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GEF FYNBOSFIRE PROJECT

INFORMATION MANAGEMENT, FIRE RESEARCH & MODELLING

AND FIRE RISK ASSESSMENT COMPONENT

Fynbos Fuel Handbook

December 2015

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Fynbos Fuel Handbook

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1. BRIEF

This work will focus on developing a handbook with descriptions and photographs illustrating different fynbos fuels as well as invasions of fynbos by key alien species or groups of similar species. The handbook could be used by managers to assess the fuels and the fire danger they posed. The proposed budget would not allow for a complete set of fuels to be characterised so the focus will be on a representative set. We envisage that the final publication would use a loose-leaf design so that sections on particular fuels can be replaced with updated data or illustrations and new sections can be easily added.

- Review the fuel studies to date to locate or identify suitable photographs of the matching fynbos vegetation type or alien plant invasions
- Identify gaps in this record and find suitable examples of the classes to sample and photograph
- Compile a standard fuel model description and photograph set for each fuel class
- Produce a handbook of fuels

2. INTRODUCTION

The ability to predict likely fire behaviour in different vegetation types is a basic requirement for identifying sources and magnitudes of fire hazards and thus for effective fire risk management (Goldammer & de Ronde 2004; Cheney *et al.* 2012; McCaw *et al.* 2012; Fernandes *et al.* 2013; Pacheco *et al.* 2015). One of the ways of predicting fire behaviour in different vegetation types is to characterise them according to the different types and amounts of fuels they contain. Well-established ways of doing this have been developed by the fire researchers and fire management agencies in various countries (Anderson 1982; Tolhurst, Shields & Chong 2008; Dowdy *et al.* 2009; Tymstra *et al.* 2010; Moreira *et al.* 2011; McCaw *et al.* 2012). A widely used approach is the one developed Forest Service of the United States Department of Agriculture (Anderson 1982) and based on the BEHAVE model inputs (Burgan & Rothermel 1984). This approach characterises the fuel loads of different vegetation types by measuring the different types and sizes of fuels, the biomass of each one and the depth of the fuel bed (Burgan & Rothermel 1984; Scott & Burgan 2005). This system was adapted for use in South Africa with the development and testing of fire behaviour models for fynbos (Van Wilgen 1984; Van Wilgen & Burgan 1985; Van Wilgen, Le Maitre & Kruger 1985), grasslands (Everson, Van Wilgen & Everson 1988) and savannah (Van Wilgen & Wills 1988) and it was recommended for use as standard fire hazard modelling system for South Africa (Willis *et al.* 2001; Van Wilgen *et al.* 2003).

In the late-1970s and 1980s the biomass of a number of different fynbos communities was measured (Kruger 1977; Van Wilgen 1982) as well as specific measures of the fuel characteristics of fynbos communities (Van Wilgen *et al.* 1985), indigenous forest communities (Van Wilgen, Higgins & Bellstedt 1990) and invasions by *Acacia saligna* and *Hakea sericea* (van Wilgen & Richardson 1985). This information was used to develop a set of vegetation-type based fuel models for a computerised catchment management system which was developed for managing fynbos (Le Maitre, van Wilgen & Richardson 1993; Richardson *et al.* 1994; Le Maitre & Marais 1995). Although each one of the vegetation types was described using a standard system (Campbell 1985), it is difficult for someone who is not familiar with structural classifications of vegetation and plant growth-forms to use this to determine the fuel types and loads in the vegetation they are managing. This problem has been overcome to a large extent by the development of photograph-based manuals which illustrate different fuel types using standardised images and describe their characteristics. Examples of these are available for a wide range of vegetation types worldwide such as (Scott & Burgan 2005) for North America or (http://www.dfes.wa.gov.au/safetyinformation/fire/bushfire/Pages/publications.aspx#5) for Australia.

This report provides an example of what a visual guide could contain and links vegetation features to fuel structure and characteristics for fynbos vegetation types. It is not intended to be a comprehensive guide to all possible fuels but to illustrate the concept of such a guide using a selected set of fynbos examples. We have also included examples of invasions by different alien shrub and tree species to illustrate the effects of invasions on fuel characteristics because invasions can modify fire behaviour in ways which make fires more difficult to manage (van Wilgen & Richardson 1985; Jayiya *et al.* 2004; Brooks *et al.* 2004). We have also described the structure and characteristics of each type in a way that should make it easy for a lay person to understand. We have included profile diagrams to help the user visualise the structure of the vegetation and the structure and characteristics of the fuels.

3. A NOTE ON FIRE BEHAVIOUR AND CONTROL

The most direct measure of the difficulty of manually fighting a fire is the radiant energy emission which is what heats the skin, clothes and other materials to the point of charring and ignition (Butler & Cohen 1998; Raj 2008). The energy output is directly related to the energy being emitted by the fire front, or Byram's fireline intensity, but research has found that fuel-bed structure also plays an important role (Alexander & Cruz 2012). Unfortunately, there are only a few modelled estimates of the radiant heat flux for fynbos fuels (Jayiya *et al.* 2004) although there are data on estimated fireline intensities and flame lengths (Van Wilgen *et al.* 1985; van Wilgen & Richardson 1985). Although flame-length (and the related flame height) are not strongly related to radiant energy output, flame length still provides a useful measure because fire-fighters can estimate it with reasonable accuracy (Cheney *et al.* 2012). It is also a useful measure of the potential hazard with a safe margin being a fire-free safety zone of at least 4-times the flame height being required to protect fire fighters from harm (Butler & Cohen 1998). In the main report we used a safety threshold of a 2 m flame length based on inputs from managers during the development of the fynbos Catchment Management System (Le Maitre *et al.* 1993; Le Maitre & Marais 1995). For a more detailed discussion of fires and their behaviour for southern Africa see (Trollope, Ronde & Geldenhuys 2004).

4. FYNBOS FUELS

4.1 Proteoid fynbos on granites and sandstones Jonkershoek

The biomass of fynbos of three different post-fire ages was sampled in Jonkershoek and divided into different components including fuels by (Van Wilgen 1982) (Table J1). This information was used to develop a fynbos fuel model for the BEHAVE fire behaviour model (Van Wilgen 1984; Van Wilgen &

Burgan 1985). The sampling was done at three sites: (a) the 4 year vegetation was sampled at Swartboskloof in a frequently burnt firebreak on sandstone talus where the reseeding protea species has been eradicated; (b) the 21 year old stand was located at Swartboskloof on sandstone talus and had vigorous proteas; (c) the 37 year old stand was located in Langrivier on granite soils and the proteas had senesced after first showing signs of senescence at about 25 years after the fire in 1942 (Van Wilgen 1981, 1982). The rainfall at all three sites was about 1700 mm/year, with about 70-% falling between April and September.

The amount available as fuel was also estimated separately (Table J1). The live biomass increased with age up until 21 years after which it declined as the tall, dominant *Protea repens* and *P. neriifolia* senesced. The dead biomass continued to increase with coarse dead fuels (>6 mm diameter, i.e. dead stems and branches of the proteas) amounting to about 18 tons per ha and 35 tons of fine fuels. Although the coarse fuels were excluded from the fuel estimates, in practice they are highly likely to burn under typical wildfire conditions, adding to the fire hazard. Using roughly the 21-year old vegetation's fuel loads, the rate of spreads of a fire was estimated to reach about 1.5 m/sec with a mid-flame wind of 25 km/h on a horizontal area[1] (i.e. under extreme conditions). Subsequent experience has shown that the four-year old fire-breaks would sustain a fire under initially acceptable conditions (Juhnke & Jury 1989) and, even at two years of age, sustained the spread of a fire through Swartboskloof when propelled by a strong south-easter (D.C. Le Maitre personal observation December 1989).

Table J1. Biomass and potential fuel loads for three sites with different post-fire ages in the Jonkershoek valley (Van Wilgen 1982).

State	Component	Biomass (t/ha)			Potential fuel (t/ha, <6 mm diameter)	
	Post-fire age (years)	4	21	37	21	37
Live	Large shrubs	0.01	32.40	16.50	10.80	4.40
	Other shrubs	0.72	1.15	5.56	0.71	3.10
	Grass-like	4.75	1.12	0.42	1.12	0.42
	Other forbs	0.84	1.82	0.35	1.80	0.35
	Total live	6.25	36.50	23.00	14.50	8.20
Dead	Litter	0.43	14.30	53.00	12.50	35.00
	Total	6.65	51.00	76.00	27.00	43.00

The different fuel types are illustrated visually below (Plates J1-J3) showing the increasing height and complexity of the vegetation as its post-fire age increased. The dominance of the grass-like species (including restios) is evident (Plate J1) with them accounting for about 70% of the total biomass (Table J1). Fires in this vegetation would be relatively easy to combat as the flames are short (< 1m high (Le Maitre & Marais 1995) but the rate of spread and, thus, the intensity can be high under extreme conditions. However, under the same conditions a fire in the mature protea stand (Plate J2), or in the senescent stand (Plate J3), could have flame lengths that exceed 5 m which means that they cannot be controlled by people on foot.

