GEF FYNBOSFIRE PROJECT

INFORMATION MANAGEMENT, FIRE RESEARCH & MODELLING

AND FIRE RISK ASSESSMENT COMPONENT

Fynbos fire behaviour modelling: applying the FARSITE model to the March 2015 fire in Jonkershoek

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Ryan Blanchard, David Le Maitre, Daleen Lötter and Greg Forsyth

Prepared by:
Natural Resources and the Environment CSIR
PO Box 320
Stellenbosch
7599

Contact person:
Dr David le Maitre
Tel: 021-888 2407
Fax: 021-888 2684
Email: dlmaitre@csir.co.za

Alternate contact person:
Greg Forsyth
Tel: 021-888 2609
Fax: 021-888 2684
Email: gforsyth@csir.co.za

Prepared for:
Tessa Oliver
GEF FynbosFire Project Co-ordinator
Winter House, Kirstenbosch
Cape Town

Tel: +27 (21) 797-5787
Email: coord@fynbosfire.org.za

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1 INTRODUCTION

Modelling of the dynamics of fire behaviour across real or simulated landscapes is a well-established component of fire ecology and has been practiced for more than two decades (Alexander & Cruz, 2013; Keane et al., 2004; Papadopoulos & Pavlidou, 2011; Sullivan, 2009). This field is continuing to develop rapidly as computing power has increased, including new developments which allow for a more physically realistic simulation of the key processes which heat fuels to the point of combustion (Finney et al. 2013, 2015). There are now many models which could be used, ranging from empirical ones through to those based on detailed physics (Alexander & Cruz, 2013; Papadopoulos & Pavlidou, 2011).

The possibility of using such models to simulating fire behaviour in fynbos, including real-time simulation for fire managers, was evaluated by the CSIR in 2013/14 (Forsyth et al., 2015). The models included the Australian models Phoenix (Tolhurst et al., 2008), FIRESCAPE (Bradstock et al., 2012; Cary et al., 2006; King et al., 2011) and Australis (Johnston et al., 2008; Johnston et al., 2006; Kelso et al., 2015), the FARSITE model developed in the USA (Finney, 2004; Scott & Burgan, 2005), and the Prometheus model from Canada (Tymstra et al., 2010).

Despite the substantial progress in model development there are still significant shortcomings in the ability to model fire behaviour because of inadequate representation of the heterogeneity in fuels, fire propagation and local wind fields and climates (Cruz et al., 2013; McCaw et al., 2012). As a result there is a need to test models, which are usually developed elsewhere, for the local conditions in which it will be applied. For example in modelling fires in the fynbos biome will require calibration of model parameters to overcome specific issues such as the modelling of ground and canopy fire spread in heterogeneous vegetation types (Alexander & Cruz, 2013; Cruz & Alexander, 2013). Three of these: Phoenix, FARSITE, and Prometheus are in operational use. The developers of the models were contacted but only the *Australis* model development team, in the form of Professor George Milne of the School of Computer Science and Software Engineering, University of Western Australia, indicated an interest in further collaboration and in testing how well the model could simulate a fynbos fire at that stage. After further assessment, though, we did not go ahead with the simulation. This decision was based on three main factors (Forsyth et al., 2015): (a) the availability of sufficiently detailed and accurate fuel models for the different fynbos vegetation types; (b) detailed maps of an actual fire showing the fire fronts at different times; and (c) the availability of high-temporal resolution weather data which represent the conditions in the area where the fire was burning and at the time of the fire. We were not able to obtain suitable data for these three factors for a historical fynbos fire at that stage so we did not attempt to simulate an actual fire. Nevertheless, we still pointed out that a fire behaviour simulation model set up for a fynbos site could be a very useful training tool for fire managers and this option should be taken further.

In February-March 2015, the situation changed because there were two large fires in areas with suitable weather data, fire records, and vegetation maps and land-cover for use in developing fuel models. The one was on the Cape Peninsula and extended from Muizenberg to Constantia and the other burnt much of the Jonkershoek valley and adjacent mountain slopes. After further assessment, the Jonkershoek fire was chosen because biomass data and fuel models were available for the dominant fynbos types in the valley and there was a weather station in the valley bottom within the burnt area and one adjacent to it on the mountain crest. We approached George Milne about testing the Australis model. His initial response was positive and we continued negotiations in parallel with the Advanced Fire Information System (AFIS) team of the Meraka Institute, CSIR, South Africa who also wanted to use the model in for a project they were planning with a team from Satellite Remote Sensing Services, Landgate, Western Australia. The negotiations were complicated which led to delays and in September 2015 we learnt that George Milne's team now had other commitments would not have the capacity to take on this modelling before March 2016.

After some deliberation we decided to test the fire growth model FARSITE (Finney, 1998) as there is local experience in developing fuel models for the US BEHAVE fire modelling system (Burgan & Rothermel, 1984; Van Wilgen & Burgan, 1985) which is used by the FARSITE model (Finney, 2004). The FARSITE model has been widely used and was found to do particularly well in a recent model comparison (Papadopoulos & Pavlidou 2011)[1]. It is also freely available. By this stage it was not possible for us to organise for formal training in FARSITE even if we had the resources available. Fortunately, there is good support and there are many documented examples. There are many parameters making FARSITE complicated to fine-tune, and our limited ability to systematically tune the model and may have affected the results.

This study involved setting up the *FARSITE* to simulate the March 2015 Jonkershoek fire, including the fuels, terrain, environmental factors and weather data. We then ran the model and compared the simulated fires against observations of the actual fire and information on the location of the fire fronts obtained from the official fire records. The overall aims of this study were to assess how easily we could set up the FARSITE and how well it could simulate an actual fire. We also wanted to evaluate the potential challenges that could face managers wanting to be able to use models like FARSITE decision-making while fighting fires. The study represents a first assessment of the FARSITE fire simulator in a fynbos environment.

