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Historical fire regimes in a poorly understood, fire-prone ecosystem: eastern coastal fynbos

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Abstract. We characterised the historical fire regime (1900–2010) in eastern coastal fynbos shrublands, which occur in a poorly studied part of the Cape Floral Kingdom (CFK). Natural (lightning-ignited) fires dominated the fire regime. Fire seasonality decreased from west (Outeniqua region) to east (Tsitsikamma region) within the study area, and between the study area and further west in the CFK. This is consistent with a west–east climatic gradient in the CFK, where rainfall is concentrated in winter in the west, and evenly distributed across months in the east. Median fire return intervals (FRIs) (1980–2010) were broadly comparable to other fynbos areas but estimates varied widely depending on whether or not the data were censored (16–26 years with and 8–13 years without censoring). FRIs appeared to be shorter in the Tsitsikamma, where rainfall and plant growth rates are higher, than in the Outeniqua. The total area burnt annually has increased significantly since 1980, coinciding with an increase in weather conducive to fires, suggesting that fire regimes may be responding to climate change. Frequent recurrence of very large fires and the virtual absence of vegetation in older post-fire age classes are potential causes for concern in achieving fynbos conservation objectives.

Additional keywords: Cape Floral Kingdom, fire cause, fire frequency, fire return interval, fire season, fire size, Garden Route National Park, shrublands, South Africa.

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Introduction

Fire is an important process in many ecosystems worldwide (Naveh 1975; Bond and van Wilgen 1996; Bond *et al.* 2005), in which it shapes the structure and composition of the vegetation (Keeley 1986; van Wilgen *et al.* 1992; Morrison *et al.* 1995). The occurrence of fires over an extended period in a given area is referred to as a fire regime (Gill 1975), described in terms of the frequency, season, intensity and size of fires (Morgan *et al.* 2001; Gill and Allan 2008). Managers of fire-prone ecosystems need to understand the historical fire regimes of the areas that they manage, so that they can better understand how the current vegetation was shaped (Morgan *et al.* 2001; Schuler and McClain 2003), and whether or not they need to intervene in cases where contemporary fire regimes may be in conflict with biodiversity conservation requirements (Seydack 1992).

Fire is a dominant disturbance in the fynbos shrublands of the Cape Floral Kingdom (CFK) of South Africa. The CFK is an internationally renowned hotspot of biodiversity (Myers *et al.* 2000), where sound fire management is fundamental to the attainment of conservation objectives (Kruger and Bigalke 1984). Fynbos (literally meaning fine-leaved bush) is an evergreen, sclerophyllous shrubland on sandy, infertile soils associated with the winter and aseasonal rainfall regions of south-western South Africa (Cowling *et al.* 1997). This vegetation type is fire prone and fire adapted, with the frequency, season and intensity of fires being important determinants of vegetation structure and composition (Kruger and Bigalke 1984; van Wilgen *et al.* 1992; Vlok and Yeaton 1999).

Within the CFK, a climatic gradient exists in which the seasonality in rainfall, solar radiation, temperature and evaporation decreases from west to east (Deacon *et al.* 1992). The Mediterranean climate (cool, wet winters and warm, dry summers) of the west contrasts with the all-year rainfall and relatively temperate conditions of the east (Schulze 1965; van Wilgen 1984; Southey 2009), with presumed effects on the fire regimes of the respective areas. Despite the climatological differences, existing guidelines for the management of fire in fynbos are largely based on research carried out in the west (Kruger and Bigalke 1984; van Wilgen and Richardson 1985; van Wilgen and Viviers 1985; van Wilgen *et al.* 1994), and little is known about the fire ecology of the eastern coastal region (van Wilgen 2009). Fires in western and inland parts of the CFK normally occur at intervals of 8–40 years (van Wilgen *et al.* 1992) although fuel loads are seldom limiting beyond the initial 2–4 years post-fire (Brown *et al.* 1991; Fernandes and Botelho 2003; Moritz *et al.* 2004; van Wilgen *et al.* 2010). Recruitment of fynbos in these areas is best after fires in summer and autumn (van Wilgen and Viviers 1985; Midgley 1989). In the east, however, recruitment success is less dependent on fire season than post-fire rainfall amounts (Heelemann *et al.* 2008); here, in addition to rainfall, conditions conducive to fires show little seasonality (Kraaij *et al.* 2012*a*). Similarly, plant growth rates may be higher in response to an increasing amount of warm-season rainfall towards the east, with effects on fuel accumulation rates and thus fire frequency.

Comprehensive fire histories in the CFK (Seydack *et al.* 2007; Forsyth and van Wilgen 2008; van Wilgen *et al.* 2010) and other temperate shrublands (Keeley *et al.* 1999; Montenegro *et al.* 2004; Syphard *et al.* 2009; Moreira *et al.* 2011) provide mounting evidence for long-term changes in fire regimes (notably increases in fire frequency), possibly related to climate change ((Piñol *et al.* 1998; Mouillot *et al.* 2002; Keeley and Zedler 2009; Wilson *et al.* 2010). In the eastern coastal CFK, weather conditions conducive to the occurrence and spread of fires have increased since 1940 (Kraaij *et al.* 2012*a*) but it is not known whether the fire regime has changed accordingly. The historic approach towards fire management in the east differed from that in the western parts of the CFK. In the west, the focus was on burning for conservation, whereas in the east, extensive fuel-reduction burning was attempted in fynbos to protect plantations of exotic pines (Kraaij *et al.* 2011).

The recent establishment of the Garden Route National Park (GRNP; Government Gazette 2009) in the eastern coastal CFK shifted the focus of management from the protection of pine plantations to the conservation of natural fynbos vegetation, and called for the formulation of new fire policies and practices, which in turn requires better understanding of historical fire regimes. In this paper, we explore the historical fire regimes in this area in terms of the seasonality, cause, size and frequency of fires. More specifically, we assess whether the west–east climatic gradient within the CFK is reflected in a west–east trend of decreasing fire seasonality and increasing fire frequency. For these purposes, we distinguish between a western and eastern region within the study area as well as comparing the historical fire regimes of the study area with well documented fire histories of other areas further west in the CFK. Finally, we ask whether the frequency of fires in the study area has increased during its recorded history, and we examine the relationship between fire occurrence and fire climate.

Methods

Study area

The study area (33.80°S, 22.59°E–34.01°S, 24.26°E) occurs within the eastern coastal CFK and comprises the coastal slopes of the Outeniqua Mountains (east of the Touw River) and the coastal slopes of the Tsitsikamma Mountains – hereafter referred to as the Outeniqua and Tsitsikamma regions (the western and eastern portions of the study area) (Fig. 1). Owing to maritime influence, the climate of the study area is temperate (Schulze 1965). Rainfall occurs throughout the year, with winter months being the driest. Mean annual rainfall increases eastwards, from 820 in the Outeniqua to 1078 mm in the Tsitsikamma Mountains (Bond 1981; Southwood 1984). The proportion of summer rain also increases eastwards (Schulze 1965; Tyson and Preston-Whyte 2000). Weather conditions suitable for fires dominate in the dry summer months in the west of the CFK, but become progressively less seasonal towards the east (Kraaij *et al.* 2012*a*). Hot and desiccating, katabatic winds that flow from the interior (known locally as bergwinds) (Seydack *et al.* 2007) occur most frequently during autumn and winter in the study area, when they increase the likelihood of fires (Southey 2009; Sharples *et al.* 2010). Lightning occurs throughout the year at an average of 30 days per year and at a mean density of <1 flashes km^{-2} year^{-1} (Kraaij *et al.* 2012*a*).

The fire-prone vegetation within the study area includes ~110 000 ha of fynbos shrublands (Mucina and Rutherford 2006) and 47 000 ha of commercial pine plantations. Fire-resistant indigenous forests occur largely on the coastal plateau to the south of this area, as well as in the mountains in fire refugia (Geldenhuys 1994). Our assessment of the historical fire regime focussed on the fynbos of the study area occurring on state land, most of which was incorporated into the GRNP in 2009. Kraaij *et al.* (2011) provide a comprehensive account of the study area in terms of its management history and challenges pertaining to fire management.

