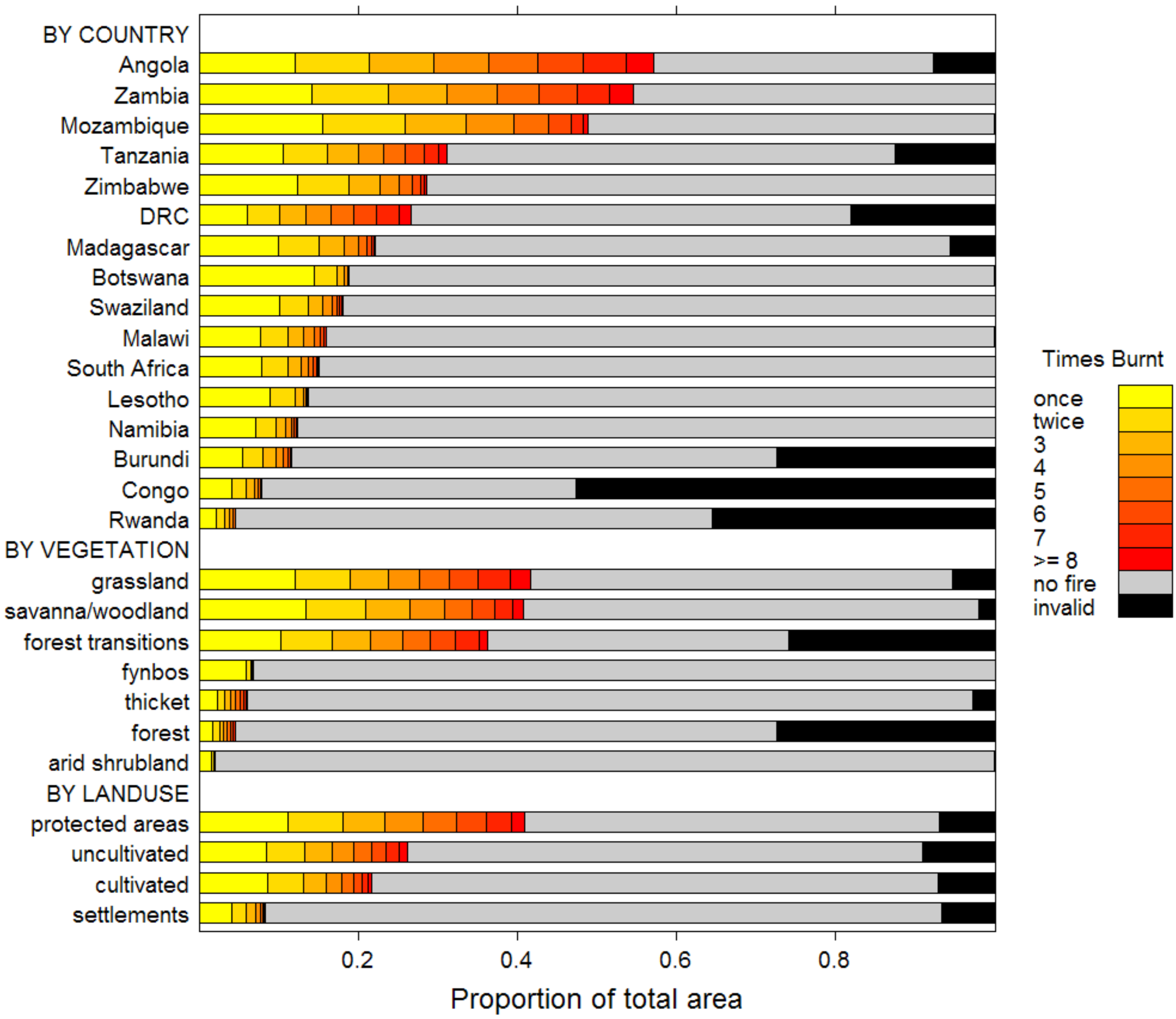

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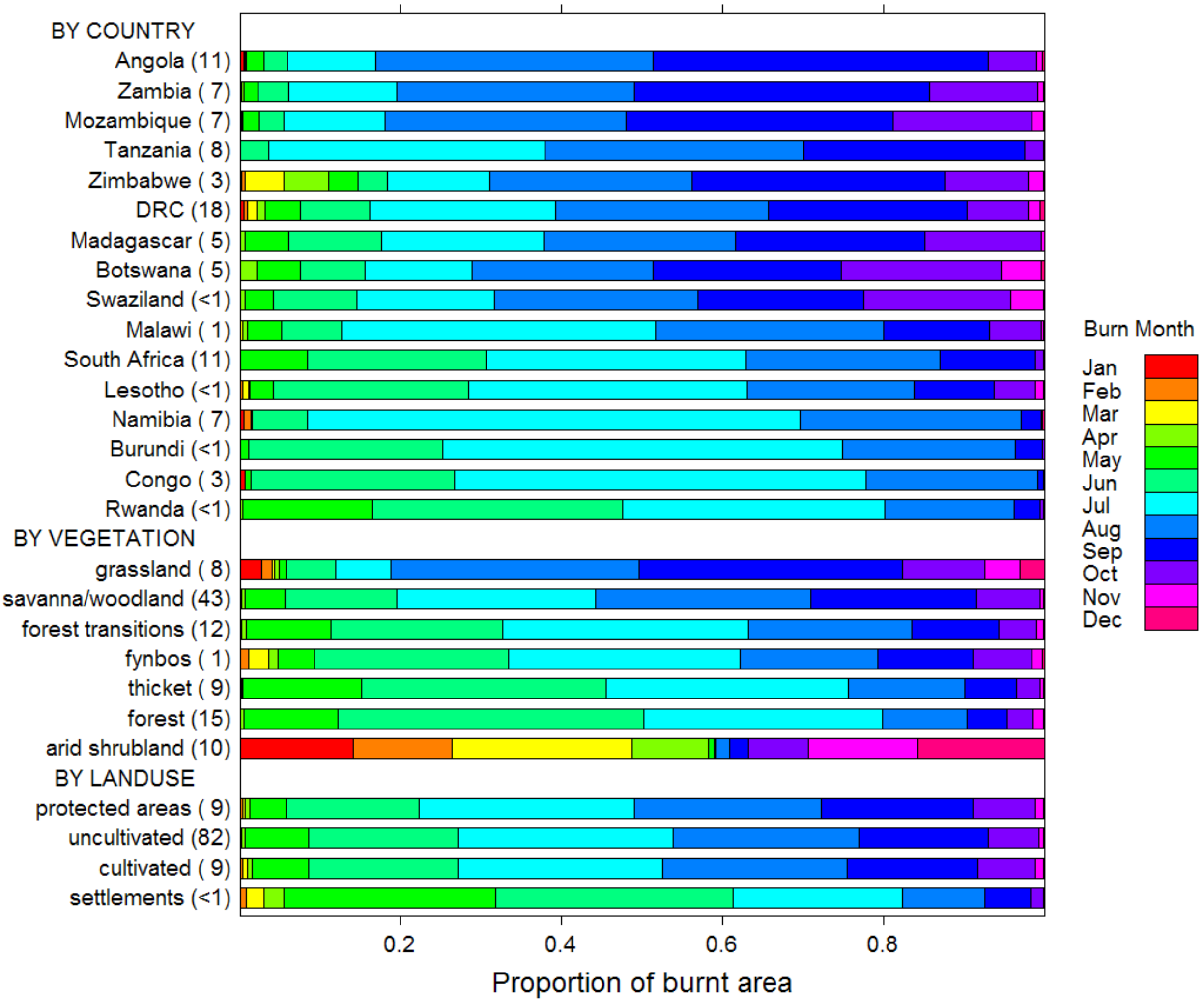

