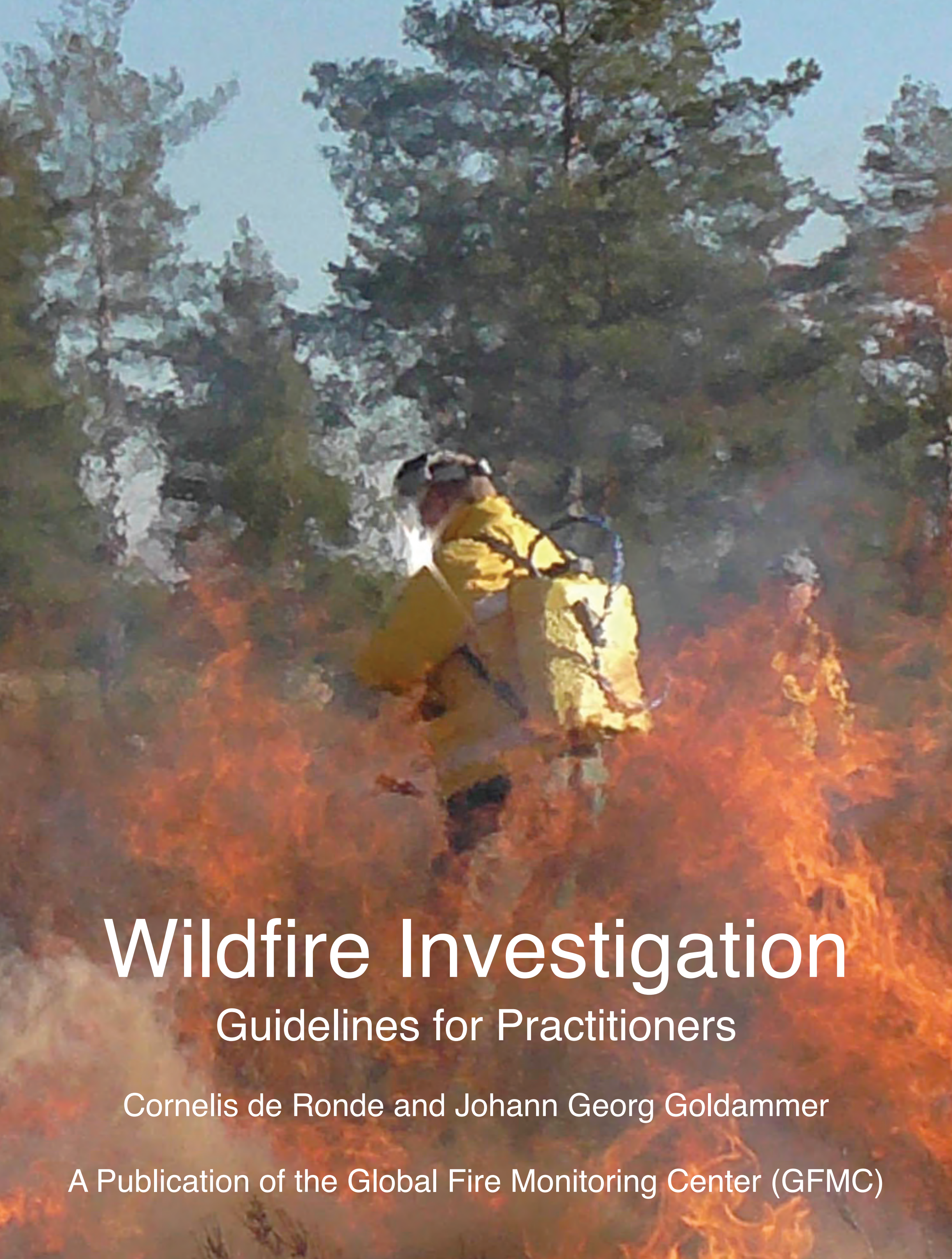

Wildfire Investigation

Guidelines for Practitioners

Cornelis de Ronde and Johann Georg Goldammer

A Publication of the Global Fire Monitoring Center (GFMC)

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Preface

The rationale for the publications of this volume is the motivation of the authors, which have been driven from two different perspectives.

The reason for the first author to initiate writing this book was to share experiences of wildfire investigation in South Africa over two decades. This included private ad-hoc investigations of relative small uncontrolled fires, to the investigation of large wildfires, which crossed a number of properties. Most of these tasks entered either in arbitration processes, settlements between parties (with or without legal assistance), appointments of expert witnesses in high courts, with subsequent court attendances (or settlements), and special investigation tasks conducted for government institutions or insurance companies. The experience gained during this period was very wide, with no single fire being equal to the next, which provided a wealth of information, including specific wildfire reconstructing processes with the use of advanced technology, with the assistance of GIS, satellite-derived information and more. These experiences form the backbone of this volume.

The motivation for the second author to join this book project was the recognition of the need to bring the expertise of the first author to other regions and countries of the world as a contribution to support the endeavor of the United Nations (UN) and its affiliated processes and networks, notably the United Nations International Strategy for Disaster Reduction (UNISDR) and the Global Wildland Fire Network, to reduce the impacts of wildfires at global level for the benefit of the global environment and humanity. The Global Fire Monitoring Center (GFMC), which is serving as secretariat and facilitator of the Global Wildland Fire Network and its representation to the UNISDR, the Wildland Fire Advisory Group, joined the book project in order to enrich national expertise by international insights and bring this to international use and benefit.

In following up the UNECE/FAO Regional Forum on Crossboundary Fire Management (UN Geneva, November 2013), in which representatives of the UNECE and other regions of the world, including Sub-Saharan Africa, met to develop visions and concrete action to enhance efficiency and effectiveness in fire management by exchange of experience and expertise among nations, the International Wildfire Preparedness Mechanism (IWPM) was launched in 2014.[1] The IWPM, hosted by the Global Fire Monitoring Center (GFMC), is a non-financial instrument serving as a broker / facilitator between national and international agencies, programmes and projects to exchange expertise and build capacities in wildland fire management and particularly in enhancing preparedness to large wildfire emergency situations.

1 http://www.fire.uni-freiburg.de/iwpm/index.htm

Wildfire investigation is an essential component of fire management since it contributes to clarify the origins and causes wildfires, but more importantly, to unveil possible deficits in fire management, gaps that should be closed by appropriate capacity building.

Sedgefield (South Africa) and Freiburg (Germany), 31 January 2015

Cornelis de Ronde and Johann Georg Goldammer

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1 INTRODUCTION

1.1 Fire History and Fire Ecology in South African Biomes

Africa is a fire continent (Komarek, 1971) and that includes South Africa. The country is characterized by a sub-tropical and temperate climate, and although most of its regions fall within the summer rainfall area, a small (but unique) percentage of the country is situated in the winter rainfall or constant rainfall climate within a temperate climatic environment. Linked to these main regional climatic characteristics, is a contrasting yearly rainfall range, extremes of which differ from <100mm/year in the far NW-part of the Northern Cape Province to >2000mm/year on the highest Western Cape mountain ranges, providing a mosaic of diverse vegetation features across a range of biomes (Kruger, 2004).

This brings me to the occurrence of wildfires in the South African biomes, causing fire damage levels ranging from "rare" to "mostly yearly", each with very specific characteristics. The wildfire investigator needs to understand the basic dynamics of each vegetation base where a wildfire occurred, otherwise he/she will not be in a position to table any meaningful findings of the investigation results.

There exists a chronic rhythm of wetting and drying. Seasonality flows a cadence of rainfall, not temperature. Thus – in the summer rainfall regions – we find wet seasons growing fuels, while dry seasons prepares them for burning, thus presenting a range of wildfire dangers (Pyne et al., 2004). These are called "dynamic fuels". Some vegetation types, however, in other regions (some with different land-uses) do not present such significant contrasting seasons. The latter are mostly called "static fuels" (Rothermel, 1972; Andrews, 1986; Andrews and Chase, 1986; Andrews and Bevins, 2000).

Many ages of early civilization of South Africa did not alter the ecology of the southern-part of the continent significantly for many years, as the country was only sparsely populated by small (mostly migrant) tribes. Lightning remained the most important factor in dictating the maintenance of biodiversity, although man used fire to some extent to assist in some agricultural activities, sometimes using fire to assist in hunting parties as well. However, these did not have a major influence on ecosystem existence and well-being, until such time when European imperialism became the vector for industrialization (Pyne et al., 2004).

As European settlement spread through the country, at times coupled to African migration as agriculture, forestry and industries developed, and in the process urban and other interfaces (such as with agricultural and forestry land) developed. These significantly altered the status of vegetation biomes and the role of fire. Not only was the maintenance of biodiversity threatened, but increased land-use for growing crops reduced ecosystem sizes structures and even existence. These changes in land-use let to not only impacting changes in ecosystems, but also the creation of "new", disturbed, ecosystems and fuels, such as industrial plantations, maize lands, sugar cane and wheat crops with harvesting waste. This created a completely new "fire environment", while newly-created Urban-Interfaces provided new fire protection and prevention challenges for fire managers (Pyne et al., 2004).

The ecology of fire in South Africa ranges from a "rare event" in e.g. the dry Karoo regions, to a 1-2 year occurrence in the wettest regions, such as in e.g. moist montane ("dynamic") grasslands. In Fynbos shrublands in the Western and Eastern Cape Provinces, fire frequency ranges mostly from 10 to 40 years, with (in the winter rainfall areas) most fires occurring during the summer. In the constant (all-year) rainfall areas more fires occur during the winter period, during Bergwind conditions (Edwards, 1984; Pyne et al., 2004). In many Fynbos areas more exposed to wildfires, fire frequency has been reduced significantly, even to a dangerous 4-6-years level, threatening the maintenance of biodiversity (own observations).

In most regions of the summer rainfall area in South Africa, particularly in the vast savanna-grassland biomes, fires are mainly caused by lightning and humans, and these fires are more frequent than in Fynbos. In arid grassland and savanna, grazing alone may suffice to maintain the grass component. Under natural conditions, however, fire is necessary to maintain the vigour of moist, sour, grassland (Edwards, 1984). In savanna grassland, fire is required to maintain a productive and stable savanna (Trollope, 1984).

Undisturbed indigenous forests, only covers a minor percentage of the land, and they are well protected against wildfire damage if left undisturbed. However, as many forest edges are disturbed by fires and/or exploitation in the past, forest edges became extremely vulnerable to fire damage, and are thus mostly reduced in size by regular fires, particularly in broken topography. As a result, surviving forest patches require special protection against fire damage (Geldenhuys et al., 2004; own observations).

1.2 Fire Management in Natural Ecosystems

In South Africa we have been fortunate in having a rich research and developed research history in most of our natural biomes, with recommendations available with regard to optimum fire frequencies, prescribed burning application, season of burn and fire management in general to ensure optimum maintenance of biodiversity. However, many of these recommendations are not applied according to these rules for various reasons such as conflicting management goals, lack of capacity and training, irregular wildfire occurrence, changes in land-use and climate change. Subsequently, in many cases the biodiversity maintenance is being threatened by lack of fuel management control (leading to unchecked fuel accumulation) and resulted in a general increase in wildfire size, intensity and related other negative impacts.[1]

1 Where applicable, fuel model examples will be provided in the text, also referenced in a fuel model set provided in Appendix I.

1.2.1 Fynbos

One of the most dominating features with regard to fire behaviour in Fynbos is its relatively slow fire rate of spread (in relation to dynamic grassland) and regular flaring when large shrubs are present. This flaring can also easily give rise to an abundance of spotting in favourable terrain when burning with a strong wind (own observations).

For the purpose of fuel and fire dynamic studies and assessment in Fynbos, the following examples can be used for fuel classifications and fuel models as part of a wildfire investigation if required (for fuel model detail, refer to Appendix I):

Fynbos types

- Moist Fynbos (uninfested, mature, S aspect, near Caledon and Garcia): Fuel models 64 and 65
- Semi-moist Fynbos (7-10 yr old, W. Cape): Fuel model 68
- Strandveld
- Dry Fynbos-Renosterveld (N-aspect Fynbos, near Garcia and mature Renosterveld, in W. Cape): Fuel models 66 and 67

The history of Fynbos management has an interesting background in the Cape Regions. Before the 1960s the Department of Forestry controlled all mountain catchments and related nature reserves in the region, and Fynbos management was mainly applied by means of regular block burning as well as rotation burning of wide firebreaks on mountain foot slopes on property boundaries. When control over the catchments was handed over to provincial nature conservation authorities, not much change in this fire management policy was experienced at first, because the foresters of these reserves were also transferred to the provincial authorities. As these foresters retired, prescribed burning application became less and less frequent and was eventually not applied at all.

As prescribed burning attempts became less and less, wildfires increased in size and intensity, and nature conservation bodies are at present bringing back prescribed burning application programmes, although at this point in time at a lesser scale as it used to be, because of lack of trained fire managers and reduced capacity (own observations).

1.2.2 Montane grasslands

Most of these grasslands are centered in the Drakensberg Mountains of the Kwazulu-Natal Province and Lesotho and adjoining escarpment. The extent of the grassland is strongly determined by climatic variables, with fire and grazing exerting considerable influence over the boundaries of the grassland biome. In the grasslands' domain, rainfall should be above 600 mm with relative cool temperatures and dry, cold winters and snow common at high altitudes.

If not grazed, the frequency of fires in this grassland – in particularly in the Drakensberg – leads to a yearly fire risk if prescribed burning is not applied before the dry wildfire season. This in turn leads to conflict between the adjoining land managers and conservation bodies, as the first advocates yearly burning of the whole Drakensberg range to avoid wildfire damage. Conservation bodies, in contrast normally recommend a 2-3-year fire rotation, which unfortunately leads to serious wildfire damage at times, also because there is conflict between the application of – and selecting – the optimum burning application season.

Grazing can have a highly significant impact on fire hazard, and when investigating such land, it is important to model grazed vs. non-grazed grassland as fire behaviour between the two fuel types are normally highly significant (fuel models 88, 91 and 92, vs. fuel models 89, 90, 93 and 94).

1.2.3 Kalahari Grasslands and shrublands

Also referred to as the "Kalahari Thornveld", this vegetation is dominated by sand dunes, plains and pans with dry fossil riverbeds. The climate of the Kalahari is semi-arid, where the rainfall ranges from 200 mm/year in the SW to 500 mm/year in the N and E, with drastic seasonal variation in yearly rainfall sometimes experienced between sub-regions.

Very little knowledge is available of fire ecology of the Kalahari, but historic occurrence of wildfires tells us that a few years with above-average rainfall can normally lead to wildfires, particularly in the natural parks (such as the Kgalagadi Trans-Frontier Park, managed by SANParks) where natural grazing is occurring irregularly depending on game stock. Serious (large) wildfires can occur, particularly in the dry riverbed vegetation, where grassland biomass is at its highest (own observation). From the few records available, it appears that wildfire frequency in the Kalahari is approximately 10-15 years, although extreme wildfires normally only occur every 30-50 years, when (particularly) riverbed tree components are mostly all killed (Bond et al., 2004; own observations). During 1977/78, 350 000 ha burnt in the Kgalagadi Park (Trollope, 1984). Fuel biomass situations in these grasslands have been modeled also for the N. Cape region for the purpose of wildfire simulation in these fuels, where this dry savanna was heavily infested with shrubs (e.g. fuel model 100).

1.2.4 Moist Savanna grasslands

These grasslands can mostly be found at altitude ranging from 500 to 1000 m on plateau type of topography, where the yearly rainfall ranges from 500 to 1100 mm (Huntley, 1984). The most desirable burning regime for grazing conditions is annual or biennial application, depending on grazing intensity and grass fuel conditions. However, fire frequency is normally between 3 and 5 years during dry seasons (Trollope, 1984).

While the herbaceous production in Central Africa, in Miombo woodlands, can be as high as 4.8 tons/ha/year, this is much less in South Africa, where the average herbaceous production is about 2.2 tons/ha/year, with a tree component of between 20 and 40 tons/ha/year (Huntley, 1984). One fuel model of the South African moist Savanna Grasslands has been developed (fuel model 98) and one for wetland Savanna Grassland (fuel model 99).

Figure 1.1. Photograph taken a few weeks after a wildfire in the Outenique Mountains near George (South Africa). A = Young Fynbos, unburned; B = Patchy-burned slopes, with non-vegetated rock sheets; C = Low profile Fynbos, burned over; D = Wetland Fynbos burned at high intensity. Photo: C. de Ronde.

Figure 1.2. Ignited prescribed fire in progress in grassland in the KwaZulu-Natal Province of South Africa. Photo: Courtesy Working on Fire.

Figure 1.3. Typical Kalahari grassland (dry savanna) with scattered tree component. Photo: C. De Ronde.

Figure 1.4. View of dry savanna grassland with dense shrub and tree cover, a in the Northern Cape Province. Photo: C. De Ronde.

Figure 1.5. View of dense indigenous forest on the Tsitsikamma plateau, with the N2 national road carving its way through the forest carefully between a few giant Outeniqua Yellowwoods in the background. Photo: C. De Ronde.

Figure 1.6. Early progress of a wildfire in Montane Grassland in the Free State Province. Note the effect of the strong wind blowing from left to right in the picture. Photo: C. de Ronde.

1.2.5 Dry Savanna grasslands

Arid savanna normally occurs in the hotter, drier, lowland valleys, where the rainfall ranges between 250 and 650 mm/year, and where calcrete soils are sometimes a common feature. The vegetation within dry savanna is diverse and includes open sparse grassland with scattered shrubs and short trees as well as dense thorn thickets, in which the herbaceous layer might be insignificant.

Herbaceous biomass production ranges from 500 to 1000 kg/ha, with a typical woody component (biomass) of about 20 tons/ha. Fire is an infrequent but significant component of this biome and damage to large stands of *Acacia* trees can be severe and common. Succession advances towards an open woodland or shrub savanna climax, but under disturbed conditions a dense thicket might develop (Huntley, 1984). No specific fuel models were developed under this heading, but fuel model 100 can be used as a close example.

1.2.6 Montane (coastal and temperate) forest

The forest biome includes the indigenous coastal forests of the coastal lowland and escarpment from the N of the Zululand coast all along the KZN and Eastern Cape coastal land as well as inland into the Drakensberg Escarpment. Montane Forests are fairly dominant on the Cape Provinces' plateau and into the adjoining mountain ranges, where it normally only occurs in smaller isolated (well-protected) patches. These forests cover <1% of South Africa.

Fire is normally not an issue where these forests are undisturbed, but were forest edges have been disturbed by earlier fires and/or exploitation, the forest adjoining the forest edge can be vulnerable to damage when fire is burning in adjoining vegetation. For that reason, forest edges should be protected at all times to save the remaining forests, while unchecked exploitation should also be forbidden (Huntley, 1984; Bond et al., 2004; own observations where wildfires occurred).

1.3 Fire Management in Agriculture, Game Management and Forestry

Land-use is changing rapidly in South Africa, and millions of hectares have been converted to agricultural land in the form of cultivated lands and land used for grazing. Ploughed lands are mostly used for wheat, maize and sugar cane, mostly creating fuels at some stage at or just after harvesting, which could present a serious fire hazard, though mostly for a restricted period of time. Harvesting slash in wheat lands is normally burned by farmers in a systematic manner, but even stubble lands can present a fire hazard, depending on the height at which e.g. wheat fields are cut (own investigation experience). Such cutting heights are sometimes alternated yearly by farmers on purpose, presenting a fire hazard some seasons, and some seasons not (pers. comm. with farmers). One fuel model has been developed to provide an example of hazardous stubble land.

The harvesting of slash from maize lands only presents a fire hazard under local conditions for a very short period of time, only just before harvesting is conducted, and then only if this coincides with very strong winds: Situations, which seldom occur as harvesting (and slash management) is normally taking place before the "strong wind season". As such, fuel situations are extremely variable, and it is recommended that such models are only developed when such wildfires in fact occur, as average models will then be of little use (own assumption).

No grassland fuel model under this category has been developed here, but a typical (rare) example is Kikuyu grass during the dry season when cured, as this is an imported grass cultivar, differing significantly from South African (natural) grasslands. However, such fuel can present a serious fire hazard where it is found.

Most South African agricultural grassland used for grazing can be classified as (i) intensively grazed, as many times found in the rural landscape near rural townships (fuel model 92), (ii) irregularly grazed grassland, such as found on large commercial grazing land (fuel model 91), and (iii) land used for game farming and nature reserves, where very little in terms of prescribed burning is applied. In such situations, mostly non-grazed old grassland is found, mostly in semi-moist to dry savanna, as well as in montane grassland (e.g. fuel models 98 and 100).

Where industrial plantations are grown for commercial purposes, a whole range of fuel models has been provided to cover examples by forest region, species and age groups, for specific silvicultural regimes applied. The fire hazard situation in industrial plantations normally changes significantly over time, after the application of silvicultural treatments (such as pruning and thinning) and after clear felling (when slash is added to existing forest floors). During early stand age, the natural base fuel also significantly adds to fire hazard as the tree stand progresses towards crown canopy closure situation, and the partly closed stands with old natural fuel remnants (such as grass and Fynbos) can then reach extremely hazardous proportions, requiring special protective care. Although not all industrial plantation fuel models could be provided here, some representative fuel models have been provided (fuel models 52 to 63).

1.4 The effect of Urbanization and Human-made Fuel Manipulation

These situations can range from rural farmlands, where homesteads are bordering directly to dangerous fuel lands such as Fynbos, dynamic grasslands or other dangerous fuels, to where informal settlements have been developed inside natural fuel lands or industrial plantations, to the edges of towns and villages, bordering e.g. agricultural land, industrial plantations, nature reserves or game farms. The same can be found where such populations are bordering any form of man-made manipulated fuels.

A classification of urban fire hazard is sometimes available, which can be used for regional integrated fire prevention plans, unchanged or adjusted (as and when required).

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2 THE ECOLOGY OF FIRE

2.1 Fynbos in the Western Cape and Eastern Cape Provinces

2.1.1 Introduction to Fynbos ecology

Fynbos is a vernacular term for fine-leaved shrubs and is a vegetation dominated by evergreen shrubs. These include small-leaved ericoid shrubs, including many species of Ericaceae, but also many shrubs of other families, including several endemic families such as Bruniaceae and Penacae. Mixed with the ericoid shrubs are taller proteoid shrubs (dominated by members of the Proteaceae). Its fire frequency is normally linked to the yearly rainfall recorded in the region where the community is growing, which ranges from ca. 250 mm in the lowlands, to 3000 mm in the highest rainfall areas in the mountain (Bond et al., 2004).

Burning triggers different stages in plant life cycles, including flowering, seed dispersal and seed germination in fire-dependent plants, perennial grasses and herbs, including orchids, lilies and other bulb plants, flower prolifically after they have been burnt, often as a facultative response to light, water and nutrient availability. Seeds only become available after a burn, so that population growth is episodic and stimulated by fire. Burning also stimulates seed release from species with serotinous cone-like structures, which store seeds on the plant for years between fires (Bond et al., 2004).

The fire ecology of Renosterveld is not well understood and we require more knowledge about the subject to conserve this rich flora. The response of Strandveld to burning is even less understood than Renosterveld. The dominant broad-leaf shrubs all sprout after burning but their seedlings are fire avoiders. Frequent intense fires in Strandveld are likely to promote the Fynbos elements at the expense of the broad-leaf shrubs. Strandveld is also very susceptible to *Acacia* invaders threatening their existence on many coastal sites as they can easily result in extreme fire intensities with a long residence time, leading sometimes to a complete absence of plant regeneration (own observations).

The succession after fire in Fynbos follows the following specific succession stages:

- Immediate post-fire phase: The first 12 months after a fire
- Youth phase: 4-5 years after a fire
- Transitional phase: Up to 10 years after a fire
- Mature phase: Up to 30 years after a fire
- Senescent phase: Final stage after a fire

One of the main features of fire exclusion for too long periods of time is that fires can today occur at shorter frequencies during the “youth phase”, which can be detrimental for the maintenance of Fynbos biodiversity.

2.1.2 The high rainfall (winter rainfall) regions of the W-Western Cape Province

During the dry summers, south-easterly winds occur frequently, blowing for several successive days. These winds are normally strong, gusting up to more than 50 km/hr (own studies from weather data). Such strong winds many times give rise to fires. In some valleys these winds are more common with the strongest SE winds experienced during the later afternoon and early evening, such as in particular experienced in the Worcester-Wolseley-Tulbagh valley (own observations and weather data studies).

From Hermanus eastwards, foehn-like Bergwinds can occur during the winter period, when dry subsiding air moves off the interior plateau of South Africa in response to strong coastward pressure gradients. Standing waves arise as the air is drawn across the coastal ranges, and strong downwash in their lee, results in warm turbulent winds where the waves reach the surface (Kruger and Bigalke, 1984).

In this region, moist, semi-moist and dry Fynbos (Renosterveld) is found, while on the coastal plateau, Strandveld is common. It is particular in the Strandveld Fynbos, where sometimes heavy infestation with certain exotic *Acacia* weeds can present serious problems, sometimes increasing fire intensities of wildfires more than ten-fold (own observations). In Fynbos growing in mountainous terrain, many other infestation problems occur, such as from *Pinus*, *Hakea* and *Acacia* spp., but these are found in specific areas, such as on the foot slopes of some mountain ranges.

2.1.3 The high rainfall (constant rainfall) regions of the E-Western Cape Province and W-Eastern Cape Province

This region includes the so-called "Southern Cape" and the "Tsitsikamma", south of the Langeberg, Outeniqua and Tsitsikamma mountains. Rainfall in the region is spread throughout the year. The most dangerous fire season is during the winter season, when strong Bergwinds occur at times, particularly where there is a significant contrast in altitude over short distances, along the southern foothills of the mountains (own observations).

The Fynbos here is mostly found in the mountainous terrain ranging from "moist" along the most-southerly aspects, to "dry" along the most northerly aspects of these mountains. On the plateau, mostly moist Fynbos is found in patches (particularly in the Tsitsikamma), but along the coast, some patches of Strandveld can be found, also growing on the coastal sand dunes (own observations).

An interesting feature of Fynbos characteristics here, is that senescent Fynbos is invaded with the "Kyster fern" (*Gleichenia polypodioides*), which retains fuel moisture very well below its dense fern-leaf canopy. As a result, mats of the species do not burn as easily as surrounding Fynbos does. However, if it eventually burns "it burns like hell" (comments from a US scientist visiting the country).

Figure 2.1. Example of mature, moist, Fynbos on the Tsitsikamma plateau in the W-Eastern Cape Province. Photo: C. De Ronde.

Figure 2.2. Prescribed burning in progress in the Drakensberg Mountains. Photo: Terry Everson.

2.1.4 The high rainfall (summer rainfall) regions of W-Eastern Cape Province

The Fynbos in this region is mostly found in the southern-most mountainous terrain, from around Humansdorp, as far as to the east in the W-Amatole Mountains, in the Hogsback area. East of this area, the natural vegetation changes to more typical montane grasslands.

Because of the climatic change here from the constant to summer rainfall regions, the Fynbos has generally-speaking a lower height profile, which can mainly be attributed to a lower rainfall level (500-750mm/year) than the Fynbos in the Southern Cape and Tsitsikamma, (where the annual rainfall ranges from 750-1200mm/year) and where the rainfall is absent during the winter season. Otherwise, not much is known of this particular Fynbos region (own observation).

2.1.5 Low rainfall Fynbos areas of the SW-Karoo and Little Karoo of the Western Cape and Eastern Cape Provinces

Apart from a "transition phase" of dry (low profile) Fynbos on the most N-aspects of the Southern-most mountain ranges of the Western and Eastern Cape Provinces and semi-moist to dry Fynbos found along the S-aspects of the Swartberg Mountains, most other Fynbos found here can be described as "Renosterveld".

Renosterveld was once also an important component of the Fynbos biome on the more clay-rich soils of the coastal forelands and inland valleys, occupying ca. 20 000 km^2. Most of this vegetation type has been transformed by agriculture, since much of its former area was suitable for crop farming. Today, only small pockets remain in e.g. the extensive wheatlands of the Cape regions (Bond et al., 2004).

One interesting feature of fire effects in Renosterveld, is its spectacular flower display. However, otherwise fire frequency normally exceeds 25 years and if it then burns under typical fire weather conditions, it normally burns in the form of a low profile fire, sometimes resulting only in patchy fire cover as a result of lack of continuous fuel layers (own observations).