1.1 The Jonkershoek wildfire

In March 2015 there was an extensive wildfire in the Jonkershoek Valley near Stellenbosch (Figure 1). This fire was apparently started accidentally in the centre of the valley on the 9th of March at about 13h00. The high air temperatures and low relative humidity helped the fire spread across and up the valley under the influence of the light north-westerly winds blowing at the time (Figure 2). The western flank of the fire on the northern side of the valley was more or less contained by the evening of the 9th but was burning in a *Pinus radiata* (pine) plantation area characterised by large dead fuels (logs, branches) following clear felling of parts of the plantation after a fire in March 2009. On the southern side of the valley the eastern flank, driven by the north-westerly winds, by-passed Swartboskloof and ran rapidly up the slopes to the east of Swartboskloof. It reached the crest of the ridge by 16h00 to 17h00 and continued to burn slowly eastwards.

[1] The Australis model was not included in this comparison

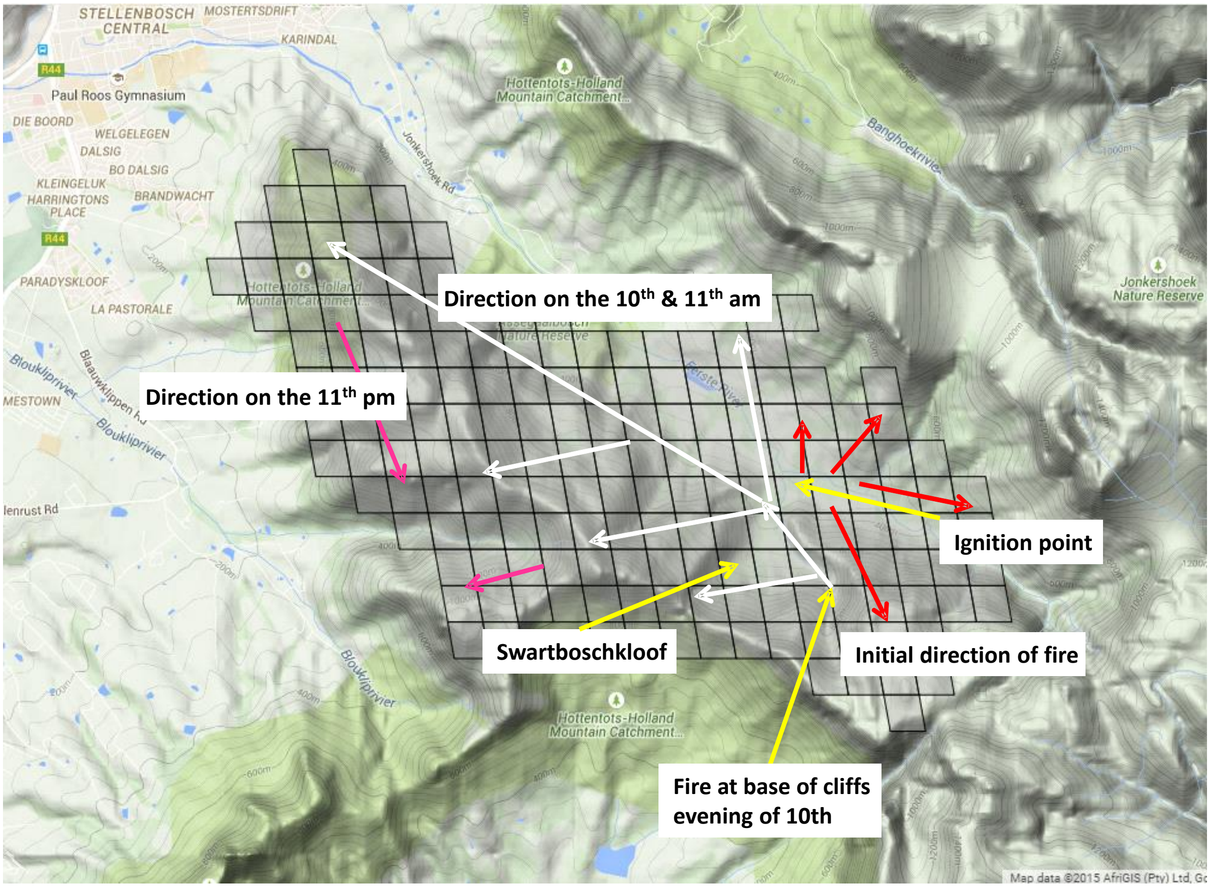

Figure 1: Location of key points mentioned in the description and the approximate pattern of spread of the Jonkershoek fire overlaid on a topographic map as displayed in the Advanced Fire Information System (AFIS, http://southernafrica.afis.co.za/). The grid indicates the rough extent of the fire based on MODIS burnt area data from AFIS.

During the night of the 9th the wind remained from the north-west, the air temperatures dropped to about 12°C low and the relative humidity rose steeply to about 90% (Figure 2). The eastern flank of the fire in the valley, which was burning in 6-year old fynbos with predominantly live fuels, appears to have burned down and gone out. The next day (10th) was relatively calm and cool, and the fire teams continued containing the fire along sections of its perimeter. During the day, the western flank of this fire continued burning down the cliffs on the eastern side of Swartboskloof (Figure 1) and by about 17h00 had reached the base of the cliffs on the eastern side. During the late afternoon the wind shifted to SE and began to blow more and more strongly (Figure 2). At about 17h30 the fire front burning downwards from the base of the eastern cliffs was caught by the wind. It flared-up and spread rapidly along the mountain towards Stellenbosch, up the slopes of Swartboskloof and Haelkop, and across the valley to the north-west.

A back-burn was lit along a firebreak on the middle slopes at the far western end of Stellenbosch Mountain (to the south-west of Karindal, Figure 1) during the morning of the 11th to prevent the fire burning right down into Stellenbosch (Figure 3). During the 11th the wind in Stellenbosch switched back to north-westerly pushing the fire back along the southern side of the mountain. The fire was largely under control by the end of the 11th but mopping up continued for days, especially in the burnt plantation areas. The total area burnt in this fire was roughly 4 700 ha.