Fire history database

We compiled a database of all fires recorded in the study area since the beginning of the 20th century by land managers of the national Department of Forestry and subsequent authorities responsible for the management of state land (Kraaij *et al.* 2011). A limitation, particularly pre-1980, was the inadequacy and selectivity of wildfire and prescribed burn reporting: wild fires were generally only reported when they would have threatened timber or other assets, whereas successful prescribed burns were often not reported in a similar traceable format (van Wilgen 1981; Marshall 1983). We distinguished between records with and without sufficient spatial information on fire boundaries to allow capturing in GIS, hereafter referred to as spatial and non-spatial records. Two discrete databases were compiled, i.e. a GIS database of spatial records, and a qualitative database of spatial and non-spatial records combined (Fig. 2). The qualitative database (1900–2010) was used to explore fire season, size and cause, whereas the spatial database was used to explore FRIs (1980–2010) and vegetation post-fire age distribution.

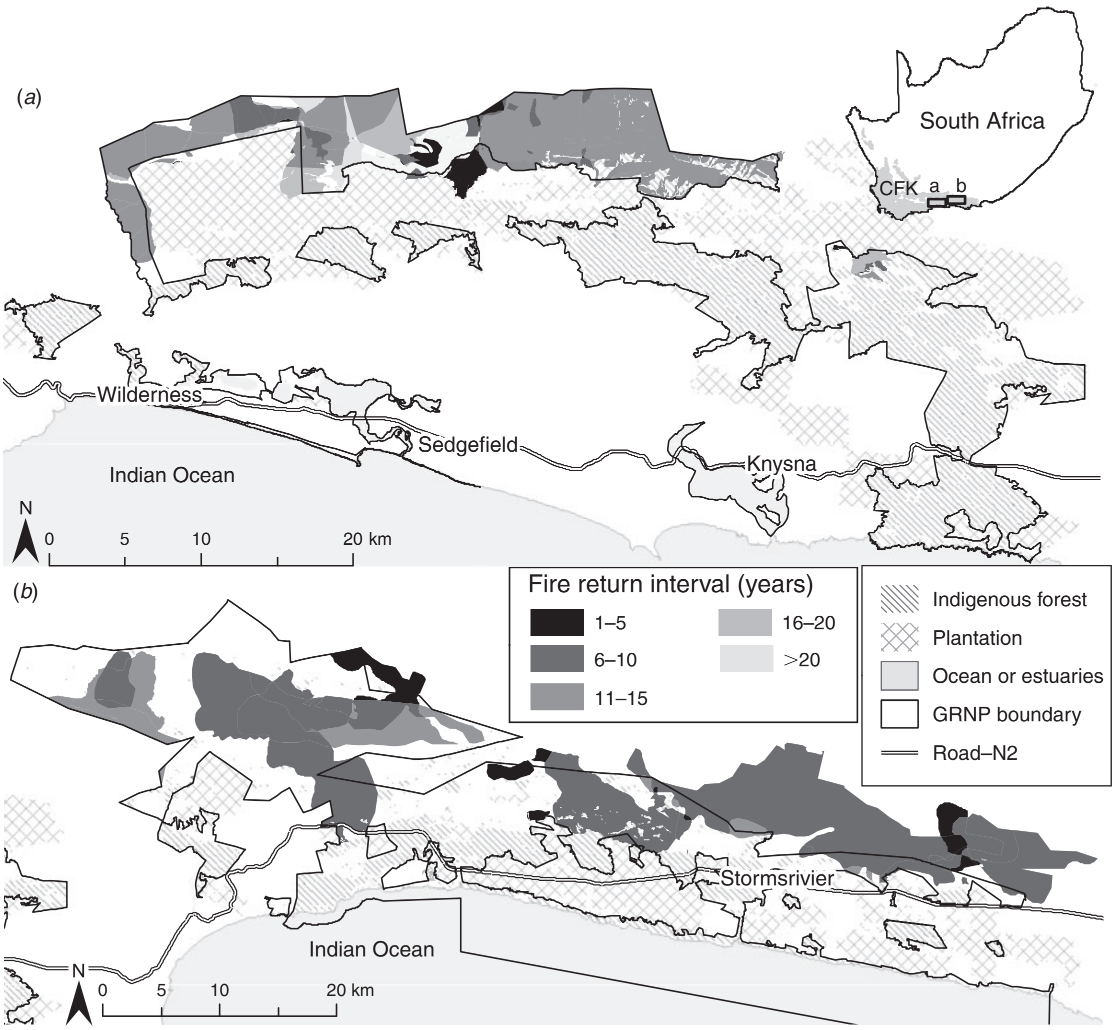

Fig. 1. The insert shows the location of the (*a*) Outeniqua and (*b*) Tsitsikamma regions of the study area in relation to the Cape Floral Kingdom (CFK) and South Africa. Shading denotes mean fire return interval per unique fire history polygon during 1980–2010. Boundaries of the Garden Route National Park (GRNP) are shown; and indigenous forest and plantations in areas for which there are no fire return intervals on record.

Fire cause, season and size

We determined the relationship between the number of fires and the area burnt on record (1900–2010) per decade, using Spearman rank correlation analysis. There were far fewer fire records in earlier years, and these accounted for a much smaller area burnt when compared with later years, suggesting that earlier records (particularly pre-1980) were incomplete (cf. Seydack *et al.* 2007; Kraaij *et al.* 2011). We compared the importance of different causes of fires, classified as natural (ignited by lightning), prescribed (burning for fuel reduction or catchment management purposes, including for grazing), accidental (including deliberate but unauthorised ignitions, escapes from cooking or warming fires, power lines and escaped prescribed fires) and unknown. Given the inadequacy and selectivity of fire reporting in terms of cause (see above), we interpreted results with circumspection.

We furthermore assessed the seasonality and size distribution of fires, assuming that the fires on record were a random sample of all fires in terms of these factors, as nothing suggested that fires have been reported differentially among seasons or fire size classes. We classified fires into size classes as very small (<10 ha), small (10–100 ha), medium (100–1000 ha), large (1000–10 000 ha) or very large (≥10 000 ha). Seasonality of fire was explored in terms of the austral seasons, defined as summer (December to February), autumn (March to May), winter (June to August) and spring (September to November). For the analyses of fire season and cause, we assessed the Outeniqua and Tsitsikamma regions separately for comparison. We used Spearman rank correlation analysis to examine the relationship between time (decades) and proportion of area burned, first by fires of different causes and second, fires of different size classes. To explore potential long-term changes, we assessed trends in the annual area burnt (since 1980, as earlier records were considered incomplete), as well as its relationship with the annual mean of daily fire weather conditions, using least-squares regression. Fire weather conditions were calculated (Kraaij *et al.* 2012*a*) in terms of the McArthur fire-danger index (FDI) (Noble *et al.* 1980). To moderate extreme interannual variability in burnt area, we used 3-year moving means of annual area burnt and annual mean FDI and log transformed these variables to conform to the assumption of normality. Finally, we compared the seasonal distribution of area burnt between the Outeniqua and Tsitsikamma regions, using contingency tables with chi-square test statistic. Statistical analyses were done in StatGraphics Centurion XV.

Fire return intervals

We confined our analysis of FRIs to the fynbos of the GRNP (extent indicated in Table 1) and to the period 1980–2010, as earlier spatial records were considered incomplete (cf. Forsyth and van Wilgen 2008; van Wilgen *et al.* 2010; Wilson *et al.* 2010). To assess FRIs, we delimited areas (polygons) of unique fire history by intersecting all spatial fire records (Forsyth and van Wilgen 2008; van Wilgen *et al.* 2010) in GIS (using ArcGIS 9.2). We only considered polygons $\geq$1.0 ha, as omission of the smallest fires is a negligible source of uncertainty in fire frequency analysis (Moritz *et al.* 2009).