2.2 Montane Grassland

2.2.1 Introduction to montane grassland ecology

The two main grassland types found in South Africa are the following:

Climatic climax grassland

Succession does not normally proceed beyond the grassland stage because the climate is too cold to permit the development of woody communities, even in the absence of fire. These are called the "True" grasslands (Acocks, 1988). These are short, sour grasslands dominated by moisture-loving species. Some temperate grass species and Fynbos shrubs also occur here (Tainton and Mentis, 1984). Trees are also rare were the grassland occurs, mainly being restricted to the Highveld, as a result of the dry and extremely frosty winters (Bond et al., 2004). On many climatic climax grassland sites, man-made and natural (lightning) fire occur at yearly or two-yearly intervals, as these grasslands normally produce a biomass of 2.5-3.0 tons/ha/year, sometimes even as high as 4.5 tons/ha/year (Tainton and Mentis, 1984). Two fuel models will be provided (models 89 and 90) to represent one-year and >one year examples.

Fire climax grasslands

These occur where the climate will permit succession to proceed beyond the grassland stage into shrubland or forest, but which are maintained as grassland by biotic factors such as fire and grazing (Huntley, 1984). These grasslands are also referred to as "secondary" or "false" grasslands (Acocks, 1988). Degradation of these grasslands leads to invasion of xerophytic Fynbos shrubs such as *Felicia* spp. When secondary grassland is protected from fire for several years, it is eventually invaded by forest-precursor shrubs, which form a dense thicket. Two fuel models will be provided to represent such fuels (models 88 and 91).

2.2.2 Kwazulu-Natal and Mpumalanga Highveld regions

The natural (protected) grassland catchment areas in these regions are managed primarily for the conservation of water resources, biodiversity and the preservation of the soil mantle. Managers of these areas aim to maintain the ecosystems in their natural state and conserve their genetic resource and diversity. Since sourveld areas do not naturally support large numbers of grazers, removal of top-growth by grazing alone is minimal, except in reserves where there are introductions of non-naturally occurring animals. Fire is therefore the only practical means of managing these areas and is consequently widely used to achieve the major aims.

In commercial agricultural areas, fire is used to maintain the composition and vigour of the grass sward to enhance animal production. The main objectives of burning grazed grassland are to:

- Burn off unpalatable growth left over from previous seasons to provide nutritious regrowth for livestock.
- Maintain the vigour, density and cover of palatable perennial grasses.
- Control the encroachment of undesirable plants in the veld.
- Reduce the extent of patch grazing.
- Protect the rangeland (and farm) from wildfires and accidental fires (Morris, 1998; Everson et al., 2004).

2.2.3 Eastern Free State and N-Eastern Cape Grassland

In the N-Eastern Cape (along the foot-slopes of the S-Drakensberg Mountains) basically the same grassland management is applicable as described in par. 2.2.1, apart for the consideration of a dominant agricultural crop land (maize) and/or industrial plantation interface now present there. This thus now demands more intensive fire protection than in the KZN Drakensberg regions, where natural grassland normally borders grazing grassland areas (own observations). This results in the yearly burning of all the mountain grassland before the fire season, with the exception of certain ecologically sensitive areas, such as natural heritage sites and areas where *Protea* communities are growing. Protection of the latter by means of a rotation burning system of 2-3 years, was achieved by means of management/conservation compromises reached to satisfy both disciplines (own experience).

In the far-eastern Free State, mainly grassland is concerned (farming and nature conservation land) requiring a 2-4 year fire rotation. It has been observed, however, that this is seldom achieved as a result of lack of prescribed burning application, and as a result large (damaging) wildfires do occur regularly in the region (own observations).

2.3 Moist Savanna

2.3.1 Introduction to moist savanna ecology

In the so-called "sourveld" grasslands of moist climates and leached, low nutrient, soils, (which are prevalent in the moist grassland and moist savanna regions), palatability is limited to about four months of the year so that plant material accumulates to provide greater fuel mass and flammability during the dry season.

In the higher rainfall regions, most savanna has a relative high production at 2-5 tons/ha/year and fires can occur as regularly as each 2-3 years. However, flame heights experienced are normally relatively low and close to the ground, although crown fires up to a height of 3-4m can occur. However, during most fires, many of the mature tree components will survive fires, even with sporadic crown fires occurring (Huntley, 1984).

An interesting feature of fire behaviour in savanna, is that bush clumps are very resistant to fire. The surface fires will skirt around the edges of clumps, leaving the centres unburned. This is normally caused by the lack of available grass within bushes, not providing continuous fuel layers necessary for carrying such fires to the centre of a bush. The most desirable burning frequency under grazing conditions in moist savanna is annual or biennial burning, depending on grazing and grass fuel conditions (Trollope, 1984).

2.3.2 Fire management within nature reserves

Where such reserves occur within moist savanna, a significant tree component normally exists, with some shrubs also present. This normally results in ideal conditions for patch burning to be applied on a regular scale, providing a suitable burning mosaic for the maintenance of savanna systems, including the provision of adequate grazing for wild animals, such as grazers (as well as browsers). However, above-average seasonal rainfall can cause above-average grassland biomass development, giving rise to extreme wildfire situations, particularly where fire-application in general has been excluded for some years in reserves. Such conditions can present a serious threat to wildlife as well as grazing provision, while even the mature tree component can be killed in the process, disturbing the whole balance of the savanna.

It is thus clear that grassland biomass should be monitored carefully, and this could also assist in reducing fire risk significantly, by providing external and internal (prescribed burned) buffer zones to avoid such disasters.

Sometimes natural savanna areas change in land-use from cattle and sheep grazing to nature conservation to converting such areas to nature reserves, and then related changes in fire regimes are not applied correctly and extreme fire hazards can develop fast. Managers need to check out such land-use changes by monitoring the grassland biomass status regularly and apply fire selectively but correctly, to meet such challenges (own experience and observations).

2.3.3 Fire and game management

Farming with game at a commercial level in moist savanna is becoming more and more popular, when commercial grassland and savanna is converted to game farming. The most important such changes in land-use can cause, is that intensive grazing (by e.g. cattle and sheep) is changed to irregular grazing by game, causing extreme fire hazard in grassland as well as in savanna communities. Such changes should soon be followed by a well-planned fire management regime incorporating fire-ecological requirements. However, most of such land changes are leading to total exclusion of fire for years, which normally causes extreme wildfires, particularly after above-average rainfall causing above-average grassland biomass.

Although such fire hazards are more common in open grassland than in moist savanna, both can be at risk, although probably less severe at lower altitudes, where the savanna status is found more frequently, creating a lesser fire risk where the tree component is more dominant (own observations).

2.4 Dry Savanna

2.4.1 Introduction to dry savanna ecology

The general fire frequency in dry savanna is at a rotation of about 3-5 years, but this will be for a lower frequency during dry periods. In general, dry savanna has a lower fire frequency than moist savanna, actual frequency being dependent on annual rainfall and linked biomass additions in grassland components (Trollope, 1984).

In some climatic regions, seasonal rainfall can fluctuate more than in others, and in the first the frequency of fires is normally over longer periods than in others. In both, bush encroachment can become a problem if fire is excluded for too long and more regular fire application can be desirable to check such problems before it gets a foothold (own observations).

In some nature conservation areas (such as the Kruger National Park) the use of fire as a management tool was excluded for long periods of time, in the believe that only natural fires (such as lighting) can provide the necessary biomass checks in a mosaic-form. However, this resulted eventually in some abnormal grass fuel accumulations, leading to damaging wildfires at an unacceptable scale, and even the loss of human lives (own observations and experience, e.g. with the 2001 "Napi Boulders" fire during 2001). It makes thus sense that block burning has been brought back in this Park as a regular application of fire.

2.4.2 In the dry North-Western regions

Most of the dry savanna in these regions is found in nature reserves and farming areas where game farming has developed as a major industry. In most of these areas, fire is applied infrequent or not at all, resulting many times in serious wildfire damage to the flora and fauna where such high intensities take place under extreme weather conditions.

The status of the burnable biomass (grass, shrubs and sometimes trees) depends on the intensity and length of grazing history, and where large herds of browsers are found (including elephants), the whole savanna landscape can be altered, making it possible to re-assess the use of prescribed burning (methods, frequency and season of burn). It might in most cases be desirable to integrate firebreaks along strategic boundaries with prescribed burning application as well as mosaic burning allowance, but this depends on the local status of fuels within reserves and game farms (Trollope, 1984).

2.4.3 In the Kalahari savanna

The main regulator of prescribed burning application in the Kalahari, is whether the land is used for farming (cattle, sheep, game) or as nature reserves (such as the Kgalagadi Trans-Frontier Park). On farms, grassland biomass management is normally well applied, although "bumper years" in terms of abnormally-high rainfall and subsequent high grass biomass addition, can lead to wildfires, which can be severe in terms of damage to all above-ground vegetation. One such a wildfire occurred in the Nossop riverbed of the Kgalagadi Trans-Frontier Park during 1977/78, which killed most of the tree component in that area, including trees exceeding 50 years of age (own observations).

Although prescribed burning should be applied selectively in nature reserves in the Kalahari Savanna in tandem with lightning fires, the technique is seldom considered. In contrast, surrounding farms normally have a more systematic approach to grassland management by means of grazing rotation, providing a much better grassland biomass control than is normally present within the nature reserves at times. However, the absence of prescribed burning application on farming land in the region, can give rise to bush encroachment (own observations).

2.5 Lowlands, Montane and Coastal (Indigenous) Forest

These forests are normally seriously threatened by outside wildfire exposure, sometimes seriously damaging the forest edge, particularly reducing forest area size of smaller forest remnants in mountainous terrain. The larger forest units (such as found near Knysna, the Tsitsikamma, Amatole, Kwazulu-Natal coastal areas and Lowveld escarpment in the Mpumalanga Province), are normally better protected against fire damage, provided the forest edges are not damaged by (illegal) timber exploitation (own observations and experiences with wildfire damage investigated in forest areas).

To avoid damage of forest edges, special fire protection regimes should be applied, including selective fire application in surrounding vegetation (e.g. in grassland and Fynbos). Fortunately most timber exploitation has been stopped, but the wildfire problem along forest edges will need special attention to protect the remaining forests in South Africa (own conclusions).

From a wildfire investigation point of view, indigenous forests are normally in the path of a wildfire being investigated and then the damage done by such a fire is normally at stake. Questions such as: “Was the forest adequately protected against wildfires?” and “could damage to an indigenous forest have been avoided?” are foremost in the investigators’ program (own experience).

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3 FUEL AND FIRE DYNAMICS

3.1 Fuel Characteristics and their Effects on Fire Behaviour

3.1.1 Fuel classes and fuel models

Fuel sizes, types and classification

Fuels can be composed of any woody or other plant material – either living or dead – that will ignite or burn. The two main fuel sizes are:

- **Fine fuels** – Grass, small branches, pine needles and leaves with a diameter of up to 6mm. They dry very fast and need little heat to ignite. If well-aerated, they will burn rapidly, but if they are compacted, they can burn very slowly.
- **Coarse Fuels** – Thicker branches, logs and stumps. These fuels dry slowly and require more heat to ignite, but once burning, will continue to burn (or glow) for extended periods of time.

Well-aerated fuels – such as South African grasslands – are known for the fast rate of spread of the fire front, particularly when curing is complete. However, grassfires have a relatively lower fire intensity per unit area (heat per unit area) than, for instance, forest (or plantation) fuels with a compacted forest floor consisting of needles or leaves. The latter dry slowly (because they are less aerated) and produce a slower fire rate of spread – though normally with a high intensity per unit area. The vertical distribution of fuel (also called surface-to-volume ratio) is therefore a very important factor determining potential fire behaviour, together with fuel volume. Fuel in grasslands, savanna and forests can be classified in three main groups, namely ground fuels, surface fuels and aerial fuels (Trollope et al., 2004).

- **Ground fuels** include the combustible material below the loose surface litter and comprise decomposed plan material. These fuels support glowing combustion in the form of ground fires. Although very difficult to ignite, these fuels are persistent once ignited (Brown and Davies, 1973). Smoldering ground fuels have the habit of sometimes slowly continuing to glow without any visible smoke above-ground during mild weather conditions, and then to "stand-up" suddenly at the first exposure of wind over the surface (own observations).
- **Surface fuels** occur as grass swards, shrublet communities, seedlings and forbs. They also include surface litter like fallen leaves, twigs and bark. All these materials are fine fuels and can support intense surface fires in direct proportion to the quantity of fuel per unit area (Brown and Davies, 1973).

- **Aerial fuels** include all combustible material, live or dead, located in the understorey and upper canopy of tree and shrub communities. The main aerial fuel types are epiphytes, branches and foliage of trees and shrubs (Brown and Davis, 1973). This fuel type supports crown fires.

Crown fires can occur where continuous fuels occur on tree crowns, such as in dense savanna and industrial plantations (Trollope et al., 2004).

The fuel classifications of Southern African natural and man-made fuels will be region-specific, but will not all be provided here, because adjustments, additions and deletions might be necessary in specific cases (mostly required per wildfire investigation). The basic fuel classifications and fuel model examples for the main regions of South Africa have been provided in Appendix I.

For fuel modeling purposes, a different fuel component classification is used for INPUT in the BehavePlus fire simulation program (tons/ha) (Burgan and Rothermel, 1984):

- 1-hr fuel load
- 10-hr fuel load
- 100-hr fuel load
- Live herb fuel load
- Live woody fuel load

3.1.2 Moisture content, moisture holding capacity and fuel moisture extinction

Fuel moisture is obtained from the atmosphere, precipitation and the ground. Local climate will determine the relative humidity of the air, and when the air temperature is high the moisture content of the fuel will be high with low humidity, providing low moisture contents. However, sudden increases and decreases in air humidity – such as when a cold front approaches or when bergwind conditions are suddenly experienced – will on their own not have an immediate effect on fuel moisture content of coarser, heavy fuels. Air humidity is significantly influenced by air temperature, wind, precipitation, time of the day, topography and other factors, which in turn all have a combined significant effect on fuel moisture content (Trollope et al., 2004).

The moisture holding capacity is the rate at which moisture is released during the drying process of dead fuels. These characteristics are thus dependent on the thickness of fuel particles, the density of the fuel component as well as its exposure to elements and subsequent drying rates.

The dead fuel moisture of extinction is the characteristic moisture content of the dead fuel above which a predictable steady rate of fire spread is not attainable. Dead fuel moisture of extinction is a fuel model parameter, used as INPUT in the BehavePlus program (Andrews, 1986; Andrews and Bevins, 2000; Andrews and Chase, 1986).

3.2 Dynamics of Man-made Fuels

3.2.1 Forest and industrial plantation slash fuels

Indigenous forests seldom have sufficient burnable material on the forest floor to carry a fire, and their moisture holding capacity is very high. These natural forests are thus normally not an issue in South Africa regarding fire-related problems inside the forests. However, man-made forests such as industrial (*Acacia*, *Eucalyptus* and *Pinus*) plantations – normally even-aged – with single tree species established per compartment, are regularly exposed to wildfires and as such require a closer look at their fuel components.

Apart from forest floor, understorey and crown fuels, these plantations are normally influenced by slash fuel additions, such as pruning and thinning slash (while trees are in stand-form) and clear felling slash (after clear felling and exploitation of timber from the felled trees). The latter is the most significant and drastic slash addition that has to be considered, as it increases fire hazard significantly and suddenly.

After clear felling, slash is either broadcasted and then burned or not burned (retained), stacked on rows or stacked in heaps, then to be burned. Each of these fuel manipulation methods has a significant effect on fire hazard after clear felling, particularly when left unburned on site (own conclusions). Such fires seldom become uncontrollable, but some escape when weather conditions change suddenly. Training of safe application of agricultural residual burning is imperative (Fig. 3.1)!

3.2.2 Post-harvest fuels: Maize, sugar cane and wheat

When maize is still standing, dry, close to harvesting, it can present a serious fire threat if ignited during strong windy conditions. Fires in such fuels have been found to create a wildfire source, which can from there spread into e.g. montane grassland. When maize has been harvested, harvesting slash (mostly dry leaves and stems) can also present some fire threat, but this can normally only present a low profile fire, which can be extinguished with ease. On most lands, farmers also burn such fuels soon after harvesting has been completed.

Sugar cane is normally burnt by farmers before harvesting by means of prescribed burning, to burnout understorey and animals (e.g. snakes and rodents). Such man-made fires seldom become uncontrollable, but some escape when weather conditions change suddenly.

However, even if becoming uncontrollable, they seldom escape from cultivated blocks, because these are normally surrounded by clean roads to provide easy access.

In wheat lands, most harvesting cutting heights seldom provide any fire threat, but in some regions, these cutting heights are yearly rotated by doubling stubble heights, which can carry a fire, which can become uncontainable, fast. Harvesting slash leftovers from wheat in e.g. the Overberg region, is normally collected on clear contours in the lands, and then burned by the farmers.

Figure 3.1. *Eucalyptus* slash prescribed burned, which later developed smouldering fire problems, which in turn gave rise to the origin of a wildfire. Photo: C. de Ronde, Herold, Outeniqua Mountains. Training of safe burning of wheat straw residuals is practiced in many countries globally where this kind of fire use is not prohibited by law. Photo: GFMC.

Figure 3.2. (a) Crown fire developing from surface fire increasing in fire intensity as it spreads through this young mixed birch (*Betula pendula*) / pine (*Pinus sylvestris*) stand in Germany, and (b) in a mature jack pine (*Pinus banksiana*) stand during a preparatory experimental burn of the International Crown Fire Modelling Experiment (ICFME) in Canada in 1991. Photos: GFMC and Brian J. Stocks.

3.3 Fuel Combustion and Fire Spread Processes

3.3.1 The combustion process

The study of fire behaviour necessitates a basic understanding of the phenomenon of combustion. According to Brown and Davis (1973) this is an oxidation process comprising a chain reaction where the heat energy released during a fire originates from solar energy via the process of photosynthesis.

The so-called fire triangle consisting of FUEL, HEAT and OXYGEN form the three essential elements (legs) of the combustion triangle. The role these three elements play in fire can be illustrated as follows (Heikkilä et al., 1993; Leone and Lovreglio, 2010):

- **Oxygen** – 21% of the air is oxygen. A reduction in oxygen to 15% extinguishes a fire. This can be achieved by either smouldering or covering the fire using sand, fire swatters, sacks and branches.
- **Fuel** – Wildfires are primarily controlled by focusing on the fuel component side of the fire triangle. This is done by confining the fire to a definite amount of fuel by means of a fire line or barriers, if available. By keeping the flames within the fire line, the fire is controlled. The fire line is usually constructing by removing the surface fuels with tools or equipment so that the mineral soil is exposed, or by wetting down the width of the fire line with water.
- **Heat** – In order to ignite a fire, fuel must be brought to its ignition temperature. If the heat drops below the ignition temperature, the fire goes out. Water is the most effective agent for this reduction of heat. Smoldering the fire with sand also helps to reduce the heat, thereby extinguishing the flames.

3.3.2 Fire spread: Surface fire spread dynamics

Besides spotting, the transfer of heat in a moving fire front is mainly due to convection and radiation. Convection currents are primarily responsible for the preheating of the higher shrub layers and tree crowns, while the radiation from the flames accounts for most of the preheating of the fuel ahead of the fire front (Luke and McArthur, 1978). Heat transfer can take place in the form of:

- **Radiation** – Transfer of heat through space, in any direction, at the speed of light.
- **Convection** – Transfer of heat by the movement of hot air and other heated gases.
- **Conduction** – Transfer of heat within a fuel unit, or from one fuel particle to another, by direct contact. This fuel heating process has little relation to vegetation fires.
- **Mass Transport** – Particularly important in wildfires, when e.g. spotting occurs.

The two parameters of Surface Fire Spread are Rate of Fire Spread (measured in metres per minute) and Fire Line Intensity (expressed in kilowatt per meter length) of the fire front. Both play a significant role in the simulation of fire behaviour.

3.3.3 Fire spread: Heat transfer, crown fires and spotting

Although the main spread of fires will be through Surface Fire Spread (see par. 3.3.2), these fire lines can give rise (through heat transfer) to torching, scorching, crown fires and spotting. With regard to the first two, the terms explain these features (Trollope et al., 2004).

- **Crown fire –** A fire that advances through the crown layer. The vertical arrangement of fuel (such as "ladder fuels"), type of fuel and volume, as well as the height of tree crowns above the surface, will determine how easily crown fires can develop. The continuation of crown fuels is also an important factor to what extent a crown fire can maintain its spread in crowns (Figure 3.2).
- **Spotting –** This is one of the most dangerous characteristics of large wildfires in terms of fire suppression. In the case of long distance spotting, burning embers are carried several km from the main fire front, to ignite new fires far ahead of the main burning fire. Chances are that this spotting will normally be on the right flank of the advancing fire front because of the tendency of the wind velocity factor to advance in a clockwise direction with increasing height (Davis, 1959). Often the direction of the upper winds is different from the direction of the surface wind, which can cause further deviation from the direction of maximum fire spread. Far-distance spotting normally only occurs in one or two spots, but shorter-distance can be experienced in abundance, becoming uncontrollable fast (own observations).

3.4 Fire Behaviour Dynamics

3.4.1 Fire behaviour parameters

Rate of Fire Spread

The rate at which a fire perimeter expands depends on fuel, wind, topographical and weather conditions. Fuel quantity, its vertical distribution, fuel type and continuity will determine how fast a fire can spread from its point of ignition, and when it will reach its *quasi-steady* state for prevailing weather conditions. If fire is ignited along a fire line, such a fire is also more intense – with a faster rate of spread – than if fire is ignited from a single point (Cheney and Sullivan, 1997).

Other factors influencing rate of spread are fuel moisture (which has a negative effect) and slope (which has a positive effect on head fires and a negative effect on back fires). Aspect is also an important factor, with dry northerly aspects promoting the rate of spread, while the moist southerly aspects reduce the rate of spread of fire. Wind speed has a positive effect on back fires burning against the wind. Air temperature has a positive effect and relative humidity has a negative effect on rate of spread. Generally, wind and fuel aeration have the most instantaneous effect on expanding the rate of spread of the fire front (Trollope et al., 2004).

In almost all forest and grassland fuel types, the rate of spread of a fire increases in direct proportion to the quantity of available (burnable) fuel. All other factors being equal, the rate of spread of a fire front in grasslands will double with an increase from 3 tons/ha to 6 tons/ha. In grass fuels, the relationship is not complicated, provided other fuel characteristics such as fuel particle size and fuel bed compactness remain constant. In forest fuels the question of fuel compactness becomes a critical parameter and in some cases both fuel quantity and compactness tend to compensate each other (de Haan, 1996).

Flame Length and Flame Height

Flame length can be equal to flame height (in no wind situations), but flame length > flame height where the wind is tilting the first down, towards the soil surface. Flame height is one of the four main fire parameters to be considered (Andrews, 1986), and is an important parameter for predicting the height of crown scorch in the canopy of trees. Another characteristic, is that the stronger the surface wind, the greater will be Flame Length >Flame Height (own observations).

Fire Intensity Parameters

The two most important ways to express fire intensity are Fire Line Intensity (kW/m) and Heat per Unit Area (kJ/m^2). Fire line intensity can be regarded as the heat released per second from a meter-wide section of the fuel extending from the front to the rear of the flaming zone (Byram, 1959), and is equal to the product of the fuel load, heat yield and the rate of spread of the fire front.

The heat per unit area is the heat released from a square metre of fuel while in the flaming zone, and is equal to the reaction intensity times the residence time. Fireline intensity and heat per unit area are regarded as two of the most important fire behaviour parameters describing fire behaviour (Andrews, 1986).

3.4.2 Type of fires

Fire can also be classified according to their position along the fire perimeter, and their forward spread in relation to the direction of the wind.

- **Head fire –** A surface fire driven by wind and/or assist by slope, assisted by slope, driving the flames towards the fuel. Can be regarded as the most rapidly spreading part of a fire perimeter. Sometimes, such as in grasslands, fuels are pre-heated so rapidly that large volumes of flammable gases do not mix sufficiently with oxygen to permit complete combustion. In this way, compacted lower layers of fuel may even remained unburned (Cheney and Sullivan, 1997).
- **Back fire (backing fire) –** A surface fire burning against the wind and/or downslope, with flames leaning backwards over the already-burned ground (Figure 3.3). This part of the fire perimeter burns slowly but efficiently and leaves little residue

Figure 3.3. (a) A backing fire spreading in an open heathland (*Calluna vulgaris*) ecosystem in Germany, and (b) in a dry grassland fuel in Kruger National Park during the Southern Africa Fire-Atmosphere Research Initiative 1992 (SAFARI-92) field research campaign. Photos: GFMC.

Figure 3.4. A large fire in progress in Mpumalanga, in an industrial plantation and surrounding montane grasslands. Note massive smoke development, indicating that special measures should be taken when this fire approaches (and spreads across) public roads in front of the head fire. Photo: Alexander C. Held.

behind. These fires also produce less smoke than head fires, and can in many cases be brought under control.

- **Flank fire –** A surface fire burning diagonally to the direction of the wind, intermediate to a head or back fire. These (fires) form the parts of a fire perimeter which burn approximately parallel to the main direction of spread of the fire front, but do not generally burn as rapidly or intense as a head fire, but spread faster and more intense than a back fire. Changes in wind direction can at any location change a flank fire into a head fire or back fire, along any location of the fire perimeter.
- **Spot fire –** A fire that occurs ahead of the main fire, and is started by burning embers carried from the head fire portion of the fire perimeter, sometimes starting new fires great distances ahead of the main fire front. As spot fires sometimes jump across fire breaks, they are sometimes referred to as "jump fires".

3.4.3 Fire weather

Wind

Wind is the most dynamic variable influencing fire behaviour. It provides more oxygen to the fire front and affects the rate at which fuels dry ahead of the fire front. This causes pre-heating in front of the fire by means of radiation from the flames, thereby preparing it for ignition and promoting the spread of the fire front.

An increase in wind speed will increase the drying rate of fuel, while the wind direction will determine in what direction the back fires and head fires will spread. The stronger the wind, the faster will be the rate of spread of the head fire burning with the wind. The stability of the air will also influence both wind speed and direction, and unstable air – as experienced in rough terrain or with an oncoming frontal system – can also change the direction and variability of the wind speed (Trollope et al., 2004).

Fire fighters should be constantly aware of the wind conditions near a fire and preferably measure wind speed regularly with a hand anemometer. If this instrument is not available, Table 3.1 can be used to estimate wind velocity.

Table 3.1. Modified Beaufort scale and field observation guide to estimate wind speed (based on Heikkilä et al., 1993, adjusted).

Wind class	Wind speed (m/s)	Wind speed (km/hr)	Field observation guide/description
1	0-1.5	0-5	Very light – Smoke rises nearly vertically, small branches sway and tall grasses sway and bend.
2	1.5-3	5-11	Light – Trees of pole size in open sway gently, leaves are loose and moving.
3	3-5	11-18	Gentle breeze – Tops of trees in dense stand sway and crested waves are formed in lakes.
4	5-8	18-28	Moderate breeze – Pole-size trees in open sway violently, dust is raised in the road.
5	8-11	28-40	Fresh – Branches are broken from trees and resisting movement when walking against it.
6	11-14	40-50	Strong – Tree damage may occur and progress is difficult when walking against the wind.
7	14-17	50-60	Moderate gale – Severe damage to trees and very difficult to walk into the wind.
8	>17	>60	Fresh gale – Intense stress on all exposed objects, trees and buildings.

Precipitation

In South Africa, this is mostly in the form of rain, but can also be in the form of dew, heavy fog, or even snow at high altitudes. Like air humidity, the occurrence of precipitation will increase fuel moisture rapidly to levels at which fires will not burn.

Lack of rainfall during periods of drought not only decreases fuel moisture, but a considerable leaf drop will occur as a result of moisture stress. Significant rainfall may cause marked growth increases in short-lived grass, and in some summer seasons the may produce above-average grass fuel loads. However, in South Africa the natural grasslands are dynamic and high summer rainfall can be followed by long dry winter periods, when curing will produce above-average available fuel and thus an increased fire hazard (Trollope et al., 2004).