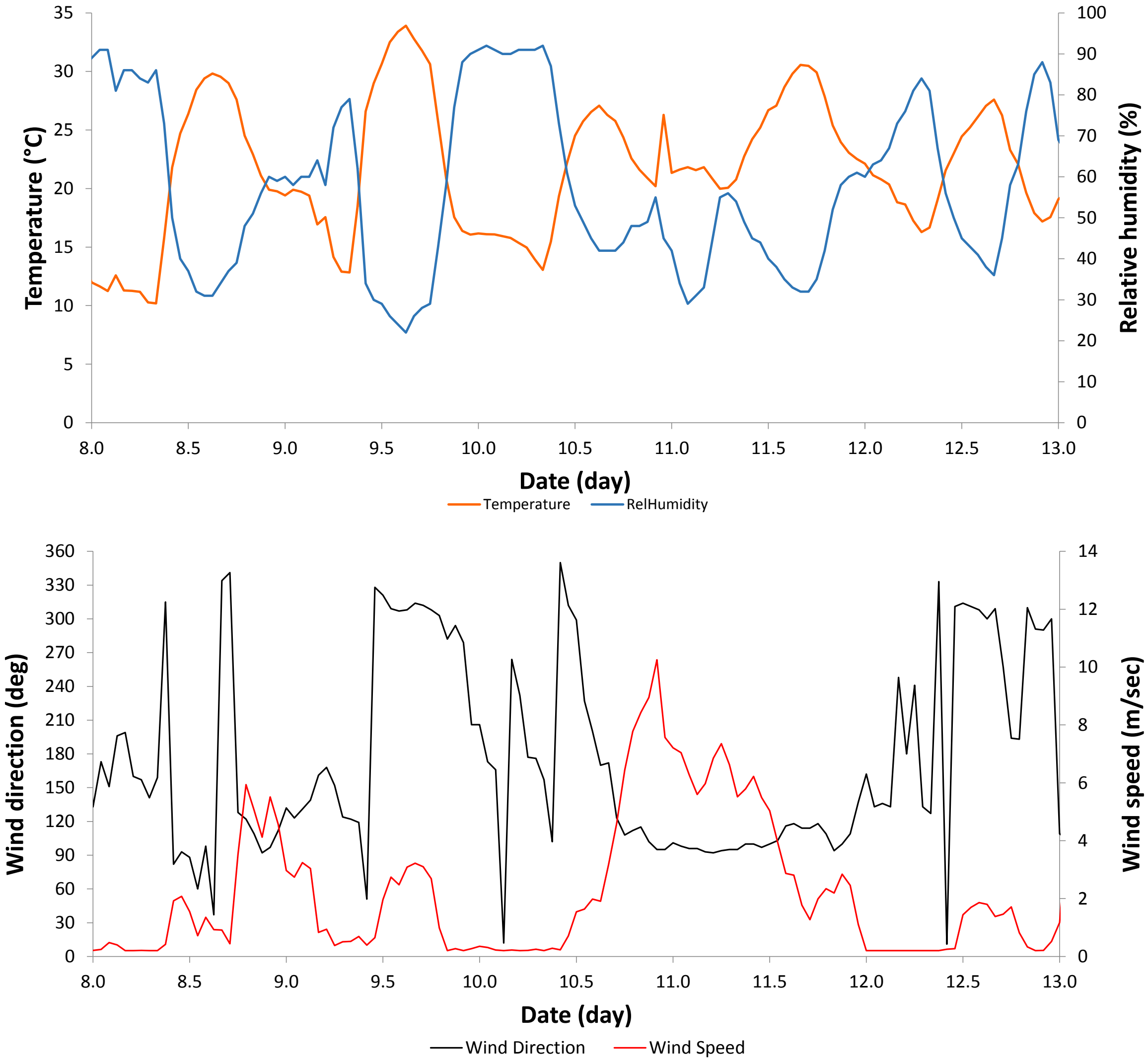

Figure 2: Weather conditions from 8-13 March at the Swartboskloof weather station in the Jonkershoek valley which is about 1.5 km from where the fire started. Note day 8.5 = 12h00 on the 8th.

The data from a second weather station, located on the Dwarsberg at higher altitude (1214m), showed that the shifts in wind direction were similar to those at Swartboskloof (320m) but the wind speeds were lower, with a maximum of 7.0 m/sec on the 10th compared to 10.3 m/sec at Swartboskloof. The air temperatures were also lower and the air humidity was higher (see section 2.3).