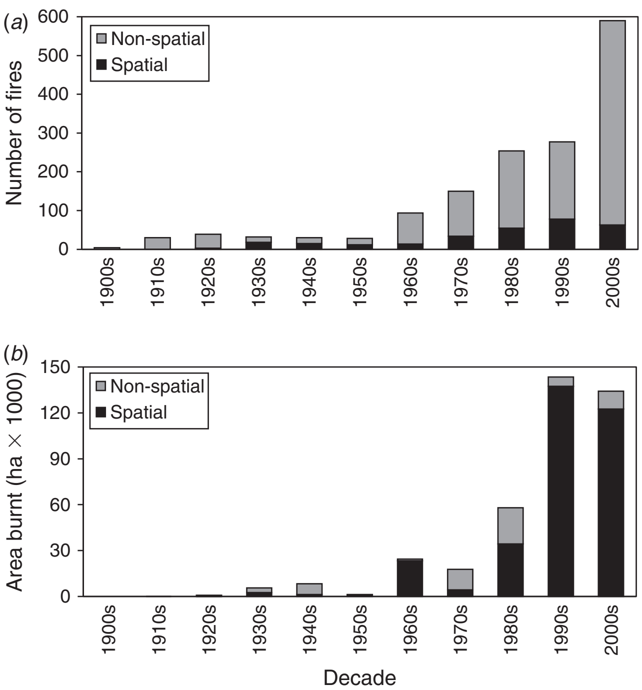

Fig. 2. Distribution across decades of fire records assimilated for the study period, expressed in terms of (*a*) the number of fires and (*b*) the area burnt. The qualitative database comprised of spatial records (which also constituted the GIS spatial database) and non-spatial records (for which fire size but not fire boundaries were known).

Each polygon of unique fire history was characterised by zero or more fires, and polygons with two or more fires had one or more complete FRIs recorded. The fire interval before the first fire on record and subsequent to the last fire on record resulted in FRIs of unknown duration, unless the first or last fire was in 1980 or 2010 respectively. Such open-ended FRIs can be accommodated in analyses through censoring (Polakow and Dunne 1999; Moritz *et al.* 2009) and are referred to as 'censored', whereas complete FRIs are referred to as 'uncensored'. We estimated FRIs in three ways in order to allow comparison with other studies using various methods: (1) by treating each polygon as a single observation point (regardless of size) and restricting the analysis to uncensored intervals; (2) by treating each polygon as a single observation point and accounting for censored and uncensored intervals and (3) by repeating the first two analyses but weighting the contribution of individual polygons by area. We used maximum likelihood survival analysis by fitting a two-parameter Weibull function to the FRI distributions (Johnson and Gutsell 1994; Moritz 2003), weighted according to burnt area (polygon size) (Fernandes *et al.* 2012). The Weibull hazard of burning $\lambda(t) = ct^{c-1}/b^c$ gives the instantaneous probability of a fire occurring in a specific time interval: the scale parameter b is the typical FRI that will not be exceeded 63.2% of the time; the shape parameter c describes the change in burn probability since the last fire (at time t) and is useful to measure how fire recurrence is affected by fuel age; hazard is constant in time (i.e. age-independent) when $c = 1$, increases linearly with time when $c > 1$, and increases exponentially when $c > 2$ (Fernandes *et al.* 2012). We also calculated the median Weibull fire-free interval, which is a central tendency measure of asymmetrical fire interval distributions (Grissino-Mayer 1999). Models were fitted to the whole study area, as well as the Outeniqua and Tsitsikamma regions separately using SAS 9.3.

The fire record (1980–2010) was furthermore examined in each unique polygon for the frequency of occurrence of short ($<$7 year) FRIs. Such intervals approximate the vegetation age below which fires result in poor or no recruitment of slow-maturing obligate reseeding plants (Kraaij *et al.* 2012*b*). The proportional distribution of current (2011) post-fire vegetation

Table 1. Extent of the study area and Outeniqua and Tsitsikamma regions and the percentages of these areas over which spatial records of fires and fire return intervals (FRIs) were recorded during 1980–2010; and the degree to which the data on FRIs were complete

	Study area	Outeniqua	Tsitsikamma
Total extent (ha)	110 020	22 590	87 429
Percentage of area burnt at least once	92.6	85.2	94.6
Percentage of area with at least one complete FRI	53.1	64.0	50.3
Percentage of FRIs censored[A]	62.5	59.3	69.6

[A]Proportion of complete FRIs expressed as a percentage of complete plus open-ended FRIs.

age classes was also calculated for the study area and Outeniqua and Tsitsikamma regions.

Results

Fire history database

A total of 1538 fires (719 in Outeniqua and 809 in Tsitsikamma) burnt 399 683 ha during 1900–2010. The area burnt and the number of fires increased in later years, suggesting that record keeping improved over time, particularly from 1980 onwards (Fig. 2). The area burnt per decade was significantly correlated with the number of fires on record per decade (correlation coefficient $r_{S'} = 0.88$, $P < 0.01$, $n = 11$). However, there were outliers, e.g. during the 1990s and 2000s when fewer fires burnt disproportionately large areas compared with the 1980s.

Fire cause, season and size

Natural fires accounted for almost 60% of the total area burnt in the study area, whereas fires of accidental, unknown and prescribed cause (in decreasing order of importance) were much less important in terms of areas burnt (Table 2). However, fires of natural or prescribed cause were less numerous than those of accidental or unknown cause. In terms of area burnt, natural fires dominated the fire regime in the Tsitsikamma, whereas prescribed fires were unimportant (Table 2). The area burnt was more evenly distributed among fire causes in the Outeniqua, with accidental fires contributing most to area burnt.

The proportion of the area burnt by natural fires per decade increased from 1900 to 2010 ($r_{S'} = 0.97$, $P < 0.01$, $n = 11$), whereas the proportion of the area burnt by accidental fires per decade decreased over the same period ($r_{S'} = -0.73$, $P < 0.05$, $n = 11$); there was no change in the area burnt by fires of unknown origin (prescribed fires were not assessed, see Methods) (Fig. 3). The proportional increase in area burnt by natural fires was particularly apparent in the Tsitsikamma since the 1990s.

Overall, the distribution of fires (of all causes) was more seasonal in the Outeniqua (Coefficient of Variation, CV, in proportional area burnt among austral seasons = 50%) than in the Tsitsikamma (CV = 39%) (Fig. 4). The proportional distribution of natural fires among seasons differed significantly between the regions in terms of area burnt ($\chi^2 = 52.1$, d.f. = 3, $P < 0.001$). Natural fires burnt the largest areas during summer and spring in the Outeniqua, whereas the distribution of natural fires was more even among seasons in the Tsitsikamma, with the smallest areas burnt in summer (Fig. 4).

Fire sizes ranged from <1 to 41 902 ha. Most (74%) reported fires were very small, and collectively these accounted for less than 1% of the total area burnt (Fig. 5). Large and very large fires were infrequent but accounted for 86% of the total area burnt. All the recorded very large fires in the Outeniqua occurred in spring, whereas very large fires in the Tsitsikamma occurred in all seasons with a peak in autumn (Fig. 6). The proportional area burnt by very large fires increased with time ($r_{S'} = 0.77$, $P < 0.05$, $n = 11$). Of the eight largest fires on record, seven

Table 2. Proportional distribution of fires (1900–2010) of different causes, expressed in terms of the area burnt and the number of fires
Results are shown for the study area and Outeniqua and Tsitsikamma regions

Cause	Study area		Outeniqua		Tsitsikamma	
	Area burnt (%) $n = 1439$	Number of fires (%) $n = 1538$	Area burnt (%) $n = 673$	Number of fires (%) $n = 719$	Area burnt (%) $n = 766$	Number of fires (%) $n = 819$
Natural	59.3	16.4	25.7	19.1	82.8	14.2
Prescribed	5.5	4.7	12.7	7.4	0.4	3.9
Accidental	20.0	53.1	34.7	45.9	9.8	59.5
Unknown	15.2	24.9	26.9	27.7	7.0	22.5

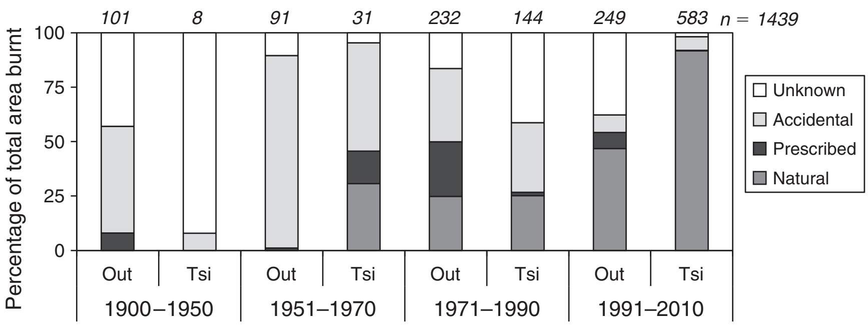

Fig. 3. Proportional distribution of fires of different causes within the Outeniqua (Out) and Tsitsikamma (Tsi) regions between 1900 and 2010 (to prevent cluttering periods longer than decades are shown). Numbers of fires recorded in the respective periods and regions are indicated in italics above the bars.