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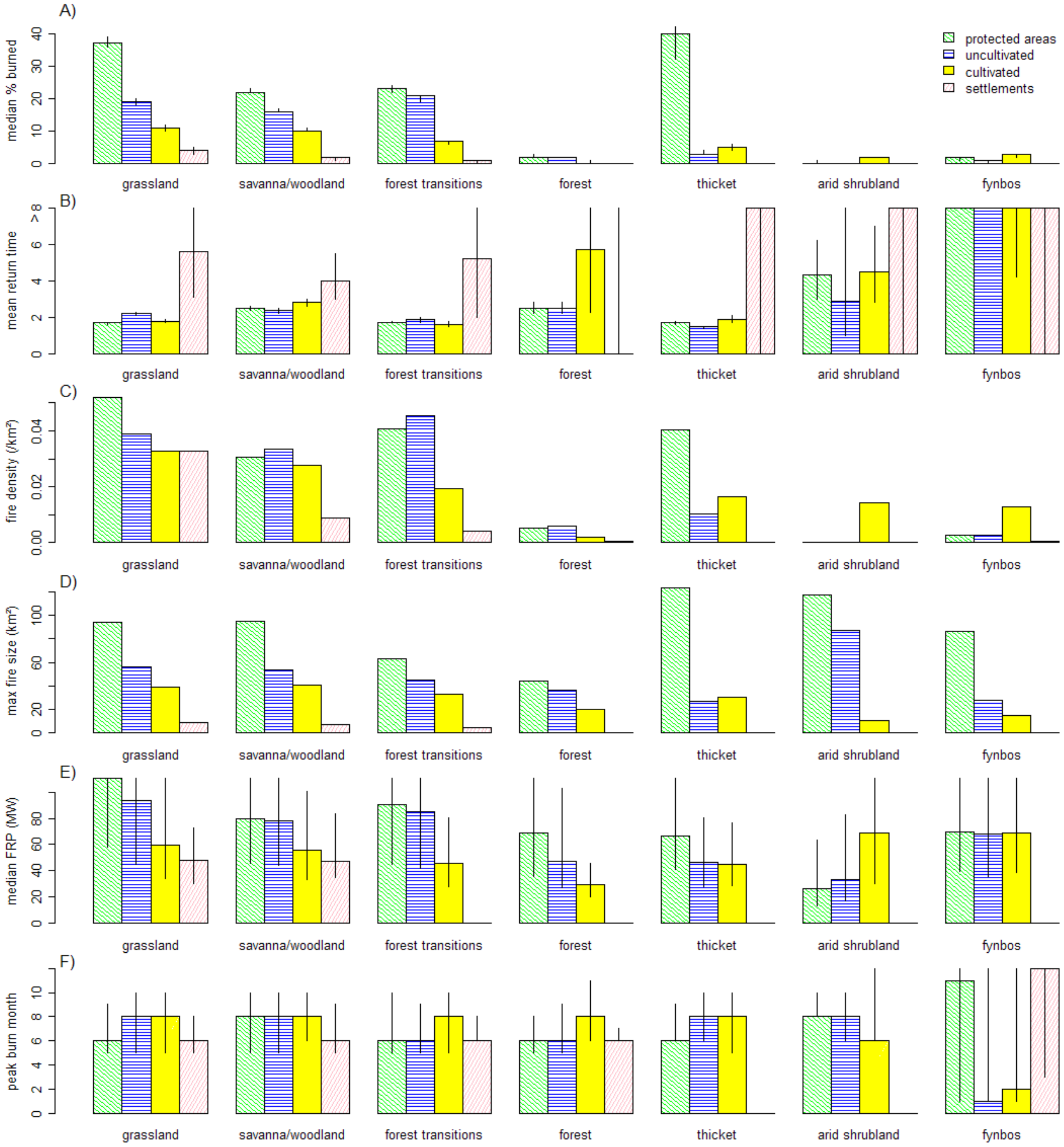

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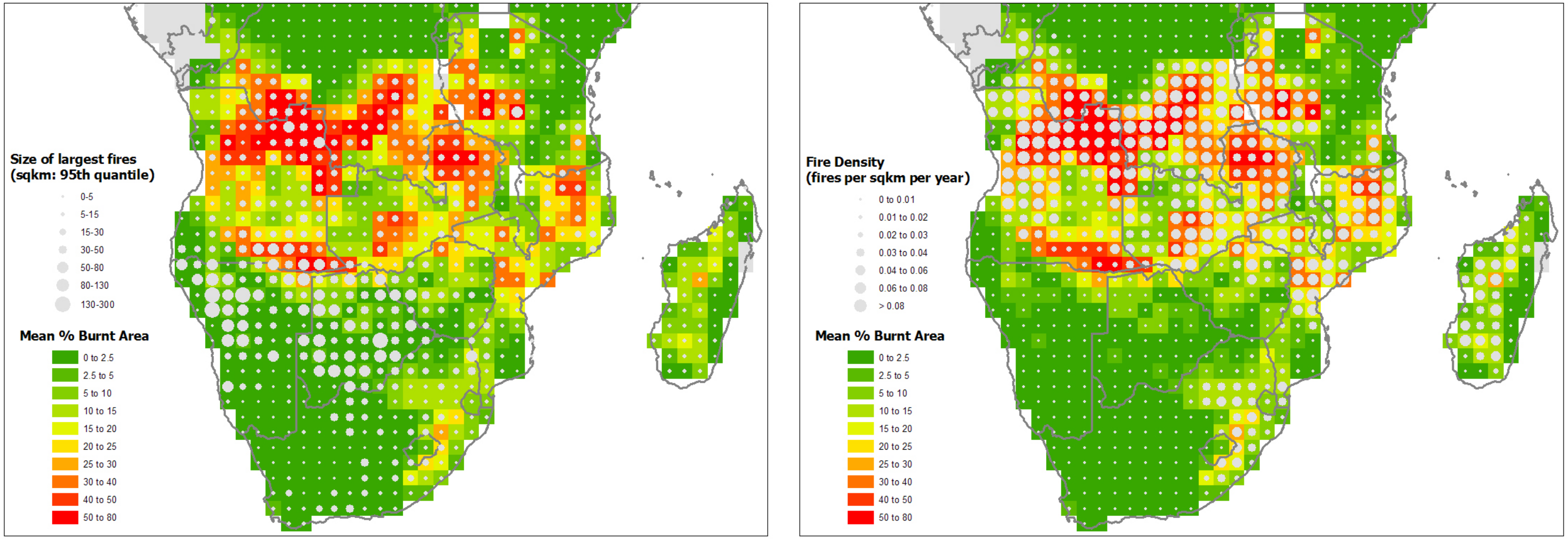