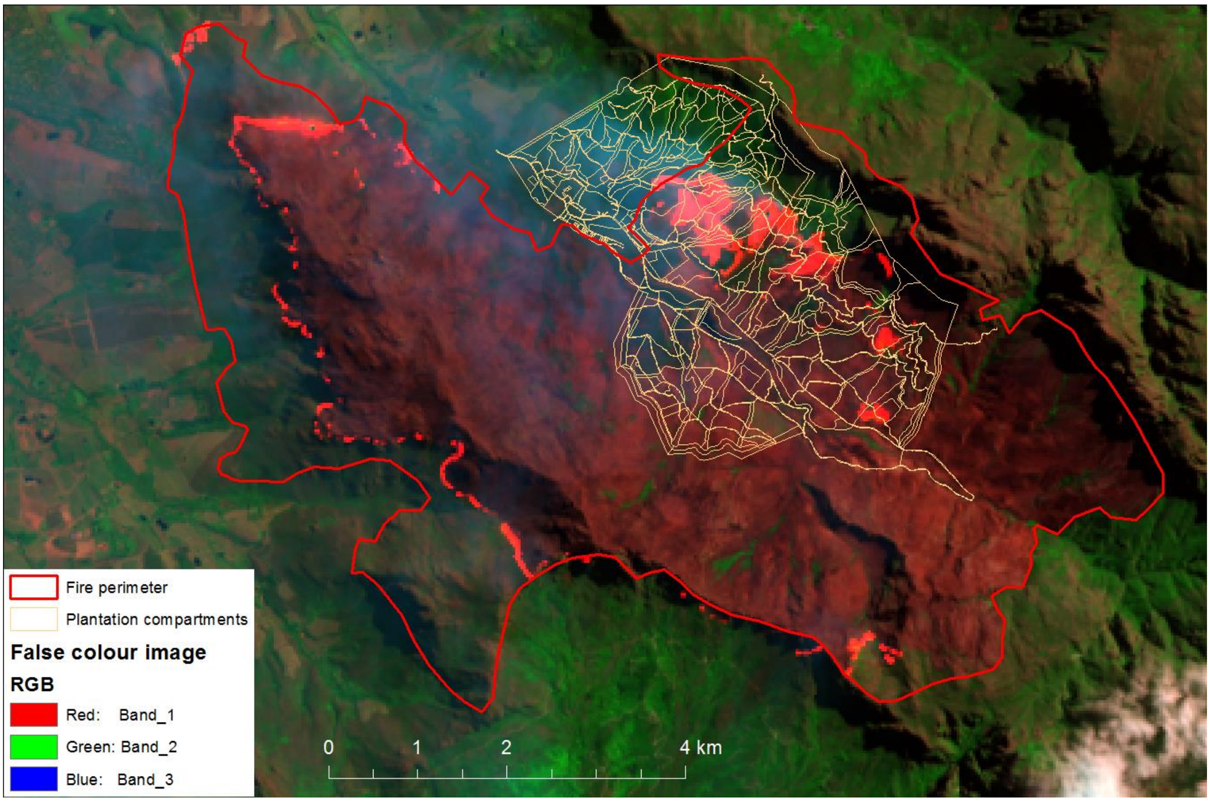

Figure 3: The location of the fire-front at 10h35 on the 11th of March 2015, the Jonkershoek plantation compartments and the final perimeter of the fire. The isolated fire at the north-west corner of the fire perimeter is the back-burn that was lit to cut-off the main fire front located to the south-east. The wind direction reversed later in the day and made the back burn unnecessary.

This fire provides an excellent opportunity for simulation in FARSITE because we have: (a) reasonable fuel models for the fynbos which is the dominant vegetation in the burnt area; (b) detailed records of the estimated location of the fire front at the end of each day and *ad hoc* observations are available for use in creating a timeline of the fire's spread; and (c) continuous records of the weather conditions during the fire from two weather stations (i.e. Swartboskloof and Dwarsberg). Combined, the two station records can be used to understand the weather conditions over the altitudinal range of almost all of the area that was burnt.

2 METHODS

2.1 Study area and input data

Data on the extent of the fire in the Jonkershoek Valley was supplied by the fire manager at the Cape Winelands District Council (Dale Nortje) as daily boundaries captured in Google Earth polygons (kml files). Further information was extracted from Landsat 8 images supplied by a member of AFIS team and included one image captured during the fire (Figure 2) and one image captured following the fire. Together, this information was used to determine the full extent of the fire boundary as well the various land cover units within the affected area (Figure 4).