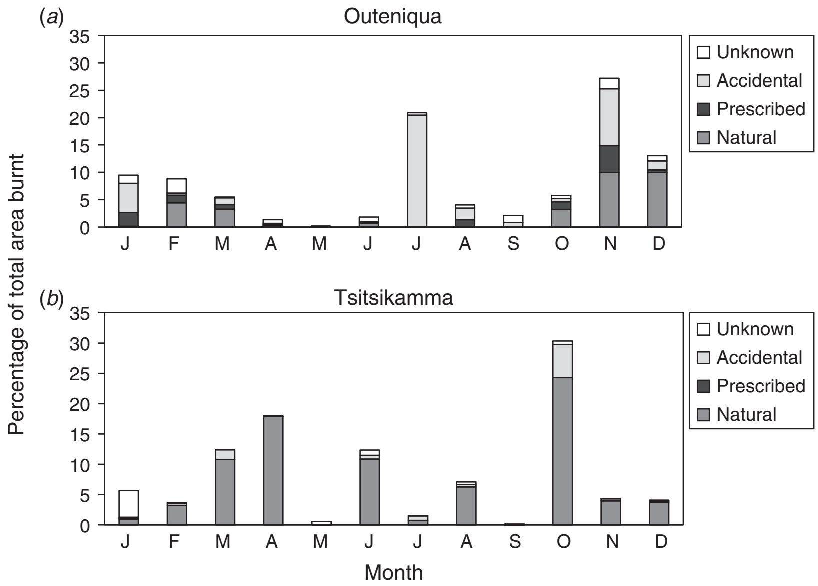

Fig. 4. Percentage of the total area burnt per month from 1900 to 2010 in fires of different causes in the (*a*) Outeniqua and (*b*) Tsitsikamma regions.

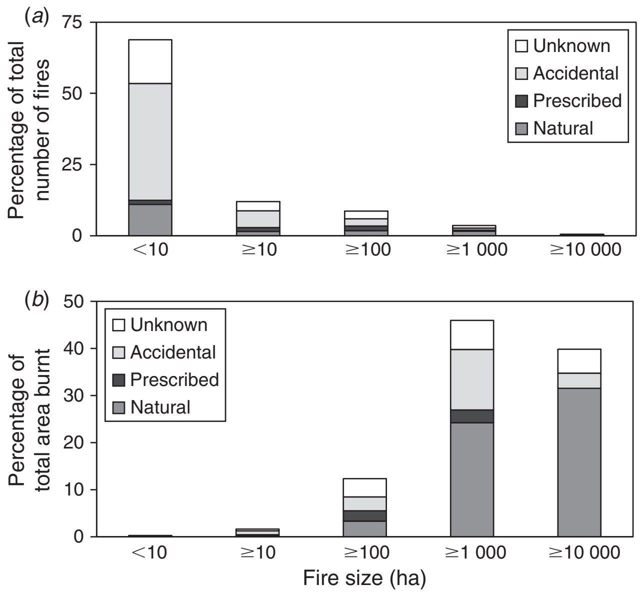

Fig. 5. Size distribution of fires in the study area from 1900 to 2010 by fires of different causes expressed as a percentage of (*a*) the total number of fires and (*b*) the total area burnt.

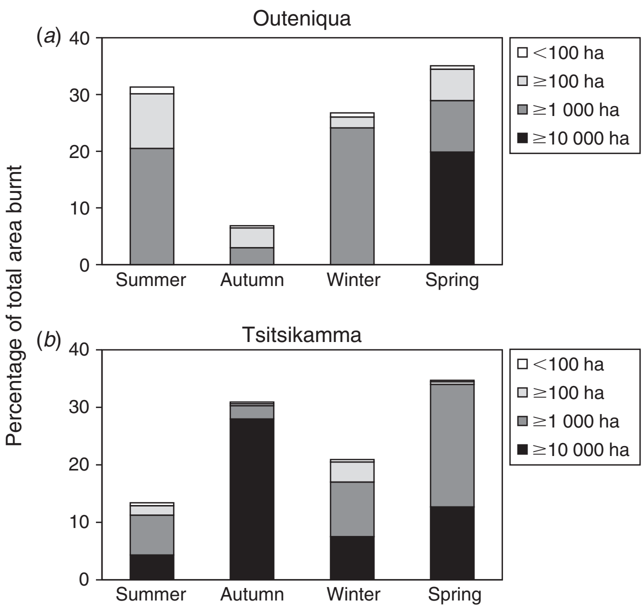

Fig. 6. Percentage of the total area burnt from 1900 to 2010 per season in fires of different size classes in the (*a*) Outeniqua and (*b*) Tsitsikamma regions.

occurred since 1990, and five were of natural cause. The total area burnt annually increased significantly since 1980 ($F_{1,29} = 4.6$, $P < 0.05$, $R^2 = 0.14$), and was significantly positively related to mean annual FDI ($F_{1,29} = 12.5$, $P < 0.01$, $R^2 = 0.30$).

Fire return intervals

Fires were (spatially) recorded over most of the study area during 1980–2010, but complete FRIs (areas with at least two overlapping fires) were recorded across only approximately half of the study area (Table 1). The percentage of FRIs that required censoring (the number of open-ended FRIs expressed as a percentage of complete plus open-ended FRIs, Table 1) was higher in the Tsitsikamma than in the Outeniqua. Estimates of median FRI varied widely (range 6.6–26.2 years) depending on the method of estimation (Table 3). Estimates of median FRI were greater if data were censored, whereas weighting by area had a lesser and varying effect. Estimates of FRI (and the Weibull

Table 3. Median fire return interval (FRI) and Weibull parameters *b* and *c* (with 95% confidence limits) for FRI distribution analysis (1980–2010) incorporating and not incorporating censoring and area weighting (see text)

Results are shown for the whole study area and for the Outeniqua and Tsitsikamma regions separately

Modelling approach area Region	Median FRI (years)	Scale parameter *b* Mean (95% Cl)		Shape parameter *c* Mean (95% Cl)		Number of intervals (uncensored, censored)
Excluding censored data; no area weighting:						
Study area	9.9	12.2	(11.4–13.0)	1.8	(1.6–1.9)	(308, 0)
Outeniqua	11.3	13.7	(12.7–14.7)	1.9	(1.7–2.1)	(231, 0)
Tsitsikamma	6.6	8.0	(7.1–8.9)	2.0	(1.7–2.4)	(77, 0)
Excluding censored data; area weighting:						
Study area	9.6	11.3	(11.2–11.3)	2.3	(2.2–2.3)	(308, 0)
Outeniqua	13.2	15.3	(15.2–15.4)	2.5	(2.5–2.5)	(231, 0)
Tsitsikamma	8.3	9.3	(9.3–9.3)	3.2	(3.2–3.2)	(77, 0)
Including censored data; no area weighting:						
Study area	17.7	22.2	(20.6–23.9)	1.6	(1.5–1.8)	(308, 513)
Outeniqua	16.9	20.6	(19.2–22.2)	1.8	(1.7–2.0)	(231, 337)
Tsitsikamma	22.5	30.8	(24.2–39.3)	1.2	(1.0–1.4)	(77, 176)
Including censored data; area weighting:						
Study area	22.1	27.5	(27.3–27.6)	1.7	(1.7–1.7)	(308, 513)
Outeniqua	16.4	19.0	(18.9–19.1)	2.5	(2.4–2.5)	(231, 337)
Tsitsikamma	26.2	33.9	(33.6–34.2)	1.4	(1.4–1.4)	(77, 176)

scale parameter *b*) based on uncensored data only were significantly lower for the Tsitsikamma (median 8.3 years) than for the Outeniqua (13.2 years), whereas the trend was reversed for estimates based on censoring (Table 3; Fig. 1). During the period 1980–2010, 10% of the study area burnt at least once at post-fire ages of $<$7 years.