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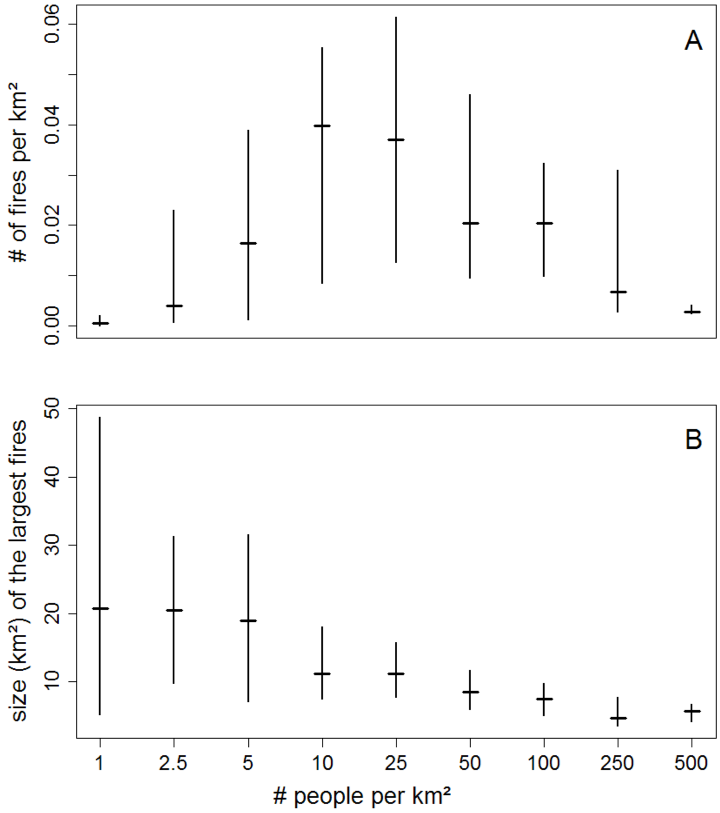

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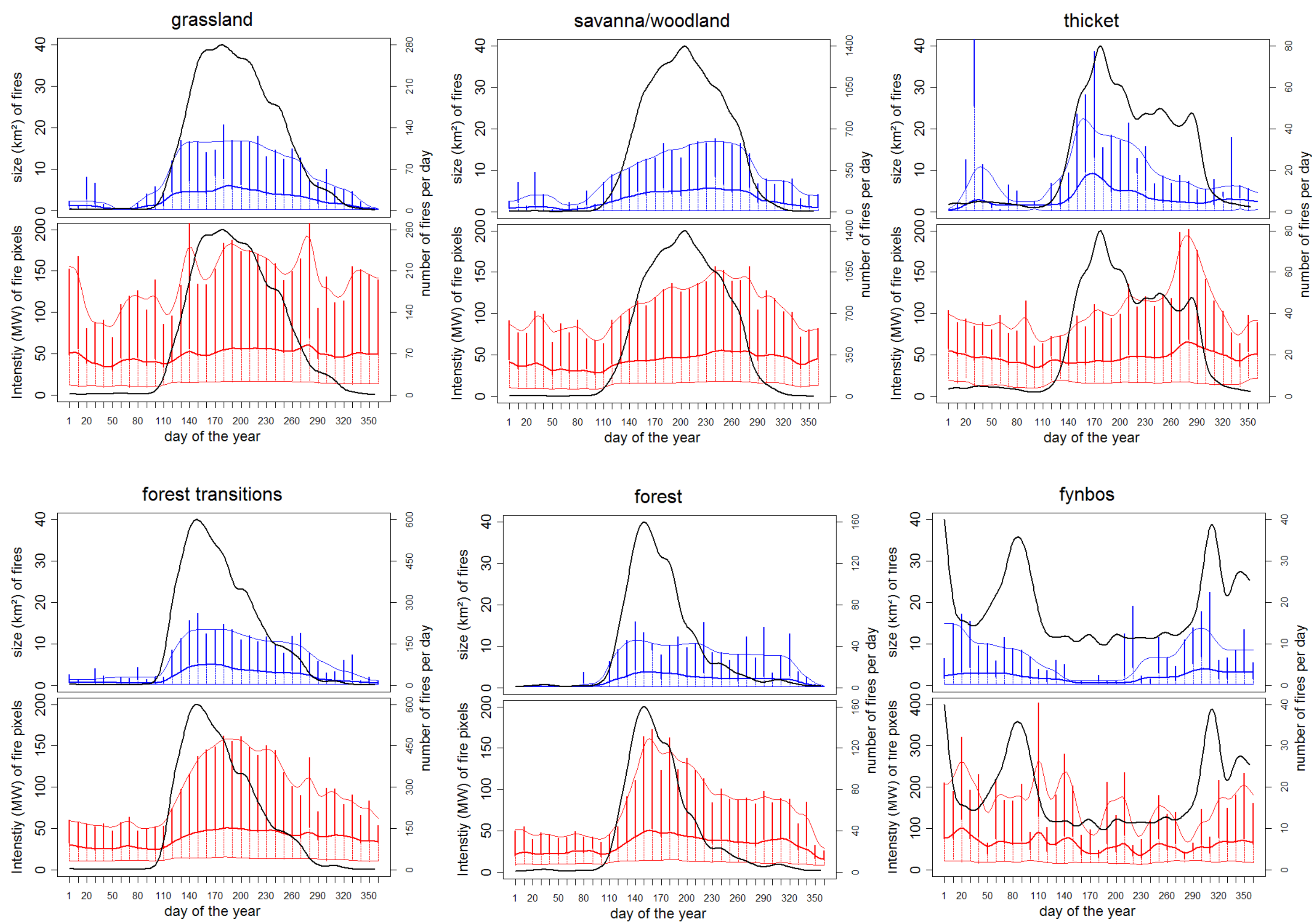

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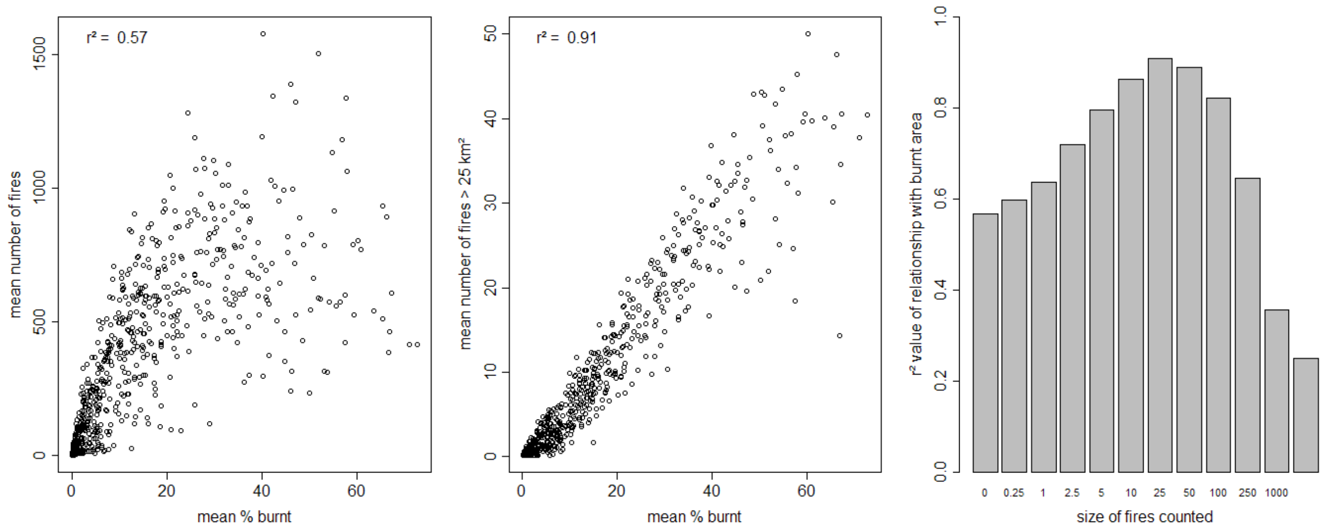