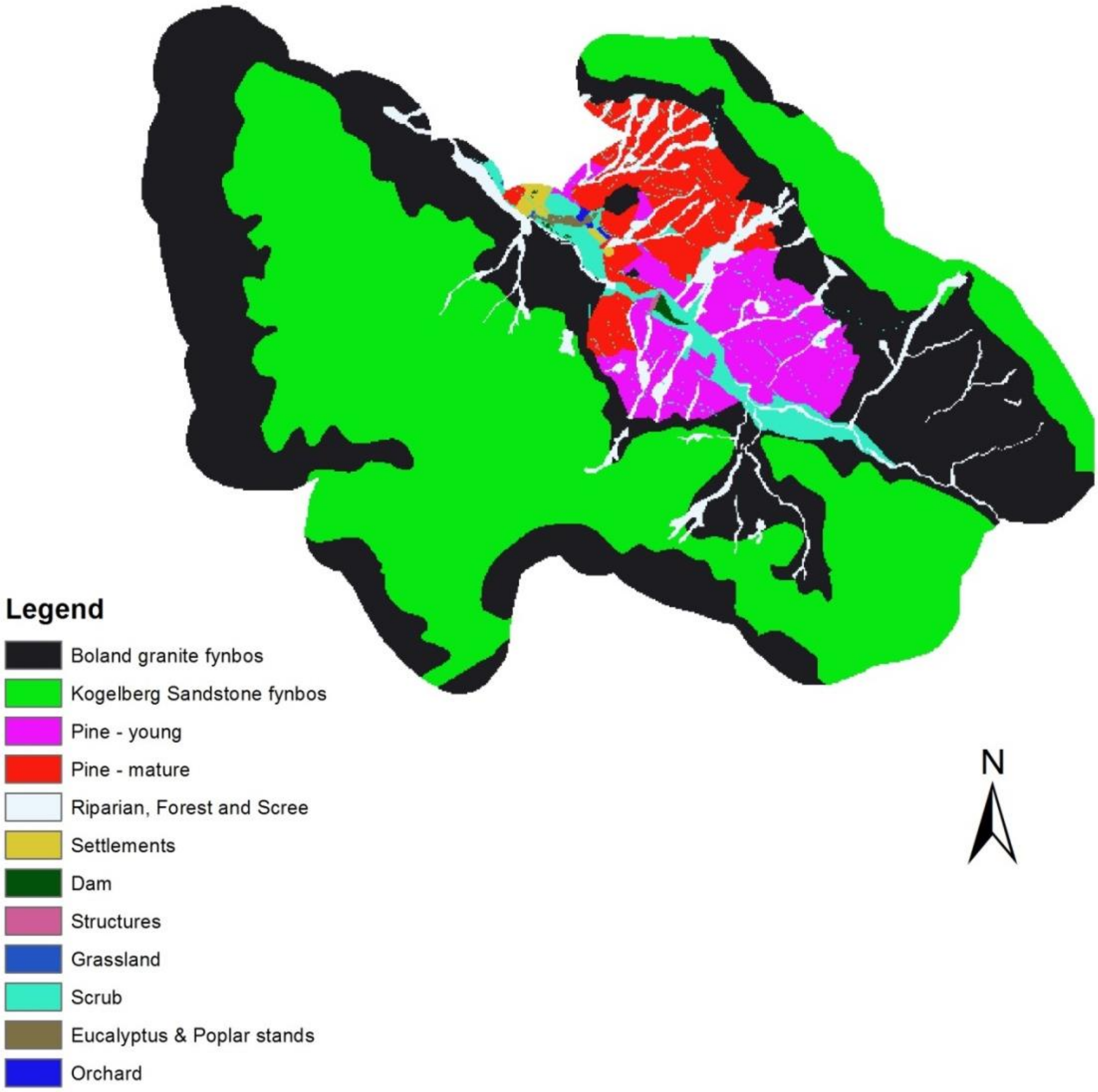

Figure 4: Distribution of the vegetation (Rebelo *et al.* 2006) and land cover types (GTI 2015) to which fuel models are assigned within the Jonkershoek study area.

FARSITE requires several spatial topography-based layers for the area within the study area boundary. We generated a boundary by buffering the perimeter of the fire by 500 m. A local digital elevation model, clipped to the boundary of the fire was used to derive *Elevation* (m); *Slope* (degrees) and *Aspect* (azimuth degrees). These are captured in a landscape (.LCP) file together with a *Fuel model distribution* layer and a *Fuel canopy layer* (Percentage cover). These layers are discussed in more detail in the following section. An overview of the files needed to run a model is located in Appendix 8.1.

2.1.1 Vegetation types and corresponding fuel models

The Jonkershoek fire burnt through four different natural vegetation types based on data from the national vegetation map (Mucina & Rutherford, 2006) (Figure 4). The natural vegetation types and other land-cover units within the study area were assigned to specific fuel models (Table 1). Fuel models are used by FARSITE to model fire behaviour predictions in relation to weather, wind and topographic conditions (Scott & Burgan, 2005). They are based on vegetation characteristics and linked to a number of fuel properties (e.g. fuel load, fuel moisture, moisture of extinction, heat content). In some cases, similar vegetation types were assigned to a single fuel model (See Table 1). In addition, the fire burnt a portion of the Jonkershoek plantation which included a variety of different land-cover types (Table 1). Plantation compartments and other features of the Jonkershoek plantation area were obtained from the forestry company, Cape Pine. The data were in an unknown projection but we were able to obtain an acceptable accuracy using the Clark 1880 datum and an adjustment of the False Easting of 70 m in the UTM (South African lo19) projection. The classification of the land-cover types, and the assignment of fuel models in the plantation area, was based on the compartment data and the use of Google Earth imagery overlaid with the boundaries of the polygons in the Jonkershoek plantation. The natural vegetation areas within the plantation areas were assigned to fuel models based on the dominant natural vegetation within each polygon. The actual plantations were separated into both young pine (4-16 years post-planting, open to just closing canopy) and old pine (older than 16 years, closed canopy) compartments as these differ in their fuel characteristics and fire behaviour.

The riparian vegetation and forest scrub areas were identified using heads-up digitising from geo-corrected ortho-photographs supplied by surveys and mapping (Flight Plan 1069 of 2006, Chief Directorate: National Geo-spatial Information, Department of Rural Development and Land Reform). These areas were assigned to a single fuel model, due to a similar vegetation structure. Fuel model data was extracted from van Wilgen et al. (1990), who described the fuel characteristics of a fynbos forest vegetation type. These scrub vegetation types are typically dominated by a mixture of medium-tall shrubs with occasional small tree species with many other shrubby and herbaceous species and occasional shrubs from the Proteaceae.

Many of the other land cover types were either not burnt during the fire or occupy a small proportion of the area and so were grouped in with the fuel models for the more representative classes. Fuel models for those land cover or vegetation types for which there were no local data were selected from those described in Scott and Burgan (2005).

To test the validity of using FARSITE as a management tool in the fynbos biome, custom fuel models were tested in the modelling platform. A single custom fuel model was assigned to Boland Granite Fynbos and Cape Winelands Shale fynbos whereas Kogelberg Sandstone fynbos required its own fuel model. The distinction lies in the differences in the biomass distribution between the fynbos vegetation types, with the sandstone fynbos having more leafless reeds (Restionaceae) and fine-leaved shrubs, and the others have more graminoids (e.g. sedges). For detailed descriptions of the vegetation structure in the natural fynbos see Van Wilgen (1981), McDonald (1987), van Wilgen et al. (1990), Werger, Kruger & Taylor (1991), Mucina et al. (2006) and Rebelo et al. (2006). Fuel model parameters were derived from published data using Van Wilgen and Burgan (1985) and Van Wilgen et al. (1985) (Table 2). Biomass estimates were calibrated based on the calculations of Le Maitre and Marais (1995). Biomass was calibrated to a vegetation age of between 6-7 years as a previous fire in February-March 2009 burnt essentially all the natural vegetation in the area burnt by the this fire. Similarly, vegetation canopy cover was estimated using expert knowledge of vegetation of similar ages.

In addition to the custom fuel models, standard fuel models were applied to fynbos vegetation types to compare the simulated fire behaviour. These were extracted from Scott and Burgan (2005) (see Table 1).