The Weibull shape parameter *c* ranged from 1.2–3.2 and was consistently reduced by censoring and increased by area weighting (Table 3). Censoring thus decreased the estimated dependency of burn probability on fuel age, whereas area weighting increased the estimated dependency on fuel age. Survival functions (Fig. 7) based on uncensored and area-weighted data only, predict that half of the study area is likely to burn at $<$10 years of age, whereas $<$3% of the area is likely to survive beyond 20 years of age. The slope of the curve for the Tsitsikamma is steeper than that of the Outeniqua suggesting shorter FRIs in the former region.

The current (2011) distribution of post-fire vegetation age classes is skewed towards the younger age classes, with 61% of the study area at 1–6 years of age, 12% at 7–12 years of age and 27% at $>$12 years of age. Less than 2% of the study area (and virtually none in the Tsitsikamma) is older than 20 years. The fynbos is younger on average in the Tsitsikamma (mean post-fire age 7.4 years) than in the Outeniqua (11.3 years).

Discussion

Fire cause

Trends in fire records from 1900–2010 indicated that natural fires dominated the fire regime in the Tsitsikamma in terms of area burnt, whereas fires of human origin accounted for almost half of the area burnt in the Outeniqua (Table 2). Prescribed burning had little influence on the overall fire regime in the study area. It accounted for $<$5% of the total area burnt since 1980 – a period for which records are regarded as reasonably comprehensive (Fig. 2) – and for only 11% during 1970–1989, when prescribed burning of fynbos is known to have been practised more widely than at any other time (Seydack *et al.* 2007; van Wilgen 2009; Esler *et al.* 2010; Kraaij *et al.* 2011). Although this result needs to be interpreted with caution (given inadequacies in the reporting of fire cause), it is supported by similar findings in other fynbos protected areas (Brown *et al.* 1991; Seydack *et al.* 2007; Forsyth and van Wilgen 2008; van Wilgen *et al.* 2010). Prescribed burning has historically been constrained by various factors, including economical, ecological, physical and political (van Wilgen 2009; Kraaij *et al.* 2011; van Wilgen *et al.* 2012), and wide-scale implementation is likely to remain unfeasible.

The relative importance of fire causes changed from 1900 to 2010: natural fires increased in areal importance whereas accidental fires of human origin decreased (Fig. 3), which is consistent with historical trends of fires in the Swartberg further inland (Seydack *et al.* 2007). The significance of natural fires in the study area (59% of the area burnt; Table 2), particularly since the 1990s (Fig. 3), is comparable to or exceed that recorded in the remote Swartberg, Kammanassie and Cedarberg Mountains (54, 50 and 43%; Forsyth and van Wilgen 2007) and far exceeds that found in more accessible fynbos areas (1–17%, mean 10%, $n = 5$; Forsyth and van Wilgen 2007).

Fire season

The distribution of natural fires was more seasonal (concentrated in and around summer) in the Outeniqua than in the Tsitsikamma (Fig. 4). This is consistent with a west–east climatic gradient across the CFK at large, from strictly winter to all-year rainfall (Tyson and Preston-Whyte 2000) and an associated trend in fire seasonality from summer–autumn-dominated to all-year round (van Wilgen *et al.* 2010). However, a detailed climatic assessment (Kraaij *et al.* 2012*a*) has not revealed a west–east gradient in terms of the seasonality of

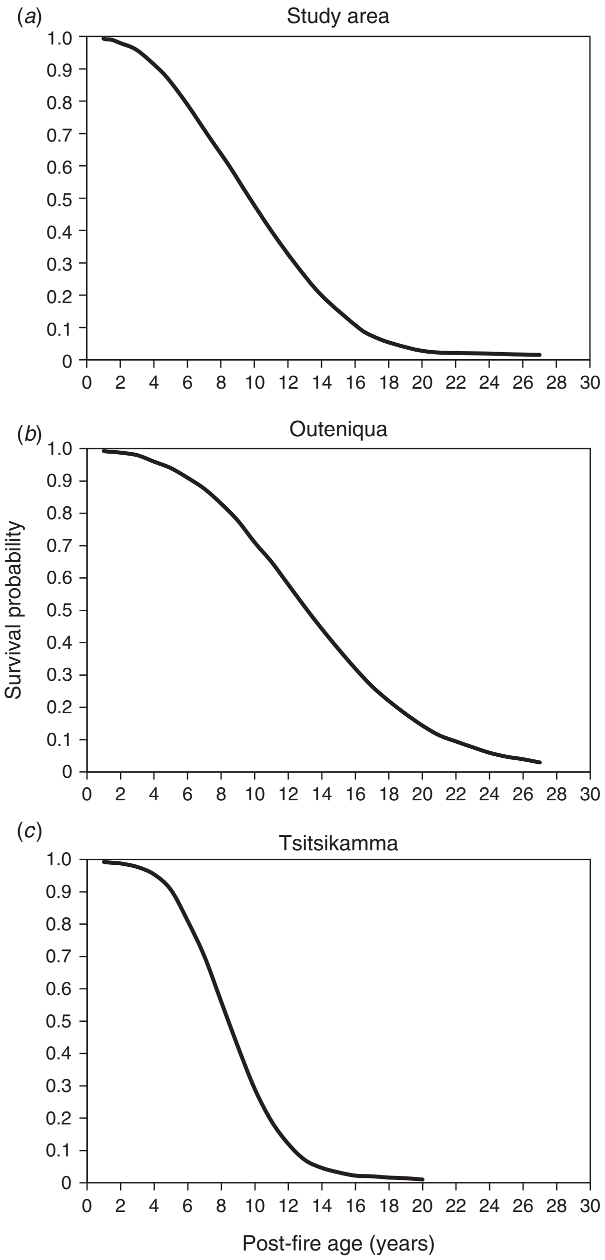

Fig. 7. Survival functions (the proportion of the area surviving without a successive fire) for the (*a*) study area, (*b*) Outeniqua and (*c*) Tsitsikamma based on uncensored and area-weighted fire return interval data (1980–2010) as modelled by the two-parameter Weibull distribution (see Table 3).

either weather conditions conducive to burning or lightning occurrence within the study area. In the Outeniqua, natural fires burnt the largest areas between November and March (Fig. 4*a*), similar to the findings of Marshall (1983) for the entire Outeniqua mountain catchment. The inclusion of fires of human origin produced peaks in the area burnt in winter and (to a lesser extent) summer, as found by Marshall (1983) and Le Roux (1969) for the Outeniqua for 1910–1965. In the Tsitsikamma, natural fires occurred throughout the year with peaks in spring and autumn, whereas summer fires were comparatively unimportant in terms of area burnt (Fig. 4*b*). Fires of human origin burnt a negligible area but numerous small fires occurred throughout the year. W. M. Brink (unpubl. data) likewise recorded little seasonality of fires on forestry estates in the Tsitsikamma during 1987–1990.