Air Temperature

The main effect of air temperature is to reduce fuel moisture. As temperatures are normally cold at night, fuel moisture will be higher and wildfires can be brought under control during these periods. However, as the temperature rises after sunrise, reaching a peak during the 12h00 to 15h00-period (if there is no sudden weather change as a result of oncoming frontal systems), this time of the day will be the time when fires reach their highest intensities. However, this pattern can sometimes be different during severe Bergwind conditions (own observations).

Relative Humidity

RH can be described as "the ratio between the amount of water vapour a unit of air contains as a given temperature, and the amount of water vapour the unit of air can contain at the same temperature and pressure". For practical purposes, the effect of atmospheric pressure can be ignored, as it is very small. A high RH means that there is a high percentage of moisture in the air and *vice versa* (Trollope et al., 2004).

The amount of moisture in the air affects the amount of moisture in plant fuels (Heikkilä et al., 1993). The RH of the atmosphere influences the moisture content of the fuel when it is fully cured (Luke and McArthur, 1978).

3.4.4 Topography

The steepness of a slope can have a pronounced effect on fire behaviour, as the degree of steepness will determine to which extent fuel is dried out before the fire front. However, in South Africa the steeper the slope and the higher the altitude, the less soil will be available for vegetation to grow in, and the more rocky the surface becomes causing gaps in available fuel; thus creating breaks in continuous fuels will be more common, providing more irregular fire spread and isolated flare ups or flaming particularly in Fynbos (own observations).

Aspect

This can have a significant effect on fuel drying rates and subsequently on northerly aspects (in the southern hemisphere) fuels are more exposed to direct sunlight. However, they also receive less rain on the rainfall shadow of prominent mountain ranges. In contrast, southerly aspects receive more rain and are thus wetter, also receiving less direct sunlight.

Slope

Slope significantly influences the forward rate of spread of surface fires, by modifying the preheating of the unburned fuel immediately in front of the flames, when burning uphill. Conversely, a down slope decreases the rate of spread of surface head fires (Luke and McArthur, 1978), and at low wind speeds, has the effect of converting a head fire into a back fire.

3.4.5 "Reading" smoke development and identification of danger areas

Unfortunately, smoke development prediction models for South Africa are still not available. However, when planning prescribed burning, the main direction of the wind should be know, and from such information smoke development – in the direction the wind blows into – should be considered, particularly if this is in line with airports and runways, public roads and intensive cultivated land it may affect (e.g. vineyards and orchards). Urban areas in its path should also be identified. In a wildfire situation, however, little can be done with smoke from wildfires, apart from precautionary measures, to pre-empt danger to the public, in which case such communities can be warned in advance. Traffic authorities should also be warned if smoke can drift across public roads, as this can cause serious vehicle accidents, and even loss of life as a result (Figure 3.4; own experience).

3.4.6 Large fire behaviour

When large wildfires develop so-called "fire-storms" (also referred to as "mega-fires") the first action that should come to mind of the fire fighters is to evacuate people in front of the head fire for safety purposes. This also goes for all fire fighters, and e.g. the application of fire (counter fires) even from flanks should rather be avoided for safely purposes and should only be attempted on flanks by very experienced fire managers, and then only to save lives and property. Such action should then rather be postponed until conditions become less turbulent and generally milder, and should then only be applied by experienced and trained fire managers.

Experienced fire managers will identify fire storm conditions from "reading" the smoke columns, weather conditions on site as well as by assessing fuels, vegetation and topography in front of head fires, and when simulating this in terms of predicted fire behaviour with computer assistance or from experience (or both). Fire managers should then also stop wasting manpower, ground and aerial fire fighting equipment because this can be dangerous and lead to futile expenses. All should remain on standby until conditions become more favourable for fire fighting action (own experience).

3.5 Characteristics of Large and Multiple Fire Spread

3.5.1 Effects of wind on fire spread

It is important to underline the dominating role that wind plays in fire behaviour. Wind is **the** most important variable effecting fire. A slight change in wind speed can affect fire behaviour significantly. Even slight increases in wind speed or changes in wind direction can make the difference between a controlled and an uncontrolled fire. The impact of wind on fire behaviour is many times underrated with serious consequences. Conversely, the general relationship between wind and fire spread can be summarized as follows:

Figure 3.5. (a) Surface fire spreading upslope in dry Fynbos (Renosterveld) during a wildfire near Wolseley, Western Cape Province, and (b) in Mpumalanga. Photo: CapeNature and Alexander C. Held.

Figure 3.6. Stand of *Pinus radiata* exposed to only a light intensity fire because of restricted available fuel on the forest floor. As a result tree crowns were only exposed to heat scorch from the flames. However, as the trees are very susceptible to wildfire damage, mortality was still recorded in most of the trees. Photo: C. de Ronde.

- Ambient wind will modify the pattern by adding an additional spreading component, so that the fan-shaped pattern on a hillside will deflect to one direction or the other, and a predominant direction of travel will be created on level ground.
- In the uncommon circumstance of a strong downhill wind, the fire will burn down the hill only to the degree that the ambient wind can overcome the fire's own tendency to burn uphill.
- In a fire having an extended perimeter, the direction of burning may vary locally in almost any direction depending mainly on the ambient wind, However this is also influenced by fuel, terrain and air currents created by the fire itself.
- High winds tend to produce long, narrow burn patterns (de Haan, 1996).
- Wind speed will take a fire from the initial spread phase into a dynamic spreading situation.
- Wind has the effect of changing the flame angle so that flames are driven into unburned fuel and as a result will create more efficient pre-heating by radiation thus facilitating increased fire rate of spread.
- In grassland fuels, an added complication is that when wind speed exceeds 50 km/hr in the open, the rate of forward spread tends to decrease. The main reason for this is that the head fire becomes narrow and tends to become fragmented into a number of even narrower heads so that a deceleration process will result (de Haan, 1996).
- In mature industrial plantation stands with closed crown canopies, wind speed (as measured 10m above a stand) can be reduced by as much as 75% inside the stand, resulting in significant reduction in the rate of fire spread (Albini, 1976, in de Ronde 1988).
- Spread models assume that the wind is blowing steadily, which is seldom the case. Sometimes large variations occur in both strength and direction. This does not appear to have a significant effect on predicting fire spread by using mean wind speed as the parameter.
- A gusty variable wind causes fire to travel irregularly, which can be extremely dangerous for fire fighters. This danger can apply in any fuel situation.
- Changes in wind direction are not only determined by surface roughness, topography or atmospheric instability but in the long term sense wind in the southern hemisphere will tend to back in direction with the approach of a cold front, changing in anticlockwise direction from north through northwest to west and southwest as the front approaches (Luke and McArthur, 1978).
- Fire whirlwinds can vary from small flame whirls a few metres in height and diameter to giant fire tornados many hundreds of metres high and encompassing an area of some hectares. They are one of the most striking features of fire behaviour, especially on large stationary fires associated with slash or debris removal.
- Very sparse grasslands may be only partially burnt if the wind is very strong. This effect will show up in aerial photographs as narrow lines of burnt ground, sometimes

not continuous, across intensively-grazed grasslands, and these are aligned to the wind direction (Cheney and Sullivan, 1997)

3.5.2 Topographical influences on the spread of fire

The steepness of a slope can have a pronounced effect on fire behaviour, as the degree of steepness will determine the extent to which fuel is dried out before the fire front. Here follow some of these effects:

- Northerly aspects dry fuel faster than southerly aspects as they are more directly exposed to sunlight. Conversely, southerly aspects are less exposed to direct sunlight and subsequently dry more slowly. This variation is very marked in Fynbos, and can subsequently influence fire behaviour significantly.
- The most important effect of slope is that it can significantly influence the fire rate of spread, making it faster uphill and slower downhill (Trollope et al., 2004).
- The combined effect of wind and slope will change the flames to a very acute angle so that once the slope exceeds 10° to 20° the flame front is virtually a sheet of flame moving parallel to the slope. In such cases the fire propagation process is almost one of continuous flame contact.
- In most South African fuel types, the fire rate of spread will accelerate burning uphill, and will most probably reach conditions on hill crests favourable for multiple spotting (own observations).
- When considering large fire behaviour, particularly in industrial plantations and in Fynbos, the effect of slope can be virtually disregarded as far as fire spread is concerned. Fire behaviour is then dominated by the spotting process, but slope continues to have a significant influence on suppression difficulty (Luke and McArthur, 1978; own experience and observations).

3.5.3 Characteristics of fire spread through varying fuel patterns

In general, well-aerated fuels will provide a faster rate of fire spread than compacted fuels because well-aerated fuels facilitate fast drying. Considering this, it is clear that grassland fuels will dry the fastest of all main fuel types found in South Africa. This is in relation to the lowest fire intensity experienced in this fuel of all fuel types. These characteristics are particularly prominent in montane grassland. In savanna, the tree and shrub component in this fuel not only reduces the rate of fire spread, but a significant tree cover also reduces fire intensity, with the exception of crowning occurring where trees are present during adverse weather conditions and a relatively older grassland fuel base.

Looking at the characteristics of fire spread in Fynbos, a wildfire in this fuel type normally causes an abundance of flare-ups, particularly where larger shrubs are common (e.g. Proteas). A high degree of exotic invaders can also increase fire intensity dramatically, although not so much the fire rate of spread, as this will remain generally below the rate of spread in e.g. grassland. However, extreme fire weather in such infested vegetation will be more common, with more spotting and flaring. Fire behaviour in general in Fynbos is also very much significantly related to age: The older the vegetation, the more extreme fire behaviour will be.

In industrial plantation fire behaviour is very much related to the degree of crown canopy closure. The more tree canopies are closed, the more compacted and "down" the fuel layers will be. In complete crown canopy closure circumstances, fuel drying rates are very slow, and this can bring even very irregular wildfires down to low profile (containable) flame heights with a constant rate of fire spread heights with a slow rate of fire spread, particularly in mature even-aged *Pinus* stands.

Comparing even-aged *Acacia*, *Eucalyptus* and *Pinus* stands, the one outstanding difference between them is that mature *Acacia* is providing by far the least burning probability, in most cases not even allowing a wildfire to burn into the stand, providing an excellent firebreak and the best line from which wildfires can be fought successfully. However, neglected *Acacia* stands (so called "Wattle Jungles") not only present a serious fire hazard, but also created serious invader problems to adjoining land, which is difficult to eradicate and which can subsequently develop into an even more serious fire hazard. Managing of *Acacia* stands is thus very important, particularly from a fire management point of view. *Pinus* stands normally do not provide the danger *Eucalyptus* stands provide because the first provides better decomposition (and thus lower fuel load levels) and lower fuel profiles (Fig. 3.6). Both *Eucalyptus* and *Pinus* slash can be regarded as some of the most dangerous fuel situations, because slash deposited from tree crowns after clear felling is normally providing a heavier loading. However, rates of fire spread in both fuel situations is normally slow and irregular, with long residence times, particularly where slash heaps are present (own observations).

3.5.4 Fuel characteristics – wind speed interactions

The denser a surface fuel the more will be its resistance capacity to wind and its subsequent reduction in wind speed. Put differently, the higher the surface-to-volume ratio of surface fuels, the more effective such fuel can reduce wind speed, because the fuel drying rate will be lower, subsequently fuel moisture will be maintained for a longer period.

One underrated characteristic in fuels is the ability to decompose surface fuels. This is normally not a factor in grasslands and savanna, as decomposition can normally maintain adequate decomposition rate to avoid fuel accumulation. However, in some abnormal fuels decomposition is too slow or even absent, such as in *Gleichenia polypodioides* (Kyster Fern), which normally invades Fynbos, which is developing beyond optimum fire-requirement age, which has the ability to accumulate fern layers of more than two metres thick, presenting extreme fire hazards during wildfires (de Ronde, 1988).

Some *Pinus* species can also accumulate forest floor material (mainly in the form of pine needles), such as *Pinus patula* at high altitude. In some cases forest floor loading of more than 800 tons/ha have been recorded (Schutz, 1981). Some Fynbos infested stands in Strandveld (with heavy *Acacia Cyclops* loading) can accumulate heavy fuel loadings, which do not dry easily, and even remain residual after wildfire, prohibiting natural regeneration of Fynbos.

Figure 3.7. Stand of *Pinus radiata* subjected to a high intensity fire with a long residence time, as is evident from the total defoliation of the tree crowns as a result of crowning fire and the abundance of ash layers on the forest floor. The trees are very susceptible to wildfire damage and complete mortality was here recorded. Photo: C. de Ronde.

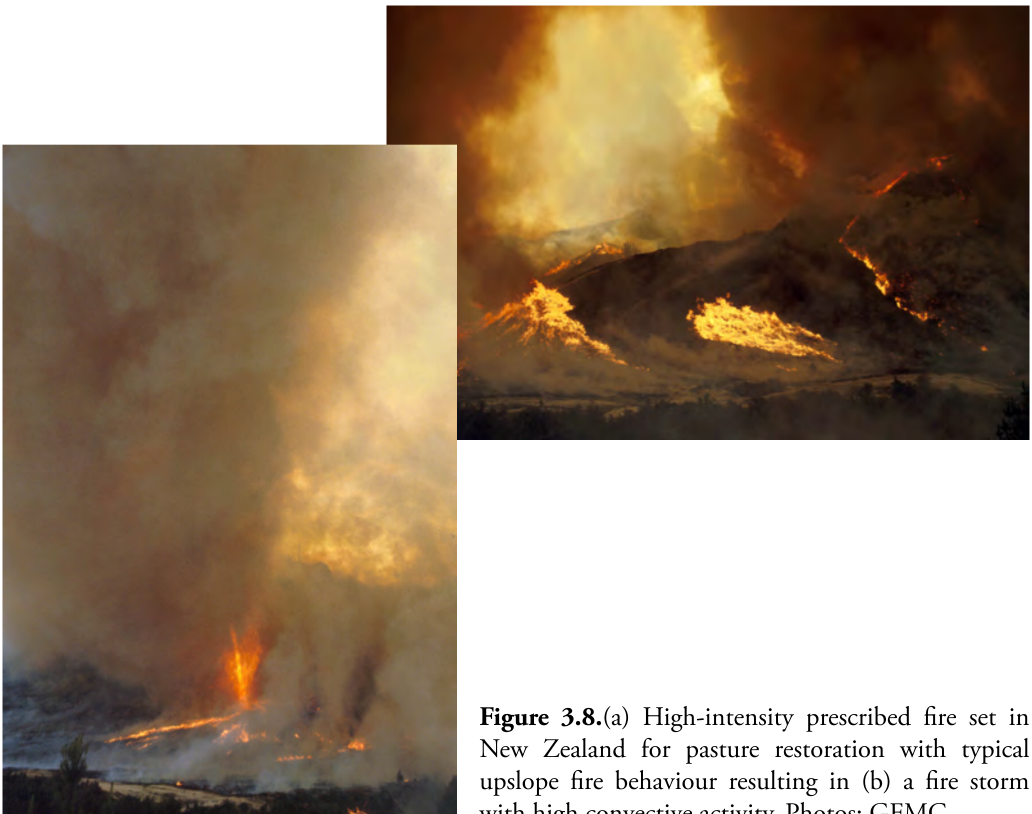

Figure 3.8.(a) High-intensity prescribed fire set in New Zealand for pasture restoration with typical upslope fire behaviour resulting in (b) a fire storm with high convective activity. Photos: GFMC.

3.5.5 Rate of fire spread – fire intensity interactions and relation to fire residence time

The slower the fire rate of spread, the higher the fire intensity will normally be, and the longer will be the fire residence time. Long residence times will normally give rise to ground fire exposure (Figure 3.7), particularly in high forest floor loadings, either in mature tree stands or in slash (deposited onto the original forest floor) after industrial plantation stands are clear felled.

Ground fires have been identified in certain fuels (particularly in industrial plantations), creating a serious added fire hazard if not guarded for long periods of time, as they can be a source of the development of "new" surface fires, which in turn can develop into wildfires again. Where such addition fires do cause further damage and this has been identified as a new fire source, this develops many times in further Legal action (own experience).

Fire residence time is thus directly related (positively correlated) to fire intensity, as the longer fuel is exposed to fire, the more chance the fire can have to increase fuel consumption on such as site, which will then also lead to increased fire intensity. This will then also increase fire residence time and possible exposure to ground fires in continuous forest floor loadings (own observations).

3.5.6 Fire storms: Development and characteristics

Fire storm situations normally develop as a result of extreme fire weather conditions (such as strong, warm and dry winds), continuous (dangerous) fuel layers as well as suitable topography (mostly in mountainous terrain). Fuels with an abundance of flaring potential and spotting, can also contribute to conditions favourable for fire storms. These conditions are normally also linked to turbulent windy conditions.

Fire storm conditions are extremely dangerous and such storms can be regarded as providing conditions too risky for the application of any counter fires, and normally warrant immediate evacuation of all people at, near or in the path of such fires. In South Africa, most mortality during Veld and Forest fires can be attributed to fire storms.

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4 CAUSE AND ORIGIN DETERMINATION

4.1 Determining the Origin of a Fire

4.1.1 When investigated within days (1-2 weeks) after a wildfire

This is the time when the evidence at the origin of a wildfire is still as fresh as it can be, unless tampering has taken place at the site, to hide material and signs. The best way to avoid this is by means of safeguarding the site with a rope, chain or any other means to protect such evidence. However, this will not always be possible, so when arriving at the site of fire origin, one should be on the lookout for such changes.

Another type of disturbance of such a site can be that some person(s) had deliberately burned fuel adjoining such a site, to confuse the investigator. Where such disturbance is a probability, it is necessary to check this out on the hand of aerial photographs, satellite images or concrete evidence from witnesses. Also do not take for granted that a fire started from one ignition point or a fire line, as experience has it that it can be ignited at a single point but that someone (or a team) used this point to start a fire line, with sometimes grave consequences (own experience).

Also check for other points of ignition, because there can be more that one, or even multiple ignition points, and such probabilities should always be checked. Never rule out other origin scenarios, until such time that all evidence has been collected, verified and checked, and a final scenario can be drawn up (own experience).

Some basic evidence, reports, such as pilot and Incidence Command logs, can greatly assist in the investigation. Topographical maps (with property boundary overlays), weather data and real-time photographs can also assist in the structuring of events. However, most important is to use the fresh evidence on site to advantage in the investigation, and take photographic evidence of this, as such proof can be lost with time as a result of decay.

The basic premise of wildland fire investigation is the same as that for structure fires, namely to determine the area of origin first and then to proceed to establish what fuel was present and what source of heat ignited it. The determination of area of origin is generally carried out by examining the fire scene for indicators of direction of fire travel. Once a pattern of these directional indicators can be established, it can be used to point back towards the area of origin. Such interpretive signs should be used strictly as *indicators* – none as foolproof and none as facts. With the complexity of interior fire behaviour, modified as it is by weather, terrain and suppression activities, it is the *predominant pattern* of indicators that must be sought out, not a single isolated one here and there (de Haan, 1996).

We prefer to collect as many as possible evidence items as possible for cross-reference to prove where the fire started, making particular use of photographs (particularly from the air at the time of the fire) and concrete evidence from the fire fighting teams on site soon after the fire became uncontrolled.

Take advantage of being appointed to investigate a wildfire site of origin so soon after the fire occurred, and get to the site as soon as possible to ensure the field evidence is fresh. This may provide an important advantage over other investigators coming on site at a later stage (own experience).

4.1.2 When investigated within 15-60 days after a wildfire

Although some evidence may be lost as a result of this delay in time after the fire, procedures to be followed can many times still be applied as explained in the previous paragraph. However, the following main features and differences in approach should be followed per main vegetation and fuel type:

Grassland

The dynamic South African grasslands can regenerate very fast after a fire, and may have changed completely even within 1 – 2 months after a wildfire. One should look at the panorama beyond the green grass return, as the dead remains of the grass may still be there, in which case it can still be used as evidence, using the laid down procedures (own experience). However, if possible, such evidence should be photographed and compared with earlier photographic evidence, if available for cross-checking purposes. Where more than one possible ignition point is present on the origin site, attempt to link such points to the initial area burnt and then try to use elimination procedures if possible (e.g. from cooking fire sites, slash ignition points and fire lines), where applicable (own experience).

Savanna

As for grasslands, although the return of grassland regeneration will here normally be less pronounced. However, for the damage done to the tree component and scrub vegetation, it is in fact better to postpone the investigation until about 1-2 months after the fire, by which time the extent of vegetation recovery will be better visible to make an assessment of this more meaningful.

Fynbos

Evidence on site in Fynbos will normally remain longer available than is the case in grasslands, but such evidence can also wear off with time. Also keep in mind that the first regeneration in Fynbos is also mainly grass and as such it may present similar "wear-and-tear" as in grassland. However, the speed and density of regeneration depends directly on the fire intensity and residence time: The more intense the fire and the longer the residence time, the slower seedlings will regenerate after the fire, with some species not returning at all after an extreme wildfire (own observations).

Industrial plantations

Within standing plantations, it is normally in order to start an investigation within 60 days, as most of the evidence (and damage to the trees) can then still be collected. The only problem will be evidence of tree crown fires, because by then the crown needles scorched will have fallen off. Crown fire evidence (important fire spread indicators) will have to be collected from aerial photographs taken after the fire.

It is in fact better to conduct an investigation a few weeks after the fire occurred, because by then ground fire evidence will be finally visible, as these fires will then be "out", and access to the evident holes in the ground (from smoldering root channels and humus pockets) can be available directly.

One of the main problems facing the investigator will be that clear felling of damaged stands will normally start immediately after the wildfire occurred, to salvage as much timber as possible before permanent mortality and further degrade sets in (de Ronde *et al.*, 1986). Investigators should communicate as soon as possible with foresters to ensure that vital key evidence (start area of fire, damage across property boundaries etc.) is not felled before the field survey by the investigator has been conducted (own experience).

4.1.3 When investigated more than 60 days after a wildfire

Grassland

More than 60 days after a wildfire in grassland, most of the grassland fuel evidence will be gone, but the fire perimeters can still provide useful material for the investigation and rocks, fencing poles, single trees, transmission and telephone poles can still be included in the field survey.

Other vegetation types

For most of those fuels the bulk of the evidence in the field should still be available, although some of this may be fading away through erosion, direct sunlight exposure, etc. When this is the case, other material (such as aerial photography, satellite images, concrete witness evidence and other indirect tools (e.g. fire simulation) should be used to supplement this lack of suitable (concrete) material available for the investigation (own experience).

In forestry regions, it is in some cases worthwhile to determine if 24-hour camera cover is available of an area where a wildfire is investigated, as this could indeed provide perfect fire origin evidence.

4.1.4 Using on-site determination methods

The basic premise of wildland fire investigation is the same as that for structure fires – determine the area of fire origin first, then establish what fuel was present and what source of heat ignited it. The following field fire origin determination methods can be used during the fire investigation:

- *Checking on wind direction* – By the time the field investigation is conducted, at least an estimated time of first fire ignition should be known. This will enable the investigator to determine what the prevailing wind direction was at the time, and the status of the site in general – at the time the fire started – can then also be considered when indicators are identified. As this should be approximately 180° in relation to this direction of fire origin, this compass direction can be used to check on the directions of indicator evidence in the field, as these will have to roughly match. The known wind direction will then also be the direction of the head fire spread (i.e. a SE wind direction of 135°E will result in the direction 315°E of head fire spread).[1] A hand-held compass is useful for this purpose (Cheney and Sullivan, 1997).
- *Determination of directional fire spread indicators* – Once a pattern of these directional indicators can be established, it can be used to point back toward the area of origin. Such indicators should be used strictly as indicators only, as none are foolproof and none are fact-safe. With the complexity of exterior fire behaviour, modified as it is by weather, terrain and suppression activities, this will then form a "predominant pattern" of indicators that must be sought out, not a single isolated one here and there. The following preferred search pattern is recommended to be applied, starting from outside the margins of the burn pattern and work progressively towards the earliest portions of a fire (Figure 4.1, de Haan, 1996; Leone and Lovreglio, 2010).
- *Fire behaviour from area of fire origin into the initial direction of fire spread* – Such an observation can also contribute to the determination (or confirmation) of the origin of a fire, and also indicate the speed at which the fire became uncontrolled (own experience). This pattern is best illustrated on the hand of Figures 4.2 and 4.3. It shows the typical effect on the crown of trees or brush as a fire starts at point "A" (nearest to fire origin) and moves out, slowly building up heat and speed. At the point of fire origin, the fire is still relatively cool as surface fuels are burned, and the nearest tree crown is still more or less intact.

  Further away from the point of origin, the fire has become hotter, and more crown volume is burned. All the crowns may eventually be consumed by the fire as it intensifies (various authors, 1978; Leone and Lovreglio, 2010). Keep in mind that with "crown damage" the first damage stage is normally crown scorch, which can eventually develop into a crown fire, which can later become a "crown fire street" in industrial plantations, particularly in Pine stands. A study of this nature should also preferably be linked to a survey of tree stem scorch pattern and the use of fire intensity models (see earlier notes in this regard in this paragraph: Own experience).

1 Hourly wind direction data from the nearest South African Weather Services automatic weather station will normally be sufficient for this purpose. However, in very broken terrain with prominent mountain ranges, the data from two such recording stations can be used, to interpolate the weather data to the fire site.

- *Grass indicators* – In the immediate vicinity of the fire origin, the fire will not have developed any particular direction and so the indicators will be confused or contradictory. Fuels in the form of grasses or weeds may still be upright or partially burned. Large fuel may be burned only at its base with fire extending into upper branches only as it moves away from the origin (de Haan, 1996). However, these indicators will be considered when investigating initial and further fire spread, and will be dealt with in detail under these paragraphs (own observations).

4.1.5 Using computer-based technology

The computer-based technology to determine the origin of a wildfire will be by comparing e.g. SPOT satellite images taken on the closest days before and after the fire occurred. From such a comparison, the origin can normally be determined considering all other factors (such wind direction and topography). Although SPOT has been found to provide the best results (best resolution) other satellite image sources should always be considered.

MODIS data (if available) should also be used as overlay for the day the fire started, by time of observation (see example, Figure 4.4). If sufficient MODIS data points are available, this direction of fire spread over time can be used to work backwards towards the origin of the fire, to confirm earlier and other findings (own observations).

We found the use of MODIS data particularly useful when considered for each day a large fire spread, filling many “grey” areas in the investigation. In most cases there are also a number of specific times when data was recorded, and – by using different colours and a time legend – this information can be used to maximum advantage.

4.1.6 Using supplementary information (e.g. wind direction and wind speed data, topographical information, photographic evidence [aerial and micro-site] and concrete [witness] evidence)

Aerial photography taken soon after a wildfire event of the general area of fire origin is probably one of the most important indicators of the origin of a fire, particularly when taken from a helicopter, because this normally provides the most stable pictures (Figures 4.5a and 4.5b). It is important to use such photographs only as indicators, because as these pictures are taken at a certain angle, actual on the ground detail is normally distorted. However, identification points (such as poles, trees, roads, buildings, etc.) can be used to advantage to identify and plot on a suitable topographical map. With the assistance of such multiple points plotted, the fire perimeter can then be drawn in on a suitable base map (own experience).

Once the basic fire perimeter has been mapped, wind direction can be considered to confirm where along the perimeter the fire originated. This could be from a single ignition point or multiple ignition points, in some cases from an ignited fireline. The variety of patterns of burns developing from different ignition types is co-determined by weather, topography

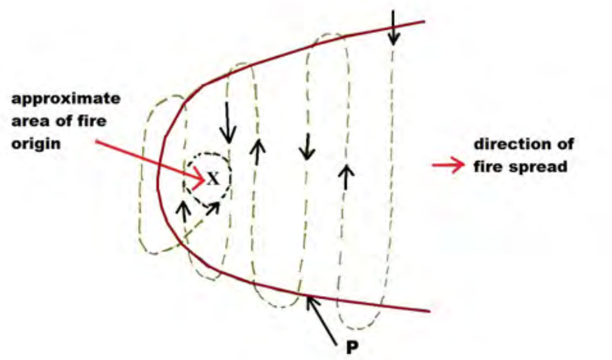

Figure 4.1. Preferred search pattern to be applied (de Haan, 1996). "X" is general area of fire origin, and "P" = Fire perimeter.