Table 1: Descriptions of natural vegetation types from the national vegetation map (Rebelo et al. 2006) and land cover types (GTI 2015) within the plantation area grouped into different fuel types for the modelling. The custom models used local fuel data, the standard models were from Scott and Burgan (2005)

Natural vegetation type or Land cover	Description of the vegetation composition and structure	Fuel model name, mnemonic (number code)	Vegetation age and estimated cover	Custom and standard fuel models	Standard fuel models
Boland Granite Fynbos	Proteoid shrubland dominated by *Protea neriifolia* or *P. repens* with a wide variety of other medium-height and short shrub and herbaceous species, soils derived mainly from granites and relatively fertile. Sedges and grasses have a higher middle and understorey cover than restios. *Protea nitida* is prominent on talus slopes, on the lower slopes and the river floodplain. At the time of the fire the proteoid shrubs had reached a height of 1.2-1.5 m and the other species around 1.0 m tall. A series of short-interval fires has reduced proteoid cover resulting in patchy distributions of the non-sprouting Proteaceae. Last burnt in 2009.	Moist mesotrophic proteoid shrubland MMP or Moderate Load, Humid Climate Grass-Shrub (Dynamic) GS3	6 year old vegetation 70%	FM14	GS3 (123)
Kogelberg Sandstone Fynbos	Mainly tall Ericoid shrubland, sometimes with high cover of tall restios, canopy cover 35-70%, up to 2 m tall, sometimes to 5 m; a diverse middle layer of shrubs,	Moist oligotrophic ericoid shrubland MOE	6 year old vegetation 70%	FM15	GS3 (123)

Natural vegetation type or Land cover	Description of the vegetation composition and structure	Fuel model name, mnemonic (number code)	Vegetation age and estimated cover	Custom and standard fuel models	Standard fuel models
	restios and sedges (< 1m tall ±30-40% cover); and a ground-layer (<0.5 m, 30-50% cover) with sedges, grasses, restios and geophytes. Ericaceae common and restios more prominent than grasses. In wetter areas *Nebelia paleaceae, Cliffortia* species and other species. Boulder and rock cover variable from 10% to >70%. Last burnt in 2009				
Cape Winelands Shale Fynbos	Occurs on shale areas amid the granites has a similar structure to the Boland Granite fynbos. *Protea coronata* often replaces the other *Protea* species typical of the granitic soils. Last burnt in 2009	Moist mesotrophic proteoid shrubland MMP	6 year old vegetation 70%	FM14	GS3 (123)
Afromontane Forest & Scree forest	Tall forest (up to 25 m, tree cover ±70%) with *Rapanea melanophloeos, Cunonia capensis, Ilex mitis, Maytenus acuminata, Podocarpus elongatus* and other forest tree species confined to kloofs, streamlines and scree areas adjacent to streams. The open sub-canopy layer comprises shrubs, ferns and other herbaceous species. A shorter (up to 8 m), more open form, dominated by *R. melanophloeos* and *Heeria argentea,* is found on scree areas away from streams. These forests have survived all the fires over the past 30 years with only scorching of the edges.	Riparian forest	90%	RF	
Riparian	Variable, from short to tall but generally tall, up to 5 m, trees with a mixture of other shrubs and sedges or restios with ferns and, in places *Prionium serratum*. Important species include *Brabejum stellatifolium, Rapanea melanophloeos, Cliffortia* species, *Searsia* species and a range of the	Riparian forest or Moderate Load, Humid Climate Timber-Grass-Shrub	90%	FM18	TU3 (163)

Natural vegetation type or Land cover	Description of the vegetation composition and structure	Fuel model name, mnemonic (number code)	Vegetation age and estimated cover	Custom and standard fuel models	Standard fuel models
	forest tree species. Typically with a high rock and boulder cover. Mature, much of this burnt in 2009 and subsequently resprouted.				
Scrub	Dominated by a mixture of medium-tall shrubby and small tree species including *Searsia* (*Rhus*) *angustifolia*, *Cliffortia* species and *Diospyros glabra* with emergent *Kiggelaria africana* and *Olea europaea* subsp. *africana*. Often includes patches or narrow strips of riparian vegetation. Mature, much of this burnt in 2009 and subsequently resprouted.	Moderate Load, Humid Climate Timber-Grass-Shrub	90%		TU3 (163)
Firebreaks	Boland Granite Fynbos, short, without the non-reprouting shrubs and with an increased abundance sprouting shrubs, sedges, tall geophytes and grasses. The 4-year old vegetation described by Van Wilgen (1984) but mean age 2 years.	Moist mesotrophic proteoid shrubland MMP	40%	FM14	GS3 (123)
Grassand	Secondary grassland with a mixture of species including *Pennisetum villosum*, *Pennisetum clandestinum*, *Cymbopogon* species, a range of herbaceous species and low shrubs. Last burnt in 2009 fire.	Moderate Load, Humid Climate Grass (Dynamic) GR6	80%		GR6 (106)
Pine young	Mainly young pine trees planted after the 2009 fire with some areas planted before 2009. Open canopy and trees 4-6 m tall. Understorey a mixture of secondary vegetation typical of disturbed sites with *Pteridium aquilinum*, *Stoebe* species, *Elytropappus rhincerotis* and other Asteraceae, sedges and grasses. Includes a high but patchy biomass of logs, branches and debris from pine trees felled after the 2009 fire which burnt part of the area.	Moderate Load Activity Fuel or Low Load Blowdown SB2	60%		SB2 (202)