[1] Fine dead fuel moisture content of 1%, coarser dead fuels 10% and live fuel 125%

Plate J1. Four-year old fynbos vegetation on sandstone talus in a fire break at Jonkershoek, near Stellenbosch. Note the absence of seed-regenerating proteas, occasional *P. nitida* (broad-leaved shrub) and the grassy nature of the vegetation. The density board is about 5 m away and is 2 m tall with 200 mm subdivisions.

Plate J2. Twenty-one year old fynbos vegetation on sandstone talus on slope adjacent to Swartboskloof. The sampling was done in the protea stand in the background. The shorter vegetation in the foreground is part of a fire break. The 2 m density board is about 10 m away.

Plate J3. Thirty-seven year old, senescent fynbos vegetation on granitic soils in Langrivier, Jonkershoek. Note the skeletons of the dead proteas in the foreground and the tall Widdringtonia nodiflora in the background. The 2 m density board is about 10 m away.

4.2 Proteoid fynbos on sandstones Kogelberg and Cederberg

Proteoid fynbos does not always get as tall or have as much fuel load as the examples for Jonkershoek. A number of experimental fires were studies as part of a season of fire study in fynbos communities in the Kogelberg, near Betty's Bay and in that Algeria, in the Cederberg (Van Wilgen *et al.* 1985). The fuel loads and observed weather conditions were used in the BEHAVE model to estimate rates of spread and fire intensities and the model did reasonably well. We have not included all the data from all the fires here but have selected some examples which illustrate the structure of the communities and their fuel loads. The Kogelberg and Cederberg sites have been described in detail elsewhere (Durand 1984; Le Maitre 1984). The Kogelberg site is situated in the Palmiet River valley, on shallow sandy and rocky fynbos soils and has a rainfall of about 1 020 mm/yr, about 77% of which falls from April to September. The dominant shrub was *Leucadendron laureolum* which can reach about 1.8 m tall (Plate K1). The understorey was dominated by restios, sedges and fine-leaved shrubs. The post-fire age was about 20 years.

Plate K1. Proteoid shrubland in the Kogelberg at the season of burn study site at an age of about 20 years, dominant species *Leucadendron laureolum*. Note the high cover of fine restios. The density board is 2m tall and about about 5 m away.

The Cederberg site is situated in the Rondegat River valley, near Algeria on sandy and gravelly soils and has a rainfall of about 660 mm/yr, about 80% of which falls from April to September. The vegetation is dominated by *Leucadendron pubescens* with some *Paranomus bracteolaris* which reach heights of 1.5-1.8 m (Plate C1). The understorey was dominated by fine-leaved shrubs, restios and grasses. The post-fire age was between 14 and 18 years and there was a wide range in biomass from 9.7-34.1 tons/ha with some plots having a high fine fuels and others a high tall shrub biomass, with the Cederberg sites having a higher biomass in general ((Van Wilgen *et al.* 1985).

Plate C1. Proteoid fynbos in the Cederberg at the season of burn site near Algeria at a post-fire age of about 14-16 years. Dominant species *Leucadendron pubescens,* note the dense, tufted restios. The 2 m tall density board is about 2 m away.

Table KC1. Mean biomass for the proteoid fynbos communities at the Kogelberg site (7 plots) and Cederbeg (8 plots). Data from (Le Maitre 1984; Van Wilgen *et al.* 1985).

State	Component	Mean biomass (t/ha)	
		Kogelberg	Cederberg
	Post-fire age (years)	20	16
Live	Tall shrub	2.9	9.3
	Other shrubs	3.4	2.3
	Restioid	3.0	3.7
	Graminoid	0.5	0.3
	Other	0.1	0.2
	Total live	9.9	15.9
Dead	Litter and standing dead	3.6	5.6
Total		13.5	21.4

The measurements taken during the experimental fires showed that there was quite a range in wind speeds (1.0-3.6 m/sec, 3.6-13.0 km/hr), humidity ranged from15-90% and dead fuel moisture from 2-13% (Van Wilgen *et al.* 1985). Although the conditions were regarded as safe to prescribed fires, there were fire escapes after two fires as well as a spot fire, all of which were soon brought under control. The biomass consumed by the fire ranged from 59-87%, the rates of spread from 0.21-0.89 m/sec, fireline intensities from 515-20 709 kW/m and the flame lengths from 1.4 to 6.0 m. Some of the high intensities and flame lengths were due to flare-ups driven by fine or herbaceous fuels which can make fire management very difficult. In general, the predicted and the observed fire behaviour matched well (r^2 values of 0.74-0.78) which suggests that the BEHAVE model can simulate fynbos fire behaviour with an appropriate fuel model although it over-predicted the high fire intensities.

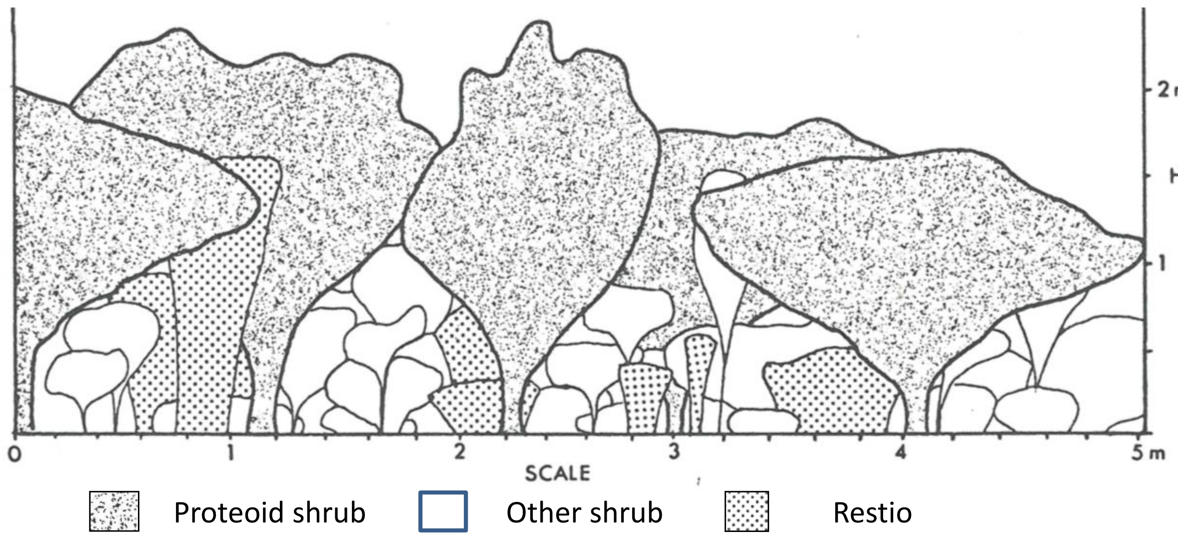

Figure KC1. A profile of the Kogelberg Proteoid fynbos community based on a 5x2.5 m transect through a dense stand of the proteoid shrubs (*Leucadendron laureolum*) (Le Maitre 1984). Note the wide range of heights and sizes among the other shrubs and restios. Litter cover not shown.

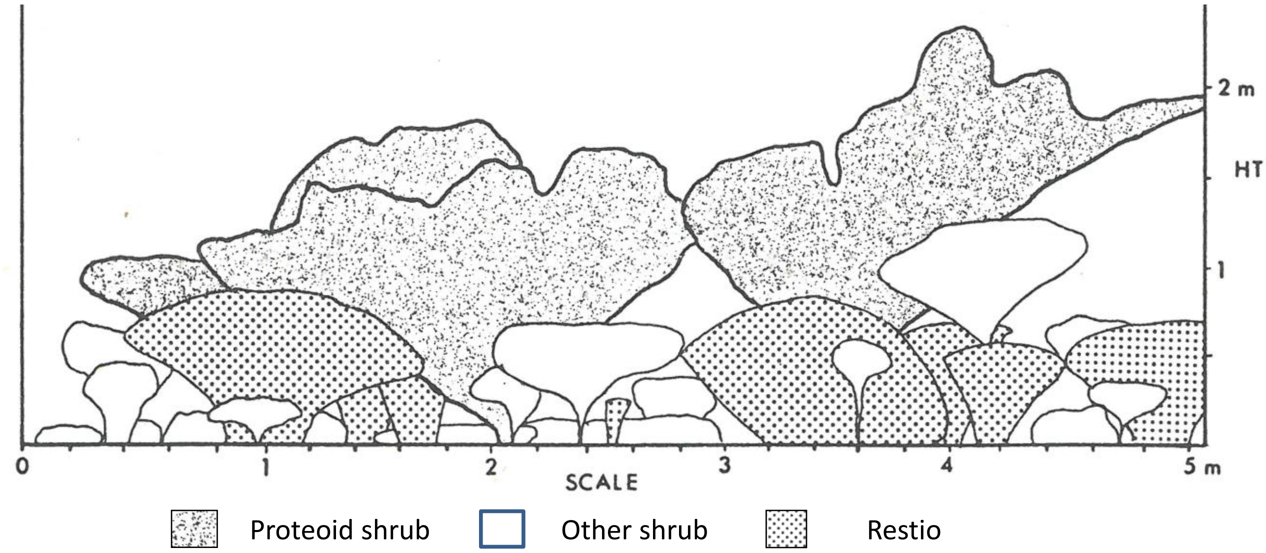

Figure KC2. A profile of the Cederberg Proteoid fynbos community based on a 5x2.5 m transect through a dense stand of the proteoid shrubs (*Leucadendron pubescens*) (Le Maitre 1984). Note the wide range of heights and sizes among the other shrubs and restios. Litter cover not shown