Bergwind conditions increase fire potential (van Wilgen 1984) and are thought to result in higher incidence, severity and size of fires (Le Roux 1969; Southey 2009). Mountain catchment managers deem the bergwind season in the study area to be from May to September (Le Roux 1969) and generally discourage burning during this time (Kraaij *et al.* 2011). Although high fire-danger conditions peak during May–August, large fires may also occur under moderate fire-danger conditions (Kraaij *et al.* 2012*a*). Extensive areas accordingly burnt in the Tsitsikamma during mid-spring (October) and autumn (March to April) (Fig. 4*b*) signifying that high fire-danger periods are not restricted to the bergwind season and may occur year round.

Fire size

The observed relationship between number of fires and area burnt (Fig. 5), with few, very large fires dominating the fire regime, is characteristic of many vegetation types globally (Keeley *et al.* 1999; Forsyth and van Wilgen 2008; Gill and Allan 2008; van Wilgen *et al.* 2010; Moreira *et al.* 2011). However, the incidence of very large natural fires seems to have increased in the study area since the 1990s (Fig. 3). It may be argued that poor record keeping in earlier years (pre-1980) led to the absence of large fires from the fire record. However, large fires are unlikely to have gone unnoticed, as seen from the large fires in the Outeniqua during the 1940s and 1960s, which were widely documented in unpublished reports. An increase over time in large fires has also been observed in the Swartberg, but has been attributed to a change in fire management policy (Seydack *et al.* 2007). An increase in the frequency of very large fires may be a cause for concern, as they would reduce FRIs over extended areas. FRIs that are shorter than plant juvenile periods may lead to local extinctions (Bond *et al.* 1984; Bell 2001), whereas skewed vegetation age class distributions may complicate fire risk management and invasive alien plant clearing initiatives (Haidinger and Keeley 1993; Esler *et al.* 2010) by spreading workloads unevenly in time.

Fire return intervals

Mediterranean shrubland communities (perhaps with the exception of those in Chile) are generally resilient to FRIs of 20–50 years (Keeley 1986; Le Maitre and Midgley 1992). In the study area, estimates of median FRIs (since 1980) are variable (8–26 years), but are broadly comparable to estimates of median FRI in other fynbos protected areas (15–55 years based on uncensored, weighted data, Seydack *et al.* 2007; 10–21 years based on censored, unweighted data, van Wilgen *et al.* 2010). Restricting the analyses to known FRIs produced lower estimates of median FRI, as found by Moritz *et al.* (2009) and Fernandes *et al.* (2012). The high level of censoring required in our study (and particularly in the Tsitsikamma; Table 1) approximates a level (75%) thought to produce unrealistic models (Fernandes *et al.* 2012). The high level of censoring, and the magnitude of its effect on estimates of median FRI, suggest that these medians are likely to be overestimates of FRI. On the other hand, estimates of median FRI based solely on uncensored data are likely to be underestimates, in that fire-free intervals are disregarded. Typical FRIs are thus likely to be intermediate between estimates based on censoring and no censoring. The variability in our results (and limitations or differences in the analysis or presentation of results in other studies) makes comparison with FRIs of other fynbos protected areas problematic. Discrepancies between results from censored and uncensored data emphasise the importance of comprehensive and long-term records for accurate characterisation of historical FRIs, and the need to ensure that similar methods of estimation have been used when comparing FRIs across studies.

Median FRI, based on uncensored data, was shorter in the Tsitsikamma than in the Outeniqua, but the trend reversed with consideration of censored data (Table 3). For our within-study comparison of FRIs, and from a management perspective, we deem the estimates based on uncensored data to be a more realistic reflection of regional differences in recent times (supported by Fernandes *et al.* 2012). Although not conclusive, our results provide some evidence for a west–east gradient of increasing fire frequency with increasing rainfall and increasing plant growth rates (Le Maitre and Midgley 1992) within the eastern CFK. Shorter FRIs may well be the norm in the Tsitsikamma and may be acceptable from an ecological point of view (cf. Kraaij *et al.* 2012*b*). Seydack *et al.* (2007) similarly found an inverse relationship between FRI in fynbos shrublands and rainfall (~plant productivity) along an altitudinal gradient in the Swartberg Mountains. However, at CFK-scale, FRIs are broadly comparable between the east and west, suggesting that variation is related to local or regional moisture regimes (Kruger and Bigalke 1984) rather than a west–east gradient within the CFK at large (cf. Kraaij *et al.* 2012*b*).

Ten percent of the study area burnt at least once at post-fire ages of <7 years since 1980, with the Tsitsikamma having experienced these short FRIs more extensively than the Outeniqua (Fig. 1). In these areas, post-fire recruitment of slow-maturing reseeding shrubs may have been compromised. Recent ecological studies in the area found that post-fire recruitment success of this functional type was near zero following a FRI of 5 years and always above replacement levels following FRIs of 7 years or more (Kraaij *et al.* 2012*b*). This suggests that minimum fire return intervals to ensure survival of this functional type would be similar to those from other parts of the CFK (van Wilgen *et al.* 2011). Further research on maturation rates of slow-maturing reseeding plant species (Lamont *et al.* 1991) and success of vegetation recovery after fires at different intervals (Morrison *et al.* 1995) would be required to confirm these preliminary findings. Further research on the frequency of repeated short-interval burns in the landscape would also be informative. Short FRIs also have implications for the management of alien invasive plant species, particularly those that are fire adapted (such as the *Pinus* species grown in adjacent plantations; Kraaij *et al.* 2011) where fire drives their rapid spread and proliferation in fynbos (Richardson 1998). The recent occurrence of very large fires at short intervals and the virtual non-existence of older vegetation age classes are undesirable, as it may cause a shortage of seed of slow-maturing obligate seeders (Kraaij *et al.* 2012*b*) and inadequate habitat diversity for fauna (Martin and Mortimer 1991) in the landscape, in addition to leaving managers unable to deal with demands for clearing of invasive alien plants.

Fuel age dependency

Our estimates of the Weibull shape parameter *c*, a measure of fuel age dependency, varied with the modelling approach. Restricting the analysis to known FRIs (uncensored data) suggested an increased dependency of fire return probability on fuel age, consistent with the findings of others (Moritz *et al.* 2009; Fernandes *et al.* 2012). Our models with censoring and without area weighting produced estimates of *c* similar to those obtained for other fynbos areas (van Wilgen *et al.* 2010). We suspect that van Wilgen *et al.* (2010) underestimated fuel age dependency by only having modelled FRI distributions without weighting by area. Nevertheless, the levels of fuel age dependency existent in fynbos do not imply that young vegetation is fire proof, as seen from our survival functions (Fig. 7). Fuel-reduction treatments designed to maintain young vegetation post-fire age classes therefore would not necessarily provide reliable barriers to fire spread, although strategic placement of areas with reduced fuel may benefit fire suppression activities by providing safer areas for firefighting (Moritz 2003; Keeley and Zedler 2009).

Long-term changes in fire regimes

We recorded an increase in the incidence of large (mostly lightning-ignited) fires since 1990. The total area burnt per year has also increased significantly since 1980 coincident with a significant increase over time in weather conditions conducive to the spread of fires (Kraaij *et al.* 2012*a*). This suggests that the increase in the extent of fires in recent decades is not an artefact of incomplete data, but a real trend, possibly related to climate change effects. Globally, and in the CFK, many areas have similarly experienced recent increases in fire frequency (Keeley *et al.* 1999; Montenegro *et al.* 2004; Forsyth and van Wilgen 2008; Syphard *et al.* 2009; Moreira *et al.* 2011), which have been associated with increases in the frequency of weather conditions favourable for fires (Piñol *et al.* 1998; Mouillot *et al.* 2002; Keeley and Zedler 2009; Wilson *et al.* 2010), or increases in human densities and related ignition sources (Keeley *et al.* 1999; Radeloff *et al.* 2005). Although we demonstrated a correlation between trends in fire occurrence and fire climate, the potential influences of (direct) anthropogenic effects (e.g. human-caused ignitions, fire suppression effort) also need to be discerned (Moreira *et al.* 2011) through long-term monitoring, which can also be used to discriminate between the effects of medium-term climatic cycles and long-term change.