Figure 4.2. Typical evidence of fire spread in Fynbos on the right of the picture, as well in the mature *Pinus radiata* stands on the left. Note the evidence of tree crown scorch caused by the high intensity of the fire in the Fynbos on the right of the firebreak. The latter was not crossed by the fire. Photo: C. de Ronde.

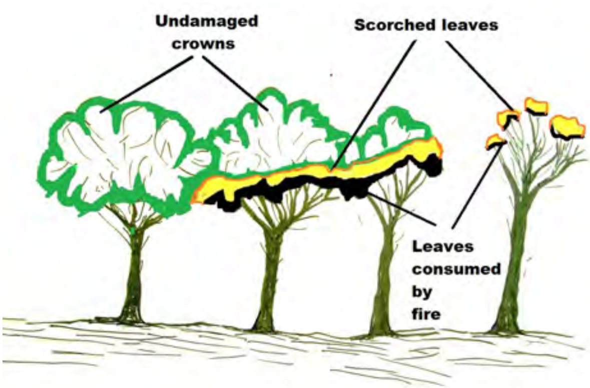

Figure 4.3. Crown scorch pattern within the ignition area through the initial fire spread zone (direction of fire spread: from left to right) (National Wildfire Coordinating Group, 1978; Leone and Lovreglio, 2010, revised by C. de Ronde).

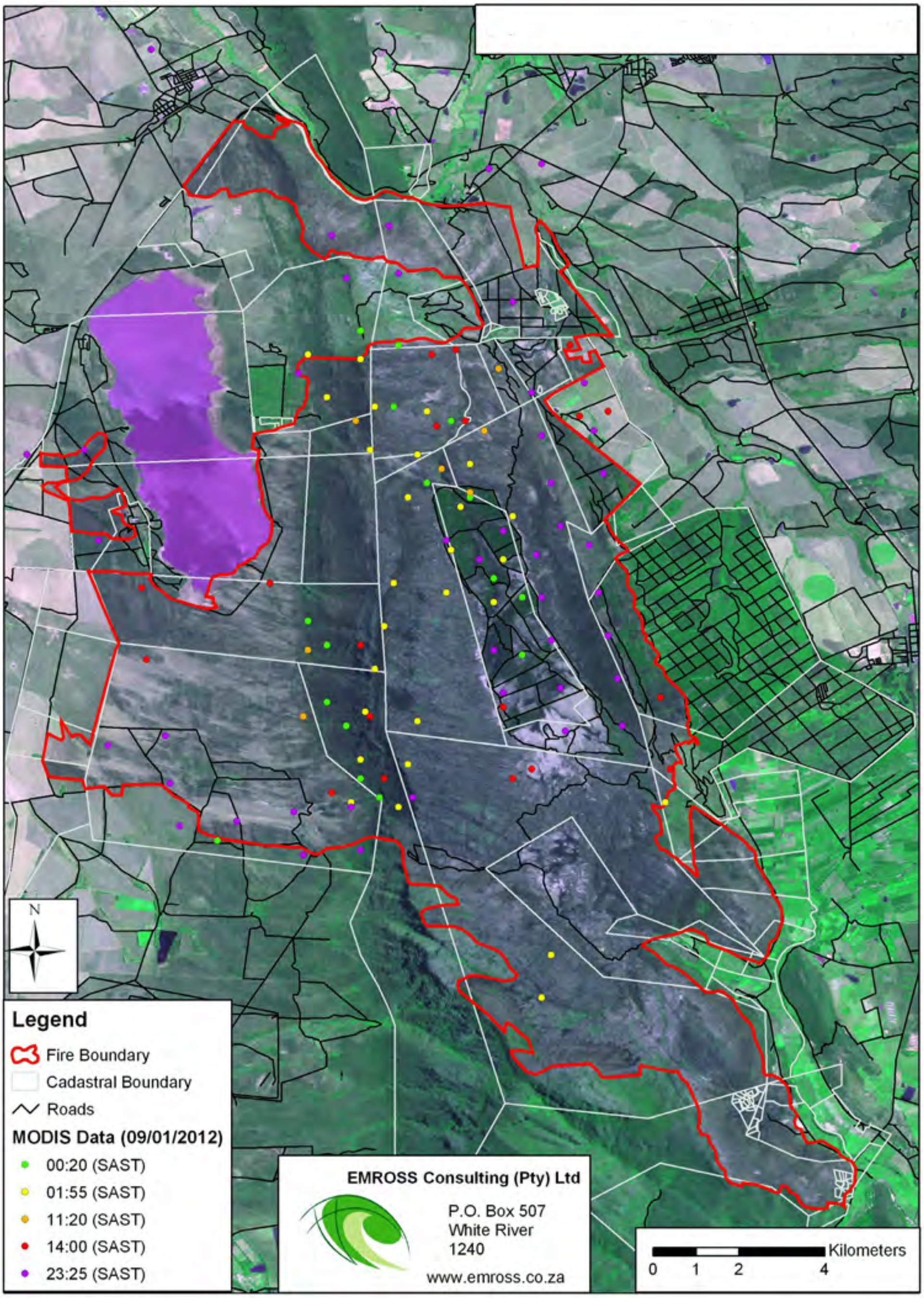

Figure 4.4. SPOT satellite image of wildfire as it was when the fire was "out", with fire spread perimeter and MODIS data overlay for first day entered (yellow dots). Developed by EMROSS Consulting (Pty) Ltd., courtesy CapeNature.

and fuel types. Figure 4.6 provides a photograph taken by the Expedition Crew 41 of the International Space Station (ISS) showing fire scars over Australia in 2014.[2]

Where steep slopes are found at or near the site of fire origin, the effect of such terrain should also be considered during the investigation, as a steep upslope fire spread will narrow the fire front because of the relatively faster rate of fire spread, while a down-slope situation will retard the spread of a fire, widening the shape of the fire (own experience).

Photographs of evidence at the site where evidence has been identified of the origin of the fire should be photographed in detail to maintain such concrete evidence for future use. Concentrate on good quality close-ups of evidence items and take pictures from various angles to ensure the best possible capture of this material (own experience; various authors, 1978).

Concrete evidence of people who observed the ignition of the fire at the site of fire origin, will still provide the backbone of material needed for the investigation, but this is seldom available. However, if such person(s) are found, obtain written statements if possible, or otherwise record the verbal evidence.

4.2 Determining the Cause of a Fire through Fire Origin Evidence

4.2.1 Using concrete (witness) evidence

It should always be a priority to collect witness evidence when investigating the cause of a fire, even if this is only in the form of informal reports of people movements at or near the fire area, towards or from, the site of fire origin. Witness evidence is particularly important if arson or negligence is expected:

- any children that could be connected to the site area,
- if the origin can be traced to a cooking fire, with a fairly long history of use, any teams working in the area at the time,
- hikers or backpackers (if the fire started at or near a hiking trail or heritage site),
- if a fire started along a regularly-used path or access road, which persons normally use the road at certain times (e.g. to and from a nearby shop),
- if the fire was ignited along a range of ignition sites (e.g. along a road), or
- if it is known that some of the labourers were recently dismissed, having a grudge against management or any other social dissatisfaction.

The sooner witness evidence is collected after the fire, the better. Memories fade away with time, and the sooner such evidence is recorded the better. However, should you start your investigation a long time after the fire took place, search for fire reports, particularly from the organization where the fire caused the damage (or spread from, to adjoining

2 For a high-resolution version of the ISS photograph please see: http://eoimages.gsfc.nasa.gov/images/imagerecords/84000/84647/iss041e55798_lrg.jpg

Figure 4.5a. Evidence of two fire ignitions starting along a roadside edge in KwaZulu-Natal (KZN), South Africa. Possible cause of fire: Arson. Photo: Courtesy FIRESTOP (KZN).

Figure 4.5b. Same fires as shown in Figure 4.5a but taken after spreading for some time uphill (initial fire spread). Note that fire on left has already spotted. Also note that a fire fighting vehicle (water tanker with pump) is already at the fire site. Note excellent evidence of the spread of both these fires. Such evidence will allow raising questions such as why the water tanker is already at the fire site at this early stage of the fire, considering the fastest driving time from its base in this situation would have taken it at least 45 minutes. Photo: Courtesy FIRESTOP (KZN).

Figure 4.6. The variety of patterns of burns developing from different ignition types (single or multiple ignitions, line ignitions) is co-determined by weather, topography and fuel types. The photograph taken by the Expedition Crew 41 of the International Space Station (ISS) in 2014 shows fire scars in Australia revealing. Photo: Courtesy NASA.

properties). In such reports it is normally possible to identified "key persons" who could either be used as witnesses, or could assist in finding the cause of the fire, or persons who could assist with the investigation (Figure 4.7). Incident Command logs, pilot logs and fire brigade reports should also be searched for pointers or clues (own experience).

4.2.2 Using on-site forensic means

In most countries, including South Africa, forensic fire investigators are available who have specialized expertise in industrial / structural fires may be able to determine the cause of a wildland fire. Wildland fires, however – particularly in the case of large fires burning through a number of properties – require an in-depth knowledge of wildland fire behaviour in natural as well as man-made fuels, and vegetation dynamics then form the basis of investigations. Then such methods are not only restricted to the site of a fire origin, but can also be used to reconstruct initial and further fire spread events. Below are some of these methods, which we found useful in wildfire investigations to determine the cause of a fire, linked to the site of fire origin (once determined):

- *Chemical analyses of top soil samples* – This method is particularly useful to determine (from a number of cooking fire sites) from which fire the wildfire originated. Many times these fire sites are placed near or on property boundaries, making it particularly important to determine from which site the wildfire originated, and from which it did not come (own experience). See Figure 4.8 (also see sub-paragraph below):
  a. The following field procedures should be followed:
     (i) Identify the cooking fire sites where the fire could possibly have originated from
     (ii) Then draw a line in the ash/sand at the fire site at each cooking site, from the centre to the direction the wind was blowing in at the time.
     (iii) Along each demarcated line, collect 5 to 7 top soil samples* (about one half spade slice per sampling site), mark them by numbers (starting from centre) with cooking site number (e.g. A1, A2, etc.).
     (iv) Sun-dry or oven-dry the soil samples, bag and dispatch to a suitable laboratory for analyses.
     *=3 sampling sites within the micro-site and 3-4 along the extended line, just outside the sites where the fire burned. This is done in this manner for statistical analyses purposes of the results.
  b. Request the laboratory for standard sample analyses to be conducted, including pH, Conductivity and then at least the main chemical elements, namely N, P, K, Ca and Mg. Where possible, ask for available and total element values. From where a fire starts, in the direction of maximum fire spread, fire effects e.g. on the topsoil will intensify as the fire progresses, and (if sampling of topsoil is conducted with 4 – 6 weeks after the fire occurred) the analyses will follow also a particular pattern in the sampling results, from the micro-site where the fire started vs. the other cooking sites and the origin if the fire can then in this way be

Figure 4.7. Evidence of the origin of a wildfire, particularly clear as the strong wind at the time blew from right to left in the picture, driving the fire in the dry grassland uphill there from where it then developed into a very serious wildfire that caused multiple damages. Photo: C. de Ronde, courtesy North-east Cape Forests.

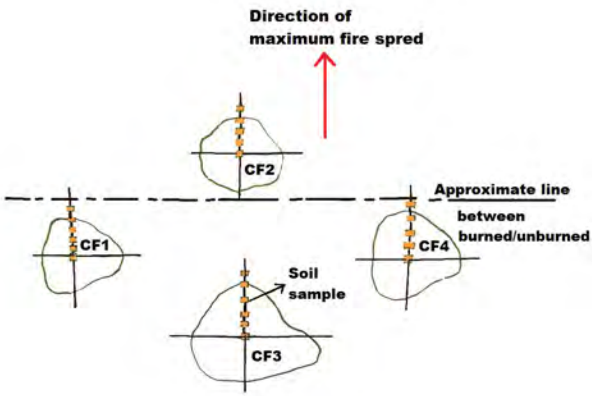

Figure 4.8. Soil sampling pattern/procedures to be applied to determine fire origin from a number of cooking fires. "CF1" to "CF4" = Cooking fire sites (developed by C. de Ronde).

Figure 4.9. Ash pattern developing in *Eucalyptus* slash and wood stockpiles after clear felling. The black ash rows are result of burning low to moderate fuel loads (post-harvest slash). The white ash patterns reveal that harvested wood stockpiles burned down resulting in long-residence time and high severity fire spots. Photo: Courtesy Brad Sanders.

determined with statistical significance. It is recommended that someone with experience in such a process is approached for assistance with these procedures and interpretation of the results.

- *Ash patterns* – Particularly in grasslands, differential burning in the lower layers of the fuel bed occurs as the flanks alternate from a backing to a heading fire. This leaves a pattern of ash of different colours (Cheney and Sullivan, 1997). In strong winds the head of a fire is always a heading fire, even during lulls in the wind. However, as the wind direction fluctuates, the fire on each flank will alternate between heading and backing. Therefore an ash pattern left on one flank will have been created at a different time than a similar pattern on the other flank. Nevertheless, these ash patterns can be used to delineate the shape of a fire and, together with eyewitness reports, can be used to build up a chronological map of fire spread (Cheney and Sullivan, 1997). Different slash management treatments applied in industrial plantations can also leave specific ash patterns (own observations; Figure 4.9).
- *Alligatoring* – This is a form of charring and is normally found on fencing posts, boards, structures and signposts. It can be either large or small and either shiny or dull-black. Large, shiny scales mean it was burned by a hot, fast-moving fire, while dull scales mean the fire was slow and not so hot. The depth of the char is a good indicator of the fire's direction of travel (Figure 4.10; de Haan, 1996; National Wildfire Coordinating Group, 1978).
- *Staining* – Rocks and other non-burnable objects that are exposed to the fire will be stained by vaporized fuels and minute particles carried by fire. The stain is shown as the shaded area in Figure 4.11 (National Wildfire Coordinating Group, 1978) and indicates that the fire moved from left to right. Objects which will show stains include beer cans, pieces of scrap metal, dirt clods and unburned vegetation.
- *Soot* – will be deposited on the side of fences toward the origin of the fire and can be noticed by rubbing your hand along the wire (Figure 4.12). On larger objects, soot deposits can also be noticed by rubbing your hand across the surface. However, in many cases there will be more positive indicators, such as protected fuel or staining. When checking a wire fence for soot, check the lower wires as they will show more evidence of soot than the higher wires (de Haan, 1996; National Wildfire Coordinating Group, 1978).

4.2.3 By investigating other wildland fire related evidence

Charring height pattern on trees and posts

As the wind blows a fire past a tree or post, the flames are drawn into the eddy zone on the leeward side (also called the "leeside") and will extend further up on that side than on any other part of the tree or post (Figure 4.13; Cheney and Sullivan, 1997). In such cases the side of the tree facing the direction where the wind came from, will show the lowest scorch height (lee- or wind side scorch height) and the side with the highest scorch will face the di-

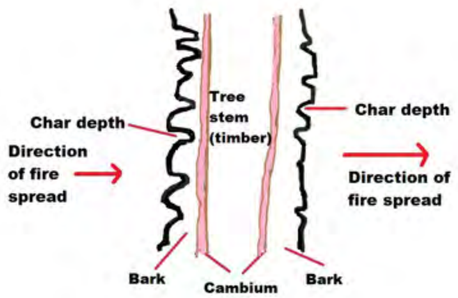

Figure 4.10. The depth of the char on wooden poles or dead tree stems is a good indicator of the fire's direction of travel (de Haan, 1996; Leone and Lovreglio, 2010).

Figure 4.11. A rock that was exposed to fire, showing stain caused by vaporized fuels and minute particles carried by the fire, shown as shaded area (National Wildfire Coordinating Group, 1978; Leone and Lovreglio, 2010).

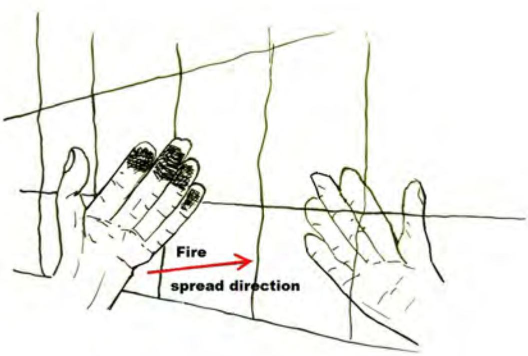

Figure 4.12. Soot deposited on the side of fences towards the origin of the fire and this can be noticed by rubbing your hand along the wire (National Wildfire Coordinating Group, 1978).

rection in which the fire is spreading (leeside). See Figure 4.14 to illustrate this. The stronger the wind, the higher will be the leeside/windside bark scorch height ratio and the lowest will be the fire residence time when the fire past the tree or post (de Ronde, 1989).[3] This scorch pattern can also be used to advantage to determine where the head of a fire spread through a tree stand (Figure 4.15). Conversely, the lower the speed of the wind the least will be this ratio. When a fire spread up a hill this ratio, the leeside/windside scorch height ration will increase further because the rate of fire spread will increase, while a downhill slope will have the opposite effect.

- *Fire intensity prediction models* – A study determined that the windside bark scorch height correlates significantly with certain fire parameters. The following three fire intensity variables used in the study (and used by Rothermel and Deeming, 1980) can be predicted from the windside bark scorch height:
  FLAME_L – Average flame length (m)
  FIRE_LI – Fireline intensity (kW/m)
  HEAT – Heat per unit area (kJ/m^2)

  The models are:
  FLAME_L = 0.272 + (0.031)(WMEAN)
  FIRE_LI = 187.49 + (23.93)(WMEAN)
  HEAT = -8065 + 1085 (WMEAN)
  (where WMEAN) = the windside bark scorch height) (de Ronde, 1989).
  The models can be used for any individual trees at or near the fire origin, but are most useful in mature industrial plantation stands (close to- or on the edge of a plantation at or near the fire origin), where a row of trees can be used along a transect to determine fire behaviour along such a line in the landscape. However, they can also be used along a row of fencing posts where a fire burnt through. It can also be used for measuring the direction of fire spread at or near the site of fire origin, though the fence, by measuring scorch ratio directions with a hand-held compass. We have particularly used the procedure to advantage in even-aged industrial timber plantations, to assist in determining the origin of a wildfire with compass direction measurements of individual trees along a transect, situated from the fire origin site into the initial direction of fire spread (own experience).
- *Destruction of a tree on windside vs. leeside* – This will always be more on the windside than on the leeside of trees, thus more intensively on the side facing the fire (Figure 4.11; de Haan, 1996; National Wildfire Coordinating Group, 1978).
- *The bevelling effect of a fast-moving fire* – This may influence the appearance of branches or twigs remaining upright. Twigs and branches facing the fire may have

3 This is the term used to describe the period of time a site is exposed to fire. The longer this period is, the more the surface of the soil is exposed to adverse fire temperatures.

Figure 4.13. Wind blowing a fire past a tree in a pine plantation and leads to the formation of an "eddy" on the leeside of the tree. Photo: GFMC.

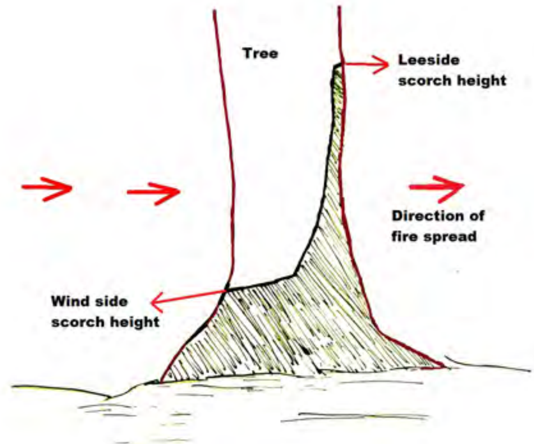

Figure 4.14. Tree showing lee- and windside scorch. Note wind direction (C. de Ronde).

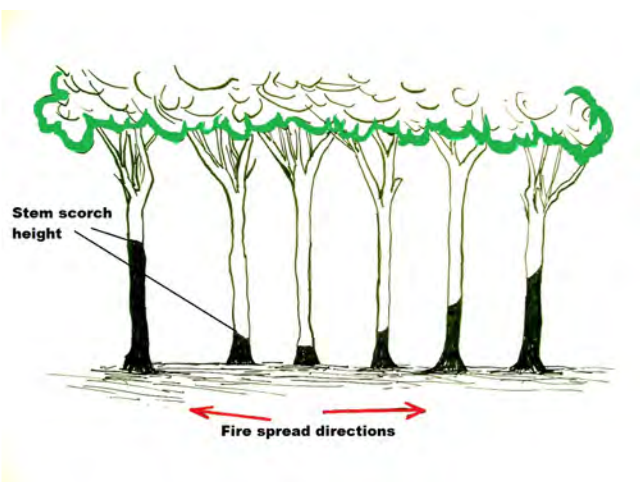

Figure 4.15. Burning pattern on tree stems, present in tree stands, where a surface head fire spread through (de Haan, 1996; Leone and Lovreglio, 2010).

flat or rounded ends while those facing away from it (leeside or downwind) will be tapered or pointed (de Haan, 1996; Leone and Lovreglio, 2010).

- *"Freezing"* – When leaves and small stems are heated, they tend to become soft and easily blown by the prevailing wind or drafts created by the fire. They often remain pointed in the same direction as they cool as the fire passes. It may be necessary to check several of these indicators to be absolutely sure of the fire's direction (Figure 4.16; de Haan, 1996; Leone and Lovreglio, 2010; various authors, 1978). Both leave freeze and leeside scorch indicate the direction of the wind through the flame zone when a fire passed a particular point (Cheney and Sullivan, 1997). A South African example of Freezing in *Eucalyptus* has been inserted as Figure 4.17.
- *Deep charring of a tree trunk or fencing post* – In the case of a slow moving, high intensity fire with a high residence time, charring of a tree trunk can cause deeper burning on the windside of the trunk than on the leeside. Such evidence is also called "cupping" (de Haan, 1996; Leone and Lovreglio. 2010; various authors, 1978). In industrial timber plantations this is particularly evident in recently-clear felled tree stands (own observations).
- *Cupping indicators* – Cupping normally occurs on the windward side of a stump (left behind from cut tree). Brush or grass (Figure 4.18; de Haan, 1996). This is the side exposed to the most wind and should be expected to burn the deepest, while the other side remains cooler and protected by the remains of the burning side. This effect takes place even in grass which can be examined closely by rubbing the back of the wrist over the burned grass. When rubbing in the direction the fire burned, there will be a velvety feeling but while rubbing in the opposite direction, you will feel some suction and prickling on the wrist. You should move your hand in all directions until the most velvety and most resistant directions are found (de Haan, 1996; Leone and Lovreglio, 2010; National Wildfire Coordinating Group, 1978).
- *Grass stem indicators* – As fire approaches a grass stem, it heats and begins to char one side first. This side is reduced in size and weakened. The effect is about the same as an undercut on a tree. Eventually, the grass stem will fall towards the weakened side, i.e. where the fire originated from. One will have to obtain several readings to arrive at an acceptable direction (Figure 4.19; de Haan, 1996; National Wildfire Coordinating Group, 1978).
- *Protected fuel indicators* – A slowly burning fire with low heat will burn only that side of the vegetation towards the approaching fire (Figure 4.20). Because of this, a larger area that burned slowly will look lighter due to ash and more complete combustion when looking away from the point of fire origin and darker when looking towards the origin of the fire (de Haan, 1996; National Wildfire Coordinating Group, 1978).
- *Surface logs* – Any item lying on the ground (but particularly logs) form a protecting buffer against an oncoming fire. This will create a burning pattern that can be used to determine from what direction the fire came (Figure 4.21; de Haan, 1996; National Wildfire Coordinating Group, 1978).

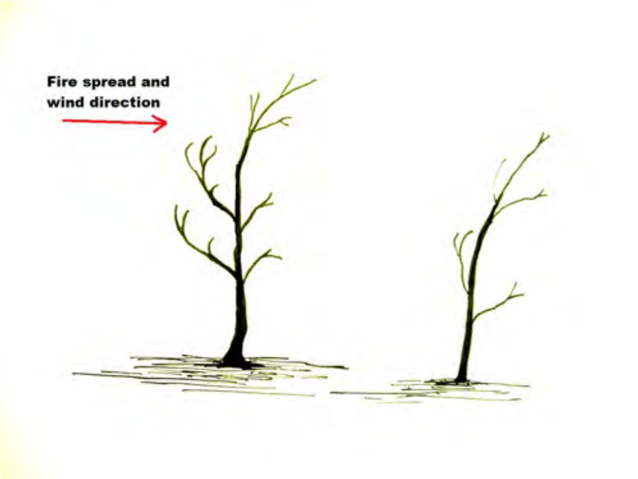

Figure 4.16. Illustrated example of freezing of branches (National Wildfire Coordinating Group, 1978).

Figure 4.17. Freezing evidence in *Eucalyptus* stand in branches and leaves, indicate that the fire spread from left to right in the picture. Photo: C. de Ronde.

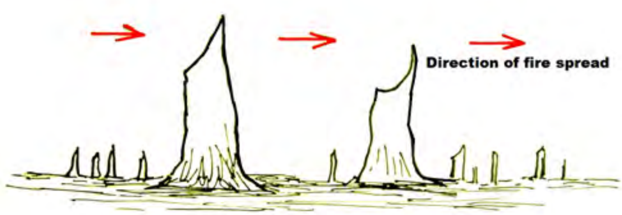

Figure 4.18. Cupping effect visible on stumps (left behind after felling, de Haan, 1996; Leone and Lovreglio, 2010).

4.2.4 Using selected fuel models and fire behaviour simulation procedures

- *Fuel models* – A representative set of fuel models will have to be available for any work in this direction, from the general site of fire origin and immediate area of initial fire spread. Although the attached fuel model set can provide some models for this purpose, each investigation site requires at least some adjustments and/or new models for its specific purposes, requiring input from a specialist in this field.
- *2-D fire behaviour simulation with BehavePlus* – We found that this computer-based program is most useful to assist in constructing the fire along any transect in the country for a range of purposes for the investigation, but in particular to confirm other evidence located close to the site of fire origin, and to determine until what time after fire ignition the fire was still containable.
- *3-D fire behaviour simulation with FARSITE* – This is the only computer-based program that can be used to reconstruct fire spread over time, over a range of fuel types, over terrain and that will simultaneously consider changing weather conditions, even with multiple ignition points. In the case of complicated fire situations, this is many times the only method to confirm the site of fire origin (and thus many times the cause of the fire), particularly when more than one ignition point have to be considered. However, it may be a costly option as a GIS expert might be needed to create the topographical files, and to map the fuel overlay.

4.3 Considering the Cause of a Fire

Possible sources of ignition

The causes of wildfires can be categorized in various groups, which have been classified in a number of classifications by a number of authors (e.g. de Haan, 1996; National Wildfire Coordinating Group, 1978). However, following the multi-year experience of C. de Ronde the following classification grouping for this purpose for South African conditions is proposed and summarized as follows:

- *Lightning* – Many years ago this used to be considered about the only source of wildfire ignition, but its role today is far more restricted and localised (own assessment). However, in some regions it still plays a prominent role, causing most fire ignitions. Some areas which are particularly prone to dangerous dry lightning during low fuel moisture conditions, are (i) the Langeberg Mountains in the Cape, (ii) drier ranges of the Drakensberg Mountains, Kalahari region and the Eastern Free State (own experience).
- *Arson (incendiary)* – This category of fire causes is far too prominent in most regions of South Africa. Arson is normally applied by a single person who has some problem with local managers/management for whatever reason, and will start igniting fuels

Figure 4.19. Grass stem pattern, indicating the direction of fire spread (National Wildfire Coordinating Group, 1978, as revised by C. de Ronde).

Figure 4.20. Protected fuel indicators in grass, indicating direction of fire spread (National Wildfire Coordinating Group, 1978).

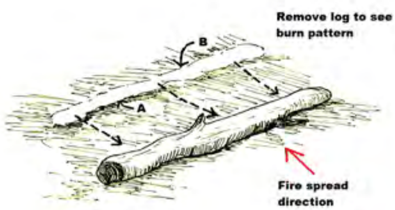

Figure 4.21. A fire burning past a log is showing a particular pattern towards/away from the direction of fire spread (National Wildfire Coordinating Group, 1978).