4.3 Moist ericoid fynbos at Jakkalsrivier, near Grabouw

The need for a better understanding of fynbos ecology and structure resulted in the compilation of a set of data on the biomass of fynbos communities (Kruger 1977). This dataset covered a wide range of communities at three sites: (a) Jonkershoek, near Stellenbosch (see section 4.1); Zachariashoek, near the Wemmershoek Dam in Franschhoek; and (c) Jakkalsrivier, on the slopes of Mount Lebanon near Grabouw. These data were collected to document both biomass and fuels but well before the idea of modelling fire behaviour became feasible, and pictures were generally not take of the specific sites where the sampling was done, but pictures are available of the vegetation types that were sampled (Kruger 1977). One of these was of a dense, moist ericoid community with emergent, tufted restios (canopy cover >80%), height 1.0-1.2 m, at Jakkalsrivier about 16 years after a fire (Plate Ja1). The site gets about 850 mm or rainfall per year, most of which falls in the winter but there is appreciable cloud cover and mist during the south-easterly winds that prevail during the summer months. The community is described as fine-leaved evergreen scrub with a high proportion of fine leaved shrubs and restios with taller Bruniaceae prominent in moister areas.

Plate Ja1. Moist ericioid fynbos in the Jakkalsrivier catchment, near Grabouw at a post-fire age of about 16 years. The vegetation is about 1.2 m tall and very dense.

The community has a high total live biomass of about 12.5 tons/ha, almost all of which is fine fuel, and 2.3 tons/ha of litter and standing dead material (Table Ja1). This is sufficient fuel to make fires difficult to control (Kruger 1977). Simulations of fire behaviour in this type of fuel indicate that flame lengths under wildfire conditions will exceed 2 m by about 7-10 years after a fire, making wildfires in these communities difficult to manage. In practice, under conditions suitable for prescribed burning, fires in this type of vegetation can be contained using firebreaks and tracers. We have created a profile diagram for such a community based on our field experience and photographs of similar vegetation and fuel types.

Table Ja1. Biomass data for a site in the Jakkalsrivier catchment near Grabouw (Kruger 1977). The community's post-fire age was about 16 years and it was dominated by Ericaceae, Asteraceae and Restionaceae with occasional Proteaceae (e.g. *Leucadendron xanthoconus*).

State	Component	Biomass (t/ha)
	Post-fire age (years)	16
Live	Shrubs	3.25
	Sub-shrubs	0.00
	Restioid	6.95
	Graminoid	1.82
	Other	0.35
	Total live	12.47
Dead	Litter and standing dead	2.23
Total		14.70

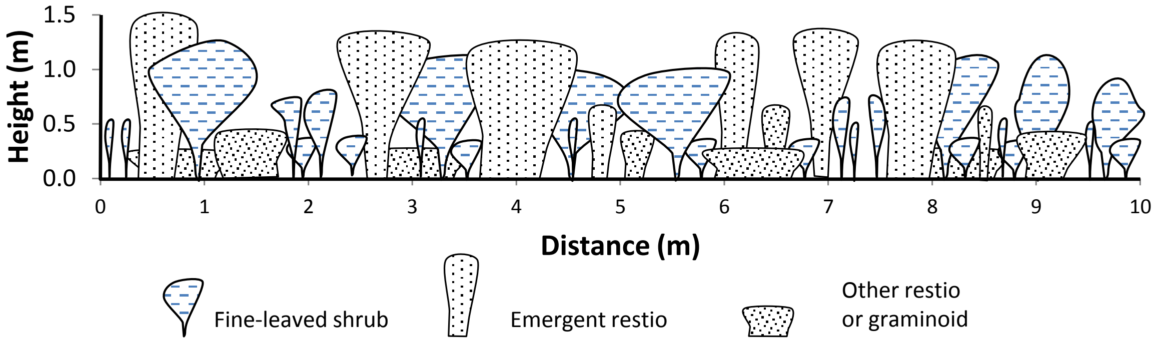

Figure KC2. A hypothetical profile of the moist ericoid fynbos community at Jakkalsriver based on a 10 m transect. Note the wide range of heights and sizes among the shrubs and other restios or graminoids. Litter cover not shown.

4.4 Renosterveld

Plate R. Renosterveld on the slopes of the mountain above Coetzenburg, Stellenbosch. Note the dominance of fine-leaved shrubs. The person is holding a 2.5 m tall ranging rod and is about 10 m away from the camera.

The climate at Coetzenburg is characterised by warm summers with regular south-easterly winds, creating a fire hazard (Jayiya *et al.* 2004). Winters are cold and wet with about 70% of the annual rainfall of 600 – 700 mm falling between April and September. The renosterveld vegetation has been subjected to disturbance in the past as indicated by its openness and the abundance of *Anthospermum* species (the darker green shrub). The vegetation is transitional between renosterveld and fynbos, and includes fynbos elements (e.g. Restionaceae). The total fuel load is 14 t/ha, almost all of which is live, fine fuels (<6 mm diameter) (Table R1) with high surface area to volume ratios (Table R2). This indicates that fires will tend to burn rapidly and intensely, and burn out quickly. The fuel bed depth of 1 m is clearly shown in the photograph (Plate R). The patchiness of the renosterveld indicates a low fuel connectivity, and that the fire is likely also to spread patchily and unevenly unless there are moderate to strong winds at the time of the fire. The sparse nature of the fuels contributes to the low rates of spread of about 0.05 m/sec in this vegetation even under extreme[2] conditions (Jayiya *et al.* 2004). The corresponding fireline intensity was 159 kW/m, heat per unit area 3 248 kJ/m^2, and the flame length about 0.75 m. There is considerable variation in the structure(Rebelo *et al.* 2006), and thus, the fuels in renosterveld. A renosterveld community on

[2] See Appendix 1 for the weather conditions used in the fire behaviour modelling

Jonaskop in the Riviersonderend mountains had a similar total biomass (14.0 t/ha) with 2.8 tons/ha of dead material, and 11.3 tons of live material, virtually all of which was shrubs (Rutherford 1978).

Table R1. Above-ground biomass of vegetation components (t/ha) of the renosterveld at the Coetzenburg site (Jayiya *et al.* 2004).

State	Component	Biomass (t/ha)
Live	< 6 mm	9
	Herbaceous Plants (< 6 mm)	1
Dead	< 6 mm	2
	6 - 25 mm	1
	25 - 75 mm	1
	Total	14

Table R2. Fuel model data for renosterveld at the Coetzenburg site (Jayiya *et al.* 2004). A: values based on van Wilgen and Richardson (1985).

Component	Model Parameter	Quantity
Fuel load/Vegetation (t/ha)	1-h	2
	10-h	1
	100-h	1
	Live herbaceous	1
	Live woody < 6 mm	9
Surface area to volume ratios (m^2m^{-3})	1-h Surface Area/Vol Ratio[A]	7215
	Live Herb Surface Area/Vol Ratio	5900
	Live Woody Surface Area/Vol Ratio[A]	4920
	Fuel bed depth (m)	1
	Dead Fuel Moisture of Extinction (%)[A]	34
	Dead Fuel Heat Content (kJ/kg)[A]	20000
	Live Fuel Heat Content (Kj/kg)[A]	20000

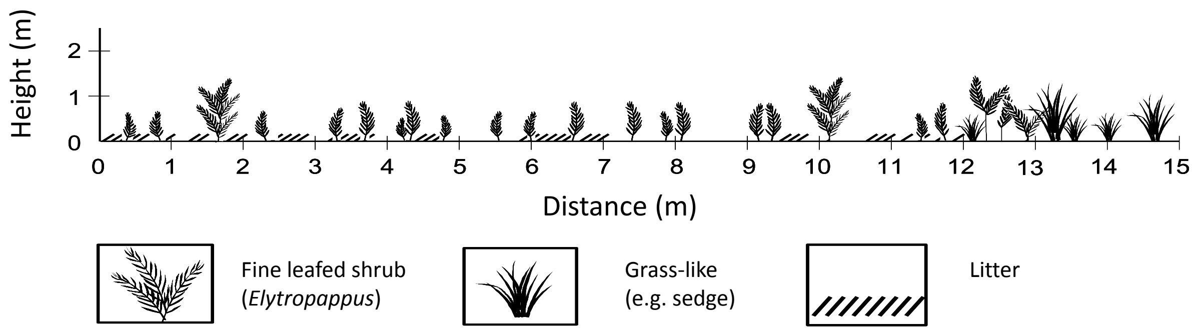

Figure R1. A profile diagram of the renosterveld at Coetzenburg based on measurements taken along a 15x2.5 m transect through the stand (Jayiya *et al.* 2004). Note the patchy distribution of the litter and shrub which is also evident in the photograph (Plate R).