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Tables

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 percentage burnt area (with 25% confidence intervals), the median fire return period (MEI) calculated over a) all pixels, and b) only the pixels that burnt (with 25% confidence intervals), the month of peak fire, and the seasonality of fire (ranging from 0: fire all year round, to 1: all fire occurred in one month). The ~ indicates that the Wiebull parametrisation did not converge so median fire return could not be calculated

Vegetation	Land use	km^2(x1000)	%burnt	c.i.	MEI all	c.i.	MEI burnt	c.i.	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

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Table 1 – continued from previous page

Vegetation	Land use	km^2(x1000)	%burnt	c.i.	MEI all	c.i.	MEI burnt	c.i.	peak month	seasonality
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
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
DRC										
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

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Table 1 – continued from previous page

Vegetation	Land use	km^2(x1000)	%burnt	c.i.	MEI all	c.i.	MEI burnt	c.i.	peak month	seasonality
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
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	(14-952)	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										

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Table 1 – continued from previous page

Vegetation	Land use	km^2(x1000)	%burnt	c.i.	MEI all	c.i.	MEI burnt	c.i.	peak month	seasonality
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
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
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

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Table 1 – continued from previous page

Vegetation	Land use	km^2(x1000)	%burnt	c.i.	MEI all	c.i.	MEI burnt	c.i.	peak month	seasonality
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

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Table 1 – continued from previous page

Vegetation	Land use	km^2(x1000)	%burnt	c.i.	MEI all	c.i.	MEI burnt	c.i.	peak month	seasonality
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

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Dear Prof Doerr,

Thank you very much for the review and for agreeing to publish this manuscript. We found the comments of the two reviewers very helpful and have attempted to resolve all of their queries. Most of their comments involved simple editing changes, but there were two aspects which required further clarification. The first was the abstract, which both reviewers found a little unclear. The second reviewer also requested that the discussion be altered to provide more explanations for the patterns observed, and to relate these patterns to global fire theory.

These concerns highlight the fact that this paper, while fundamentally very descriptive, raises some very important theoretical issues in fire ecology. We found it difficult to do justice to both of these aspects in one paper: the value of this paper lies in the fact that it integrates different sources of information to describe a range of fire regime characteristics, but this inevitably reduces the space for discussion on particular aspects (such as fire-size distributions, or the methods for calculating fire return intervals). In particular, we agree with reviewer 2 that many of these results cry out to be compared with results in other savanna regions on the globe, and in other biomes with different fire regimes. However, we believe it would be impossible to do such comparisons justice within the limits of this paper. We do highlight points of agreement and departure from current global fire theory, and we do reference literature from other continents and other fire-systems which provide complimentary data. In response to Reviewer 2's comments we have also altered the discussion to make more effort to explain the patterns in terms of global theory, as well as our understanding of the system (see detailed comments below). We believe that this has substantially improved the paper, but inevitably there are still many unanswered questions which will have to be satisfied by further research focussing on cross-continental and inter-biome comparisons. We are currently involved in such work and it promises to be very exciting.

Major changes:
1: We have altered the abstract to improve the flow, and to add clarity on the particular aims of this paper.
2: We have modified the introduction as recommended by reviewer 2
3: We have altered the discussion to include a more comprehensive interpretation of the patterns which emerge.

Minor changes: see response to individual comments below.

Best Wishes
Sally Archibald

Reviewer 1:
Summary:

This is a comprehensive paper quantifying fire regime variables in southern Africa over the period 2000-2008 using remote sensing data. I expect this will be widely cited. I am especially impressed with the quality and information content of several novel figures (which I suspect were generated in R?would be good to say so in the Methods under ?Analysis?, which really should be a subheading under Methods), and the clarity of the writing. I have no major criticisms but a good number of minor comments that, if considered and addressed, would improve the clarity of the paper even more.

REPONSE: Thank you. We have clarified the software used (R) and we have renamed the headings in the methods section as suggested.

Comments:

Abstract. I thought the first two paragraphs flowed poorly. It is good background material, but the second sentence reads like the purpose of the paper by saying ?are explored? without saying by whom (prior studies or this study?), making it seem out of place.
DONE: In conjunction with other comments from reviewer 2 we have altered the first paragraph to read: "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."

We have altered the 50 word summary to read "This paper provides baseline information for managers and scientists hoping to understand fire in southern Africa. It also highlights instances where findings from this region both conform to and challenge current global theories on fire."

Line 55. Make ?population? plural.
DONE: thank you

Line 56. Make ?scale? plural or add an article before ?regional?.
DONE: changed to "scales"

Line 60. Change ?representatives of all the? to ?representative?.

DONE: This clumsy sentence has been changed to: "Furthermore, the samples did not include the full range of climate and vegetation on the subcontinent" at the suggestion of the second reviewer.

Line 62. Change ?data available from remotely sensed data? to ?available remotely sensed data?.
DONE: thank you

Line 64. By temporal bias I take it you mean the time of day, and not the day, since the sampling interval is higher than daily frequency? Please clarify.
DONE: This sentence has been changed to: "The first satellite 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)"

Line 67. Change ?Fire Radiative Power (Wooster et al., 2003; Giglio, 2007). Fire radiative power (FRP)? to ?Fire Radiative Power (FRP) (Wooster et al., 2003; Giglio, 2007). Fire radiative power?. Acronyms should be spelled out following first mention.
DONE: Thank you

Lines 70, 71, Fig. 5 caption, maybe elsewhere. Separate numbers and units with a space, i.e., ?1 km?.
DONE: we have corrected this throughout the document

Lines 81-82. I would not call ignition frequency or fire size distributions more elusive than, say, fire duration or Fire Radiative Energy (FRE). So change ?the most elusive information of all: to ?elusive fire regime information such as?.
DONE: thank you. Although we do think that it is very difficult to obtain information on ignition frequency.

Lines 83-84. You might rephrase as ??nuanced view of fire regimes in Africa.?
DONE: Thank you

Paragraph beginning line 139. I take it that it was necessary to impute the missing data for June 2001 because you wanted to perform time series analysis. However, currently no justification is provided for why you didn?t just leave June 2001 with no data.
DONE: It is not possible to calculate an annual sum of burned area unless all data for that year are available. We could have excluded the 2001 fire year from our analysis, but as we only had 7 years of data we thought it better to fill it and test our filling algorithm. We make this clear with the subheading "annual sums" and the sentence "In order to calculate an annual sum for 2001 the following method was used to fill these data."