Figure 4.22. Site of a roadside warming fire (near a taxi halt) which has been used various times in the past (see branch-piece remnants and soil discolouration at and around point "X", with evidence of fire escape from this site in the direction as indicated by the arrows. This developed into a large wildfire, as the fire spread into mature *Eucalyptus* nearby. Photo: C. de Ronde.

under sometimes the worst of fire weather conditions. Such ignitions can take the form of single ignition points or a number of points e.g. along a road, and the guilty persons are not easy to track down. This still remains one of the most dangerous sources of wildfire (own experience). Friction with the labour force of large forestry, nature conservation reserves and at farms, should thus always be handled with utmost care and tact to avoid labour unrest (own experience).

- *Prescribed burning application* – This includes the burning of debris or slash (e.g. after harvesting or tree clear felling). The reasons for this can mostly be traced to inexperience regarding the wrong burning day selection of burning methods applied, and can many times be attributed to lack of experience in fuel appraisal and linked fire behaviour predictions. Training of fire managers can normally assist in reducing damage as a result of such mistakes (own experience).
- *Counter fire measures gone wrong* – Amazingly, this has developed in one of the main causes of (i) existing fires being increased in magnitude and (ii) are also caused counter fires never reaching the main wildfire front, but becoming uncontrolled on its own. Lack of fuel appraisal and linked fire behaviour assessment can again be contributed to such fires (or fire additions). In my experience, counter fires applied during large, multiple, fires have gone wrong in 80% of applications identified (own experience).
- *Camp and cooking fires* – Most of these ignitions are caused from cooking (or warming) fires in the field, in the forestry, nature conservation and agricultural environment. We found that such fires can many times be attributed to carelessness of looking after such fires to ensure that they are – and remain – “out” (Figure 4.22).
- *Smoking and children* – Such fires can be caused by smokers (including by children) and children playing with matches and other ignitable devices. Many times dagga smokers fall asleep in the wildlands, and then igniting such fires from smoldering cigarettes, or warming fires.
- *Outside causes of wildfire ignition: Equipment use and railroads* – In grassland fuels, the use of equipment is particularly a common cause when welding is applied to e.g. wire fences of other structures. However, we have come across ignition in harvested wheat lands from faulty exhaust systems underneath vehicles. Note: In countries where catalytic converters are prescribed these constitute a major source of ignition when vehicles are halting on harvested wheat fields or grasslands. Railroads are a continuous threat of fire ignitions within these railroad reserves, or even beyond their boundaries if prescribed burned (own observations).
- *Miscellaneous* – These are any fire ignitions that cannot be classified in the above categories. Examples are: Rolling rocks from mountains. These rocks can be moved

by man or during construction (e.g. new roads or road maintenance). However, also rocks moved by baboons or as a result of earthquakes.[4]

Testing fire cause(s): Hypotheses by means of elimination

If the cause of a fire is not immediately (obviously) clear, then a short list of possible causes should be drawn up, or rather a list of possible cause that could NOT have been possible. This will leave a short list of possible causes to consider. For example: If there was no lightning, then you can eliminate lightning as a cause. Also, if there are no railway lines within several kilometres, you can eliminate railway operations as a possible cause. Another example is that in the middle of a wilderness area where no equipment can be, this can also be eliminated from the list.

Fire ignition source indicators

Here follows a list of descriptions of indicators which will identify the actual "thing" or "object" which ignited the fire. Once you have determined the source of ignition, this can then be classified according to the cause classes provided earlier under this paragraph:

- *Lightning* – Physical evidence of such strikes is normally present in the form of striking marks on trees or poles, splinters from logs or trees and disturbed earth. Another indicator is the knowledge that the fire origin was in the path of a recent electrical storm. Remoteness and improbability of human activity may also be indicators.
- *Incendiary Devices* – This normally involves the use of devices such as matches, cigarettes, candles, rope, wire, tape or rubber bands, which may appear in many forms and combinations. A cigarette found at the source of fire origin should be used to search around this micro-site for the remnants of tape, string of rubber bands used to attach a match. These together would indicate an incendiary rather than e.g. a smoking fire. Where no evidence is found, one can locate the ignition point and then determine the height above ground level where the device was applied. Stubble height, and an area of more complete combustion, will indicate the point of application (de Haan, 1996; National Wildfire Coordinating Group, 1978).

References

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De Haan, J.D. (1996). Kirk's Fire Investigation (fourth edition), Chapter VIII. A Brady Prentice Hall Publication, New Jersey, USA.

4 Author C. De Ronde has personally experienced such rock fall events during the 1969 earthquake in the Wolseley/Ceres/Tulbagh region, when a powerful 6.4 (Richter scale) aftershock was measured. This occurred in the early evening (when it was just dark), and within one minute the whole of the Witzenberg mountainside was alight from numerous ignitions as a result of rocks that became loose, rolling down the slope.

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5 RECONSTRUCTING WILDFIRE SPREAD

5.1 Fire Reconstruction Procedures

5.1.1 Determining burned over land and wildfire perimeters

It is very important that the exact perimeter of a fire is determined accurately, as it has to be used as a basis for the wildfire reconstruction process. Only when the complete fire perimeter is mapped (to be done once the fire is completely "out") that fire spread can be reconstructed in various stages, and possible additions by counter or other fires can serious be considered and quantified in terms of land burned over in addition to the main fire area burnt (Figures 5.1 and 5.2). Such a map of the area with the fire perimeter put on as overlay will then form the base map for further investigations and evidence overlays, e.g. with MODIS data points.

It is particularly during large wildfire events that it is normally not possible to determine where exactly the (final) fire perimeter is situated in the landscape. Sometimes, however, the fire perimeter can clearly be visible in the field (Figure 5.3). This is made even more difficult to determine in rugged mountainous terrain where access on the ground is restricted. Such a situation should soon be clear for the investigator, and then various other means will have to be considered to determine this outstanding data.

Sometimes multiple fires are suspected when a large wildfire is investigated, and then the full picture of areas burned over and final fire perimeters needs to be constructed with the required degree of accuracy, as this created a base for further investigations needs to be accurate and reliable. See paragraph 5.1.7 for more detail about recommended methods and tools that can be used for this purpose.

5.1.2 Developing fuel model sets for reconstruction purposes

For the larger wildfires, fuel model sets will have to be created and tested for a range of purposes, such as:

- Simulating 2-D fire behaviour (with BehavePlus, Andrews, 1986; Andrews and Chase, 1986; Andrews and Bevins, 2000) during the initial fire spread period, from its origin site until a significant change in fuel and/or topography caused the fire to change behaviour significantly. This is useful for e.g. a calculation to determine until when a fire was containable, and by what means.
- Simulating 2-D fire behaviour over specific distances, for specific fire behaviour testing, such as the calculation of maximum spotting distances, e.g. across firebreaks or roads. The effectiveness of such breaks, by calculating to what extent such breaks could have stopped a fire from spreading further.
- For simulating fire behaviour conditions, and to use this with weather and terrain input to determine what conditions were when a specific counter fire was applied.

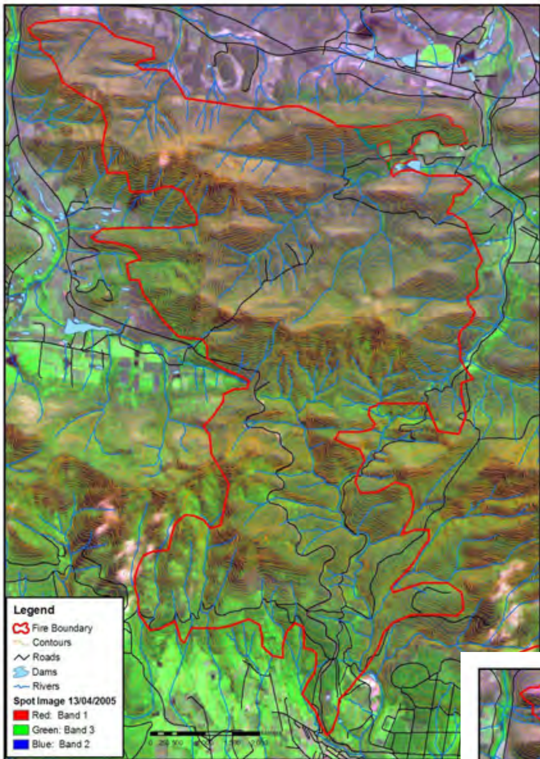

Figure 5.1. SPOT satellite image of an area in the Outeniqua Mountains, north of George (Western Cape Province, South Africa) before the fire occurred, with actual wildfire perimeter drawn in as overlay. Source: Courtesy EMROSS (Pty) Ltd and MTO Forestry (Pty) Ltd.

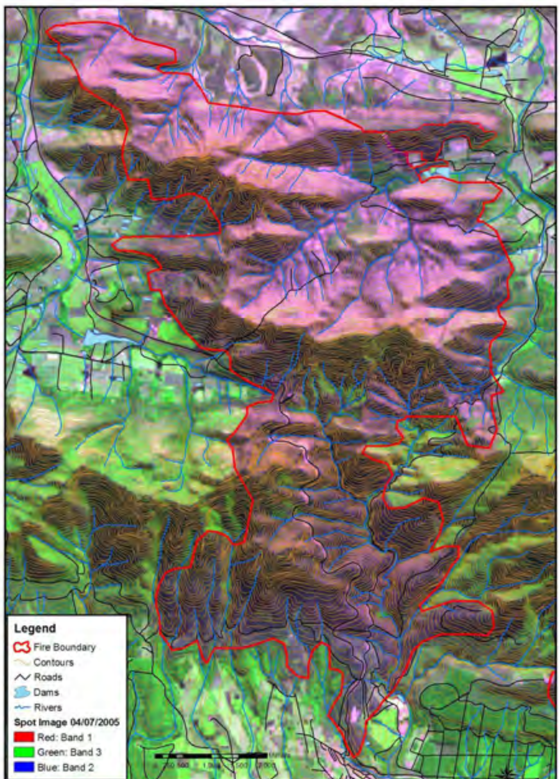

Figure 5.2. SPOT satellite image of burned area displayed in Figure 5.1, nine days after the fire occurred, with fire perimeter drawn in. Source: Courtesy EMROSS Consulting (Pty) Ltd. and MTO Forestry Pty Ltd.

- Fuel classification for the main vegetation types burned over by the fire for fuel/fire dynamic determination in the landscape (normally a set of 6 to 10 fuel models will be sufficient for this purpose).
- For 3-D simulation of fire spread, using FARSITE (Finney, 1996).

In most cases, a set of fuel models of six to ten representative models should be adequate for most conditions, covering the most representative fuels burned over by the fire. In South Africa, a fuel model database is available for this purpose (de Ronde, unpublished. Also see Appendix I). This database can be used as a guide, while some models can be adjusted to suit specific means. However, experience has taught me that in most cases the best results can only be obtained by developing a new fuel model set for each large wildfire. The writer can perform such services, but more fuel and fire modeling specialists are urgently required for this country (own experience). The approach suggested will be to select a fuel model from the Appendix I list of available models and then to adjust such models in such a way that it represents a particular fuel/vegetation situation affected by the fire, as close as possible (also refer to pars. 5.2.3 and 5.3.4).

Developed fuel models should be tested against concrete evidence in the form of wildfire observations or photographic evidence and – if this is not available – against existing models of a similar nature, with as input weather and topographical input from real wildfire-time data. The use and development of fuel models for particular wildfire situations, will require the input from an expert who has been trained for this purpose. For investigators interested in such courses, please contact the authors for more detail.

5.1.3 Studying fuel conditions, dead fuel moisture contents and grassland curing state

It is important that this contributing information is collected, because this can be provided to arrive at more accurate BehavePlus fire behaviour simulation input and output, for various investigation purposes. Specific fuel conditions are particular important to be used for surface-to-volume ratios (m^2/m^3) calculations. For this purpose, estimated heights of understorey can be used to arrive at the status of fuel aeration, together with % living or dead fuel ratio estimates, to arrive at these density estimates (SAV). Photographic evidence of burned over vegetation examples (as well as – in particular – living vegetation examples normally found along fire perimeters close by) has been found to be most useful for this purpose (own experience).

Dead fuel moisture contents of various fuels can accurately be obtained from the BehavePlus "Moisture Scenarios" sub-program provided, where the TSTMDL sets ("high", "medium" and "low" moisture contents) will be adequate, as the only alternative will be labour-intensive (and expensive) fuel sampling, drying and weighing, which will at any rate not reflect exact conditions when the fire occurred (own experience).

The grassland curing rate will be in the case of most grasslands in the South African fire situations 100%, and BehavePlus input, can then be calculated accordingly. However, where wildfires occurred in regions where grassland does not always cure completely, such percent-

Figure 5.3. Although this fire occurred two months ago, this part of the fire perimeter is clear and can be mapped. Photo: C. de Ronde.

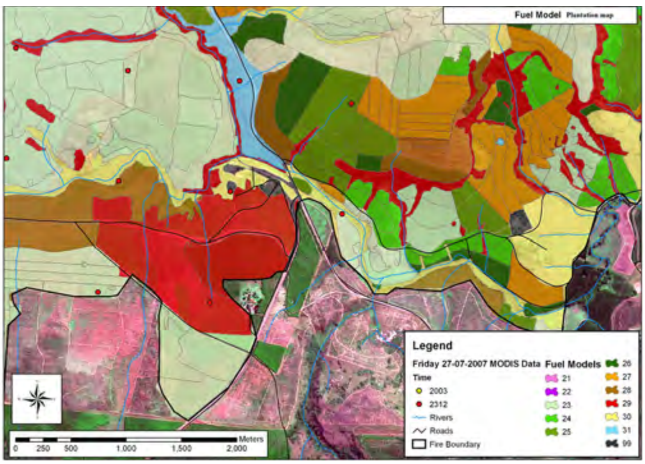

Figure 5.4. A fuel classification for an industrial plantation, with some grassland between main blocks, developed by C. de Ronde and drawn on topographical map as overlay by EMROSS Consulting (Pty) Ltd. (courtesy Komatiland Forestry – KLF).

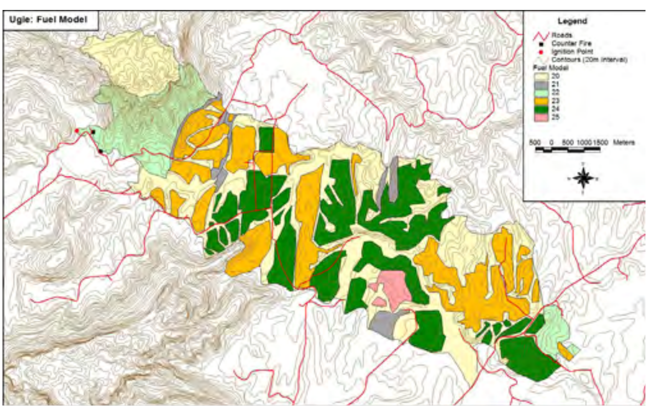

Figure 5.5. Base map of industrial plantations exposed to a wildfire. A fuel classification has been added for better fire damage assessment, as developed by C. de Ronde and map created by A. Emery from EMROSS (Pty) Ltd.

ages will have to be estimated and subsequently used for BehavePlus runs (such as is many times the case along the sub-tropical Zululand coast of South Africa).

5.1.4 Collecting historical weather information and weather data before, during and immediately-after a fire event

This forms a vital part of the wildfire investigation and because of this, it is important that the best possible data is used. From experience in South Africa, it was determined that the automatic weather station network database from the SA Weather Services should be used selectively, because these datasets are relatively expensive. There are however certain important pre-determined considerations/investigations to be made, before the weather data is ordered:

- Contact the SA Weather Services and advise them of the location of the fire, so they can propose which automatic stations should be selected/are available close-by, and request grid references for each.
- Plot these stations on a normal geographical map with a scale ruler, so that direct distances can be estimated from each stations' site to the wildfire site of fire origin, and then lines have to be drawn between these points. In the case of each station, then calculate their direction in relation to the wildfire site (in degrees).
- Search for any significant topographical barriers between the stations and the wildfire site, such as prominent mountain ranges. It is also useful to consult for boundaries between climatic regions and the regions' characteristics (Kruger, 2004), particularly with regard to rainfall. It is equally useful to consult Low and Rebelo (1996) to determine boundaries between main biomes and vegetation types in South Africa, before deciding on automatic weather stations to be selected.
- If a weather station site is close to the wildfire origin site (within 10 km) this should be adequate and no further stations should be selected for the weather data to be ordered. However, also consider where the final fire spread, as this could be on the other side of a significant mountain barrier in a completely different micro-climate, in which case another station (or stations) will have to included.
- Where no station is situated close to the origin of the fire, also consider that most frontal systems move along the SA coast (and bordering inland areas) from west to east, in which case the closest stations west and east of the fire site should be collected. This will make it possible to interpolate the data between the two stations to the fire site. Where only one station is available nearby the fire site, extrapolation methods will have to be use to arrive at representative conditions at the site of fire origin, by means of estimating the speed of weather condition movement from west to east.
- Order hourly weather data for the month in which the fire occurred (or for two months in cases where the fire started just prior to month-end and ended during the next month), asking for relative humidity (%), air temperature (°C), wind direction

(degrees) and wind speed data (the latter normally provided in metres/second, which has to be multiplied by 3.6 to arrive at km/hour).

- Also consider ordering 5-minute weather data for specific (critical) periods of fire spread (at least for the first day of fire spread), per 24-hour period. Request wind direction, average 5-minute data as well as wind gust data for each period.
- Study historical weather patterns for the area where the fire occurred. For instance, in South Africa this would be particularly important if the fire occurred during typical Bergwind or NW wind conditions (or SE winds in the Western Cape, South Africa, during summer).
- Consider the use of privately-run automatic weather stations close by. However, attention should be paid if these weather stations are accurately calibrated and have a higher time-resolution weather data storage (e.g., desirably intervals shorter than half-hour or hourly weather data, etc.).

5.1.5 Using 5-minute weather data and graphics to determine weather conditions during critical periods during the wildfire event

The availability of 5-minute wind data recordings (wind direction, average 5-min wind speed and wind gusts) are critical for the wildfire investigation process, even if this has to be extrapolated or interpolated from surrounding automatic weather stations to the fire site. This data is mostly used for the critical one or two hours after first fire ignition, and also for other critical periods during the fire spread process, such as where firebreaks were breached by the fire or when counter fire were applied. It is then also widely used as input for selected 2-D BehavePlus (BP) fire simulation runs, thus providing a vital contribution to the fire reconstruction process, particularly when combined with concrete witness reports and field indicators.

We found it most useful to create a combination of graphs and/or histograms to illustrate wind data better, particularly when separating wind directions and wind speed (average 5-min and gusts-data) for better illustration. This makes it in particular easier to be understood by the legal profession, as it provides (with a good base map, etc.) a professional illustrative picture, which they always appreciate.

5.1.6 Creating an applicable topographical base map with property boundary overlay

Electronic base-maps with contours and property boundaries overlays, work best (Figure 5.5), particularly if this is also used to overlay all important points in the landscape, such as (i) site of fire origin (normally marked as “x”), and any other points where important events took place, (ii) where firebreaks were breached (Figure 5.6), (iii) where the fire spotted across a road, river or other barriers (such as mountain ridges), and otherwise any important reference points in the landscape.

Such maps should preferably be prepared on hard-cover plastic A0 size, as these are normally put upright on a stand in Court and used as such during the Court proceedings (particularly when evidence is led). Another example is provided in Figures 5.7 (before the fire). The use of a GIS expert to prepare such maps is strongly recommended to do such a job professionally. To create a suitable fuel classification from this info, also requires some BehavePlus fuel modeling and fuel model testing experience.

5.1.7 Selecting supportive tools such as satellite images before, during and after the fire (i.e. LANDSAT and SPOT), daily MODIS fire data and aerial photography

Whenever satellite images are considered or even when these are not used at all (such as in the case of official topographical maps), the use of MODIS data is also strongly recommended, as this will provide fire spread data on a grid free of charge, where recorded, and is significantly accurate for the purpose. Again, the use of a GIS expert is then recommended, because such data points are provided in GIS grid reference-form and should also be mapped by date/time – with a proper legend – on base maps.

With regard to the choice of satellite images before and after the fire (if this has been identified as a necessity for wildfire reconstruction purposes), LANDSAT is most accurate, but from experience also the least useful, because of the relatively poor resolution compared to e.g. SPOT satellite images.[1]

However, where LANDSAT images can be purchased for a relatively low price, SPOT images can cost between US$ 1000.00 and US$ 5000.00 depending on the size of the area covered by the fire(s) and how these images match the total area burnt (even a relatively small site can require 1-4 images to cover an area), for before and after the fire-images. Thus a minimum of two and maximum of eight images should be purchased. Again, the use of an "all-rounder" GIS expert is recommended to screen and select images, because the purchasing of wrong images can be very costly!

5.2 Reconstructing Initial Wildfire Spread

5.2.1 Plotting, measuring and photographing fire indicators in the field

Where possible, any field evidence/indicators should be mapped on a base map, or (if scale is too small, or objects are too close for mapping purposes), these micro-sites should be described in the photo caption. Where applicable, the heights of e.g. crown and stem scorch should be measured and such measurements should also be mentioned in photo captions. It

1 For South African readers: Images can be purchased in South Africa through the CSIR, Hartebeeshoek, Pretoria.

Figure 5.6. View of property boundary (red line), within picture taken from land exposed to the wildfire which spread from the property in the background towards the site in the foreground. The status of the firebreak at the neighbours property is clearly overgrown by succession, even visible two years after the fire occurred. Photo: C. de Ronde.

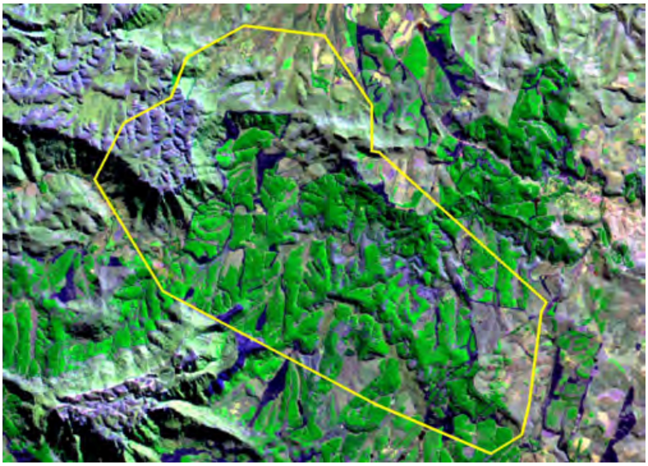

Figure 5.7. Satellite image of a landscape before a wildfire occurred. Source: EMROSS Consulting (Pty) Ltd.

Figure 5.8. SPOT satellite image of a wildfire area, while fire spread is in progress. As the exact GMT time of such an image is known, the fire spread status of the fire at the time can be regarded as direct evidence. Source: Map provided by EMROSS Consulting (Pty) Ltd.

is also important to describe micro-sites in the photo captions with regard to (i) position in the landscape and (ii) site of indicator(s) in relation to other points or lines in the landscape for easy identification purposes. Evidence of fire behaviour should also be described, with direction of fire spread indicated on the photograph with arrows.

Where specific indicator types are numerous (e.g. stain on rocks, stem and crown scorch in industrial plantations), such evidence should be grouped to try and determine any particular pattern (such as a steady increase in fire intensity experienced). Again, photographs can illustrate such patterns sometimes much better than long descriptions can do. Finally, make sure you explain exactly where a particular set of indicators has been recorded in the landscape, and/or mark this on a base map (with perimeter or area marked).

The following field indicators are particularly useful in reconstructing fire behaviour during the initial fire spread period:

- Freezing of branches and leaves
- Stain on rocks
- Scorch patterns on trees and fencing poles (wind- and lee-side stem or pole scorch patterns always measured in a range, row or transect)[2]
- Spotting evidence in vegetation or tree stands (to indicate evidence of spotting take-off and landing sites), with a good photographic range taken of all individual items or indicators
- Evidence of surface fires becoming crown fires (or "crown fire streets") particularly in industrial plantations
- In further studies, fire intensity models (de Ronde, 1989) can be used to calculate fireline intensity and rate of fire spread, using scorch height ratios
- Ash patterns (also see par. 4.2.1)
- Grass indicators (also see par. 4.1.4)

5.2.2 Using daily MODIS fire data

It was earlier explained how this data can be used when mapped as satellite image overlay, to identify daily spread by time, using different colours per time recorded. It is particularly when these data points are plotted on separate maps (satellite image or just topographical maps), that this data is most illustrative when a fire was found to be spreading uncontrolled over a number of days. In the case of the latter, a separate map of the same nature can be used to illustrate all points on one map as well, when comparing areas burned over per day. One such a combined map was provided earlier (Figure 5.2).

2 This is particularly useful when reconstructing specific fire events, from the origin of the fire into the direction of initial fire spread, with particular reference to (i) fire rate of spread and (ii) fireline intensity.

5.2.3 Using suitable 2-D fire behaviour programs

The authors have investigated the use of a European fire simulation program for this purpose (at the time still in the development stage) and – at least for the purpose of wildfire investigation – we found it to be not suitable for this purpose. However, after using (and testing) BehavePlus (and before this BEHAVE) for more than 28 years, we found the latest version of BehavePlus (BP5) the most useful to use for 2-D fire behaviour simulation, for both local (South African) fuels as well as Mediterranean fuels in S. Europe, provided custom fuel models can then be developed and tested for this purpose (Rothermel, 1972; Burgan and Rothermel, 1984; Andrews, 1986; Andrews and Chase, 1986; Andrews and Bevins, 2000).

As BehavePlus was further developed and expanded over the years (most probably as a result of popular demand), more modules were added and others improved further, adding more exciting options to the use of the program. It is useful to consider all options carefully before selecting such modules for input, as too many of them may spoil the outcome, and will make it difficult to read and understand. However, by all means, experiment with such input inclusions, as we have not yet tested them all to satisfaction. It must be kept in mind, however, that this is a US-based and developed program, and that some of these options may not be very useful for local use.

5.2.4 Aerial and ground photography at the time (or just after) the fire occurred

Aerial topography is today presenting new exciting concrete evidence of fire behaviour and other fire related events (such as when and where counter fires were used), because spotter pilots now make a point of it to record all important fire events during daytime (seldom at night though).

Sometimes concrete evidence of wildfires can be photographed from the air from a satellite when actual fire spread was in progress (Figure 5.8). We have used such evidence occasionally because it is not always available, but it is worthwhile to explore. As the aerial firefighting fleet in South Africa was expanded, with more fixed winged water bombers as well as helicopters (with buckets) now used operational at an increased rate (with both spotter and water bombers), this also provides a very useful additional source for aerial photographic material.

The use of other aerial photography after a wildfire event (at a larger scale) is also useful in assisting to determine wildfire perimeters, fire origins and the status of firebreaks, and can in this way complement satellite images, if used for larger fires (before and after the fire). Use of these, however, depends largely on availability and requirements.

Photographs taken on the ground still form the core of evidence to be collected soon after a fire, while aerial photography will perform a more important role as the fire progressed from its site of fire origin. Both can be regarded as being equally important.

Unmanned Aerial Vehicles (UAV) or Unmanned Aerial Systems (UAS) involving remotely controlled helicopter or fixed-wing drones are becoming increasingly important for monitoring ongoing fires for decision support, or for high-resolution post-fire (fire effects) monitoring. The Global Fire Monitoring Center (GFMC) used drones to monitor prescribed burning operations on terrain contaminated by Unexploded Ordnance (UXO) and the fire effects (Goldammer et al., 2012).

5.2.5 Real-time witness evidence

Determine who was first on the site of fire origin, because such a possible source of concrete evidence can be vital in determining the cause of the fire. However, this is sometimes not available and subsequently you may in the case of some fires determine that it was in fact the property owner or the land manager that was (according to report) first on the site of fire origin. In this case the cause of the fire could probably be directly linked to the ignition of the fire. Such a probability is normally strengthened if the owner/manager of the property (where the fire started) refuses to talk to the investigator. Then alternative witness evidence of fire ignition will have to be explored.