Natural vegetation type or Land cover	Description of the vegetation composition and structure	Fuel model name, mnemonic (number code)	Vegetation age and estimated cover	Custom and standard fuel models	Standard fuel models
Pine mature	Pines older than 15-18 years with a closed canopy; variable understorey, mainly scattered clumps of plants and extensive areas of needle litter but in recently closed stands similar to young pines. No recent fires.	Moderate Load Conifer Litter TL3	100%		TL3 (183)
Eucalyptus	*Eucalyptus* firebreak retained for fire wood production purposes when the others were removed some decades ago, not maintained. Tall trees (10-15 m) with a canopy cover of 50-70%, ground layer of bark and other litter with scattered herbaceous plants. No recent fires.	Moderate Load Broadleaf Litter TL6	70%		TL6 (186)
Poplar	Mature poplar stands of tall (10-20 m tall) with a variable understorey layer with scattered or clumped small trees (*Olea, Podocarpus*) and a surface layer of poplar litter (coarse and fine) with scattered herbaceous species. Fire burnt through understorey with occasional ladder fuels	Moderate Load Broadleaf Litter TL6	90%		TL6 (186)
Olive orchard	Not well managed or maintained, will burn, highly flammable undergrowth dominated by Asteraceae, grasses and sedges (<1.0 m tall, canopy cover 50-70%). Olives emergent, flammable.	Moderate Load, Humid Climate Timber-Grass-Shrub (Dynamic) TU3)	70%		TU3 (163)
Dam, ponds	Open water	Non-burnable #8			#8 (98)
Offices, settlement, stables, campsite, grass	Areas with offices, buildings, lawns and gardens, will not support a fire	Non-burnable #1			#1 (91)
Road, quarry, dam wall	Gravel or tarmac surfaces and bare soils	Non-burnable #9			#9 (99)

Table 2: Parameters for the custom models used in the FARSITE fire behaviour models. #: SAV = Surface-area to volume ratio

Custom Fuel model name	*Granite and Shale Fynbos*	*Sandstone Fynbos*	*Riparian and Forest Scrub*
Fuel model code	FM14	FM15	FM18
Parameters			
Dead fuel load (Mg ha^{-1})			
1 hr	4	6.6	12.96
10 hr	0.95	3.130	2.22
100 hr	0.12	0.33	1.08
Live fuel load (Mg ha^{-1})			
Live Herbaceous	5	19.1	0.69
Live Woody	6	3.13	18.24
Fuel model type -	Static	Static	Static
Dead SAV 1 hr fuel	72	72	72
SAV# L – herbaceous	59	59	59
SAV – L woody	49	49	49
Fuel bed Depth (cm)	90	90	130
Extinction moisture	34	34	34
Heat dead (Kj/Kg)	20000	20000	20702
Heat live	20000	20000	20702
Fuel moisture content			
Dead (%)			
1 hr	10	10	10
10 hr	10	10	10
100 hr	10	10	10
Live (%)			
Herbaceous	125	125	125
Woody	125	125	220

2.1.2 Weather Data

Weather conditions leading up to and during the fire event have a strong influence on fire behaviour. FARSITE requires hourly data on air temperature, relative humidity, wind speed, wind direction, cloud cover and rainfall. The weather data for the period before (1-8 March) and during the fire (9-12 March) were obtained for the:

- Dwarsberg weather station at high elevation (Table 3), data managed by the Fynbos Node of the South African Environmental Observation Network; and
- Swartboskloof weather station in the valley centre, data managed by the Climate Section of the Agricultural Research Council in collaboration with CapeNature.

The data were collated and analysed to assess and interpret the trends and means (Table 3). The week before the fire was moderately windy and very hot, with maximum temperatures hovering around 30 °C and reaching 41.5 °C on the 3rd of March (Figure 5). The minimum temperatures were more than 20°C at the beginning of this period but dropped steadily to reach a low of 10.2 °C on the 8th before rising again.

Table 3: Summary of the weather conditions during the fire period (9-11 March) from two nearby weather stations, Swartboskloof and Dwarsberg.

	Swartboskloof	Dwarsberg
Elevation (m)	320	1214
Maximum temp (°C)	33	24
Minimum temp(°C)	10	9
Precipitation (mm/day)	0	0
Maximum wind speed (km/h)	37	25.1
Maximum relative humidity (%)	92	97
Minimum relative humidity (%)	22	29

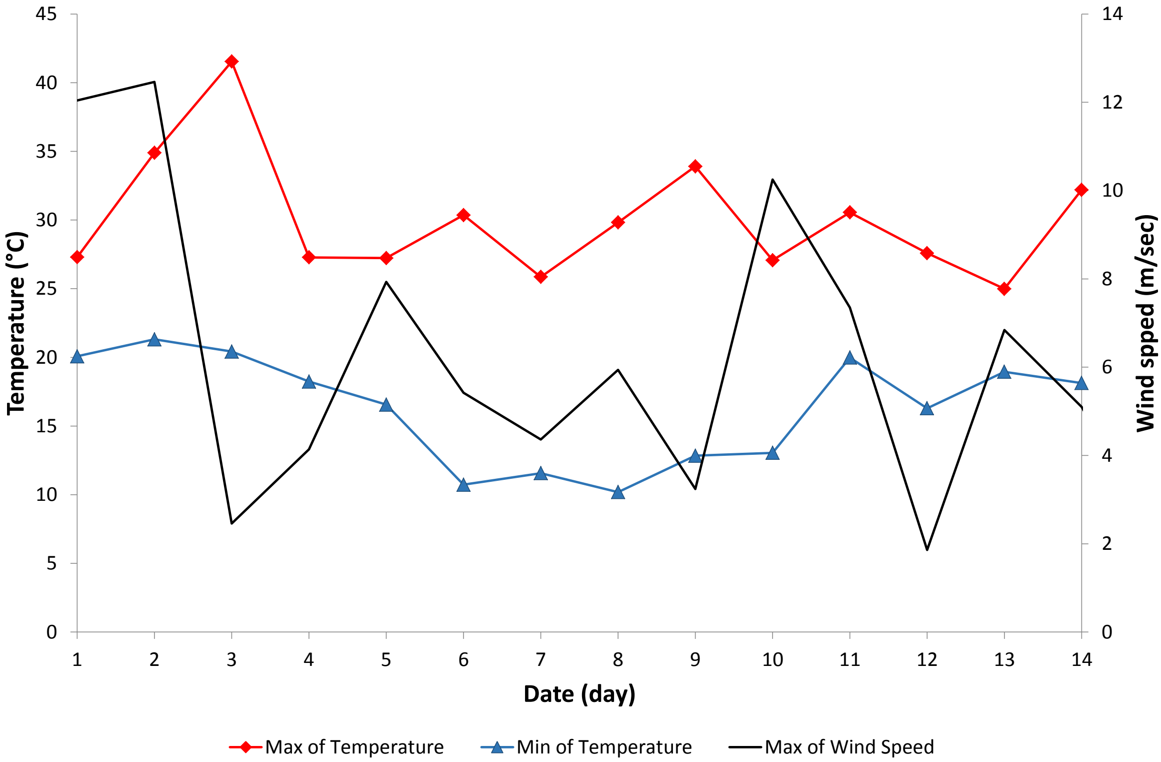

Figure 5: Temperature and wind speeds during the fire period including one week prior to the fire as measured at the Swartboskloof weather station.