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References

Bell DT (2001) Ecological response syndromes in the flora of southwestern western Australia: fire resprouters versus reseeders. *Botanical Review* **67**(4), 417–440. doi:10.1007/BF02857891

Bond WJ (1981) Vegetation gradients in the southern Cape Mountains. MSc thesis, University of Cape Town, South Africa.

Bond WJ, van Wilgen BW (1996) 'Fire and Plants', Population and Community Biology Series 14 (Chapman and Hall: London, UK)

Bond WJ, Vlok J, Viviers M (1984) Variation in seedling recruitment of Cape Proteaceae after fire. *Journal of Ecology* **72**, 209–221. doi:10.2307/2260014

Bond WJ, Woodward FI, Midgley GF (2005) The global distribution of ecosystems in a world without fire. *New Phytologist* **165**, 525–538. doi:10.1111/J.1469-8137.2004.01252.X

Brown PJ, Manders PT, Bands DP, Kruger FJ, Andrag RH (1991) Prescribed burning as a conservation management practice: a case history from the Cederberg mountains, Cape Province, South Africa. *Biological Conservation* **56**, 133–150. doi:10.1016/0006-3207(91)90014-Z

Cowling RM, Richardson DM, Mustart PJ (1997) Fynbos. In 'The Vegetation of Southern Africa.' (Eds RM Cowling, DM Richardson, SM Pierce) pp. 99–130. (Cambridge University Press: Cambridge, UK)

Deacon HJ, Jury MR, Ellis F (1992) Selective regime and time. In 'The Ecology of Fynbos. Nutrients, Fire and Diversity.' (Ed. RM Cowling) pp. 6–22. (Oxford University Press: Oxford, UK)

Esler KJ, van Wilgen BW, Te Roller KS, Wood AR, Van der Merwe JH (2010) A landscape-scale assessment of the long-term integrated control of an invasive shrub in South Africa. *Biological Invasions* **12**, 211–218. doi:10.1007/S10530-009-9443-2

Fernandes PM, Botelho S (2003) A review of prescribed burning effectiveness in fire hazard reduction. *International Journal of Wildland Fire* **12**, 117–128. doi:10.1071/WF02042

Fernandes PM, Loureiro C, Magalhães M, Ferreira P, Fernandes M (2012) Fuel age, weather and burn probability in Portugal. *International Journal of Wildland Fire* **21**, 380–384. doi:10.1071/WF10063

Forsyth GG, van Wilgen BW (2007) An analysis of the fire history records from protected areas in the Western Cape. Council for Scientific and Industrial Research (CSIR), Report Number CSIR/NRE/ECO/ER/2007/0118/C, prepared for CapeNature. (Stellenbosch, South Africa)

Forsyth GG, van Wilgen BW (2008) The recent fire history of the Table Mountain National Park, and implications for fire management. *Koedoe* **50**(1), 3–9. doi:10.4102/KOEDOE.V50I1.134

Geldenhuys CJ (1994) Bergwind fires and the location pattern of forest patches in the southern Cape landscape, South Africa. *Journal of Biogeography* **21**, 59–62. doi:10.2307/2845603

Gill AM (1975) Fire and the Australian flora: a review. *Australian Forestry* **38**, 4–25.

Gill AM, Allan G (2008) Large fires, fire effects and the fire-regime concept. *International Journal of Wildland Fire* **17**, 688–695. doi:10.1071/WF07145

Government Gazette (2009) Department of Environmental Affairs and Tourism, Number 31981, Notice Number 248, 6 March 2009, pp. 2–7. (Pretoria, South Africa)

Grissino-Mayer HD (1999) Modelling fire interval data from the American Southwest with the Weibull distribution. *International Journal of Wildland Fire* **9**, 37–50. doi:10.1071/WF99004

Haidinger TL, Keeley JE (1993) Role of high fire frequency in destruction of mixed chaparral. *Madrono* **40**, 141–147.

Heelemann S, Proches S, Rebelo AG, van Wilgen BW, Porembski S, Cowling RM (2008) Fire season effects on the recruitment of non-sprouting serotinous Proteaceae in the eastern (bimodal rainfall) fynbos biome, South Africa. *Austral Ecology* **33**(2), 119–127. doi:10.1111/J.1442-9993.2007.01797.X

Johnson E, Gutsell SL (1994) Fire frequency models, methods, and interpretations. *Advances in Ecological Research* **25**, 239–287. doi:10.1016/S0065-2504(08)60216-0

Keeley JE (1986) Resilience of Mediterranean shrub communities to fires. In 'Resilience in Mediterranean-type ecosystems.' (Eds B Dell, AJM Hopkins, BB Lamont) pp. 95–112. (Dr W. Junk Publishers: Dordrecht, the Netherlands)

Keeley JE, Zedler PH (2009) Large, high-intensity fire events in southern California shrublands: debunking the fine-grain age-patch model. *Ecological Applications* **19**, 69–94. doi:10.1890/08-0281.1

Keeley JE, Fotheringham CJ, Morais M (1999) Reexamining fire suppression impacts on brushland fire regimes. *Science* **284**(5421), 1829–1832. doi:10.1126/SCIENCE.284.5421.1829

Kraaij T, Cowling RM, van Wilgen BW (2011) Past approaches and future challenges to the management of fire and invasive alien plants in the new Garden Route National Park. *South African Journal of Science* **107**(9/10), 633. doi:10.4102/SAJS.V107I9/10.633

Kraaij T, Cowling RM, van Wilgen BW (2012*a*) Lightning and fire weather in eastern coastal fynbos shrublands: seasonality and long-term trends. *International Journal of Wildland Fire.* [Published online early 15 October 2012] doi:10.1071/WF11167

Kraaij T, Cowling RM, van Wilgen BW, Schutte-Vlok A-L (2012*b*) Proteaceae juvenile periods and post-fire recruitment as indicators of minimum fire return interval in eastern coastal fynbos. *Applied Vegetation Science.* [Published online early 29 May 2012] doi:10.1111/J.1654-109X.2012.01209.X

Kruger FJ, Bigalke RC (1984) Fire in fynbos. In 'Ecological Effects of Fire in South African Ecosystems.' (Eds PV Booysen, NM Tainton) *Ecological Studies*, vol. 48, pp. 67–114 (Springer-Verlag: Berlin, Germany)

Lamont BB, Connell SW, Bergl SM (1991) Seed bank and population dynamics of *Banksia cuneata*: the role of time, fire and moisture. *Botanical Gazette* **152**(1), 114–122. doi:10.1086/337870

Le Maitre DC, Midgley JJ (1992) Plant reproductive ecology In 'The Ecology of Fynbos. Nutrients, Fire and Diversity'. (Ed. RM Cowling) pp. 135–174. (Oxford University Press: Oxford, UK)

Le Roux PJ (1969) Fire fighting in the Southern Cape with special reference to chemical methods of control. MSc thesis, University of Stellenbosch, South Africa. [In Afrikaans]

Marshall AH (1983) A description of the vegetation of the Outeniqua catchment area and the occurrence of fires in this region. Forestry Diploma dissertation, Saasveld Forestry College, George, South Africa.

Martin R, Mortimer J (1991) Fynbos: too frequent burning poses threat to Cape Sugarbirds. *Promerops* **199**, 6–8.

Midgley JJ (1989) Season of burn of serotinous fynbos Proteaceae: a critical review and further data. *South African Journal of Botany* **55**(2), 165–170.