Line 152. These dates suggest that you did define the burn year from April thru March as suggested by Boschetti and Roy (2008), which conflicts with your implication on Line 137 that you may have chosen to use the calendar year instead. You need to clearly state after Line 137 which definition of the annual burn year you chose.
DONE: The data product ran from April 2000 to March 2008 at the time of analysis. In order to have 8 years of data we needed to include all months. We did not use the year 2000 or the year 2008 in our calculation of annual sums, because these were performed over a calendar year. To avoid misunderstanding we have deleted the words "April 2000 to March 2008" from this sentence and added this information to line 132 where it belongs.

Lines 155, 308. I believe ?fuelled? is misspelled.
DONE: According to various dictionaries "fueled" is the American spelling and "fuelled" is the UK spelling. The IJWF is happy with UK or US spelling as long as we are consistent, and the rest of our paper is written with UK spelling. We therefore use "fuelled" throughout but we are not happy to use any spelling system the publisher requests.

Paragraph beginning line 184. So to be clear, two concurrent fires contained within the same 1-degree grid cell would be counted as a single fire? It would be good to state the limitation(s) imposed by spatial (and temporal) resolution in such terms.
DONE: The scale of the cell is 500 m by 500 m (i.e. 0.25 km2). Any fires smaller than 0.25 km2 would not be identified. We do go into this at some length in the cited paper (Archibald and Roy 2009) – and compare it with field data, but for clarity we add a sentence here: "As the resolution of the input data is 0.25 km2 (a 500 m MODIS pixel) any fires smaller than 0.25 km2 would not be identified or included in the final count."

Line 204. It seems ?index ecosystem response? would be better phrased as ?ecosystem response index?.
DONE: Thank you for catching this typo. It has been changed to "index of ecosystem response to fire"

Line 209. You?ve already defined FRP, don?t do it multiple times. You could add (FRP) following the ?Fire Radiative Power? in line 197.
DONE: Thank you

Line 218. By ?the sub-satellite point? do you mean ?nadir?? How much larger is the 4.8 x 4.8 km pixel area at the equator compared to at Cape Agulhas?
DONE: Yes we mean at nadir and we have altered the text. The distance between samples is 3km at nadir with an oversampling factor of 1.6, which

means that individual pixel sizes are around 4.8km by 4.8km. Over South Africa the distance between samples is 3.7 km which means the pixel size is 5.9km by 5.9 km.

Line 220. Why not April 2004 thru March 2005, to conform to your burn year definition (if that?s it) or January thru December 2004 (if that?s your definition)?
NOT DONE: Unfortunately these were the only data that were made available to us.

Line 222. Do you mean head vs. back fires?
DONE: Yes… we have added this in brackets.

Line 238. By my count there are 14 African countries (including Madagascar, but not other oceanic island nations like Mauritius, Comoros, or Seychelles) wholly south of the equator and 6 African countries intersected by the equator.
NOT DONE: Yes, we included the Congo and the DRC in this analysis because although they are not wholly south of the equator the majority of their land masses are. We performed all calculations only on the part of these countries that is south of the Equator. We clarify this in the methods.

Line 301. I believe a close parenthesis is needed after ?100%?.
DONE: Thank you

Line 398. Change ?must account? to ?most likely accounts? or ?almost certainly accounts?.
DONE: We have changed this phrase to: "and we suggest that this is what accounts for the differences in annual burnt area and fire size."

Paragraph beginning line 409. Could it also be said that the patches of grass frequently burnt in densely populated Malawi are so small that they probably go undetected?
DONE: Yes, that is the point that we are trying to make. The patches that do burn will burn frequently, and estimating fire return times on these patches gives reasonable results. We alter the text to clarify our point. "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 (c.i. 2.9-11.8) which is a more reasonable estimate for this system."

Line 458. I found myself wanting an explanation for why Africans light so many fires. I know that they give many reasons, the most illuminating that I?ve heard is, ?Because my father did? (to paraphrase). This topic would be a paper by itself. Can you cite anything?
DONE: There are several good references for this, but I would very much like to see more work on it. We add these sentences "The frequency with which people

in Africa light fires, and their proactive approach to using fire as a management tool is well known (Laris2006,Kull2004,Frost1999), and is often cited in explanations for why Africa is such a "fiery continent" (Crutzen1990). Our research highlights other more complicated relationships between human land use and fire regimes."

Line 486. The open parenthesis should be moved to precede Cochrane, not 1999.
DONE: Thank you

Line 487. To say that your previous pub found fire to be primarily under environmental control, with humans having only secondary control, might seem to conflict with the main (perhaps) finding of this paper. You should rephrase this so that this paper does seem to complement this earlier finding (as you close by stating), not contradict it.
DONE: We have altered this paragraph as follows: "We have previously published findings (Archibald2009) 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 inter-annual variability in fire (Archibald2010). This 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 inter-annual patterns emerge."

Some of the text in the Figure captions is more typically placed in the results, especially interpretive text like in the latter portions of the captions for Figs. 7-9. However, it strikes me as more sensible practice to more closely associate some interpretation with the figures, so I am not opposed to this.
NOT DONE: I am happy to follow the journal's style in this and will delete the discursive text if required.

Fig. 1. It appears that there is a larger proportion of gray pixels in Malawi relative to the surrounding area, which seems unlikely to be attributable to greater cloud cover. Why would higher human population density produce more invalid pixels? I understand greater fire exclusion there depressing the fire activity, but that shouldn?t invalidate the pixels.
NOT DONE: This is simply due to the fact that the fire frequency layer is placed on top of the "invalid pixels" layer. It therefore masks out the information on cloud cover in areas which burn. In fact, the entire region of the same latitudinal zone as Malawi has similar number of invalid pixels (about 5 over the 8 year time period, which is not enough to invalidate the burned area data… we excluded pixels which were invalid 16 or more times in the time period from the analysis). We can not think of a better way to present this information

Fig. 2. The caption doesn?t distinguish between the gray and orange bars. Which color represents the burnt areas, and which the entire region?
DONE: Thank you we have corrected this.

Fig. 3. Redo the legend so ?Times Burnt? is only in the title (capitalize), without ?times? in the row labels as well.
DONE: Thank you

Figs. 3, 4. The ?South Africa? label has a dot between the words.
DONE: Thank you

Fig. 7. Replace the ?-? in the caption with a comma.
DONE: Thank you
Fig. 8. The caption states ?number of fires each day? while the right-side Y-axes on the figures are labeled ?number of fires per day?. Change the labels to match the caption.
DONE

Table 1. This is valuable and very useful but long so should be an Appendix.
AGREED, although the main aim of this paper is to make these data available to researchers and fire managers in Africa so it should be easy to access.

References. The first two (Archibald) refs should indicate ?In Press? or ?In Review?. The Ciesin (2005) ref is missing information needed to easily find it. Is there a website?
DONE. Thank you

There are inconsistencies in the font, size, and style of headings and subheadings, but I trust the editors/publisher will fix these.