4.5 Strandveld

Plate S1. Strandveld in the Koeberg Nature Reserve, near Melkbosstrand, north of Cape Town. Note the dead fuels, tall restios and the evergreen shrub clumps. The person is holding a 2.5 m tall ranging rod and is about 2 m away from the camera.

The study site is situated in the Koeberg Nature Reserve (18° 26′ E, 33° 41′ S), about 30 km north of Cape Town on the west coast. The reserve is situated on land owned by Eskom and is regarded as critical conservation area and a key part of the proposed West Coast Biosphere Reserve (CMC 2000, Heijnis *et al.*, 1999; Maze and Rebelo, 1999). The climate is Mediterranean with most of the rain falling during the winter half-year and temperatures are strongly moderated by the proximity to the Atlantic Ocean. The annual rainfall is almost 414 mm (Colvin *et al*. 2002). Wind direction is due south to south-east, especially during the dry summer months, with winter rainstorms being associated with north-west and south-west winds (Heineken, 1987).

The Western Strandveld, which is considered part of the Fynbos biome, includes a number of different strandveld types (Rebelo *et al.* 2006) with the one at Koeberg, where this study site was located, being Cape Flats Dune Strandveld. In some ways strandveld is structurally closer to the thicket vegetation found on the east coast with clumped, broad-leaved evergreen shrubs, succulent shrubs, tall restioids and a diverse herbaceous flora. It can burn under hot, dry conditions but generally does so infrequently. Young strandveld appears more like fynbos when regenerating and can burn as it has more fine fuels. However, there are many areas where unwise burning in the past resulted in the underlying sandy soils becoming wind eroded. Until the 1970s these were rehabilitated using introduced Acacia species, resulting in extensive areas invaded by *Acacia cyclops* and *A. saligna* which have higher fuel loads (van Wilgen & Richardson 1985; Jayiya *et al.* 2004). Overall, the biomass of strandveld is quite low at 18 t/ha (Tables S1 and S2), with only about 33% being fine live or dead fuels and a substantial amount of coarse dead fuels. If the site had been sampled during the winter growing period for the herbaceous species, or if a large restio clump had been included in the fuel sampling, then the live herbaceous biomass would have been substantially greater. The low quantity of fine fuels supports observations that the strandveld can burn but does not do so regularly or frequently, and that it will require hot, dry conditions and strong winds to sustain extensive fires. This argument is supported by the simulated fire behaviour where the rate of spread under extreme conditions was only about 0.08 m/sec, the fireline intensity 359 kW/m, the heat per unit area 4 217 kJ/m^2, and the flame length about 1 m (Jayiya *et al.* 2004).

Table S1 Above-ground biomass of strandveld vegetation components (t/ha) at the Koeberg site (Jayiya *et al.* 2004).

State	Component	Biomass (t/ha)
Live	< 6 mm	5
	Herbaceous Plants (< 6 mm)	0
Dead	< 6 mm	1
	6 - 25 mm	2
	25 - 75 mm	9
	Total	18

Table S2 Fuel model data for strandveld at the Koeberg site (Jayiya *et al.* 2004). A: values based on van Wilgen and Richardson (1985).

Component	Model Parameter	Quantity
Fuel load/Vegetation (t/ha)	1-h	1
	10-h	2
	100-h	9
	Live herbaceous	0
	Live woody < 6 mm	5
Surface area to volume ratios (m^{2}m^{-3})	1-h Surface Area/Vol Ratio[A]	7215
	Live Herb Surface Area/Vol Ratio	0
	Live Woody Surface Area/Vol Ratio[A]	4920
	Fuel bed depth (m)	1
	Dead Fuel Moisture of Extinction (%)[A]	34
	Dead Fuel Heat Content (kJ/kg)[A]	2000
	Live Fuel Heat Content (Kj/kg)[A]	2000

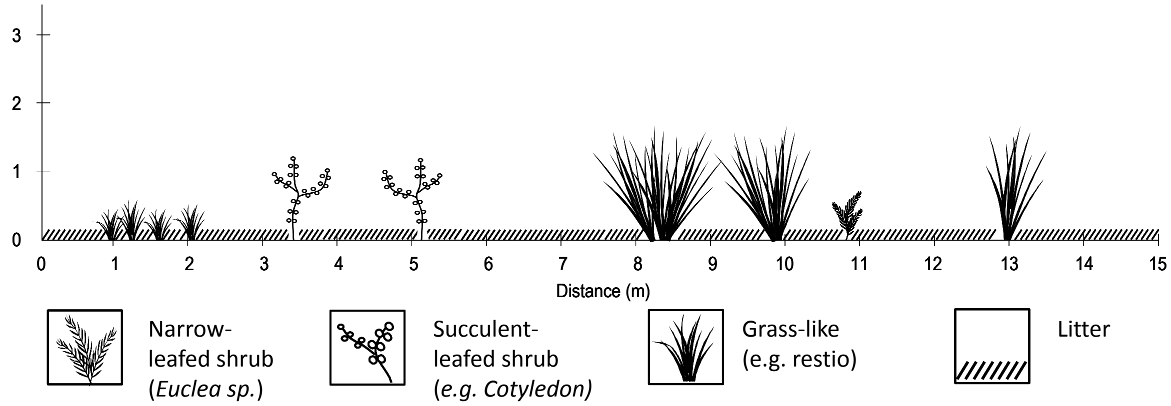

Figure S1. A profile diagram of the strandveld at Koeberg based on measurements taken along a 15x2.5 m transect through the stand (Jayiya *et al.* 2004). Note the nearly continuous litter cover and the presence of tall restios in this transect.

5. INVASIVE SPECIES FUELS

5.1 Hakea in proteoid fynbos on sandstones

Various studies were made of the *Hakea* sericea invasions. These included an assessment of the impacts of *Hakea* invasions on fuel loads and on fire behaviour on Vergelegen farm, near Somerset West (van Wilgen & Richardson 1985) (Plate H1). *Hakea sericea* had invaded and displaced a community comprising a mixture of *Protea repens* and *P. neriifolia*, which would probably have been similar to the 21 year old proteoid community described in section 4.1. The density of the *Hakea* stand was about 8 900 stems/ha, far higher than those estimated for the proteoid fynbos of about 1 300-1 500 stems/ha (Le Maitre 1984), and the post-fire age was estimated as 9 years. The soils were a mixture derived from granites and sandstone talus and the rainfall was about 1 200 mm/yr, falling mainly in the winter. Invasion by Hakea sericea significantly increased both the live and the dead components compared to proteoid fynbos (3.0 and 1.6 fold respectively) although much of this biomass was in live material >6 mm in diameter so that the fuel load increased 1.6 fold (Table H1). The mean surface to area volume ratios for *Hakea sericea* leaves were considerably larger than those for *Protea repens* (Table H2), primarily because of their needle-like form. The fuel heat content was also somewhat lower. Measurements of the moisture contents of the fine live material over the four seasons showed that it was lower for Hakea (110%) compared to the Protea (155%). The *Hakea* shrubs average about a metre taller that the proteas they have displaced as well as being relatively dense (Figure H1). The density, and the very dense packing of the fuel in their canopies, may influence the fire behaviour with dense *Hakea* stands sometimes failing to burn even under wildfire conditions.