Another sensitive issue that could come out of the preliminary investigation is the probable use of counter fires that became uncontrolled. It is normally very hard to obtain any such concrete evidence from witnesses, and "cover-ups" are commonly experienced. However, fire fighting staff on site can always be approached, while Incidence Commanders are many times other good sources of evidence (either verbally or from IC reports). Lastly, photographs taken by pilots may also reveal such concrete evidence. However, check if you can find photographic evidence for a period when you know spotters were operational in the air, as many times such evidence is not provided to investigators because such evidence could be damaging for a particular fire manager. In such cases a diplomatic approach will almost always provide such evidence, if being hidden from the investigators.

Where counter fires have "gone-wrong", this might not have been the fire managers' fault, but this can sometimes be attributed to a sudden unexpected change in e.g. wind direction. Such changes can of course be traced from weather data for confirmation purposes. It is always necessary to conduct these parts of the investigation with utmost care, because it is most of times extremely sensitive evidence. Never arrive at a conclusion unless all evidence has been checked and cross-checked, and then only when the investigation is concluded. Even then, such evidence will only be provided to the senior manager of the institution on which instructions the investigation was conducted, and its Legal representative(s) (where applicable).

5.2.6 Incidence Command and pilot log recordings

These records can be used to advantage when a wildfire's spread is investigated. It can e.g. provide accurate evidence about command decisions as well as wildfire event recordings. In the case of pilot logs, this information is many times provided on photographs taken on site, with day/time recordings inserted. Incidence Command logs can provide accurate records of a range of events as the wildfire progressed, including personal IC comments (sometimes about success and failure of counter fires applied). At times, photographs can be used to confirm pilot log entries, particularly of specific events, relating to the effectiveness of firebreaks or attendance of fire fighting crews. An example is provided (Figure 5.9).

5.2.7 Calculating probable spotting events

If direct spotting evidence in the form of spotting take-off and spotting landing sites is not readily available, the probability (likeliness) of spotting can be calculated by using BehavePlus 2-D fire behaviour simulation that can be used to calculate maximum spotting distance (Andrews, 1986; Andrews and Chase, 1986 and Andrews and Chase, 1986). As input, a representative fuel model can be selected or developed/tested, with known weather conditions and topography as input. Apart from the SURFACE module, the SPOT option can then be included to calculate "maximum spotting distance". The probability of such possible spotting events can then be checked in the field by means of identification of indicator evidence.

Sometimes multiple spotting events were photographed by spotter or bomber pilots, while such critical events were in progress. When such concrete evidence is available, it is obvious that it should be used to advantage, as it is indeed important to know how large wildfires behaved during critical periods during further (advanced) fire spread events (Figure 5.10).

5.3 Reconstructing further Wildfire Spread Stages

5.3.1 Using SPOT image overlays before and after the wildfire event

An example of the use of SPOT images, from before and after the fire, has been provided in Figures 5.6 and 5.6a. In most cases of large and multiple fires to be investigated, such images have provided a range of possible overlays and data collection potential, providing a range of evidence which normally outweighs its purchase price by far. Put in a different way, without these images, an investigation will provide much less (and many times poorer) evidence and may even put the whole investigation case at risk during future legal proceedings.

It is important that only the best possible images are selected though (thus images without any clouds or haziness), even if this means backdating the "before fire image" a number of weeks or even months. However, in the case of the "after fire images" required, such images will have to be selected for the critical period "within weeks of the fire" occurring, because less time will be available between the requesting date and the fire end time. Fortunately there are normally a few very clear days after such fires, but in the case of Bergwind conditions experienced, such choices can be restricted. A GIS/satellite image specialist is best to attend to such selection processes.

Aerial-type of evidence, about other fire spread events, can also be collected for different purposes, such as the collection of evidence to illustrate the effectiveness of firebreaks (or absence thereof), or fire fighting action evidence at critical places in the landscape.

5.3.2 Determining (and drawing-in) fire perimeters

An example on how this can be done has been illustrated in Figures 4.7. Note that this example shows a wildfire that burned through grasslands as well as in industrial timber plantations. Where the fire spread through the latter, the damage done could be divided into three categories in mature stands with closed crown canopies, namely (i) partly crown scorch from a relatively mild surface fire, (ii) complete crown scorch as a result of a higher intensity surface fire and (iii) tree crown consumption as a result of a surface that developed into a crown fire. On the ground (or just above the tree crowns) these three crown categories will show in general green, brownish-grey and black colours. However, in this example of the SPOT image after the fire, they show as green, light-purple and bright/darker-purple, because the base background has been set in a purple colour base (Figure 5.2). Such knowledge is important to ensure that the fire perimeter is drawn-in correctly (own experience).

5.3.3 Plotting daily MODIS data to assist with reconstructing fire spread over time per day

The use of MODIS data points as overlay on SPOT satellite images (particularly after a wildfire with fire perimeters drawn-in) has been illustrated in Figure 4.4 (single day) and Figure 5.2 (multiple days). We found that it was particularly the daily MODIS data that was most useful to reconstruct further wildfire spread, as other evidence is very scarce when fires develop into such fire intensity levels, with many times multiple spotting, crown fire and even "fire storm" events.

5.3.4 Using selective 2-D fire behaviour simulation procedures

2-D fire behaviour simulation should only be used in cases where the status of the fuel – where the fire was burning – was known at the time, or where specific photographic evidence of such vegetation is available, taken soon after the wildfire occurred. During further fire spread (thus after the initial fire spread events), we found that such evidence is particularly useful when investigating firebreak crossing sites, sites of spotting across clean road surfaces, and sites where counter fires were applied (and where such a fire met the main fire front). Where wildfires jumped power line reserves, such evidence might also be available and indeed useful, but only where you know where the head fire crossed such an obstacle.

BehavePlus should be used for this purpose with available (or developed and tested new) fuel models, with specific topographical and weather data input, making use of the SURFACE, SIZE and SPOT modules available in the program (Andrews, 1986; Andrews and Chase, 1986; Andrews and Bevins, 2000).

5.3.5 Using selective 3-D fire spread simulation procedures

Two computer-based programs are available for this purpose, namely FARSITE (Finney, 1996; 1998) and FLAMMAP (Finney *et al.*, 2004). While FARSITE has been developed to simulate fire spread only over a range of topographical parameters and fuel models, FLAM-

Figure 5.9. Assessment of wildfire damage from the air (and linked fire behaviour evidence) can provide a wealth of answers if done soon after a wildfire. Photo: Courtesy North East Cape Forests (NECF).

Figure 5.10. Multiple spotting events photographed by an unknown spotter pilot. The available fuel responsible for this extremely high intensity wildfire just "dried up" in front of the head of the fire (bottom left corner in picture), causing multiple spotting from this site (which also happened to be the end of a slope on the mountain ridge in this landscape), creating ideal conditions for such spotting. Photo: Courtesy CapeNature.

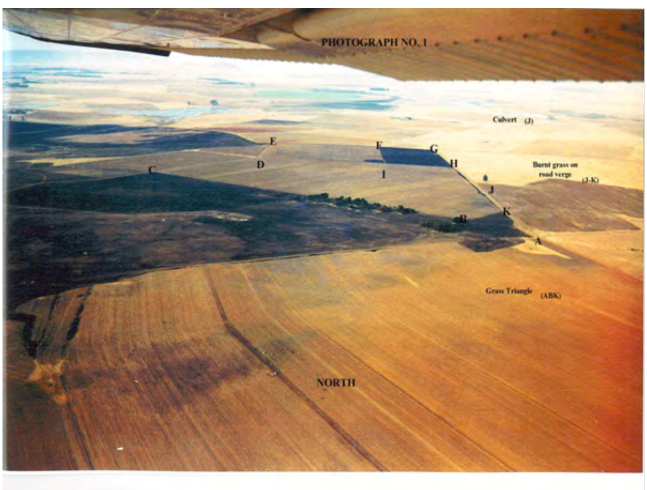

Figure 5.11. Aerial photograph of wildfire scene with reference points (as indicated in the text of the investigation report) just as an illustration added. Photo: Nico Steinberg, spotter pilot (Courtesy Safcol).

MAP provides basically the same procedures, but for a range of fire behaviour parameters (including fire spread), using one fire parameter at a time.

FARSITE or FLAMMAP are designed for users familiar with fuels, weather, topography, wildfire situations and the associated terminology. Because of its complexity, only users with the proper fire behaviour training and experience should use anyone of these two programs.

In the case of wildfire investigations in Southern Africa, these two programs should only be considered in the case of multiple fire events of wildfires that burned over large areas of land, causing extensive damage resulting in the loss of land, crops, properties and sometimes even human lives. The reason for this is that it might be necessary (even by experienced investigators) to involve GIS databases and satellite images, while the investigator should also have an advanced level of fire behaviour simulation knowledge, including the development and testing of suitable custom fuel models, which could be a rather time-consuming and costly process. However, conversely, these programs can provide a range of evidence otherwise not possible to obtain elsewhere, and is in specific cases thus strongly recommended.

5.3.6 Aerial photography of real-time fire spread evidence

Aerial photographs can play an important role in the presentation of wildfire spread evidence, together with other related evidence (such as evidence located on the ground, concrete witness evidence and fire spread indicators). Where applicable, reference points must then also be drawn electronically on such pictures, relating to reference in the investigators' report (Figure 5.11), using e.g. the "Paint" option in MS Word. Many times this reflects the only evidence of further wildfire spread (past the initial fire spread stage) that can be related to evidence that can be used in Legal proceedings (own experience).

5.3.7 Incidence Command and pilot log recordings

This type of incidence recordings were unfortunately in the past not always well kept (or sometimes not at all), but its importance has now been identified as extremely important for investigation as well as for Legal purposes, and are nowadays mostly well-kept in regions where Fire Protection Associations have been established. Such logs of incidents as they occurred during fire fighting (from the ops room and from the air, bomber and /or spotter pilots that were on the wildfire scene) can be very effective, and can supplement aerial photographs, as well as satellite images.

During relatively small wildfires, Incidence Command posts are normally not created as the fire incidences are relatively short-lived. However, today Incidence Commanders are normally appointed for all larger (and multiple) Veld and Forest wildfires, and thus provide a very important control. Where such wildfires burn over a number of days (which can occur particularly in the case of fynbos and industrial plantation wildfires), Incidence Commanders work in approximately 8-12 hour shifts and it is important that IC logs are being kept updated all the time for continuity purposes.

Pilot logs are normally (or at least should) be drawn up after all fire fighting or spotting flights, particularly because such services are expensive and the customers ordering such services would like to have insight in these notes to check if such services can be regarded as "money well spent". Such reports (IC as well as pilot logs) should include instructions from IC's to pilots and vice versa, as such decision-making events normally have to be checked realistically by wildfire investigators.

5.3.8 Determining irregular fire behaviour and spotting evidence in the field

Spotting events can form an important part of the evidence, to e.g. prove that a fire was uncontrollable at any point in time during further fire spread stages. Any irregular fire behaviour observed, photographed or evidence located of in the field, can (for a start) indicate if spotting could have occurred (such as direction of spread indicators, crown fire evidence, spotty defoliation by the fire and evidence of significant direction of fire spread changes). Where such evidence is located, the fire investigator should be on the lookout for spotting evidence in the form of (i) spotting take-off sites, (ii) spotting landing sites and (iii) fire spread indicators on both sides of roads, rivers, power lines, firebreaks and railway lines.

5.3.9 Checking of known (and unknown) counter fires applications

Quite often the applications of counter fire (back burning), which had been reported to the wildfire investigator, were the least harmful ones, including the counter fires which were applied correctly (or at least where no additional damage was experienced). The methods of counter firing depend on a range of circumstances such as terrain, wind direction and strength, type of vegetation/fuel (and fuel moisture status) and availability of a safe ignition line. Counter firing should be applied only by experienced fire bosses/managers. The decision should be made by on-site personnel only and will obviously need an assessment of all factors influencing the wildfire and the counter fire on the ground.

One popular method of counter fire application is to ignite a line parallel to the left or right flank of the main fire, starting by "anchoring" the start of such a fire to the flank selected, and then to continue creating a counter fire line parallel to this flank, preferably along a safe (fuel-free) line in the landscape. However**,** we have identified the following (mostly disastrous) mistakes when counter fires are applied:

- <u>The creation of a fire line at an approximately 90° to the direction of maximum fire spread</u> (many times starting such a line close to the area of fire origin), is an action that can be described as "chasing the main fire with another fire". The consequences of such action (in my experience) are mostly always negative, sometimes doubling fire damage, or even worse. Apparently the idea behind this is to "close up" the flanks of a wildfire, but the results are extreme, as a fire line provides much higher fire intensities than a fire from one ignition point (or even a few ignition points). *Such ignitions should not even be considered, but unfortunately some are still applied regularly* (example of one of the few successful counter fires, Figure 5.12).

- Igniting a counter fire in variable wind conditions: This can result in a flank fire becoming a head fire, resulting in endangering of fire fighter lives. When wind directions are variable (normally linked to a lull in wind speed, followed suddenly by wind gusts) an ignited fire line can become a spotting head fire within seconds. In South Africa fire fighters have died as a result of such wrong action and in such conditions the application of such a fire line should be forbidden under all circumstances. *Under variable wind conditions, no ignition lines should be created. Wildfires, where such unpredictable wind conditions have been recorded, can almost always be a cause of serious problems.*
- Following a "safe" ignition route, can become a nightmare if such routes are not in the form of straight lines, in which case a controllable fire line can turn into a spotting head fire within seconds and become uncontrolled. *Always keep ignition lines straight.* Concrete evidence of such mistakes are mostly identified from aerial photographs.
- Where slash heaps are causing flare ups or created uncontrolled fire sources, to ignite the heaps not yet ignited "to burn out the area or compartment". The consequences of such action can be disastrous and lead to more damage. Even though it means to guard such burning heaps for long periods of time (the apparent reason for burning out such an area), such action under adverse weather conditions can only "add more fire", which can easily bypass existing fire flanks with serious consequences. *Such unnecessary and dangerous actions should be avoided*. Aerial photography from spotters on site normally "identify" such mistakes with ease.
- To attempt to create a counter fire right in front of the head of a wildfire: Such action can be extremely dangerous in front of extreme wildfire behaviour with strong winds and multiple spotting, even if there is a safe line where to ignite-from. Such ignition lines may become uncontrolled, may result in spotting over the safe lines, and may expose fire fighters to becoming trapped by the fast (and unpredictable) head of a fire, or be surrounding by spotting landing sites (and then subsequently also be trapped). One can argue that one must apply such a fire line long before the head of the fire reached such a line, but this is no acceptable argument, because (i) the spread against the wind and/or slope will be extremely slowly, creating only a thin line from where such a line is applied, it is easily breached by the fire head and (ii) only a "small fire island" can be created that might not even be reached by the fire, as the head of such a fire could easily deviate away from it. *Because of these extreme dangers, never attempt such an ignition fire, because many lives have been lost in this way in the past in South Africa*. Only when conditions have significantly improved, counter fires can be applied and then – provided the wind speed has been reduced to low head wind levels, and/or when topography is favourable – can then be used to advantage. Then such fires should only be applied under the strict control of an experienced fire manager, who has a proven record of the application of counter fires. If extreme

wildfire conditions persist, fire managers should rather revert to flank fires and even then under strict controllable conditions.

- Where there are indications that the application of such fires ahead of head fire fronts have "gone wrong", the investigation of such fire application probabilities should be done thoroughly with all available means, as the outcome of such investigations is extremely important – although this should be done with extreme caution and consideration of all factors. FARSITE-use is one option we have applied successfully for such investigation purposes where concrete evidence is lacking.
- Burnouts gone wrong. Such burning action should be left until the critical (extreme) conditions of a wildfire have been significantly reduced, because otherwise such fire ignitions can easily go wrong. *Always apply burnouts when weather conditions are favourable for such action and fireline burning with the wind should always be avoided.*
- As summary of the above situations, the "window" during which counter fires can be applied is rather restricted and this should always be remembered as accepted as a *fait accompli*. Accept this as a reality, and never apply a counter fire if not 100% sure all aspects have been considered carefully, and then it should only be applied by experienced fire bosses. *This is where most problems arise-from: Fire bosses "think" they are doing the right thing, but then they make the wrong decision. Lack of training in fuel assessment and fire application training is in South Africa one of the main problems identified. Fortunately we now have some fire managers who have a proven record of the application of such fires and can be trusted with such dangerous tasks.*

When listening to witness evidence it often becomes apparent that a counter fire (or counter fires) might have been applied. Normally the party that appointed the wildfire investigator will cooperate and provide all the necessary detail of fire ignitions applied, but even here, sensitive information may not have been provided (or information tabled may be "twisted"). For that reason (and because a fire investigator should be independent at all times) it is important that the investigator investigates all possible counter fire events, from the fire's escape from the area of origin, right up to the wildfire having been brought under control.

It may be advisable to leave the investigation into possible counter fires, until most information and evidence has been collected, as by then the investigator should have a clear indication of what happened (by counter fire applied, because their numbers could during some wildfire events easily exceed ten in number!) and the reconstruction process of these events can then begin seriously. Start with determining if there is any outstanding material or evidence, such as logs, photographs, or witness evidence from people on site at the time. Sometimes such evidence is withheld from the investigator, but in other cases such material might not have been requested, for some reason.

If the time and site of the counter fire has been determined (even if only in the form of an estimate), one can start exploring existing evidence and material (maps, satellite images, MODIS data, photographs and field evidence). Any evidence of fire behaviour, which cannot be linked to the fire behaviour of the main fire, should be investigated, or at least the investigator should attempt to explain such evidence. Always search for answers in different directions (e.g. topography, fuels, weather data, maps, images, photographs, field evidence and witness evidence) as they should all match and create a "mosaic of evidence" that can be used in Court with confidence. Also explain such evidence in your report, even if this is sensitive information (the truth and nothing but the truth).

5.3.10 Reconstructing wildfire spread, from area of initial fire spread until the fire was brought under control

This process has now been discussed in parts throughout Chapters 4 and 5, and results need to be checked systematically for any gaps or shortcomings, from the area of wildfire origin until the fire was finally brought under control. We would like to suggest that this is being checked by day-events, and this will be assisted greatly by MODIS data overlaid on SPOT image base maps. These daily maps actually form a welcome base from where shortcomings in the reconstruction process can be identified.

The wildfire reconstruction results should be dealt with systematically and provided in the wildfire investigation report (to be dealt with later in this book). This may make most reports somewhat bulky, but rather ensure that all information and data is included than leaving some critical issues out. As time goes by, one will see that new evidence will most probably crop up, which should be noted. Rather than updating the report regularly, it is suggested that such "late" information is kept on record, and this can then be used to rather update the report when arbitration (or legal action) is eminent.

5.4 Investigating and Reconstructing Wildfire Disasters

Although basically the same procedures have to be followed as described earlier in this chapter, there are some deviations to be considered because of some special circumstances, particularly where loss of life has been experienced. First of all it should be kept in mind that such occurrences are always very emotional, and one has to be extremely careful to make any assumptions or early conclusions. For that reason, always make the findings of an investigation known only when everything has been checked and double checked, particularly because such findings will in many cases be exposed to the public at large and the press. Adding to this, a very emotional family and relatives of persons, who lost their lives, and it is clear that one should never attempt such investigations on your own, but rather as part of a team.

The second issue to remember is that it is most important not only to identify mistakes made by people involved in such a wildfire disasters, but also to ensure that solutions to the problem(s) are well documented and published, to ensure that such losses of human lives are avoided in the future. Legal processes might delay such reports and publications for a number of years, but revised training programs should ensure that such topics are covered in formal and informal courses, to make sure that such technology transfers are arranged as soon as possible.

Figure 5.12. Clear indication of a firebreak being used as safe ignition line to ignite a counter fire from. See line between black burned-over area (plantation on the right) and firebreak on the left. Obviously, a wildfire does not stop spreading in a straight line in the landscape, as can be observed in the background of the picture. Photo: C. de Ronde.

Figure 5.13. Plantation wildfire in progress. Note high intensity surface fire on the left of the tarred road under *Pinus patula* (closed) crown canopy, while the fire on the right of the road is burning in younger stands with very high fire intensities and common flare-ups, about to spot across the tarred road from right to left (flames just visible in the distance behind the vehicle). Photo: GFMC archive.

Figure 5.14. Wildfire in progress in old fynbos shrubs, with helicopter with water bucket in attendance. The line of fire visible higher up the slope is a very high intensity backing fire burning down slope, while the fire at the foothill in the picture is an ignited counter fire. Photo: GFMC archive.

We will discuss two such wildfire disasters as they occurred in South Africa and – although both were well covered in follow-up courses, formal and informal training – we will refrain from any detail about these fires from which they could be identified. Both these wildfire cases could years ago be regarded as being *sub justice*, but we do not want to cause any personal embarrassment or pain to anyone who was involved, and will subsequently not mention anyone's name, places/locations or other information that could be regarded as problematic in this regard. Where such text or photographs are is still considered to be linked to any particular wildfire history situation, this was definitely not the intension of the authors of this book, and we apologise for this if it still occurred. "Ghost names" are used where necessary.

Both example wildfire disasters have not really been made public, but both occurred in South Africa more than ten years ago. In both wildfires more than ten people lost their lives. A short discussion of both fires by C. de Ronde – with lessons learned – will be provided below:

The "No-escape fire"

This fire was known to have escaped from a fire burning in slash deposited on that site after clear felling, timber exploitation and removal, so that the origin of the fire did not have to be investigated further. However the cause of this fire required some further attention, because it started from a slash burning source, which escaped when the NW wind strongly came up making the slash fires uncontrollable, with an abundance of spotting within minutes, spreading further thereafter in extremely dangerous (young) plantation fuels mixed with years-old (and cured) montane grassland. The end-result (in strong NW wind) was an extremely intensive wildfire regularly developing in a typical "fire storm".

The first question required to be answered, was of course (i) if the controlled slash burn should have been applied at all, (ii) if the sudden change in weather conditions (strong NW wind) could have been foreseen, (iii) if the fire was guarded at the time, and if so, why the fire escaped at all. Further questions that are normally added are (iv) if there were any shortcomings in fire fighting equipment, manpower and their training and (v) if the response to the fire was in time and correct, particularly with regard to aerial support. None of the details about the outcome of this part of the investigation will be described, as they were complicated and providing mixed results. However, readers of this should apply all procedures as discussed earlier in this and earlier chapters, if they get involved in such a wildfire investigation.

The second question to be answered will be with regard to fire fighting command issues and fire fighting procedures applied, as it was during further fire spread that the mortalities were experienced. During the investigation it came out that a fire commander send a mobile team on the ground to the head of the fire to combat the fire, and it is here that the fatalities occurred. When the team arrived at this site, they were not only faced with a fast-spreading spotting fire, but also with no escape route. Some decided to break out of the trap by means of driving through the fire front, which they managed to do, but with serious injuries to

Figure 5.15. Extreme fire behaviour at an early stage of the "No-escape fire" (initial fire spread) as seen from the air by a spotter pilot in attendance. Photo: Johan Heine, Forest Fire Association (FFA).

Figure 5.16. Extreme fire-storm situation developing from the "No-escape fire". Note multiple spotting experienced (see bottom of picture). View as photographed by spotter pilot. Photo: Johan Heine, FFA.

some of the fire fighters as a result of direct fire exposure. Those who remained behind, where burned over and died.

The main lesson learned is that *never should a fire fighting team be send to the head fire front of an uncontrollable wildfire for whatever reason, particularly if there is no escape route from there.* Linked to that should be to *rather to consider evacuation of all human beings in the front of the fire that could be caught by the fire, as a matter of first priority.*

Nowadays Incidence Control Commanders in South Africa are well trained in wildfire management, and such rules should thus be automatically applied. This specifically refers to fynbos and forestry (grassland or fynbos based) regions, but unfortunately there are other fire-regions in the drier areas of South Africa where (at the time of writing) there are still serious organizational short-comings in this regard (the writers' opinion).

The "Lion-scare fire"

This wildfire burned over a major area of a nature reserve in dry savanna Bushveld, and the investigation found that the origin of the fire was a picnic site next to a public road within the reserve, and was caused by negligence from tourists. Within a few days, more than 250 000ha was burned over. Although the field investigation was conducted in air temperatures exceeding 40°C, we were able to conduct certain basic procedures described earlier in this report to determine the site of fire origin, with the assistance of a helicopter. It needs to be mentioned that the circumstances in which we had to conduct this investigation were quite frightening (apart from the extreme heat dehydrating us), as two groups of White Rhinoceros showed up on both sides of the investigating site, and none of the investigators were properly armed.

We also used the 3-D fire spread simulation program FARSITE to simulate the spread of this fire, also marking and simulating fire spread from a counter fire attempt along one of the public roads through the Reserve. This counter fire attempt ended at a disastrous note when this fire became suddenly uncontrolled in gusting wind conditions, killing and seriously injuring some of the Nature Reserve staff. The worst was still to come, as the FARSITE fire simulation runs indicated that not only did the counter fire attempted kill and seriously injured some of the Nature Reserve staff, but that the latter fire was also the fire that burned over the other persons killed by this fire, and not the fire that originated at the picnic site.

The lessons learned from this fire were numerous, and the nature conservation staff were updated and trained in all issues coming out of the investigations, or having been identified as shortcomings in fire prevention measures. Here are some of the issues highlighted:

- *The "no-burning" policy of dry savanna nature reserves (total fire exclusion policy) does not work and results in fuel accumulation with sometimes disastrous consequences.* Apart from firebreaks since then created along strategic lines, the use of mosaic block-burning was successfully implemented under the guidance of Prof. Winston Trollope (one of the most outstanding fire ecologists in the field of fire and savanna), which corrected this problem effectively.

Figure 5.17. Experienced personnel working on farms and forestry enterprises are often quite skilled in improvising counter firing operations without having advanced ignition tools in place. The photograph shows backburning in grasslands of Kenya. Photo: GFMC

Figure 5.18. and 5.19. Coordination with aerial observers will assist decision making on the ground for counter firing operations. The photographs show backburning in grasslands of Kenya. Photos: GFMC

- *Counter fires should only be applied by trained fire bosses who know the region well, under the guidance of experienced fire managers.* If such persons are not available, counter firing should rather not be applied at all.
- *If public sites are exposed to barbecue fire, they should be well isolated from the surrounding vegetation in the form of protective firebreaks to avoid wildfires.*
- *Should a wildfire still occur, these should be investigated by a qualified wildfire investigator as soon as possible after such a wildfire occurs.* I investigated this fire more than a year after it occurred and was lucky to still find sufficient evidence on the ground indicating where the fire originated from.

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6 FIRE PREVENTION

6.1 South African Standards

As the status of firebreaks always forms an important issue in wildfire investigations, it is important that independent investigators determine not only the status of firebreaks, but all fire prevention measures at a regional level. They should also assess regional requirements in this respect are (norms of the region). Although the norms for a particular region may not always provide optimum firebreak specification requirements, in Court proceedings it is seldom that a finger can be pointed at landowners if the regional norms are met.

The following comments refer to the situation in South Africa: The norms for the country (also referring to the greater Southern African region) with regard to fire prevention requirements are mostly determined by the characteristics of the prominent biomes and/or land-use and climatic characteristics to consider (particularly yearly rainfall). Once the important regional biomes have been identified, we need to learn more about these biomes in terms of (i) its maintenance of biodiversity, (ii) fire related problems, optimum rotation and fire intensity requirements, (iii) status of alien vegetation, (iv) urban-interface problems in the region and otherwise any information that can assist in understanding fire prevention needs and problems.

Investigators have to be careful, however, before recommendations regarding firebreak specifications are presented as evidence in Court in South Africa. Although we have the highest regard for this countries' legal profession, one has to be careful to prove any point always beyond doubt. Never look for only one way in which to present such evidence, but always more than one. This in fact is always a good policy in all matters to be tabled on Court.

We have over the years come to the conclusion that there is in South Africa much room for improving integrated fire protection measures at regional level, particularly with regard to (i) firebreak and buffer zone routes and widths; (ii) the need to move away from property boundaries as and when required (because these are sometimes the worst fire protection lines in the landscape, because men decided on such property boundary lines), and (iii) the fact that very few people know how to calculate real fire prevention requirements, because they do not know how to asses this. Only if one works from a regional fuel model base can one determine such needs (Calvin et al., 2004).