Review 2

Overall comments:

The paper provides some interesting and valuable analyses of African fire regimes from a very rich dataset. Overall I found the paper generally well written and easy to read. The introduction should be improved by shortening and refining the background information, and by improving the motivation for the study. The dataset could be (and is in some cases) used to test specific hypotheses, yet I don’t feel that this is well set up in the introduction. Similarly, the discussion lacks explanations for some of the key patterns found in the

dataset. The discussion should be improved by linking the patterns back to potential mechanisms, and by placing these interpretations into the context of fire regimes and fire ecology outside of African systems. If the discussion were as rich as the data analysis, the paper would be significantly improved.
THANK YOU:

Detailed comments:

Throughout the paper

- “remotely-sensed products” is used inconsistently (with “-“). Also, acknowledging that remote sensing is not my expertise, shouldn’t this be “remote sensing product” or “remotely-sensed data product”? That is, the product is not remotely sensed, but it comes from remote sensing (or remotely-sensed properties). A remotely-sensed product does not make much sense (to me).
DONE: We have changed this throughout to “remotely-sensed data product” or “remote sensing data”.

- Use of parenthetical comments within parenthetical comments in confusing with “(“ identifying both. Consider “(for initial parenthetical comment and then “[“ for second, etc.?
NOT DONE: Except for one instance this occurred when a reference was cited within a parenthetical comment (for example if I were to cite Wooster and Roberts (2009) within this comment). We are unsure how to correct this without changing the formatting of all citations, which would be undesirable in terms of the IJWF’s style. We have corrected the one instance where two parenthetical comments were inside each other by changing the one to comma’s.

- I found if difficult to figure out the years that the data covered. Most frequently you write “eight years of data”, but you do not tell the reader which eight years these are. This is important. I assume the eight years are 2001-2008.
DONE: When we first introduce the data we add the sentence “They covered the period April 2001 to March 2008”

Abstract

The abstract could use a statement of motivation to start off, instead of the passive description of what was done.
DONE: See comments to Reviewer 1 above. We have altered the first paragraph of the Abstract to introduce our aims and research approach more clearly. We have also altered the 50 word summary sentence.

L18: "overall pattern" – do you mean the spatial or temporal pattern? Can you be explicit here?
DONE: Throughout the paper we are focussing on spatial aspects rather than temporal aspects. We have altered this section of the abstract to focus on fire regime characteristics.

L20: "remotely sensed fire products" → inconsistent with use of line 2, and does not make sense. "fire products from remotely-sensed data" makes more sense.
DONE We have changed this to "remotely-sensed data on fire"

Introduction

Overall, the introduction reads a bit long. I think there is more in there than needed to motivate this study, and the short paragraphs (e.g., some with only two sentences) make it a bit choppy. Seems like the key background information the reader needs is related to: (1) development and current state of remote sensing data, including strengths and weaknesses; (2) background information on the fire ecology of southern Africa, including state of knowledge on fire regimes and dominant explanations for the observed patterns; and (3) purpose of this study.
DONE: We are glad the reviewer appreciates the importance of including background information on fire ecology in southern Africa – which is often ignored in remote-sensing studies, giving the impression that there was no previous knowledge. From the reviewer's comments it appears that the paragraphs which require reduction are the ones referring to the usefulness of the information for policy makers and for scientists. We have edited this section and reduced the words from 252 to 173. We have also improved the flow of the introduction by simplifying sentences and combining paragraphs.

L29: "The Fire Continent" (remove double quotation mark)
DONE: Thank you

L34: "Earth" instead of "earth"
DONE: Thank you

L45: Are you referring to the "distribution of fire" in space and/or time? Can you be explicit?
DONE: Throughout this manuscript we are focussing on spatial patterns. We believe we make this clear in the introduction 1: by elaborating on the spatially-explicit nature of the satellite data and what this can contribute towards our understanding, and 2: by introducing our analysis as a comparison of the spatial patterns of different characteristics of a fire regime in relation to the factors which influence fire. In the particular instance the reviewer highlights here we

have changed the text to read: "What the satellite data provide, which had not been available before, is a spatially-explicit and comprehensive view of fire in Africa".

L54: Again, some reference to the spatial and temporal scales that you are implicitly referring to here would be helpful.
PARTIALLY DONE: In this sentence we are summarising the definition of a fire regime from the literature, and not referring to our particular study. It is therefore inappropriate to specify the temporal and spatial scales. However, we add the words "at a certain location", and in the next paragraph, when we introduce the data, we mention the spatial and temporal scales of the available data. In the final paragraph, when we introduce our analysis, we explain the spatial categories that we used to summarise the data (country, vegetation type, land use type, and also by 1-degree grid cell). We agree that we are not explicit about temporal scale in the last paragraph and we have added the sentence "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."

L56: Consider reference to Flannigan et al. 2009 for thorough review of how fire regimes may respond to climate change.
NOT DONE: ? Would the reviewer like us to replace the Bowman 2009 reference with the Flannigan 2009 reference? We believe that both research articles satisfactorily corroborate the point we are trying to make, but the Bowman reference more generally refers to "global change" rather than "climate change".

L 57: "regional scales" (?), and what do you mean by these processes"? The latter is vague.
DONE: Corrected the typo – thank you. We have changed the text to "these feedbacks" to indicate that we are referring to the previous sentence.

L60: "Furthermore, the samples did not include the full range of climate and vegetation on the subcontinent."
DONE: Thank you

L63: "satellite-derived fire products"
DONE: Thank you

L67: Introduce "FRP" acronym here, after the first use of Fire Radiative Power, then start the second sentence this line with FRP. Also, can you describe the units of FRP here, instead of later on in the paper?
DONE: Thank you

L81: "The most elusive information of all" does not add much content to the introduction.

DONE: this sentence has been changed following the advice of reviewer 1.

L85: "…only on active fire data, i.e., the number…"
DONE: Thank you

L92: The use of "point" here to refer to a spatial scale is confusing. Surely you don't mean that you can describe the fire regime at a single point, with only 8 years of data. Also, I think many would argue that you are not providing a "full description" of the fire regime.
DONE: the word point has been changed to "location". Agreed, according to our definition of a fire regime (frequency, seasonality, intensity, severity, fuel consumption and spread patterns of fires) we are not giving comprehensive information. We have deleted the word "full".

Methods

L140: "To fill in these data in…"
DONE: Following suggestions of the other reviewer we changed this sentence to: "In order to calculate an annual sum for 2001 the following method was used to fill these missing data"

L 148-151: This is a good way to test the effects of the June 2001 data gap (and your method for filling it in). However, I found the description slightly confusing. I believe the "< 1%" statistic refers to the maximum error from any single prediction of July area burned (for 2002-2007). This would be the most relevant statistic. Your statement "for all six years", was slightly confusing and made me think that you combined the six years worth of data (thus making it not comparable to estimating one year of June area burned). Also, why not include a prediction for July 2001 in this sensitivity analysis? It's not clear why you only did this for 2002-2008.
DONE: Thank you for the feedback. We have changed the last sentence to read "The results of this test showed the filling algorithm to be very accurate (all six years had r^2 values > 0.96 and mean absolute errors < 1%)". The test compares the recorded annual burned area against the burned area estimated when one month of data is removed and filled. We therefore could not do this test on any year which did not have the full compliment of data, which is why we did not run it on the 2000, 2001, or 2008 fire years.