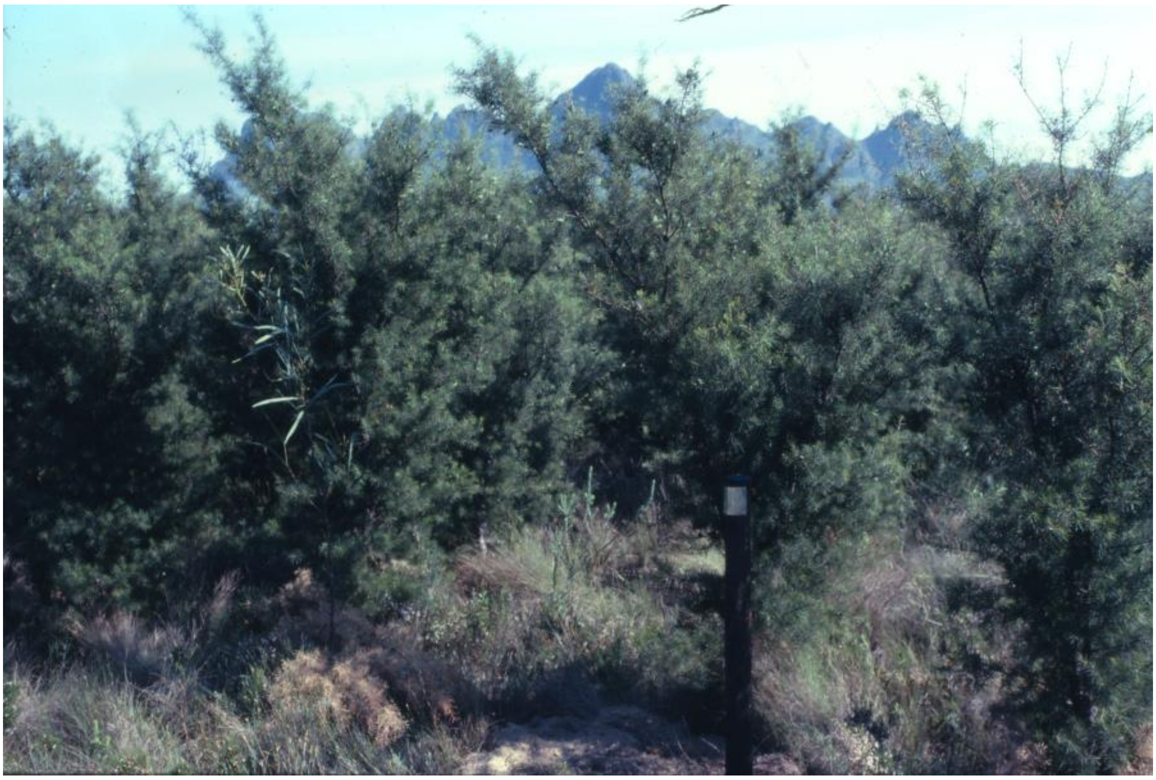

Plate H1. Dense *Hakea* invasion on Vergelegen farm, similar to the stand sampled by van Wilgen and Richardson (1985). The tar pole in the foreground is about 1.2 m tall.

Table H1 A comparison of the above-ground biomass of proteoid fynbos and *Hakea sericea* invaded fynbos (t/ha) at the Vergelegen site (van Wilgen & Richardson 1985). The proteoid fynbos biomass is the mean of the 14 sites reported by (Van Wilgen *et al.* 1985).

State	Component	Size class	Proteoid fynbos	Hakea
Live	Dominant shrubs	>6 mm Φ	4.45	18.08
		<6 mm Φ	2.1	10.99
	Other shrubs	>6 mm Φ	0.46	1.18
		<6 mm Φ	2.32	0.83
	Herbaceous plants	<6 mm Φ	3.76	1.3
	Total live		13.09	32.38
Dead		>6 mm Φ	0.71	0.5
		<6 mm Φ	4.04	6.39
	Total biomass		17.84	39.27
	Total fuel		12.22	19.51

Table H2 A comparison of the fuel characteristics of proteoid fynbos and *Hakea sericea* invaded fynbos (t/ha) at the Vergelegen site (van Wilgen & Richardson 1985). 1: based on *Protea repens* (Van Wilgen 1984).

Component	Model Parameter	Proteoid fynbos[1]	Hakea
Fuel load/Vegetation (g/m2)	1-h	4	6.25
	10-h	0.95	0.45
	100-h	0.12	0.12
	Live herbaceous	5	1.3
	Live woody < 6 mm	2.24	11.8
Surface area to volume ratios (m^2/m^3)	1-h Surface Area/Vol Ratio	7215	7215
	10-h Surface Area/Vol Ratio	357	357
	100-h Surface Area/Vol Ratio	98	98
	Live Herb Surface Area/Vol Ratio	5900	5900
	Live Shrub Surface Area/Vol Ratio	4920	8450
Fuel Heat Content (kJ/kg)		20000	18500
Fuel bed depth (m)		1.4	2
Dead Fuel Moisture of Extinction (%)		34	34
Midflame wind conversion factor		0.6	0.6

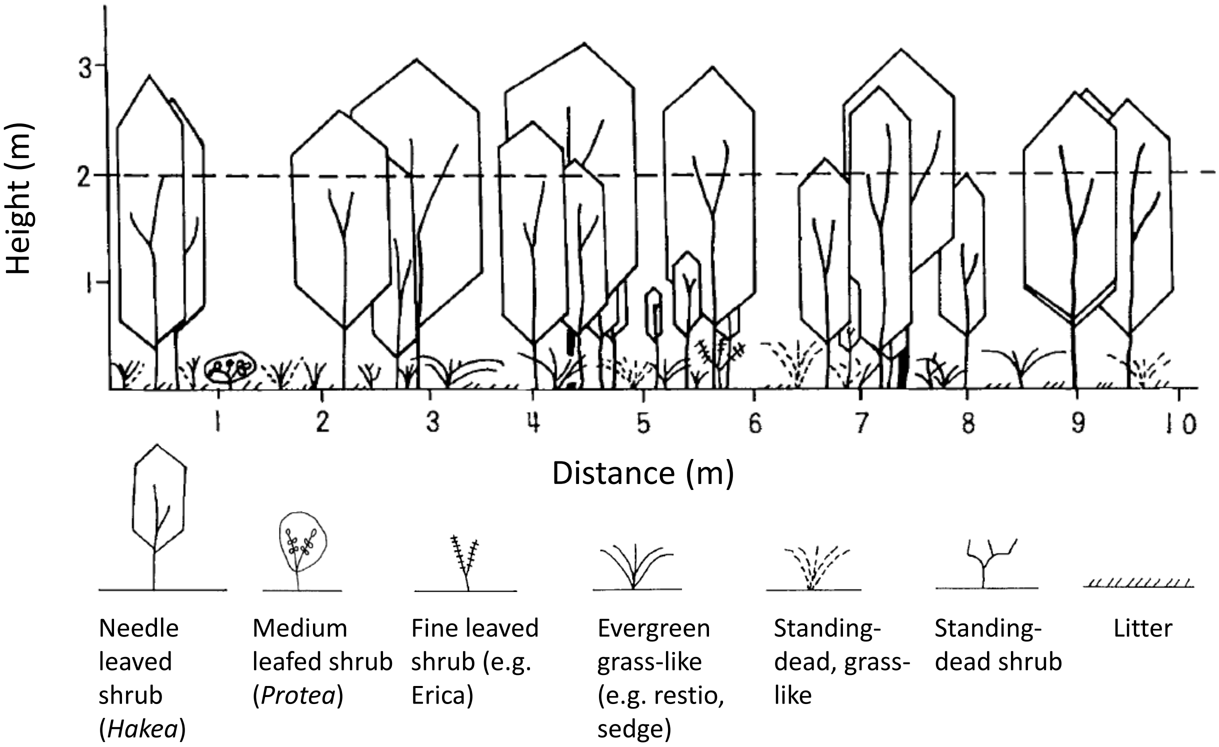

Figure H1. A profile diagram of the *Hakea sericea* invaded stand at Vergelegen based on measurements taken along a transect through the stand (van Wilgen & Richardson 1985). The dashed line indicates the fuel bed depth used in the fire behaviour model.

The rate of spread in the *Hakea* invaded stand was similar to proteoid fynbos under low fire hazard conditions but the differences increased as the fire hazard was increased, reaching about 2.5 m/sec compared with about 3.5 m/sec in the proteoid fynbos (van Wilgen & Richardson 1985). The fire intensity was also slightly lower in the invaded stand (±47 000 kW/m) than in the fynbos (±54 000 kW/m). A fungus disease kills *Hakea sericea* (Richardson & Manders 1985), this will increase the fine dry fuel load and could increase fire intensities and rates of spread.

5.2 Acacia saligna in open proteoid fynbos on sandstones

The study site was located on the middle slopes of Muizenberg mountain above Boyes Drive on sandstone-derived soils and sandstone talus. The rainfall is about 1 000 mm/yr and the natural vegetation would have been an open to closed proteoid shrubland with species such as *Protea lepidocarpodendron*. This vegetation had been largely displaced by a dense invasion of *Acacia saligna* with a density of about 9 800 stems per ha. The post-fire age was about 20 years. This work was done shortly after the release of the biocontrol agent (*Uromycladium tepperianum*) in 1981 (Morris 1997) so the *Acacia* growth was still vigorous and survivorship and stand densities were high. This is no longer the case although populations still persist due to the phenomenal seed output of the young plants (Wood & Morris 2007; Richardson & Kluge 2008). *Acacia saligna* invasion increased the total live biomass about 3.3 fold (Table As1), particularly the live material >6 mm in diameter, and the fine dead material about 2.8 fold. The herbaceous components of the fuel (e.g. restios), which are important for fire continuity, were virtually eliminated. However the fuel mass only increased 1.5 fold, which is still a substantial increase, albeit lower than the *Hakea* invasion (see section 5.1). The surface to area volume ratios were marginally higher than for the fynbos and the energy content was lower (Table As2). The Acacia invasion resulted in a significant increase in the height of the stand from about 2 m to 6 m (Figure As1, Plate As1). Measurements of the moisture content of the fine, live Acacia fuel showed that it averaged about 270% compared with 155% for the protea.

Table As1 A comparison of the above-ground biomass of proteoid fynbos and *Acacia saligna* invaded fynbos (t/ha) at the Vergelegen site (van Wilgen & Richardson 1985). The proteoid fynbos biomass is the mean of the 14 sites reported by (Van Wilgen *et al.* 1985).