Montenegro G, Ginocchio R, Segura A, Keely JE, Gómez M (2004) Fire regimes and vegetation responses in two Mediterranean-climate regions. *Revista Chilena de Historia Natural* **77**, 455–464. doi:10.4067/S0716-078X2004000300005

Moreira F, Viedma O, Arianoutsou M, Curt T, Koutsias N, Rigolot E, Barbati A, Corona P, Vaz P, Zanthopoulos G, Mouillot F, Bilgili E (2011) Landscape–wildfire interactions in southern Europe: implications for landscape management. *Journal of Environmental Management* **92**, 2389–2402. doi:10.4067/S0716-078X2004000300005

Morgan P, Hardy CC, Swetnam TW, Rollins MG, Long DG (2001) Mapping fire regimes across time and space: Understanding coarse and fine-scale fire patterns. *International Journal of Wildland Fire* **10**, 329–342. doi:10.1071/WF01032

Moritz MA (2003) Spatiotermporal analysis of controls on shrubland fire regimes: age dependency and fire hazard. *Ecology* **84**(2), 351–361. doi:10.1890/0012-9658(2003)084[0351:SAOCOS]2.0.CO;2

Moritz MA, Keeley JE, Johnson EA, Schaffner A (2004) Testing a basic assumption of shrubland fire management: how important is fuel age?

Frontiers in Ecology and the Environment **2**(2), 67–72. doi:10.1890/1540-9295(2004)002[0067:TABAOS]2.0.CO;2

Moritz MA, Tadashi JM, Miles LJ, Smith MM, de Valpine P (2009) The fire frequency analysis branch of the pyrostatistics tree: sampling decisions and censoring in fire interval data. *Environmental and Ecological Statistics* **16**, 271–289. doi:10.1007/S10651-007-0088-Y

Morrison DA, Cary GJ, Pengelly SM, Ross DG, Mullins BJ, Thomas CR, Anderson TS (1995) Effects of fire frequency on plant-species composition of sandstone communities in the Sydney region: inter-fire interval and time-since-fire. *Australian Journal of Ecology* **20**, 239–247. doi:10.1111/J.1442-9993.1995.TB00535.X

Mouillot F, Rambal S, Joffre R (2002) Simulating climate change impacts on fire frequency and vegetation dynamics in a Mediterranean-type ecosystem. *Global Change Biology* **8**, 423–437. doi:10.1046/J.1365-2486.2002.00494.X

Mucina L, Rutherford MC (Eds) (2006) The vegetation of South Africa, Lesotho and Swaziland. In 'Strelitzia', vol. 19, pp. 158–159 (South African National Biodiversity Institute: Pretoria, South Africa)

Myers N, Mittermeier RA, Mittermeier CG, Da Fonseca GAB, Kent J (2000) Biodiversity hotspots for conservation priorities. *Nature* **403**, 853–858. doi:10.1038/35002501

Naveh Z (1975) The evolutionary significance of fire in the Mediterranean region. *Vegetatio* **29**(3), 199–208. doi:10.1007/BF02390011

Noble IR, Gill AM, Bary GAV (1980) McArthur's fire danger meters expressed as equations. *Austral Ecology* **5**, 201–203. doi:10.1111/J.1442-9993.1980.TB01243.X

Piñol J, Terradas J, Lloret F (1998) Climatic warming, wildfire hazard, and wildfire occurrence in coastal eastern Spain. *Climatic Change* **38**, 345–357. doi:10.1023/A:1005316632105

Polakow DA, Dunne TT (1999) Modelling fire-return interval T: stochasticity and censoring in the two parameter Weibull model. *Ecological Modelling* **121**, 79–102. doi:10.1016/S0304-3800(99)00074-5

Radeloff VC, Hammer RB, Stewart SI, Fried JS, Holcomb SS, McKeefry JF (2005) The wildland–urban interface in the United States. *Ecological Applications* **15**(3), 799–805. doi:10.1890/04-1413

Richardson DM (1998) Forestry trees as invasive aliens. *Conservation Biology* **12**(1), 18–26. doi:10.1046/J.1523-1739.1998.96392.X

Schuler TM, McClain WR (2003) Fire history of a ridge and valley oak forest. USDA Forest Service, Northeastern Research Station, Research Paper NE-724. (Delaware, OH)

Schulze BR (1965) 'Climate of South Africa. Part 8. General Survey.' (Weather Bureau, Department of Transport: Pretoria, South Africa)

Seydack AHW (1992) Fire management options in fynbos mountain catchment areas. *South African Forestry Journal* **161**, 53–58. doi:10.1080/00382167.1992.9630425

Seydack AHW, Bekker SJ, Marshall AH (2007) Shrubland fire regime scenarios in the Swartberg Mountain Range, South Africa: implications for fire management. *International Journal of Wildland Fire* **16**, 81–95. doi:10.1071/WF06015

Sharples JJ, Mills GA, McRae RHD, Weber RO (2010) Foehn-like winds and elevated fire danger conditions in southeastern Australia. *Journal of Applied Meteorology and Climatology* **49**, 1067–1095. doi:10.1175/2010JAMC2219.1

Southey D (2009) Wildfires in the Cape Floristic Region: exploring vegetation and weather as drivers of fire frequency. MSc thesis, University of Cape Town, South Africa.

Southwood AJ (1984) Policy memorandum: Tsitsikamma Mountain Catchment Area. Department of Environment Affairs, Forestry Branch. (Knysna, South Africa)

Syphard AD, Radeloff VC, Hawbaker TJ, Stewart SI (2009) Conservation threats due to human-caused increases in fire frequency in Mediterranean-climate ecosystems. *Conservation Biology* **23**(3), 758–769. doi:10.1111/J.1523-1739.2009.01223.X

Tyson PD, Preston-Whyte RA (2000) 'The Weather and Climate of Southern Africa.' (Oxford University Press: Cape Town, South Africa)

van Wilgen BW (1981) An analysis of fires and associated weather factors in mountain fynbos areas of the South-Western Cape. *South African Forestry Journal* **119**, 29–34. doi:10.1080/00382167.1981.9630220

van Wilgen BW (1984) Fire climates in the southern and western Cape Province and their potential use in fire control management. *South African Journal of Science* **80**, 358–362.

van Wilgen BW (2009) The evolution of fire and invasive alien plant management practices in fynbos. *South African Journal of Science* **105**, 335–342.

van Wilgen BW, Richardson DM (1985) Factors influencing burning by prescription in mountain fynbos catchment areas. *South African Forestry Journal* **134**, 22–32. doi:10.1080/00382167.1985.9629590

van Wilgen BW, Viviers M (1985) The effect of season of fire on serotinous Proteaceae in the Western Cape and the implications for fynbos management. *South African Forestry Journal* **133**, 49–53. doi:10.1080/00382167.1985.9629574

van Wilgen BW, Bond WJ, Richardson DM (1992) Ecosystem management. In 'The Ecology of Fynbos. Nutrients, Fire and Diversity'. (Ed. RM Cowling) pp. 345–371. (Oxford University Press: Oxford, UK)

van Wilgen BW, Richardson DM, Seydack AHW (1994) Managing fynbos for biodiversity: constraints and options in a fire-prone environment. *South African Journal of Science* **90**, 322–329.

van Wilgen BW, Forsyth GG, De Klerk H, Das S, Khuluse S, Schmitz P (2010) Fire management in Mediterranean-climate shrublands: a case study from the Cape fynbos, South Africa. *Journal of Applied Ecology* **47**(3), 631–638. doi:10.1111/J.1365-2664.2010.01800.X

van Wilgen BW, Govender N, Forsyth GG, Kraaij T (2011) Towards adaptive fire management for biodiversity conservation: experience in South African National Parks. *Koedoe* **53**(2), 982. doi:10.4102/KOEDOE.V53I2.982

van Wilgen BW, Forsyth GG, Prins P (2012) The management of fire-adapted ecosystems in an urban setting: the case of Table Mountain National Park, South Africa. *Ecology and Society* **17**(1), art8. doi:10.5751/ES-04526-170108

Vlok JHJ, Yeaton RI (1999) The effect of overstorey proteas on plant species richness in South African mountain fynbos. *Diversity & Distributions* **5**, 213–222. doi:10.1046/J.1472-4642.1999.00055.X

Wilson AM, Latimer AM, Silander JA, Jr, Gelfand AE, de Klerk H (2010) A hierarchical Bayesian model of wildfire in a Mediterranean biodiversity hotspot: implications of weather variability and global circulation. *Ecological Modelling* **221**, 106–112. doi:10.1016/J.ECOLMODEL.2009.09.016