L 154: Can you describe why you decided to exclude pixels with more than two invalid data points per year? Why two? Also, it would be helpful to describe how many (what proportion of) data points fit this criterion.
DONE: We ran several sensitivity analyses on the different criteria for classifying an invalid pixel. The aim was to exclude pixels where it was possible that fires occurred during months when the data were invalid. Any pixel which burned in a year was therefore automatically considered valid. Of the remaining unburned

pixels we chose to be very conservative because it would do less harm to exclude a pixel than to falsely classify a burned pixel as unburned. In previous analyses we excluded all pixels which had 6 or more months of invalid data (i.e. more than half the year invalid). 48% of the data were invalid at least once in the 8 year time period. 14% of the data were invalid 16 times over the time period (on average twice a year), and 3 % of the data were invalid 48 times over the time period (half of the time).
We have added this information to the manuscript: "Because we were more interested in accuracy than comprehensiveness we were conservative in our approach to invalid data: we excluded all pixels which had invalid data more than two times a year on average (14% of the dataset)"

L 163: "…are well developed, they require"
DONE: thank you

L171-171: "The fire return period…" (?)
DONE: Thank you

L 173: In addition to citing the reference, can you describe how you fit the Weibull model to the return intervals? E.g., maximum likelihood technique?
DONE: We used the "Survreg" function in the "survival" package of R which can fit a range of distributions to censored or uncensored survival data. The function uses maximum likelihood to estimate parameters. We have added a sentence to describing the software and packages used.

L 192: This statistic is used a lot, but in many different ecosystems. It is very important to know what ecosystems this has (and has not) been found in; e.g., boreal forest is very different than grasslands. Do you expect to relationship to hold in southern African ecosystems?
PARTIALLY DONE: No, we did not expect it to hold – for a number of reasons. Theoretically the rule is based on the fact that forest fires show power-law distributions - which means that the variance remains constant and extreme events become important in characterising the system. In grasslands we do not expect such strong power-law distributions because of the rapid re-growth of fuel after a fire (the effect of previous fire events on the probability of future fire events becomes less important). There is another, more mundane reason why we do not expect it: the grassland systems in question (inhabited African savannas) large fire events are unlikely to occur simply because the landscapes are so fragmented. We are involved in more theoretical work to explore the internal (power-law distributions and feedbacks) and external (landscape fragmentation) controls on fire size distributions but there is not enough space to go into this in this manuscript. We thought it was important to demonstrate, however, that this rule does not hold, because it has management implications.

We are not quite sure what the reviewer expected here. We discuss these results in some detail in the discussion but we do not think the methods section is a good place to go into it. We have, however, added a sentence stating that we did not expect this rule to apply in our systems.

L 198: Include units (kW/m) after "…length of the burning front."
DONE: Thank you

L 209: Include units with definition of FRP: "…(FRP, mW/pixle).
PARTIALLY DONE: This was already included in the next sentence. We have added the abbreviation to make this more obvious.

L 211: Exponent for units of J/g should be superscript
DONE: Thank you

L 260: "Spatially-explicit datasets…"
DONE: Thank you

Results

L 296-299: Numbers reported here do not match up with Figure 2. E.g., text reports 55%, 150 people per km2, 320 mm, and 25% seasonality, whereas figure shows limits of 59%, 140 people per km2, 340 mm, and 29% seasonality. These should be consistent.
DONE: Apologies for the error
L 302: Missing closed parentheses here.
DONE

L 321-322: This sentence seems more like a discussion point, not a result.
NOT DONE: Yes, and we do make this point in the discussion (lines 409-420). However, we feel it is important to highlight this issue and have left this sentence in the results as well.

L 331: "…burns very little, it shows some…"
DONE: Thank you

L 336-337: Confusing sentence here.
DONE: We have changed the sentence to: "Annual burned area is greatly reduced outside protected areas in areas which are utilised by humans and their cattle, and further reduced in areas of cultivation and settlement"

L 343: Should use "FRP" instead of writing this out, once the acronym is introduced.
DONE:

L 345: "…variations of a grass-fueled fire regime…"
DONE

L 349: Could delete from "When one maps…it is clear that".
DONE: Thank you for the suggestion.

L 374-376: Again, this sentence seems more like an interpretation of the results, which I expect to find in the discussion, particularly with the word "suggest" in there.
DONE: We have moved this entire paragraph to the discussion

Discussion

L 393-399: This is a good point, and it is highlighted nicely. On line 398, however, "…it is this that must account for…" seems a bit strong. How about "…it is this that could possibly account for…" or "…likely accounts for…"?
DONE: We have changed this phrase to "…and we suggest that this is what accounts for the differences in annual burnt area and fire size."

L 411-420: This is an important point, but I find this discussion lacking some important detail and thus a little weak. Why are space-for-time substitutions not appropriate for Africa? Is it specific to Africa, or is there something you can show here to make this valuable to any ecosystem type or fire regime? For example, can you quantify what you mean by "small" and "high"? You mention earlier (L 163-165) the assumption of landscape homogeneity when calculating fire return intervals. Thus, your example using the political boundary of Malawi makes little sense, or at least does not provide good support for your opening statement. Unless Malawi represents a homogenous vegetation type, the reader should not expect the fire return interval distribution from the entire country to be meaningful ecologically. Is the strongest point from this example that there is high spatial heterogeneity in the fire regime across Malawi?
DONE: We appreciate that perhaps we did not generalise this discussion enough. Space-for-time substitutions are inappropriate in any system where some parts of the landscape never burn. We have altered this paragraph to apply to Africa as well as the globe by adding these two sentences: "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". And "This problem can be accommodated by ensuring that homogenous areas are selected on which to perform space-for-time substitution, but when summarising by quarter-degree grid square for climate modelling, for example, this is not possible."

We would also like to point out that the example cited was for savanna/woodland vegetation in uncultivated regions in Malawi, so it could be expected to have a relatively homogeneous fire regime considering that topographic and climatic variation in Malawi is not high. We have clarified this in the text as well

L 415: "…applying the Weibull distribution…" should be "…fitting the Weibull distribution…".
DONE: thank you

L 421-432: I am confused by this discussion and am having a hard time seeing the patterns discussed in the text when I look at Figure 8. Also, the text states that the expected pattern (based on Yates et al. and Williams et al.) if for "fires lit in the early dry season [to be] smaller and less intense than fires which occur late in the dry season", while the figure text notes an "…expected pattern of larger fires early in the fire season, and more intense fires later in the fire season." Which one is it? This may be the source of some of my confusion.
DONE: sorry for the confusion. The figure text notes that ONLY THE THICKET shows the expected pattern. To avoid confusion we have altered this text to read: "From Yates(2008) and Williams(2008) one would expect small fires early in the fire season, and larger, more intense fires later in the fire season. Savannas 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 FRP's (note the difference in scale)."

If the black line in Fig. 8 represents the number of fire each day, and thus can be used to identify the start/end of the fire season, then it looks to me like the fire season starts around Julian day 100-120. For "savanna/woodland", "forest transitions", and "forest", it does appear that fires in the "early" fire season are smaller and/or less intense than those in the "late" fire season, which is in contrast to your interpretation (in the text). Some of my confusion may also stem for the subjective interpretation of "early" and "late". Can you be specific in what you mean here?
DONE: Again, apologies for not making our point clear. Yes, we agree with your interpretation of the figure. We have changed the text to read: "Yates(2008) and Williams(2008) have shown in northern Australia that fires lit in the early dry season are smaller and less intense than fires which occur late in the dry season. A southern African analysis does not support this pattern (Figure 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."