State	Component	Size class	Proteoid fynbos	Acacia
Live	Dominant shrubs	>6 mm Φ	4.45	35.32
		<6 mm Φ	2.1	4.98
	Other shrubs	>6 mm Φ	0.46	1.3
		<6 mm Φ	2.32	1.45
	Herbaceous plants	<6 mm Φ	3.76	0.09
	Total live		13.09	43.14
Dead		>6 mm Φ	0.71	3.58
		<6 mm Φ	4.04	11.44
	Total biomass		17.84	58.16
	Total fuel		12.22	17.96

Table As2 A comparison of the fuel characteristics of proteoid fynbos and *Acacia saligna* invaded fynbos (t/ha) at the Vergelegen site (van Wilgen & Richardson 1985). 1: based on *Protea repens* (Van Wilgen 1984).

Component	Model Parameter	Proteoid fynbos[1]	Acacia
Fuel load/Vegetation (t/ha)	1-h	4	11.5
	10-h	0.95	3.14
	100-h	0.12	0.45
	Live herbaceous	5	0.09
	Live woody < 6 mm	2.24	1.45
Surface area to volume ratios (m^2/m^3)	1-h Surface Area/Vol Ratio	7215	6460
	10-h Surface Area/Vol Ratio	357	357
	100-h Surface Area/Vol Ratio	98	98
	Live Herb Surface Area/Vol Ratio	5900	5900
	Live Shrub surface Area/Vol Ratio	4920	6460
Fuel Heat Content (kJ/kg)		20000	18700
Fuel bed depth (m)		1.4	0.3
Dead Fuel Moisture of Extinction (%)		34	34
Midflame wind conversion factor		0.6	0.6

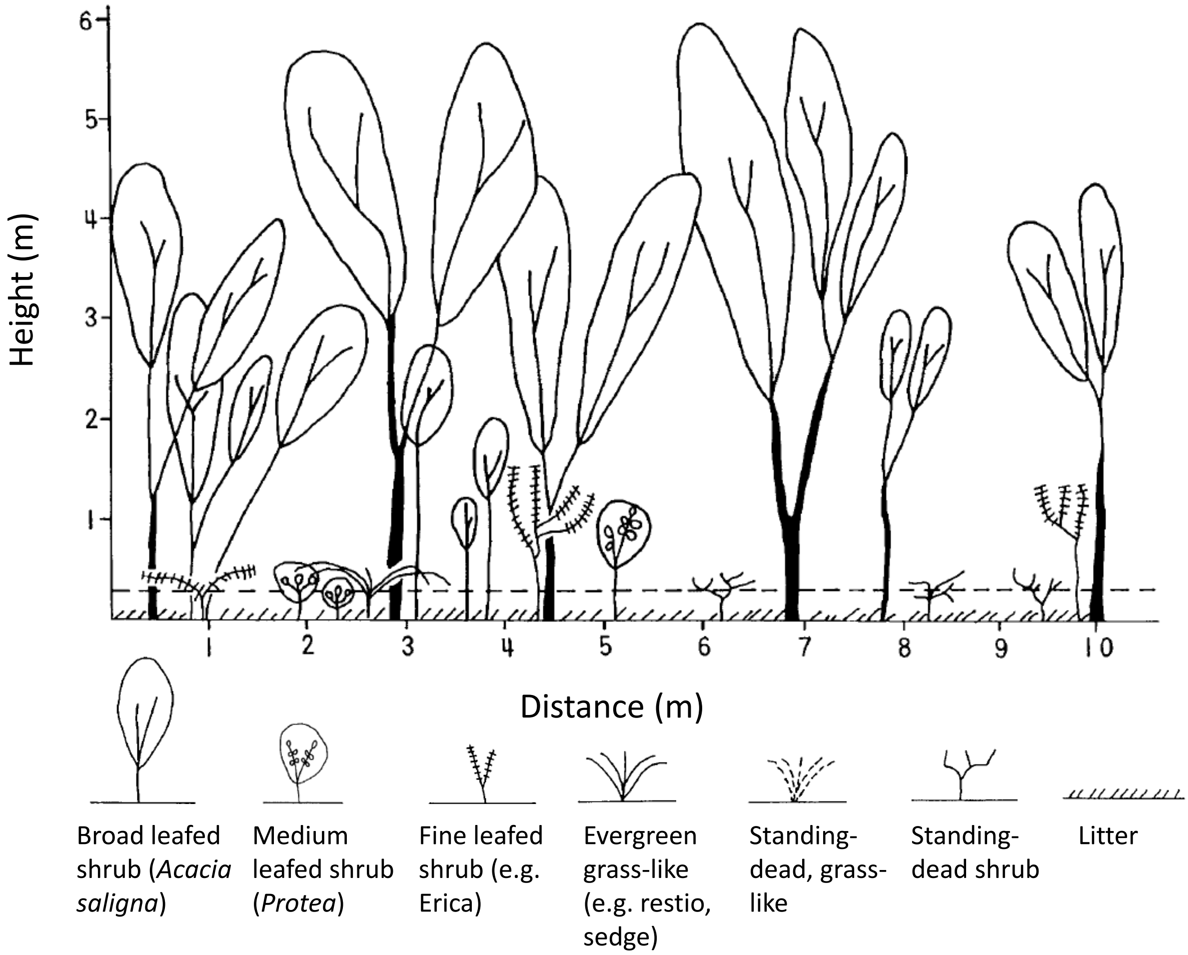

Figure As1. A profile diagram of the *Acacia saligna* invaded stand at Muizenberg based on measurements taken along a transect through the stand (van Wilgen & Richardson 1985). The dashed line indicates the fuel bed depth used in the fire behaviour model. Note the sparse middle layer between the canopies of the *Acacia* and the remnant fynbos.

Plase As1. View of a dense *Acacia saligna* stand similar to the one sampled by Van Wilgen and Richardson (1985). The person in the photograph is about 1.7 m tall.

The rate of spread in the *Acacia* invaded stand far lower than that in the proteoid fynbos under all fire hazard conditions and reached a maximum of only about 0.5 m/sec (van Wilgen & Richardson 1985). The moisture content of the *Acacia* was so high that it simply will not burn under average conditions and the live shrub fuel was reduced to 1.45 tons/ha to exclude material that does not burn, and the fuel bed depth to 0.3 m to represent the understorey which does burn. The fire intensity was also much lower in the invaded stand (<11 000 kW/m) than in the fynbos (±54 000 kW/m) under extreme conditions. Following further modifications (fuel bed depth 4 m, woody fuel load 650 g/m^2) based on observations after a clean burn in an *Acacia saligna* stand, a rate of spread of 3.3 m/sec and fire intensity of 64 400 kW/m was simulated under extreme conditions. This was higher than for the proteoid fynbos. The fungal biological control agent results in the deaths of the young *Acacia* plants, the die-back of branches and entire trees and the accumulation of the woody galls, all of which increase the fuel load and may enable these stands to carry fires under wildfire conditions.

5.3 *Pinus pinaster* in renosterveld

Plate P. *Pinus pinaster* invaded renosterveld with mature pines and some *Acacia longifolia* and *Hakea sericea* at Coetzenburg, Stellenbosch. Note the height of the pines, the coarse dead fuels on the ground and the renosterveld species in the foreground. The person is holding a 2.5m tall ranging rod and is 10 m away from the camera.

The climate at Coetzenburg is characterised by warm summers with regular south-easterly winds, creating a fire hazard (Jayiya *et al.* 2004). Winters are cold and wet with about 70% of the annual rainfall of 600 – 700 mm falling between April and September. The area was invaded by *Pinus pinaster* many years before and the different tree heights suggest that there may be two cohorts (Figure P). The trees are now mature but still not forming a completely closed stand. *Acacia longifolia* has also invaded this site but is not dominant. The natural renosterveld vegetation on this site is shown in Plate R. The total biomass at this suite was 104 t/ha (Table P1) with 83 t/ha, (80%) being fine live and fine dead (<6 mm diameter) fuels, indicating the potential for high intensity fires. The amount of live plant material <6 mm in diameter was 68 t/ha which is 7.9 times greater than in the renosterveld (Table R). Likewise, the dead plant parts were 9.9 times greater, and the total fuel load (dead and live) was 8.1 times greater than at the renosterveld site (Table R1).

The *BehavePLus* model was unable to simulate fuel bed depths greater than 1.8 m so the resulting fire behaviour simulations packed the fuel into this layer (Jayiya *et al.* 2004) (Table P2). The resulting simulations would not, therefore, represent the conditions prevailing during a crown fire which is likely to happen under wildfire conditions in fuels like this. The (unrealistic) simulated fire behaviour under extreme conditions was a rate of spread of about 0.9 m/sec, fireline intensity of 65 396 kW/m, heat per unit area 15 861 kJ/m^2, and the flame length about 6.2 m (Jayiya *et al.* 2004). This is a very intense fire indeed. Its rate of spread probably is substantially reduced by the artificially dense fuel bed necessitated by the constraint on fuel bed depth. There are ways of dealing more effectively with modelling crown fires (Coen 2005; Alexander & Cruz 2012; Cruz & Alexander 2013; Andrews 2014; Molina *et al.* 2014) but they fall outside the scope of this study.