Although there might thus be a significant "gap" between the regional norms and real firebreak requirements in a region, these norms might be a good starting point, particularly if expert witnesses are standing for the Defendant(s) in Court cases. In many cases this is the only sure way to make satisfactory progress in effective legal defense (various High Court experiences: The author). Of course this also provides the expert witness with an opportunity to also table real fire prevention requirements, tabled with adequate motivation. This is particularly useful because all Court proceedings are recorded, and will then be permanently on record.

6.2 Legal Requirements in South Africa

It is important that we know (and understand) the Law with respect to crucial aspects of the Act in operation in South Africa (Act 101 of 1998). For the purpose of this important Legal base in this country, we have selected a few sections about some important issues regarding this Act, to be considered for wildfire investigations in South Africa.[1]

(a) **Firebreaks**

Veldfire Prevention through Firebreaks

This aspect is covered by Chapter 4 of Act 101 of 1998. *Chapter 4 places a duty on owners to prepare and maintain firebreaks*. This duty is described as follows:

Duty to prepare and maintain firebreaks

12. (1) Every owner on whose land a veldfire may start or burn or from whose land it may spread must prepare and maintain a firebreak on his or her side of the boundary between his or her side of the boundary between his or her land and nay adjoining land.

(7) Owners of adjoining land may agree to position a common firebreak away from the boundary.

(10) A fire protection association may make rules different from subsections (2) to (6) if the new rules are approved by the Minister, in which event members are bound by the new rules and exempt from subsections (2) to (6).

Requirements for firebreaks

- An owner who is obliged to prepare and maintain a firebreak must ensure that, with due regard to the weather, climate, terrain and vegetation of the area
- It is wide enough and long enough to have a reasonable chance of preventing a veldfire from spreading to or from neighbouring land
- It does not cause soil erosion; and
- It is reasonably free of inflammable material capable of carrying a veldfire across it

1 For investigators operating outside South African boundaries, it might be good idea to investigate how this Act compares to Acts in force in the country where the wildfire investigation is taking place.

Figure 6.1. Example of prescribed burning inside industrial plantations, as part of a weed control and fuel reduction program. Photo: GFMC.

Figure 6.2. Regional secondary road in the Northern Cape Province, widened to act as firebreak as well in duel-purpose role. The unburned grass in the road reserve edges are normally also added to strengthen the firebreak before the fire season, in the form of prescribed burned strips. Photo: C. de Ronde.

Figure 6.3. Where specific (and serious) wildfire threats exist, the norms for the region may not be sufficient, and much wider firebreak widths may be required to provide effective fire prevention, even in drier regions (such as here in dry savanna farmland with a significant shrub cover, along a common property boundary). Photo: C. de Ronde.

(b) **Fire fighting**

Readiness for fire fighting

17. (1) Every owner on whose land a veldfire may start or burn or from whose land it may spread must-

- Have such equipment, protective clothing and trained personnel for extinguishing fires as are
    1. Prescribed; or
    2. In the absence of prescribed requirements, reasonably required in the circumstances;
    3. Ensure in his or her absence responsible persons are present on or near his or her land, who, in the event of fire, will
       - Extinguish the fire or assist in doing so; and
       - Take all reasonable steps to alert the owners of adjoining land and the relevant fire protection association, if any.

Action to fight fires

18. (1) Any owner who has reason to believe that a fire on his or her land or the land of adjoining owner may endanger life, property or the environment, must immediately-

- Take all reasonable steps to notify
    1. The fire protection officer or, failing him or her, any member of the executive committee of the fire protection association, if one exists for the area; and
    2. The owners of adjoining land; and
    3. Do everything in his or her power to stop the spread of the fire

The investigator should not only just read what this Act's details are all about, but also how certain aspects of the Act can be interpreted for practical application. This is particular useful in the case where one has to consider the application of firebreak systems outside property boundaries, for improved fire prevention at regional level.

6.3 Considering Effective Fire Protection Measures

Under specific wildfire hazard conditions, firebreak specifications might have to exceed the norms for a region, in which case it is important that (in particular) the routes of such a firebreaks are considered objectively, as such protection lines in the landscape (normally called "buffer zones", although many times actually widened – fuel-free – strategic lines in the landscape, further strengthened before the fire season by means of prescribed burning)

Figures 6.4 to 6.6. Posters and bumper sticker highlighting the needs of wildfire prevention at local community level in East Caprivi, Namibia, developed by the project "Integrated Forest Fire Management" under the Namibia-Finland Forestry Programme in 2001. Source: M. Jurvélius. Photo documentation: GFMC.

require maximum effectiveness. Such buffer zone lines can be placed to follow major (fuel-free) road systems (Figure 6.2), or selected common property boundary lines, particularly if there is no alternative option in the surrounding landscape (Figure 6.3). Such considerations should in particular be considered where a wildfire investigation is pointing to serious (life-threatening) Urban-Interface problems (Calvin et al., 2004; De Ronde et al., 2004).

Apart from the fact that such problem areas may have been pointed out as so-called "hot-spots" requiring immediate attention, a wildfire investigation may have to table future recommendation to avoid future wildfire problems referring to some examples of "hot-spots" in a particular region, even in drier grassland or savanna biome areas.

It is important that wildfire investigators not only point fingers at inadequate firebreak systems when investigating wildfires, but also table what should be done to avoid (or at least significantly reduce) wildfire hazard and related damage. It is particularly useful if investigators can illustrate their experience and knowledge in respect of such recommendations. Also ensure that such recommendations are realistic, and can be applied in a cost-effective way. This will not only make a significant contribution towards reducing wildfire damage in a region, but such evidence can also in future be used in related wildfire investigations, and will most certainly confirm the investigators' integrity.

6.4 Responsibilities and Fire Prevention System Control

There are many problems with regard to which organization should (at the time of writing) take responsibility for regional fire prevention control in South Africa, but there are positive signs that this issue is receiving attention at the highest level. In the case of some South African regions, the development of such improved regional fire prevention systems are well advanced and are being implemented. However, in other areas nothing has been done to date to improve the status of firebreaks. We will not elaborate on the situation in this country, other than just stress the point that in many regions there is in fact still "substantial room for improvement".

The investigator should take stock of the regional status of fire prevention in relation to the wildfire he/she is investigating, and subsequently has to act in such a manner that his action suits circumstances as and when required. We have experiences that there is many times a complete or significant lack of knowledge of fire prevention requirements, even at regional senior management level. Such shortcomings need to be identified and dealt with as and when required, particularly in Court proceedings.

Many times, legal requests for expert witness' "terms of reference" in fact specify that an investigation should be focused (or even be restricted) to firebreak requirements only. However, in most of such "restricted" investigations the investigator will find that it is impossible to restrict an investigator to such narrow terms of reference only, and you may find that you have to table specific motivations for investigation terms of references' extension.

Figures 6.7 to 6.9. Taking responsibility in fire prevention by local communities: (6.7) Information of community leaders and administrators; (6.8) handing over of hand tools and (6.9) involvement of the youth right from the beginning of individual community activities in Nepal and Mongolia. Photos: GFMC.

Some comments regarding the effectiveness of Fire Protection Associations (FPAs), is that the improvement of the whole system (with a new restructuring process, appointment of so-called "Umbrella Fire Protection Associations" – UFPAs – and other streamlining measures related to capacity improvements), are at the time of writing making great progress and development is still ongoing in some regions.

One issue that will have to be sorted out, is that the responsibilities for (a) fire fighting (also under specific control), (b) fire prevention development at regional level, planning and application as well as (c) prescribed burning application, should fall under fire prevention management control, although fire prevention application might have to be supported by some fire fighting resources. This issue is at present in South Africa still full of uncertainties and needs some careful consideration, particularly with regard to management and control of the various disciplines, as pointed out.

6.5 Capacitating Local Communities in Wildfire Prevention – A Globally Increasing Endeavor to Reduce Wildfire Threats

The involvement, empowerment and capacitating of local rural communities in fire management, including wildfire prevention, is essential. Local approaches aim to capacitate local communities in the proper application of land-use fires (managed beneficial fires for controlling weeds, reducing the impact of pests and diseases, generating income from non-timber forest products, creating forage and hunting, etc.), wildfire prevention, and in preparedness and suppression of wildfires. Community-based approaches can play a significant role in those parts of the world where human-based ignitions are the primary source of wildfires that affect livelihood, health and security of people. The activities and knowledge communities generally practice are primarily those associated with prevention. They include planning and supervision of activities, joint action for prescribed fire and fire monitoring and response, applying sanctions, and providing support to individuals to enhance their fire management tasks. Communities can be an important, perhaps pivotal, component in large-scale fire suppression, but should not be expected to shoulder the entire burden.[2]

In general many countries globally and particularly in Subsaharan Africa use public information and education tools such as posters or billboards displayed in Figures 6.4 to 6.6, complemented by street theater and community meetings. The principles of community-based forest management are now applied globally in community-based fire management. Figures 6.7 to 6.9 provide examples of the next steps: Capacitation of farmers to manage community forests, prepare fire management plans and learn to use hand tools for basic

2 For a comprehensive collection of materials and sources on participatory fire management: See the GFMC website "Community-Based Fire Management": http://www.fire.uni-freiburg.de/Manag/CBFiM.htm

Figures 6.10 and 6.11. Training courses for the safe application of prescribed fire for post-harvest residual disposal on wheat fields in Georgia (South Caucasus) and for safe fuel reduction burning in natural pine forests of Mongolia. Photos: GFMC.

activities in managing prescribed and controlling moderate-intensity wildfires. Most important is the training of farmers and shepherds in the safe application of prescribed fires on agricultural lands and pastures to avoid uncontrolled escape fires (Figures 6.10 and 6.11).

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7 FIRE FIGHTING ISSUES

7.1 Fire Fighting Capacity

7.1.1 Equipment: Minimum requirements for property owners

Assessment of the minimum requirements with regard to fire fighting equipment is normally linked to the number of workers available for fire fighting on a property, which can be trained for this purpose and then mobilised in case of a wildfire threat. However, there will also be reasonable limits in what can be expected in this regard from property owners, which (i) will also depend on the regional availability of manpower and equipment for fighting (ii) the degree of fire hazard normally presented and (iii) financial capacity (what can reasonably be expected from property owners).

The main regional fire fighting forces normally heavily depend on the fire brigades from District Municipalities, many times supported by Working on Fire (WoF) fire fighting teams, their equipment and aerial support during the dangerous fire season, where (and when) the fire hazard is high. From experience it is clear that regional fire fighting capacity is many times not sufficient, but that is something the authorities are working on continuously within financial constrains. The local Fire Protection Associations (FPAs) should be responsible for identifying, quantifying and coordinating capacity-improvement efforts, but the reality is that some of the FPAs are not fully operational yet to take control of this responsibility.

In the drier regions of South Africa – where only occasional fire hazards can develop, many times years apart from each wildfire problem – much more should be done to address lack of fire fighting capacity, as was well illustrated in the dry savanna biomes of South Africa, during the 2011 and 2012 fire seasons in the Eastern Free State and the Northern Cape Province. During these seasons, some of the worst wildfires in history were experienced where it was least expected, and when fire fighting capacity was at the lowest possible level. For background reading, please refer to Brits and Heine (2004) and Calvin (2004).

7.1.2 Considering property owner capacity

Wildfire investigators have to assess such capacity in relation to (i) minimum regional needs, (ii) maximum capacity that can be expected reasonably from a property owner, (iii) regional support units available, (iv) size and locality in relation to the property and (v) actual minimum requirements needed in the area at a regional scale (per major property unit and by region). Investigators should assess a property capacity with regard to fire fighting carefully, and fully motivated for Court proceedings, if required. Many times fire fighting capacity also has to be developed to suit local land-use best, particularly on forestry and agricultural land.

Working on Fire, fire fighting teams and equipment are today coming more and more in the foreground in South Africa, as the main provider of fire fighting support in the most hazardous regions, at all levels, such as in the form of (i) trained manpower, (ii) fire fighting equipment and (iii) aerial support, which is already making a significant difference in many regions in the country. Aerial support in particular is now used regularly in most veld and forest fires, in forestry and in agricultural regions, but also in the larger nature reserves, managed by organizations such as SANPARKS, CapeNature and at provincial level.

The smaller fire fighting units are normally best suited for farming or forestry land, where fast response and access to fire sites are of vital importance (Figure 7.3). Such vehicles can equally be used to get proto-teams and their basic equipment to the fire site as fast as possible (Figures 7.4 and 7.5). Also refer to Brits and Heine (2004).

7.1.3. Considering type of equipment and specifications

While smaller properties are normally quite adequately equipped with "bakkie-sakkies" or even just fast mobile vehicles that can carry proto-teams, larger properties normally have to consider making use of larger capacity fire fighting units, particularly in the forestry and agricultural sectors. However, at regional level, district municipalities and organizations such as Working on Fire, normally provide the bulk of heavier equipment, as they will form the front line in case of large uncontrolled fires. In the most dangerous regions, aerial support is today normally also provided during the fire seasons according to optimum use (normally helicopters with buckets in the Cape regions, and both helicopters and fixed-winged water bombers elsewhere). These aerial support units are more and more becoming most effective fire fighting norms, for the regions most exposed to wildfires (Figures 7.6, 7.7 and 7.8; Brits and Heine, 2004).

Most of the times, Working on Fire is providing vital support to District Municipal fire brigades, that are already positioned to provide the bulk of fire fighting services in a region. Although these units normally already provide a range of heavier-types of fire fighting equipment, their aerial support is normally rather limited or even non-existing. It is here where WoF is playing a very important role.

Wildfire investigators require more than just background knowledge when assessing the capacity and effectiveness of fire fighting when investigating all aspects of a wildfire, always keeping in mind where there is room for improvement or even negligence is involved.

7.1.4. Regional fire control unit

Control over multiple (or very large) wildfires can be extremely testing and complicated and well qualified and experienced Incident Commanders (ICs) should here be in control. Nowadays ICs are adequately trained for this purpose, particularly fire chiefs from District Municipal fire brigades. These are today mostly well qualified to control multiple-disciplined fire fighting units.

Figure 7.1. A fire fighting truck in operation during a grassland wildfire. Photo: Courtesy Working on Fire.

Figure 7.2. A locally-manufactured fire truck operating in a farming region, structured on the chassis of an old Defense Force truck. Photo: C. de Ronde.

Figure 7.3. A typical small capacity fast response fire fighting unit ("bakkie-sakkie") as used most in the agricultural and forestry sectors. Photo: Courtesy Working on Fire.

Figure 7.4. Working on Fire small fire fighting units with basic fire fighting tools loaded. Photo: Courtesy Working on Fire.

Figure 7.5. A Working on Fire team on parade. These teams are well trained and always ready to go on immediate action where operational based for this purpose. Photo: Courtesy Working on Fire.

Figure 7.6. Water bomber ready for take-off. Photo: Courtesy Working on Fire.

Figure 7.7. A helicopter with bucket in operation over an extremely-hot wildfire. Photo: Courtesy Working on Fire.

Figure 7.8. Heavier firefighting trucks with large capacity water holding owned by forestry enterprises. Such units are normally used for fighting support or mopping up. Photo: Courtesy Working on Fire.

Figure 7.9 and 7.10. Accidental fire in KwaZulu-Natal, South Africa, a classic African rural environment. Would a better preparedness by proper education and availability of a simple fire beater have made a difference? Photos: Courtesy C. Austin, Working on Fire.

It is important that such ICs are also formally trained in fuel and fire dynamics and related fire-use (e.g. in the application of counter fires), but in South Africa this aspect of formal IC training is still a serious shortcoming and non-available. The results of inadequate training in this field is subsequently resulting in wrong fire application from time to time, that can even result in added wildfire damage (see earlier comments about this subject under chapters 4 and 5) (see also par. 7.2 concerning ICS matters).

Although my recent wildfire investigations conducted show a significant improvement in regional wildfire control in some areas, in others there is still a complete lack of structured, organised, regional wildfire control, which can have serious consequences on the potential for wildfire damage restriction. Wildfire investigators must be fully aware of such potential shortcomings. Such problem areas will only be identified when all fire fighting-related aspects are investigated fully, particularly with the assistance from spotter pilot logs and photographs, fire bosses reports, IC reports, wildfire post mortem investigation reports and other fire reports.

7.2 Incident Command System

7.2.1 Regional controlling body

No doubt that the most senior fire brigade unit (most of times from the District Municipality) normally also has the best trained Incident Commander, and that he automatically takes over control in the case of very large fires in a region. In such cases we do not recommend any change in the future, with the exception of the need for further training in ICS to make provision for a team of ICs, because many fires are sometimes uncontrolled for days, and ICs need to be relieved from time to time.

After FPA restructuring, newly appointed UFPOs should also be sent to an ICS course as a matter of priority, followed by District Municipal fire brigade chiefs and assistant chiefs.

Wildfire investigators should make sure what the regional status of wildland fire controlling bodies is in a region where a wildfire is investigated, as this will make it easier to explain many problems with regard to fire fighting action observed, and what recommendations should be made to improve (i) training levels and (ii) any changes in streamlining command structures in the region fire fighting forces.

7.2.2 Training level and effectiveness

Where no trained ICs are available in a region at all, suitable persons could be sent for ICS training. If this happens to be a shortcoming in a region where an UFPO has recently been appointed regardless being untrained in ICS, such a person could be sent on such a course first, before more are to follow from local fire brigades.

After a wildfire has crossed numerous property boundaries and burned uncontrolled for a number of days, shortcomings in ICS training should soon be identified by the wildfire investigator appointed to investigate the fire. However, regardless the level of ICS training of ICs, serious mistakes can still be made because of lack of wildfire assessment and control training and training in fuel and related fire dynamics, with particular lack of training and experience in counter fire application. Such commanders should then be send on such training courses as well, as ICS training does not make provision for this.

Following our observations, lack of wildfire assessment and control can be identified in more than 90% of cases where "counter fire application has gone wrong", indeed increasing wildfire damage or even doubling damage levels. Such wrong fire application can have such serious consequences that more than 50 fire fighters in South Africa have lost their lives as a direct result of such wrong-doing. Subsequently, we recommend a complete ban of such fire application, except where fire managers have been especially trained for this purpose.

7.2.3 Selection of Incident Commanders

District Municipal fire chiefs should automatically be appointed for such a position at regional/UFPA level, whether trained as ICs or not. If not trained adequately, such ICS training should be arranged as soon as possible as a matter of priority.

Then there is the case for more IC appointments, as in many cases wildfires can burn for days, and ICs should be relieved in time to remain fresh and on guard. Such additional (trained) ICs should preferably be from organizations other than District Municipalities, such as (i) prominent nature conservation bodies (e.g. CapeNature, SANParks) and (ii) senior forestry managers or agricultural bodies. Where permanent FPAs exist within UFPAs, these should also be trained in ICS.

7.2.4 Investigating ICS events during the wildfire

Although any ICS problems could become apparent during a wildfire investigation, it is important that such "preliminary indications" are handled with the correct degree of diplomacy, only reporting on such events when evidence of such "wrong action" have been proved from different directions and different witness sources. However, if such probabilities exist, these must be investigated regardless who has been involved in such events.

From experience we found that it is all available evidence combined that will eventually lead to the identification of critical events during a wildfire, but in particular from using IC logs, spotter pilot logs and other fire manager reports where available. Photographs from spotters (or fire bosses on site) can also assist in this reconstruction process, as well as fire spread evidence (from field indicators and/or satellite images before and after the fire).

7.3 Effective Use of Aerial Fire Fighting Support

This type of aerial fire fighting (or use for "trooping") is becoming more and more prominent as aerial resources are becoming available. However, as such services are relatively expensive compared to firefighting resources on the ground, it becomes extremely important that such resources are used selectively and correctly. Following the evolution of aerial fire fighting support in South Africa over a number of decades and in particular over the last years it is clear that their use and control is becoming more and more sophisticated and also more effective.

Most of the aerial support is today under the control of Working on Fire, who deploy these resources today as and where required in all South African regions. What started off as the so-called Forest Fire Associations (FFAs), mainly based in the Mpumalanga and Kwazulu-Natal provinces, are today operating in most regions, cleverly shifted around to be available at the start of fire seasons, for the whole of such danger periods. Private-owned spotters, bombers and helicopters are contracted out for fire fighting purposes as well, making impressive fire fighting fleets available in the case of multiple wildfires and large wildfire situations.

Selectively more use of helicopters (with water buckets) is particularly facilitated more in difficult (mountainous) terrain, where these machines are also used in a spotter role. However, the combination of fixed-winged spotters and water bombers is still mostly used in forestry and agricultural regions of Mpumalanga and Kwazulu-Natal.

However, if there is one shortcoming in their skills at times, it is their background knowledge of fuel (and related) fire dynamics in different fuel situations, although the pilots normally assess local (on the ground) weather and topographical conditions very well. A short crash course (region specific) fuel and fire dynamics is recommended where such lack of experience exists, and can also be recommended by wildfire investigators where such problems have been identified during fire fighting operations.

7.4 The Role of Working on Fire (WoF) Teams and Equipment

In South Africa the role of this organization is significant and should be supported in all respects. Their supporting role in fighting fires is vital for this country, because WoF staff is well trained and their equipment a much needed improvement to (sometimes old and outdated) local government machines. Their aerial support in particular is needed and ground and aerial firefighting capacities are already being extended to all regions of South Africa.

Particular for the interim, they are also providing excellent supporting services to fire prevention services under the control of FPAs, particularly where such services have not yet been firmly established or still absent. Until such time as to when all FPAs are fully operational throughout the country (the ultimate goal) their “plug-gap” approach to prevention services of fire (in particular the application of prescribed burning) should thus be fully supported until such time that FPAs are fully in control of their responsibilities.

Figure 7.11 and 7.12. Training of Mongolian forest workers in Fireline safety, use of hand tools and tactics for prescribed fuel reduction burning in natural pine (*Pinus sylvestris*) forests. Note the use of air blower for controlling surface fires burning in grass and litter layers – a quite light and efficient hand tool. Photos: GFMC.

Figure 7.13 and 7.14. Training of German forest rangers and forest workers in systematic application of prescribed fire for heathland (*Calluna vulgaris*) regeneration and the utility of the techniques for counter firing (back burning). Photos: GFMC.

7.5 Utilization of Private Fire Fighting Teams and Equipment

In some regions private fire fighting resources are very prominent, and their use in fire fighting support should be utilized to the full, and this should be well negotiated and planned before the fire season, by the responsible regional FPA/UFPA. Such private organizations normally also look after their own fire prevention measures as well, maintaining their own fire protection units in the landscape well. However, should such regional fire prevention structures (e.g. boundary firebreaks and buffer zones) be planned to be used across property boundaries and that joint structures are required, their services are as important to provide a significant contribution also in this direction, and should be carefully negotiated with them to ensure full cooperation.

Some of these organizations (such as forestry companies, mines, agricultural cooperatives and nature reserve organizations) are many times active members/owners of FPAs, and should remain functioning as such, even if some regions are to be restructured under UFPAs. Most are also active within UFPA boundaries and will attend their meetings regularly.

In some regions where wildfires occur, FPAs and UFPAs may be non-existing or at an early stage of development, in which case this role is fulfilled sometimes by private companies, with many times some serious shortcomings. Care should then be taken by wildfire investigators not to "point fingers" to such organizations unnecessary, but rather to highlight their role as "volunteer fire fighting organization". Many times this can be done even during legal processes, when investigators should rather concentrate on "minimum fire prevention requirements under the norms for a region" then attempting to table what should be required for most effective sire prevention measures. The latter can rather be mentioned under "future proposals for future measures".

7.6 Capacitating Local Communities in Wildfire Self Defense: The International Perspective

Chapter 6.5 covered examples of the role and opportunities for community involvement in wildfire prevention at international level. Similarly increasing initiatives are practiced to involve and capacitate local communities in self defense against wildfires. Many of the initiatives involve volunteer fire service units, local public service units responsible for forestry or conservation, and local farmers and other land users, as well as residents living at the wildland/urban interface, enabling them to respond swiftly to wildfires by initial attack before the professional units will arrive on scene. The role of local volunteers and other local community members should be clearly restricted to contribute controlling wildfires in the frame of the availability of technical means and by observing personal safety. Limitations for volunteer involvement have to be set in order not to endanger their health and lives.

In Europe guidelines have been developed for rural populations, local communities and municipality leaders that provide guidance to fire prevention and also for self defence at the initial stage of a fire, allowing the often rapid and efficient control of wildfires in the early stage of spread (Goldammer et al., 2013). Swift initial attack by local residents has often prevented the spread of a small fire to a larger wildfire that may become difficult to control. Figures 7.9 and 7.10 show a very typical, classical situation of a fire starting in rural grassland, which escaped from a small property and developed in a large wildfire – a fire that probably could have been avoided by proper education, training and availability of hand tools.

Apart of capacitating rural residents there is a need for training other professional groups such as personnel working in forest enterprises / forest services, national parks or conservation areas and other land management authorities or land owners. While fire suppression may not belong to the tasks of many of such professional groups, their involvement in fire prevention and in a rapid response to a wildfire in its early stage of development. Figures 7.11 to 7.14 provide examples of trainings in prescribed burning and application of counter fires in Mongolia and Germany. The goal of this training is to acquaint forest workers with regeneration and fuel reduction burnings, involving tools and tactics that can handled by this "firefighter reserve" until the professional fire services will arrive on scene.

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8 CONCLUDING REMARKS: WITNESS REPORTS, DAMAGE CONSIDERATIONS, INSURANCE, ARBITRATION AND MORE

8.1 Damage Considerations[1]

I normally refrain myself from getting involved in wildfire damage quantum calculations, and rather leave this to experts in their various fields. Agricultural and Forestry quantums (i.e. professional calculations of wildfire damage) form an important part of civil legal action and are excellent examples of professional experts doing an important job in a different specialized direction. In many cases legal cases are then also split in two parts. Namely the "Merit" part and the "Quantum" part, the first being the investigation into the wildfire occurrence and merits thereof.

However, I have come across some serious shortcomings in this field, particular in the field of grassland wildfires, where some of the basic rules of fire impacts and fire ecology are just not known to the Quantum professionals (many times supported by ecologists and range management experts), and I have experienced actually being drawn into the Quantum-calculation process because of my knowledge and experience of Veld and Forest Fire wildfire damage impacts and short and longer-term consequences. It is here that I sometimes feel that wildfire investigators can play a significant supporting role, because of the lack of expertise generally being available in South Africa in this field. The following are a list of possible misunderstandings in specific fire impacts, particularly to ecologically-related quantum calculations and estimations, where well-qualified wildfire investigators (with an ecological background) can sometimes assist:

- Quantum calculations where wildfires occurred in montane grassland or savanna, including realistic estimations of loss of grazing calculations.
- Calculations of damage, fire impact and restoration expenditure of indigenous forests damaged by fire.
- Damage calculations where wildfires burned through nature reserves, including loss of grazing, death of some wild animals, natural habitat restoration and loss of income from tourism.

Normally I would recommend to rather "steer clear" of any involvement in Quantum damage calculations, unless formally approached by legal persons. In such cases, listen realistically to such explanations of shortcomings, and study existing expert witness reports if already available for shortcomings. Then decide if you (as a wildfire investigator) should

1 These concluding remarks are written by C. de Ronde by reflecting / summarizing his personal experience and expertise in wildfire investigations

get involved. If no such documents are available, ensure that all realistic avenues have been explored to identify and appoint quantum expert(s).

8.2 Expert Witness Reports

It is important that I spend some time on discussing these reports, as from experience I know this is a vital part of the wildfire investigation process, and the contents of these reports can make the difference between a "failed" wildfire investigation or a "great success story". These reports reflect the outcome of a wildfire investigation and should be as comprehensive as possible.

Expert witness reports should not be confused with "Expert Witness Summaries" handed in by the legal team of the Defenders in a Court case to the Plaintiff legal team (or *vice versa*). This is normally being drawn up by the head of such as team (normally an Advocate of Senior Advocate, with Attorney assistance) and will basically summarize the contents of the expert witness report provided, but the wildfire investigator normally provides either advice or editing services for this purpose.