L 422: "…smaller and less intense than fires which occur late in the dry season" contrasts with the figure text of "…expect pattern of larger fires early in the fire season, and more intense fires later in the fire season."
DONE: Apologies. The figure text has been changed to agree with the manuscript text.

L 424: You refer to June in the text, but the figure has only Julian days – can you note the Julian day that equals June 1, for reference?
DONE: we have re-written the text.

L 425-426: "These data make sense…" is a weak statement.
DONE: Changed to "One explanation for this divergence is that these two savanna systems have very different seasonal patterns of burning."

L 432: "…(e.g., Govender…)
DONE: thank you

L 437: Missing parentheses in front of "Brockett ".
DONE: thank you

L 445-447: I'm missing an explanation for this breaking of the "rules". Why do you think that number of fires, instead of area burned by large fires, is the better indication of the annual area burned?
DONE: We have added the sentence: "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."

L 448-455: Doesn't this analysis contradict what is noted in the previous paragraph? Also, it is an observation that "very small fires do not contribute significantly to annual burnt area", not a theory. It's not like this is something predicted that has not been observed.
DONE: these results were intended to follow directly from the previous paragraph and are a test of this statement. We have re-written the paragraph as follows to make this more clear: "To test how different fire sizes contribute to the total burned area we regressed 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, etc km^2). 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 were counted, and then decreases (Figure 9)…"

Conclusions

L 459-460: "… up to a certain extent; Figure 7A),…"
DONE: thank you

L 465-466: Lightning is only briefly mentioned on page 16, with no data or references, yet is a conclusion of the study? If you're inferring patterns related to lightning (or lack there of), some data on lightning should be presented or referred to and highlighted more clearly in the discussion (before the conclusions). This is a very interesting and important point, but without knowing about the seasonal distribution of lightning, it's difficult for me to assess this conclusion.
PARTIALLY DONE: Agreed, we do not present information on lightning. We have altered the text to reference this statement by referring to Figure 4 which shows seasonal patterns of burning. See Archibald et al GCB 2009 for information on the seasonal patterns of lightning.

L 467-478: Do you think lightning would be a limiting factor in the absence of human? Would African systems burn in the absence of humans? There are few systems that don't/didn't burn in the absence of human (e.g. New Zealand), so this would be an important point.
NOT DONE: We think this is an interesting question and are exploring theoretical models looking at when and how ignitions become limiting in savanna systems. However, we can not make any statements on this at this stage.

L 470-471: To my knowledge, it's generally thought that large area burned in boreal forests is due to persistence of high pressure systems, which maintain warm, dry conditions for long periods of the fire season. Interannual variability in lightning is not typically needed to explain interannual patterns in area burned.
DONE: Possibly we made too many assumptions here. We are not familiar with boreal fire regimes but the two literature sources cited provide evidence that a) lightning fires burn the majority of the area (Dewilde and Chapin) and b) climate variables affect total area burned (Balshi 2009). For clarity we have excluded the reference to lightning as a possible cause of inter-annual variability because we have no information on how variable lightning is in these systems. Thank you for the reference, which we have added.

L 473-475: Sentence does not make sense.
DONE: we are not sure what does not make sense. We hope that this new formulation is clearer: "This hypothesis is confirmed by research into the inter-annual variability of fire in southern Africa (Vanderwerf (2004) Archibald(2010): burned area is not as strongly linked to climate variability in this region as it is in other parts of the globe."

L 479: "…frequent fire, which…"
DONE.

L 477: "idea" seems like a weak word here. Is this a theory?
DONE: thank you

L 481: Missing parenthesis before "Hennenberg".
DONE: thank you

L 485: "…transformation of forest, such as…"
DONE: thank you

L 492-493: I think it's a stretch to state that the patterns you describe "isolate the mechanisms" controlling fire in this region. The patterns provide very important information that helps deduce the mechanisms, but they do not reveal the mechanisms themselves. You would need experiments to do that.
AGREED: we change this to "explore".

Figure headings

P 21, Figure 5: Starting with "comparing" is odd and doesn't add much; this could be "Aspects of the fire regime stratified by…".
In the text you use "quartiles" to refer to different locations within a distribution, but here you refer to "percentiles". Shouldn't these be consistent?
It would be more consistent with the rest of the paper to write "per year" as opposed to "per annum".
"5kmx5km" → "5 km x 5 km"
DONE: Yes, thank you. These changes have been made.

Caption for Fig. 6: "Areas with the largest fires….(A), but fire density…(B)" would be helpful.
DONE: thank you

Figure 7: "Showing how population density affects A…" is vague, and starting with "Showing" is odd. Could be "Population density and fire occurrence."
DONE: thank you

Figure 8: space after "8". You refer to "Savannas" in the figure caption, but the figure only reports data for "savanna/woodland". The references in the figure caption should be consistent with the titles in the figure.
DONE

Figure 9: Could be "Relationship between number of fire and area burned."
DONE

Figures

With the exception of the maps, I don't think the color adds much to these figures, and in some cases is distracting.
PARTIALLY DONE: We can exclude colour from Figures 2 and 8 but believe that the colour aids interpretation of the other figures, which are all displaying information in several different types of categories at once.

Fig. 2: This figure has a lot of useful information in it, and I think its value can be improved with some modifications. (1) Y-axis tick labels would be helpful for each variable. Two to three numbers on each provides the minimum amount of information to learn from these plots. (2) Are the % sand data ever referred to? If not, should be deleted. (3) I assume that the left (larger) column for each variable is the range of that variable for the entire region, while the left is the range for the pixels that burned. This should be labeled in the figure and described in the text more clearly.
PARTIALLY DONE: 1: We previously tried adding y-axis tick labels but feel that it makes the figure too confusing. 2: We have added a sentence "Soil texture does not appear to be related to fire occurrence at this scale." We believe this is an interesting result and would like to keep it in. 3: Thank you. We have made this more clear in the caption.

Figures 3-4. Any way you can provide sample size for total number of fires in each category, or simply note if the sample size is > 30 for all categories (for example)? Interpreting these proportions requires knowing something about the total number of samples in each category.
DONE: We have added information on the percentage of the total land mass covered by different categories. Just to clarify: these figures are quantifying the "Area burned" not the "Number of fires"

Figure 5: not sure that color adds much to this figure.
NOT DONE: We believe that the colour helps to interpret the figure. We have attempted to ensure that this figure will also be interpretable if printed on a black and white printer.

Tables

Table 1: When presenting the "MEI" can you define this acronym? What is it: median return interval? Use of ":" for confidence intervals is odd. Why not "-" to refer to the range?

DONE: In the caption we defined the MEI as the “Fire return period”. In fact, it is the median return period estimated from the Weibull distribution. We clarify this in the caption.

Precision of numbers varies within a single variable, but should be the same if all data coming from same source. E.g., seasonality value of “1” should be “1.0”, and if MEI is reported as “4.8” then it should also be reported at “57.0” (not “57), OR round all values equally.

Can “South.Africa” be changed to “South Africa”?
DONE

References

First two Archibald references has odd “.” at end.
DONE