Table P1. Above-ground biomass of vegetation components (t/ha) in the pine invaded area of the Coetzenburg site (Jayiya *et al.* 2004).

State	Component	Biomass (t/ha)
Live	< 6 mm	68
	Herbaceous Plants (< 6 mm)	0
Dead	< 6 mm	15
	6 - 25 mm	19
	25 - 75 mm	2
	Total	104

Table P2. Fuel model data assembled for *P. pinaster* invasions for Coetzenburg site (Jayiya *et al.* 2004). A: based on van Wilgen and Richardson (1985).

Component	Model Parameter	Value
Fuel load/Vegetation (t/ha)	1-h	15
	10-h	19
	100-h	2
	Live herbaceous	0
	Live woody < 6 mm	68
Surface area to volume ratios (m^2m^{-3})	1-h Surface Area/Vol Ratio[A]	9817
	Live Herb Surface Area/Vol Ratio	0
	Live Woody Surface Area/Vol Ratio[A]	9817
	Fuel bed depth (m)	2
	Dead Fuel Moisture of Extinction (%)[A]	34
	Dead Fuel Heat Content (kJ/kg)[A]	18700
	Live Fuel Heat Content (Kj/kg)[A]	18700

The profile diagram emphasises the fact that much of the fine, live fuel is located in the canopy of the pine trees and more than 6 m above the ground (Figure P). The low fuel loads on the ground would tend to result in a low rate of spread and fire intensity as long as the fire remained in this layer but, if conditions were suitable for it to spread to the canopy (e.g. via dead branches or up the bark) then the situation could change entirely. Canopy fires are very difficult to combat so very effort should be made to prevent them by removing the tall trees or clearing the ground around and beneath them of fuel to minimise the possibility of a canopy fire (Safford, Schmidt & Carlson 2009; Price & Bradstock 2012). The issue of dealing with and reducing fuel loads in the wildland-urban interface is dealt with in a separate study (Forsyth & Le Maitre 2015).

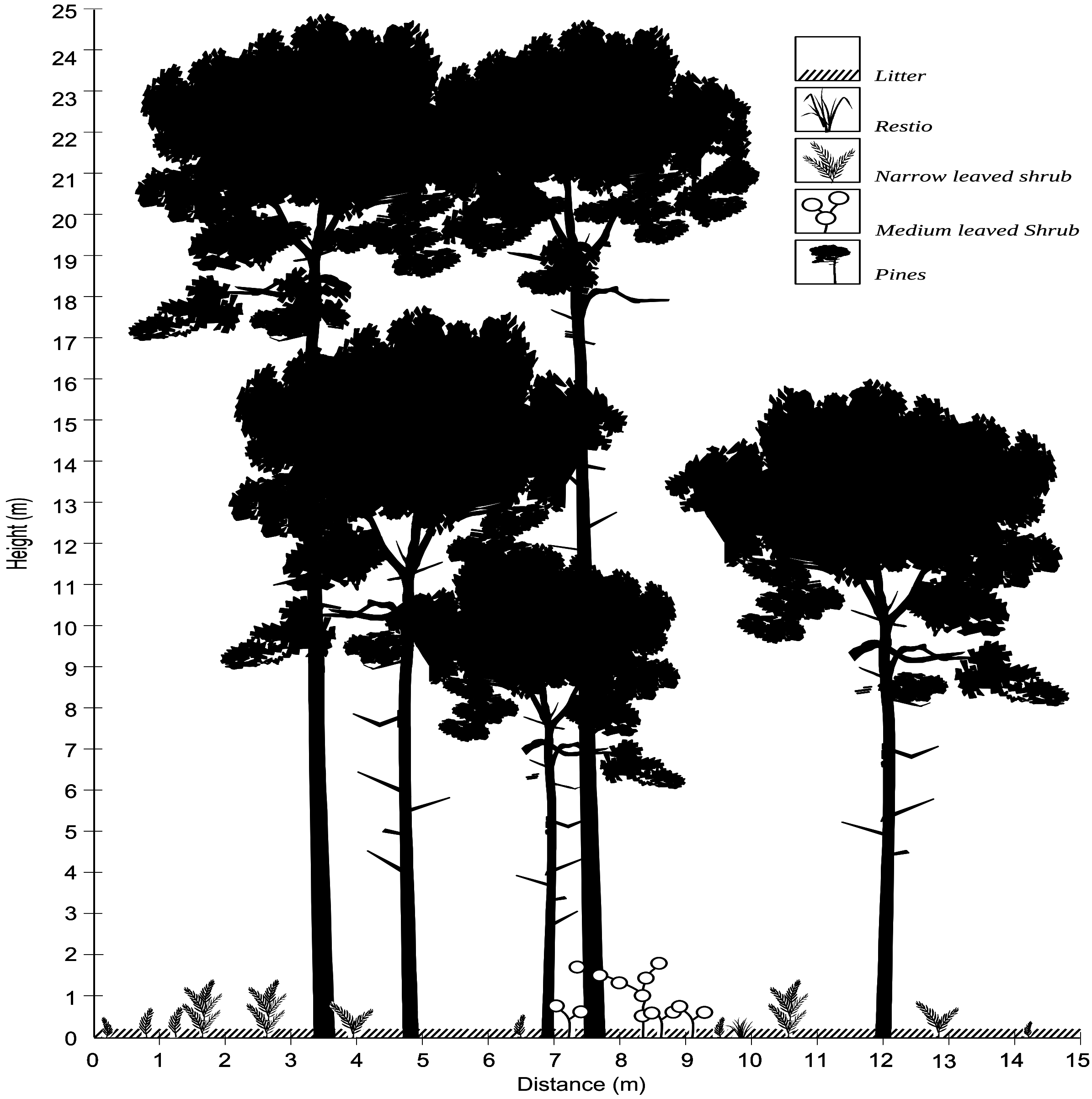

Figure P. A profile diagram of the pine invaded stand at Coetzenburg based on measurements taken along a 15x2.5 m transect through the stand (Jayiya *et al.* 2004). Most of the live, fine fuel is located more than 6 m above the ground and the litter cover is continuous. See Plate P for a view of this stand.

5.4 *Acacia cyclops* in strandveld

Plate A1. *Acacia cyclops* in strandveld at the Koeberg site. The person with the 2.5 m ranging rod is standing about 3 m from the camera. Much of the dead fuel is hidden within the canopies of the acacias and the grass ground layer is also evident between the trees.

At Koeberg, the total fuel load (dead and live) reached 57 t/ha, more than half of which was dead fuels, and almost all of that was fine fuels (Tables A1 and A2). The fuel mass increased by about 3.1 times compared with the strandveld vegetation, while the live plant material (<6 mm) and dead material increased 4.8 and 2.5 times, respectively. The habit of retaining fine twigs gives A. cyclops stands a much higher fine, dead fuel load than *A. saligna* stands (see van Wilgen & Richardson 1985). However, the high mortality rate in older *A. saligna* stands, due to the effects of the biological control fungus (Wood & Morris 2007), has increased the fuel loads in old stands of this species. Although the *A. cyclops* is much taller than all but the largest strandveld shrubs (Figures A1 versus S1), this has little impact on the fuel bed depth. The simulated fire behaviour under extreme conditions was a rate of spread of about 1.0 m/sec, fireline intensity of 63 936 kW/m, heat per unit area 62 651 kJ/m^2, and the flame length about 12.5 m (Jayiya *et al.* 2004). These levels of energy output would make the fires impossible to tackle using fire fighters and the fire would first have to be damped down to levels where people could tackle the fire directly.

Table A1. Above-ground biomass of vegetation components (t/ha) in pristine and invaded area of the Koeberg site (Jayiya *et al.* 2004).

State	Component	Biomass (t/ha)
Live	< 6 mm	24
	Herbaceous Plants (< 6 mm)	0
Dead	< 6 mm	25
	6 - 25 mm	4
	25 - 75 mm	4
	Total	57

Table A2. Fuel model data assembled for *Acacia cyclops* invasions at the Koeberg site (Jayiya *et al.* 2004). A: based on van Wilgen and Richardson (1985).