Some wildfire investigators are requested by their Legal teams to actually provide a summary for this purpose, for them to copy in this specific report-form, but I found this to be inadequate and not providing the legal team with detailed preparation material for the case. However, where finance is restricted for legal procedures, this could be requested. I can only recommend to rather avoid such "shortcuts" in the investigation process, and when requested to do this, this should be discussed thoroughly with the legal team, pointing out the dangers of such task reductions.

The preferred procedure should be to rather table a report which is as comprehensive as possible and (if required) a realistic budget ceiling should rather be decided. However, even this can give rise to loss of information, when there are unforeseen complications coming out of the investigation.

Many times wildfire cases are not going to Court at all, but those that do follow the long way all the way to the High Court, may require up to a number years of an experts' attention, including Court attendance and acting as expert witness. Some investigations could provide such excellent investigation outcomes, that the case is settled out of Court, in favour of the investigators' legal team. Arbitration might be decided, or cases might be settled otherwise (many times when the investigations are completed and the Legal team decides what action to take).

The Annex to this Chapter 8 provides a typical "table of contents" of an expert witness report. Please keep in mind that all wildfire investigation and reporting processes are different, and that the items provided below should by no means be used as a template for your report. Many sub-chapters/chapters are not applicable, while others may have to be added. Also keep in mind that the Legal Team should be advised of this proposed reporting structure, particularly where financial constrains are a reality. The investigator then has the option to go for a shorter structure or process in general, or motivate for more input. However, I think any omission could harm the case's strength significantly and that this should be negotiated with the Legal team, to cover you. Preferably, a written list of instructions should be provided to the wildfire investigators.

8.3 Investigating a Fire on Insurance Company Instructions

From experience I know that such requests can be received at any time after a wildfire: Sometimes within weeks or a few months, but other times even a number of years after the wildfire event (even more than ten years in one extreme case I was asked to investigate). It is in the latter cases where the wildfire investigator needs to have an open mind and consider reconstruction options available.

I have in one investigation even been requested to investigate a wildfire in montane grassland 12 years after it occurred, and a number of uncontrolled fires in fact burned through the area to be investigated, after the wildfire occurred to be investigated again, within this 12-year period. At a glance, this might appear to be an impossible task and a waste of time at first. However in this case, I was pleasantly surprised, about the evidence I could still dig out during the reconstruction process, and subsequently this "impossible" case was turned around in favour of the insurance company.

There are very few specific recommendations I can provide, if any at all. I can only suggest that the investigator should approach such cases positively with an open mind. Make sure your preliminary proposals to the insurance company are to the point and objectively. From experience I can mention that I have never turned down such investigation requests, and most of them had a positive and fruitful outcome for the insurance company involved. However, no two wildfires are similar, and the investigator should always explore all quarters. The only cases I turned down were those typical "last minute" and impossible requests, in some cases even a few days before the start of a High Court case. This is of course an impossible situation.

8.4 Considering Arbitration or Court Action

Arbitration is more and more an option considered seriously by legal experts, particularly in the case of complicated wildfires. This still does not rule out the important role of the wildfire investigator, because such an investigation and report should support the attorneys' involved in such as case. However, the disadvantage of such an approach is that this process can take many years, and might then still provide a disappointing outcome. A plus-point in such cases is that some attorneys and advocates in fact specialize in arbitration processes, and can become quite good (and successful) at it.

Arbitration is simply another approach, without the formal Court processes. There are still the same role players involved (including an appointed Judge), but they normally before-hand accepted that this will all be about a compromise, without clear 100% winners or losers.

Otherwise, keep in mind that only 10-20% of all wildfire investigations end up in High Court, and that 80-90% of the remaining cases are settled in other ways. It is indeed very satisfying when a wildfire investigation and report completed leads to positive outcomes in favour of clients, but unfortunately this does not always happen. In my experience, the more wildfires I investigate, the more these turn out to be successfully completed as the investigator gains experience. However, I never take obvious success for granted, as there can always be some unpleasant surprises in the path of an investigation.

8.5 The Role of the Veld and Forest Fire Specialist in Wildfire Investigations

As everything n this world, persons in the Legal profession will explore your records via the internet, in wildfire investigation cases, to determine what chances they have of a positive outcome of the investigation process if they appoint you as an investigator. Believe me, they can dig into Court case records you might all have forgotten about!

That brings me to the importance of an investigator being independent in his investigation, and to be quite honest about this, even if this means the tabling of results which your client probably does not want to hear about. For instance, I found that the truth of counter fire events can sometimes be very uncomfortable if "things went wrong" at the time. Whatever the circumstances, investigators should always stick to "the truth and nothing but the truth" and not let them be influenced by advocates or attorneys, for whatever reason. Normally these professionals will appreciate such a straight forward independent approach, but in a few individual cases they may be forced to try to make you accept their personal view, which might be biased. Some of those persons may want to manipulate investigators to better their own goals or you may land in deep waters in Court. Should you be caught out in the process because you were fed with wrong information, remember to admit your mistake, whatever might be the consequences. If you continue to fight any such evidence, you will just "dig a larger hole for yourself" and the truth will eventually still come out.

The biggest problem in South Africa is that the few experienced Veld and Forest wildfire investigators that I have come across (also in Court) have today all retired, and the younger generation (upcoming) investigators in this field have still mostly not developed into experienced Veld and Forest wildfire investigators. However, a few are showing great promise for the future.

Unfortunately there is no shortcut to becoming an experienced Veld and Forest Fire investigator, but – with the dedication expected from you to play the role as an independent investigator – you will get there eventually. Also remember that no person can take your experience away and this should ensure that the younger generation Veld and Forest Fire investigators will gain more experience and confidence after each investigation. I also hope that this book can assist young and upcoming Veld and Forest Fire investigators to "get there" to fill this need.

The reader might have noticed that the bulk of the demand for such investigations will be for civil purposes and not for criminal investigations, as in South Africa – where such investigations are sometimes also conducted for criminal purposes and forensic investigators are normally used in the latter cases. True, such (criminal) investigations (mostly to the cause and origin of such fires) are normally better suited for forensic investigators as indeed they are the best experts available in this highly specialized field. However, but there is no reason why a Veld and Forest Fire specialist could not assist or even take the lead here. The need for this differs from one investigation to the next, and each should be assessed on its own merits. Funding for such criminal investigations are seldom available, and because of the critical shortage of specialist Veld and Forest Fire investigators in South Africa, so I am quite happy if our experienced forensic colleagues take over this role, even if this is only for the interim. However, where the cause and origin of a fire to be investigated only forms a relatively minor part of a Veld and Forest Fire investigation, an experienced investigator in the latter field will be better suited.

In countries other than South Africa, the situation could of course be completely different and the demand for Veld and Forest Fire investigators could likewise be completely different for both criminal and civil investigations required. To start with, an Act such as the one in South Africa (Veld and Forest Fire Act 101 of 1998) could maybe only exist in a different form (or maybe not at all) and this could change the whole wildfire investigation scene. I would thus urge readers from other countries to recognize any such differences and to use the contents of this book in a way suiting their particular circumstances, keeping in mind that my experiences in this field were only in South Africa.

8.6 Who Qualifies as a Veld and Forest Fire Investigator?

I am afraid that this is a controversial issue in this country, mainly because the field of expertise is so wide and specialists in this field *per se* are so few. My opinion is that some disciplines still have a role to play in this field, although this might only cover a particular aspect of Veld and Forest Fire Investigation, provided they do not attempt to get involved in other aspects outside their field of expertise. Here are some examples of such expert professions:

- Forestry scientists
- Ecologists
- Range Land Management specialists
- Forensic scientists
- Conservation management specialists

Now consider the disciplines today operating actively in the field of Veld and Forest Fire Investigation:

- Fuel and Fire dynamics
- Fuel model development and use
- Fire behaviour simulation procedures
- Fire ecology
- Fire management
- Forensic fire cause and origin investigations
- Fire fighting
- Wildfire spread reconstruction, also with satellite based and advanced electronic procedures
- Legal and Fire Act experts
- Meteorologists specializing in fire weather
- And more

The reader can appreciate that (particular) in complicated wildfire investigations the Veld and Forest Fire Investigation specialist is seldom (if ever) capable of becoming an expert in all these fields, and that specialists in some of the mentioned professions should always be considered and appointed to assist (always in consultation with the Legal team, if appointed).

8.7 Concluding Remarks

This is by no means a perfect handbook, but could be updated as and when new technology becomes available. It should thus be regarded as a "handbook where upgrades could be considered at some stage", depending on the demand for this book. The subjects covered may have to be changed in the future and the book should be flexible enough to cater for such events and needs. I value my personal experiences very important in this field, and see this product thus as a reflection of experiences, rather than a normal textbook.

The writers did not ask for any advice regarding the structure of this book, what contents should be included or what material must be omitted, thus leaving ourselves probably wide open for criticism. However, we are satisfied that this book will indeed provide a "window" of some extremely interesting careers in the wildfire investigation field, as well as research and development in fire-related experience from earlier years, which provided us with a much better understanding of fuel and fire dynamics and fire effects. This "background knowledge" has then also been used in this book to advantage, because we strongly feel that without this knowledge-base a Veld and Forest fire investigator cannot do his or her job properly.

ANNEX to Chapter 8
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9 GLOSSARY

Under this paragraph a list of the most important terms used in this report is provided. However, for more comprehensive terminologies we refer the reader to look at the glossary web page of the Global Fire Monitoring Center (GFMC).[1]

Abbreviation/term	Definition
1-hr Fuel Load	Weight of the 1-hr dead fuel per unit area. The one-hour (1-hr timelag dead fuel category includes dead fuel from 0.00-0.64 cm)
10-hr Fuel Load	As for 1-hr fuel load, but includes 0.64-2.54 cm
100-hr Fuel Load	As for 1-hr fuel load, but includes 2.54-7.62 cm
2-D	Two-dimension (e.g. fire simulation)
3-D	Three-dimension (e.g. fire spread)
5-Minute Weather Data	Data collected every five minutes from an automatic weather station
Air Temperature	The temperature of the air, measured in degrees C (°C)
Altitude	Height above sea level (expressed in m)
Anchor Point	The point where a counter fire line is connected to the main fire perimeter (normally along a fire flank)
Arson	Willful ignition of malicious burning of a fuel with criminal intent to cause damage
Aspect	The direction a slope faces in relation to the sun or the alignment of the landscape to solar radiation
Available Fuels	The proportion of the available fuel that would burn under specified burning and fuel conditions
Backing Fire	A low intensity fire or part of a fire which burns against the wind and/or slope
Bark Scorch	The scorch from a passing fire visible on the bark of a tree, or on a pole surface
Base Map	A map intended as a base onto which other information id added, either as manual annotations, or digitally as new map layers in a Geographic Information System (GIS)
Beaufort Scale	A system for estimating wind speeds based on observation of visible wind effects. A series of descriptions of visible wind effects upon land objects or sea surfaces is matched with corresponding series of wind speed ranges, each being allocated a Beaufort number

1 http://www.fire.uni-freiburg.de/literature/glossary.htm

Bergwind	South African term for a dry, hot, down-slope winds. Also called “Foehn” winds or “Mistral”
Burn Out	The intentional burning of parcels of fuel to prevent fire spread. This is normally carried out to consume fuel between the control line and the fire edge
Buffer Zones	Wide, continuous, fire/fuel breaks created for wildfire protection purposes
Ca (Element)	Calcium
Coarse Fuels	Fuels that are more than 6 mm in diameter. Coarse fuels can either be living or dead.
Compactness (of Fuels)	The density of fuel particles
Crown Fire	A fire burning freely in the upper foliage of trees and shrubs
Crown Fire Street	The path of a crown fire in a straight line, when spreading through an even-aged industrial timber plantation
Crown Scorch (Height)	Browning of needles or leaves in the crown of a tree or shrub due to burning which has killed but not consumed the vegetation
Counter Fire Line	A planned operational burn which is lit between a control line and an advancing wildfire to take advantage of in-drafts towards the fire front
Cupping Indicators	A concave or cup-shaped char pattern found on the ends of grass stems, small stumps and the limbs of shrubs and trees. Grass stems, stumps, and/or twigs that face the oncoming fire will usually be blunt or rounded, while those facing away from it will usually have sharply pointed or tapered ends.
Curing (of Grassland)	A process that leads to the reduction in moisture content of dead vegetation.
Dead Fuels	Fuels with no living tissues
Dead Fuel Moisture	The moisture contents of dead fuels
Detection	A wildfire detection system
Direction of Fire Spread	The direction of fire spread with the wind and/or slope
Fine Fuels	Fast-drying dead fuels which are less than 6 mm in diameter. Fine fuels ignite readily and are rapidly consumed by fire when dry
Fire Behaviour	The reaction of a fire to the influences of fuel, weather, and topography
Fire Breaks	An area on the landscape where there is discontinuity in fuel which will reduce the likelihood of combustion or reduce the likely rate of fire spread

Fire Danger Index (FDI)	A quantitative indicator of fire danger, expressed either in a relative sense or as an absolute measure
Fire Dynamics	The detailed study of how chemistry, fire science, and the engineering disciplines of fluid mechanics and heat transfer interact to influence fire behaviour
Fire Ecology	The study of the relationships and interactions between fire, living organisms and the environment
Fire Effects	The physical, biological, and ecological impacts of fire on the environment
Fire Fighting Capacity	The capacity to fight fires with regard to manpower, equipment and fire managers.
Fire Front	Any part of the fire perimeter that displays continuous combustion
Fire Hazard	Any situation process, process or conditions that can cause a wildfire or that can provide a ready fuel supply to augment the spread or intensity of a wildfire, all of which pose a threat to life, property or the environment. Much of this is dominantly linked to accumulated fuel conditions.
Fire Intensity (Models)	The rate at which a fire releases energy in the form of heat at a given location and at a specific point in time, expressed as kilowatts per metre (kW/m) or kilojoules per metre per second (kJ/m/s)
Fire Line Intensity	The intensity of a fire as measured along a line of flame front, expressed in kW/m
Fire Perimeter	The entire outer boundary of a fire
Fire Prevention	A collective term for all proactive activities that are implemented with the aim of reducing the occurrence, severity and spread of wildfires
Fire Risk	The calculation of the probability of a wildfire occurring and its potential impact on a particular location at a particular time. Wildfire risk is calculated using the following equation: Fire risk = probability of occurrence x potential impact
Fire Storm	Violent convection caused by a large continuous area of intense fire
Fire Residence Time	The time that a fire burns at a particular time or line
Flame Length	The total extension of a flame measured from its base at ground level to the flame tip. Flame length can be greater than flame height if flames are tilted due to wind or slope.
Flame Height	The vertical extension of a flame. Measurement of flame height is calculated perpendicular from ground level to the tip of a flame. Flame height will be less than flame length if flames are tilted due to wind or slope.
Flank Fire	A fire spreading or predicted to spread parallel (approximately at a right angle) to the prevailing wind direction or slope.

Flare up	A short and sudden increase in fire activity
Fuel	Any material that can support combustion within a wildfire environment.
Fuel Aeration	The degree of surface-to-volume ratio (SAV) in relation to fuel height
Fuel Combustion (Process)	The consumption of fuel in the burning process
Fuel Consumption	The amount of a fuel that is removed by the fire, often expressed as a percentage of fuel load
Fuel Layers	The classification of fuels according to their height in relation to the ground surface
Fuel Load	The amount of fuel present within a particular area
Fuel Management	The process of managing fuel loads or fuel arrangement
Fuel Model	A name/number of a fuel situation, normally compiled to be used in fire simulation processes
Fuel Moisture Content	Water content of a fuel expressed as a percentage of fuel weight when oven dried
Fuel Moisture Extinction	Characteristic moisture content of the dead fuel above which predictable steady state of fire spread, is not attainable
Fuel Pattern	The pattern of fuel particle arrangement on a particular site
FPA	Fire Protection Association (South Africa)
Fynbos	Type of South African shrubland, only found in the Cape regions of South Africa
Grass Stem Indicators	The pattern of the charred remains of grass stems. These remains will have a different appearance dependent upon the direction of fire spread and the intensity of a fire.
Grassland	An area predominantly covered by one or more species of grass
Head Attack	A method of fire suppression which involves the release of water or fire retardant from the air directly onto the head of a wildfire. Such tactics should always be avoided by ground crews (by means of a counter fire application), as a result of the danger involved.
Head Fire	The leading part of an advancing wildfire, at a particular point in time
Heat per Unit Area	A measure of the fire intensity, measured over an area of one square metre (expressed in terms of kJ/m^2)
Hot Spot	A small burning area within a fire perimeter which requires suppression action as part of the mop-up phase of suppression

Ignition	The initiation of combustion
Incident Command	A standardized emergency management system, which is specifically designed to allow its users to adopt an integrated organizational structure equal to the complexity and demands of a single or multiple wildfire incidents.
Indirect Attack	Any suppression methods implemented away for the fire perimeter
Initial Attack	Suppression work completed by first responders arriving at a wildfire incident
Initial Wildfire Spread	The period of fire spread, from the origin of a fire to an identified area, at a particular point in time
K (element)	Potassium
Leeside (of tree or pole)	The side of a tree or pole away (opposite) the side where the wind is blowing from
Lightning	The discharge of electricity within the atmosphere either between two clouds or between a cloud and the ground
Live Herb Fuel Load	Weight of this class of fuel per area
Live Woody Fuel Load	Weight of this class of fuel per area. It includes foliage and very fine stems of living shrubs, normally with an SAV of 3.281 – 6.562 m^2/m^3.
Mg (element)	Magnesium
Moisture Holding Capacity	The capacity of a plant, tree of fuel particle to hold a specific moisture content for a particular time
Mop Up	The act of extinguishing a fire after it was brought under control. Mop-up involves carrying out all necessary to prevent re-ignition
N (element)	Nitrogen
P (element)	Phosphate
Precipitation	Mostly in the form of rainfall, but can also be in the form of snow and hail
Prescribed Burning	A planned and supervised burn carried out under specified environmental conditions to remove fuel from a predetermined area of land and at the time, intensity and rate of spread required to meet land management objectives

Rate of Spread	The rate of spread of a fire front, normally expressed in terms of metres per minute or km/hour
Relative Humidity (RH)	The relative air humidity normally measured as a percentage
SAV	Surface-to-volume ratio
Slash	Pruning, thinning and clear felling material removed from trees, or all material from felled trees
Slash Fuels	As for slash
Smoldering Fire	A fire burning underneath the soil surface in humus material or root channels, where lack of oxygen will normally prohibit the fire source from developing in a surface fire. Unless the fire surfaces. Also called a ground fire.
Spotting	"Jumping" of a fire across a certain distance of the terrain, topographical barrier, road, firebreak or river, or any other sites where fuel is not available to the fire in continuous layers
Spotting Landing Site	The site identified as the place where the fire (normally in the form of burning embers) landed
Spotting Take-off Site	The site identified as the place where the fire (normally in the form of burning embers) became airborne (took off).
Surface Fire Spread	The spread of a surface fire burning in surface fuels across the landscape
TSTMDL	Test Model (Module in the fire simulation program BEHAVE
UFPA	Umbrella Fire Protection Association (in South Africa)
Understorey	Vegetation found beneath the canopy. Understorey vegetation is normally found growing or lying on the ground.
Windside (of tree or pole)	The surface of a tree or pole facing the direction where a fire is coming from (wind direction)
Windspeed (average)	The average speed of the wind, normally measured in terms of m/sec or km/hour

Appendix 1.

Table of representative custom fuel model examples developed for South African fuel and vegetation types

Fuel Model	Species / Status / Age & Location	1H Fuel	10H Fuel	100H Fuel	Live Fuel	Woody Fuel	1Hr SAV	Herb SAV	Woody SAV	Fuel Bed Depth	Dead Fuel MC	Dead Heat Content	Live Heat Content	Crown Canopy Cover
	Even-aged Industrial Plantations													
52	Wattle CF slash KZN	15.0	5.0	3.0	0	0	5500	5000	5000	1.0	17	19500	19500	15
53	2-3 yr old Wattle KZN	8.0	1.0	0.5	1.0	1.0	6500	5000	5000	0.4	20	19500	19500	15
54	2-3 yr old Euc, Mpu	10.0	1.0	0.5	0.5	2.0	6500	6000	6000	0.3	20	21000	21000	25
55	4-5 yr old Euc, Mpu	12.0	1.0	0.5	0	0	6600	3600	3600	0.25	20	21479	21479	50
56	6-8 yr old Euc, KZN	12.0	1.0	0.5	0	0	8200	7000	7000	0.2	31	21500	21500	50
57	Mature >8 yr Euc, Mpu	25.0	5.0	2.0	0	0	6500	3500	3500	0.17	31	20985	20985	70
58	Eucalyptus slash, Mpu	25.0	7.0	2.0	0	0	6000	5000	50000	0.6	28	21480	21480	30
59	Eucalyptus copp, Mpu	10.0	1.0	0.5	0.5	2.0	6500	5000	5000	0.3	20	21000	21000	30
60	Pine < 5 yr old, KZN	5.0	1.0	0.5	2.0	0	6600	3600	3600	0.25	20	21479	21479	50
61	Pine 6-8 yr old, KZN	5.0	8.0	5.0	0	0	5600	5000	5000	1.0	17	18500	18500	20
62	Mature pine stands KZN	28.0	1.5	0	0	0	6500	6500	4900	0.15	30	18000	18000	40
63	Pine slash KZN	28.0	4.0	1.5	0	0	6500	4900	4900	0.4	29	21000	21000	60
	Fynbos Shrubland													
64	Uninfested Fynbos Caledon	10.4	13.2	13.2	0.5	8.8	6200	5000	4000	1.5	20	20485	20485	40
65	Old Fynbos S aspect Garcia	10.4	13.2	13.2	2.5	4.0	6200	5000	3500	1.6	25	20485	20485	55
66	Old fynbos N aspect Gar.	12.0	2.4	1.2	0.1	3.7	5000	4000	4000	0.9	19	19500	19500	40
67	Mat. Renosterveld W. Cape	8.5	11	6.0	1.0	4.8	6200	5000	4000	0.6	20	18400	18400	40
68	Semi-moist Fynbos 7-10 yr W. Cape	6.0	12	8.5	3.5	2.0	6200	5000	5000	0.5	20	21000	21000	25
	Abnormal / Infested / Vegetation/Fuel													
82	Mature Wattle KZN	25.0	2.0	1.0	0	0	6500	5000	5000	0.15	28	19500	19500	50
83	Old maize-land Mpu.	10.0	2.0	1.0	0	0	6500	6500	6500	0.25	19	19300	19300	20
84	Power line fuel KZN	5.0	0	0	0	0	7500	5000	5000	0.8	14	18500	18500	10
85	Brushwood/bush KZN	40.0	9.5	5.0	5.0	5.0	5500	5000	5000	0.7	20	20000	20000	30
86	Fynbos/Ac. weeds WC	11.5	3.2	0.5	0.1	1.5	6500	5900	6500	1.5	24	18700	18700	50
87	Pine/Fynbos W. Cape	13.0	15.0	20.0	1.7	5.0	4200	3000	3000	1.5	20	20485	20485	50

Fuel Model	Species / Status / Age & Location	1H Fuel	10H Fuel	100H Fuel	Live Fuel	Woody Fuel	1Hr SAV	Herb SAV	Woody SAV	Fuel Bed Depth	Dead Fuel MC	Dead Heat Content	Live Heat Content	Crown Canopy Cover
	Montane Grassland & Savanna													
88	Grazed Grassland / Wetland cured, Mpu.	1.5	0	0	0	0	7500	6000	5000	0.2	13	18488	18488	10
89	1-yr old grassland, ungrazed cured Mpu.	3.0	0	0	0	0	6500	5000	5000	0.4	13	18988	18988	10
90	Ungrazed grassland/ Wetland Cured >1-yr old Mpu.	4.0	0	0	0	0	7500	6000	5000	0.5	13	18488	18488	20
91	Irregularly grazed, cured 1-2-yr old NE Cape	3.0	0	0	0	0	5100	3100	3100	0.6	13	18800	18800	10
92	Intensively grazed, cured, 1-2 yr old NE Cape	2.0	0	0	0	0	4000	3100	3100	0.4	13	18800	18800	10
93	Montane grass cured, ungrazed NE Cape	3.0	0	0	0	0	4900	4000	4000	0.6	13	18900	18900	10
94	1-yr old grassland, cured, ungrazed Mpu	3.0	0	0	0	0	4921	3000	3300	0.8	13	18400	18400	10
95	As for FM 75, 2-yr old Mpu	4.0	0	0	0	0	4921	3500	3000	1.0	13	18400	18400	10
96	As for FM 75, 3-4 yr old, Mpu.	6.0	0	0	0	0	5900	3500	4500	1.1	13	18622	18622	20
97	2-yr old wetland, cured, Mpu	5.0	0	0	1.5	0	3250	2850	3300	0.8	15	17989	17989	20
98	Moist savanna grassland KZN	5.0	0	0	0	0	6000	4000	4000	0.3	15	19500	19500	30
99	Wetland savanna grassland with isolated trees KZN	5.0	0	0	0	0	5000	3500	3500	0.6	14	19500	19500	20
100	Dry savanna grassland with dense shrubs NC	2.5	1.0	1.0	1.5	2.0	4000	3000	3000	1.0	17	20500	20500	40

LEGEND – MAIN SOUTH AFRICAN FUEL AND VEGETATION CLASSES USED

Fuel Models	Main Classes	Description
52 – 63	Even-aged industrial plantations	Commercial plantations as established in the summer rainfall-regions of South Africa
64 – 68	Fynbos shrubland	Natural shrubland as found only in the Western Cape and western portions of the Eastern Cape
69 – 81	Montane grassland and savanna	Natural vegetation as found in the summer rainfall regions, in dry and moist rainfall regions of the summer rainfall areas
82 – 88	Abnormal / infested vegetation / fuel	Fuel and vegetation as found in cultivated lands and infested biomes

LEGEND – ABBREVIATIONS USED: SPECIES/STATUS/AGE & LOCATION

1-yr	One year old
Ac.	*Acacia* spp.
Asp.	Aspect
Cal.	Caledon, Western Cape, South Africa
CF	Clear felled stands, including slash left after timber exploitation and removal
Copp.	Coppicing of even-aged *Eucalyptus* stands only, where stumps are allowed to resprout to form basis for re-growth of trees
Euc.	*Eucalyptus* spp.
Fuel Mod.	Fuel Model
Gar.	Garcia, Riversdale, Western Cape Province, South Africa
KZN	Kwazulu-Natal Province of South Africa
Mat.	Mature
MC	Moisture Content
Mpu.	Mpumalanga Province of South Africa
N	Northerly
NE Cape	North East Cape Region, Eastern Cape Province, South Africa
Pine	*Pinus* spp.
S	Southerly
WCape	Western Cape Province, South Africa
WC	Western Cape
Yr	year old (age)

BehavePlus Parameters

1H fuel	One hour fuel loading (tons/ha)
10H fuel	Ten hour fuel loading (tons/ha)
100H fuel	Hundred hour fuel loading (tons/ha)
Live fuel	Live fuel loading (tons/ha)
Woody fuel	Woody fuel loading (tons/ha)
1H SAV	One hour fuel surface-area-to-volume ratio (m^2/m^3)
Herb SAV	Herb fuel surface-area-to-volume ratio (m^2/m^3)
Woody SAV	Woody fuel surface-area-to-volume ratio (m^2/m^3)
Fuel depth	Fuel bed depth (m)
Dead fuel moisture content	Dead fuel moisture content (%)
Dead heat content	Dead fuel heat content (kJ/kg)
Live heat content	Live fuel heat content (kJ/kg)
Crown canopy cover	Crown canopy cover (%)






Wildfire Investigation – Guidelines for Practitioners – is a publication of the Global Fire Monitoring Center (GFMC) aiming at sharing experiences of wildfire investigation in South Africa over two decades with other regions and countries of the world. The guidelines are a contribution in support of the endeavor of the United Nations (UN) and its affiliated processes and networks, notably the United Nations International Strategy for Disaster Reduction (UNISDR) and the Global Wildland Fire Network, to reduce the impacts of wildfires at global level for the benefit of the global environment and humanity.

Wildfire investigation is an essential component of fire management since it contributes to clarify the origins and causes of wildfires, but more importantly, to unveil possible deficits in fire management, gaps that should be closed by appropriate capacity building.

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The Global Fire Monitoring Center (GFMC)

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