Component	Model Parameter	Value
Fuel load/Vegetation (t/ha)	1-h	25
	10-h	4
	100-h	4
	Live herbaceous	0
	Live woody < 6 mm	24
Surface area to volume ratios (m^2m^{-3})	1-h Surface Area/Vol Ratio[A]	6400
	Live Herb Surface Area/Vol Ratio	0
	Live Woody Surface Area/Vol Ratio[A]	6400
	Fuel bed depth (m)	1
	Dead Fuel Moisture of Extinction (%)[A]	30
	Dead Fuel Heat Content (kJ/kg)[A]	18500
	Live Fuel Heat Content (Kj/kg)[A]	18500

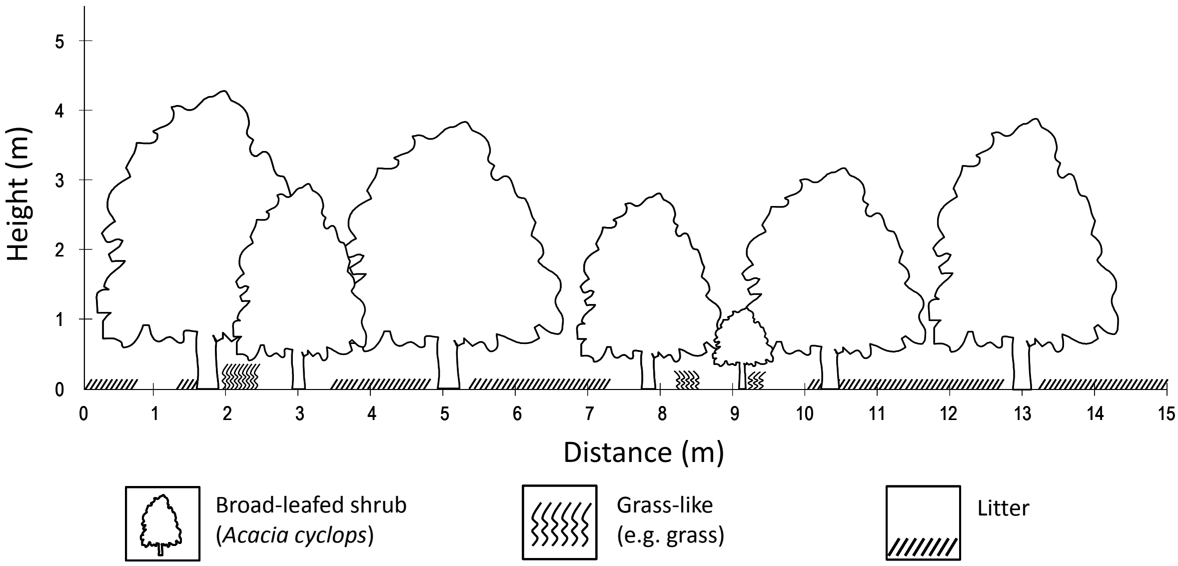

Figure A1. A profile diagram based on a 15x2.5 nm transect through the Acacia invasion (Jayiya *et al.* 2004). Note the virtually complete dominance of the *Acacia*, the abundance of the litter and the presence of grasses in the understorey.

6. DISCUSSION

The first attempt at providing a visual guide to fuel types and fuel characteristics was the report by (Jayiya *et al.* 2004). This study extends that work to a greater range of fynbos fuel types and also covers a range of species invasions based on readily available information. We have managed to gather data for a range of structural types and characteristics which we believe would be useful to people involved in fire management.

This study is not intended to be comprehensive or definitive but, rather, to demonstrate what such a fynbos fuel guide could look like. It is not intended to replace the Fire Manager's Handbook on Veld and Forest Fires (see http://saif.org.za/71-2/) which is deals generally with fuels, fire behaviour and fire management in general in the South Africa context with sections on fynbos. Other useful books with more general information are the *Wildland Fire Management Handbook for Sub-Sahara Africa* (Goldammer & de Ronde 2004) with sections on fire ecology including fynbos (e.g. Bond *et al.* 2004) and fire management in fynbos (e.g. Everson *et al.* 2004) and the earlier Veld management in southern Africa (Tainton 1999). Nor is it intended to replace training materials or the information provided through the FireWise programme (http://www.firewisesa.org.za/), rather it is intended to complement them with specific information on fynbos vegetation and fuels.

We would welcome feedback from potential users on usefulness of the different kinds of information we have provided and whether there is additional information we could provide.

7. RECOMMENDATIONS

1. That a set of standardised vegetation type fuel models be developed for the fynbos based on the approaches used in Australia and the USA. A first approximation was developed by (Le Maitre & Marais 1995) but was based on very limited data and did not include any visual aids. The current national fire-ecotypes only distinguish between two very broad types in the Fynbos biome: Fynbos and Renosterveld (Le Maitre, Kruger & Forsyth 2014) but there are many more types and it is important that managers are provided with guides which can help them to characterise the fuels in their area.

2. We have not been able to find any data on fuel loads and characteristics for the southern and eastern parts of the fynbos biome. This is a gap that needs to be addressed, especially for the grassy forms prevalent in the Tsitsikamma and further inland and east to the Zuurberg near Grahamstown.

3. Similar guides could be developed for grassland and savannah environments. Particular thought needs to be put into how to design guides for the vegetation types where the fuel loads depend on high rainfall seasons, or sequences of seasons, such as the low rainfall Sour Grasslands and Sweet Grasslands, and Arid Woodland fire-ecology types (Le Maitre *et al.* 2014).

4. An integrated fire management system, like the LANDFIRE approach being implemented in Australia (Rollins 2009), would build on the AFIS system by providing more detailed vegetation and fuel maps to assist fire managers in determining areas with high fire hazards and planning prescribed fires and for fuel reduction and in managing fuels in the wildland-urban interface (Arroyo, Pascual & Manzanera 2008; Ager, Vaillant & Finney 2010; Ager *et al.* 2014; Spies *et al.* 2014).

8. GLOSSARY

BEHAVE – a fire behaviour model developed for the Forest Service of the United States Department of Agriculture based on fire modelling work done in laboratories; it was first made available in 1984 (Burgan & Rothermel 1984) and was used for fire behaviour modelling in fynbos (Van Wilgen & Burgan 1985). The BehavePlus model is a further development and has a more user-friendly interface (Andrews 2014).

Ericoid – plants with tiny to small (microphyll), tough leaves; characteristic of many species in the fynbos; often from the Ericaceae (e.g. *Erica*), Fabaceae (legumes e.g. *Aspalathus*) or the Asteraceae (daisy family e.g. Metalasia).

Fire or fireline intensity – this is a measure of the amount of energy being released at the flaming front of the fire; it is the product of the rate of spread, the fuel mass per unit area, and the heat or energy content of the fuel (Byram 1973); it is a useful measure of instantaneous energy outputs but the fire severity, which combines the intensity and the duration of the fire at a point is more ecologically meaningful (Keeley 2009). It is a rough measure of whether or not people will be able to safely suppress a fire or not (Gill & Stephens 2009), depending also on the protective equipment they have.

Fire or burn severity – a measure of the cumulative eff3ect of the fire intensity i.e. the energy radiated by the fire from the moment of ignition through to the extinction of the flames and cooling of the coals and embers. It measures both the total radiated energy and the duration of the period of energy output (Keeley 2009). It is a much more meaningful ecological measure because it is the combination of energy and time that can heat plant tissues under the berk and kill them

Fuel bed depth (m) – a measure of the depth of the material that is likely to burn in a fire and, together with the fuel mass, an indication of how densely the fuel is packed.

Fuel Heat Content (kJ/kg) – a measure of the amount of energy that would be released if a kg of the fuel was burnt.

Fuel Moisture of Extinction (%) – the moisture content at which the fuel will no longer be able to burn without an external heat source; this differs for dry and live fuels but is more important in the dry fuels as these are crucial for sustaining the fire.

Fuel size classes – the BEHAVE model, and others derived from it, consider potential fuels to be only the material with a diameter of less than 6 mm; this includes non-spherical objects (e.g. leaves) provided that the width times the thickness comes to less than the equivalent of 6 mm in diameter (i.e. a perimeter (width x thickness) of less than about 28.3 mm). This is because the model is designed to simulate the behaviour of the fire front (the flames) and not fire burnout time and other aspects which would require different model algorithms and data.

Graminoid – plants with a grass-like growth form including species from the Poaceae family (grasses) as well the Cyperaceae (sedges); some people include the restioids in this group

Herbaceous – can refer broadly to all non-woody plants (e.g. geophytes, annuals) and other soft-stemmed and leafed species; sometimes included grasses and sedges

Proteiod – shrubs with relatively broad (mesophyll) and tough leaves, generally from the family of the Proteaceae: e.g. *Protea, Leucadendron, Leucospermum*

Restioid – clumped, often tufted plants with leafless stems, sometimes finely-divided and curly sometimes straight; flowering stems usually straight; wide range of habits (e.g. tufted, sprawling) and heights (0.1 m to 2.5 m tall).

Surface area to volume ratios (m^2m^{-3}) – a measure of the relationship between the surface area and the volume of a plant part; it is an indication of flammability with high ratios indicating that it can burn readily, even when green.

Woody – plants with stiff to bendable, woody stems which break-off when bent back on themselves; can include species with a herbaceous stem anatomy such as some of the Asteraceae.

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10. APPENDIX: Weather Parameters and Fuel Moisture Contents in simulating fire behaviour used by Jayiya et al. (2004), based on those used by Van Wilgen & Richardson (1985).

Degree of fire Hazard	Low	Moderate	High	Extreme
Air Temperature (˚C)	15	20	30	40
Relative Humidity (%)	50	40	25	15
Windspeed (Km/h)	1.8	7.2	18	25.2
Slope (degrees)	0	0	0	0
Dead Fuel moisture content (%)	9	8	6	4
Live fuel Moisture Content (%)				
Uninvaded Renosterbos	180	150	140	130
Uninvaded Strandveld	180	150	140	130
A. cyclops	180	150	140	130
P. pinaster	180	150	140	130