FARSITE accepts two types of weather inputs namely, i) stream and ii) gridded. Stream data assumes constant values for the region modelled whereas gridded data is based on interpolated wind values which change with respect to topography. These two types were used to compare the accuracy of fire simulations. Stream data are easier to use because interpolated data requires additional modelling to be done on weather data to prepare them for use in FARSITE. For this assessment, the WIND NINJA program developed by the Fire, Fuel and Smoke Science Program of the United States Forest Service (http://www.firelab.org/project/windninja) was used to derive interpolated wind streams. These are reported to increase the accuracy of the fire modelling by more accurately representing the effects of topography on the wind.

2.2 Model validation

Following Jahdi et al. (2014) an error matrix was developed based on the actual and simulated fire perimeters to define the frequency of presence/absence values of burned areas. This was done in ArcGIS® (ESRI 2014) by adding two raster layers of the fire scar and the simulated fire. Frequencies were determined based on the attribute table of the new raster layer. Sorensen's coefficient (Legendre and Legendre, 1998) was to determine the accuracy of the simulated fire scar (Arca et al., 2007; Salis et al., 2010.). Sorensen's coefficient (SC), an indicator of the exclusive association between observed and simulated burned areas, was calculated as follows:

$$SC = \frac{2a}{2a + b + c}$$

where *a* is the number of cells coded as burned in both observed and simulated data, *b* is the number of cells coded as burned in the simulation and unburned in the observation, and *c* is the number of cells coded as unburned in the simulation and burned in the observation (Arca et al., 2007).

Typical SC coefficient values range between zero and one, with values close to one indicating very high agreement between simulated and observed fire perimeters (Arca et al., 2007). Visual comparisons are also an important initial screening tool and can be used to estimate model accuracy prior to extensive analysis (Finney, 2000). This technique was used to determine how well calibration techniques were being carried out.

2.3 FARSITE simulations

A number of FARSITE simulations were compared to determine which of the fuel models provided the best simulation of the Jonkershoek fire. We began by experimenting with differing fuel models and changing values within the fuel models as the initial simulations sometimes showed a failure to sustain or spread the fire. The effects of the winds on the fire behaviour were investigated by changing the format of the wind input data and comparing the accuracy of the simulations. We also analysed the sensitivity of model to alterations in the fuel moisture values. Fuel moisture values of *live herbaceous* and *live woody* biomass were reduced between 10-50% to assess how this changed the accuracy of the simulations.

The final results compare the following models as well as the effect of different wind input data:

a) Standard FARSITE fuel models

b) Custom fynbos fuel models using generic fuel moistures

c) Custom fynbos fuel models with altered fuel moistures

For all comparisons the duration of the simulated fire was set for three days (9-11 March 2015). We decided that the fire suppression efforts of the fire fighters would be excluded from this study as this would have made the modelling more complicated, especially as helicopter water bombing was used and we would have to assess how successful it was in addition to direct suppression by firefighters. Excluding suppression could allow the simulated fire to spread unrealistically far but, as it also would give an indication of what might have happened without suppression, we thought this would be useful. All spatial data were converted to the required formats using Geographic Information Systems (GIS) and the grid resolution for all spatial layers was 20m.

3 RESULTS

We produced many simulations in the course of learning how to use the model but only present those based on what we think are the most defensible and insightful model parameterisations and fuel model selections.

3.1 Total fire scar comparison

All the models under-estimated the final extent of the fire and largely excluded Stellenbosch Mountain from being burnt (Figure 6). Most of the simulations did not result in the fires spreading far enough down or up the Jonkershoek Valley. The fire spread patterns we noted during the simulations suggested that the spread was being driven more strongly by the topography than the wind. Our observations were the same for all the different model setups, despite the effort to correct for wind heterogeneity within the confines of the valley by using the gridded wind data.

The Sorenson Coefficient (SC) values of the different simulations range between 0.28 and 0.76 (Table 4). As expected the standard FARSITE models did not burn as well as the custom fynbos models (Figure 6) which we believe is mainly because the standard shrubland models did not include sufficient fine fuels (restios, sedges, grasses, fine-leaved shrubs) in the shrubland understorey and the grass-shrub models lacked tall shrubs. This was the only model where stream wind performed better that the gridded wind input data. The custom fynbos model with generic fuel moistures with gridded wind as an input resulted in SC values of 0.6 (simulation B). However, further analysis showed that increased accuracy can be achieved when the vegetation was artificially dried out to levels much lower than would be expected given the preceding (or antecedent) weather conditions (Table 4). Decreasing the moisture in the live herbaceous biomass to 70%, live woody biomass to 100% and 1, 10, 100 hour fuel moistures to 8% resulted in an SC value of 0.76 (simulation F) . Overall this model correctly simulated 86% of the fire scar, whereas 14% was under estimated and 45% was overestimated. This type of experimentation with different values for different variables illustrates the processes that we followed while becoming familiar with the FARSITE fire simulator.

We did not include the back burn or separate the area burnt by this fire from the main fire (see Figure 3), so the estimate of the fire boundary in simulation F is more accurate than it appears at face value. The extension of the fire beyond the known perimeter to the north-west in F appears incorrect, but the location of the perimeter on this section was the result of active suppression and containment.

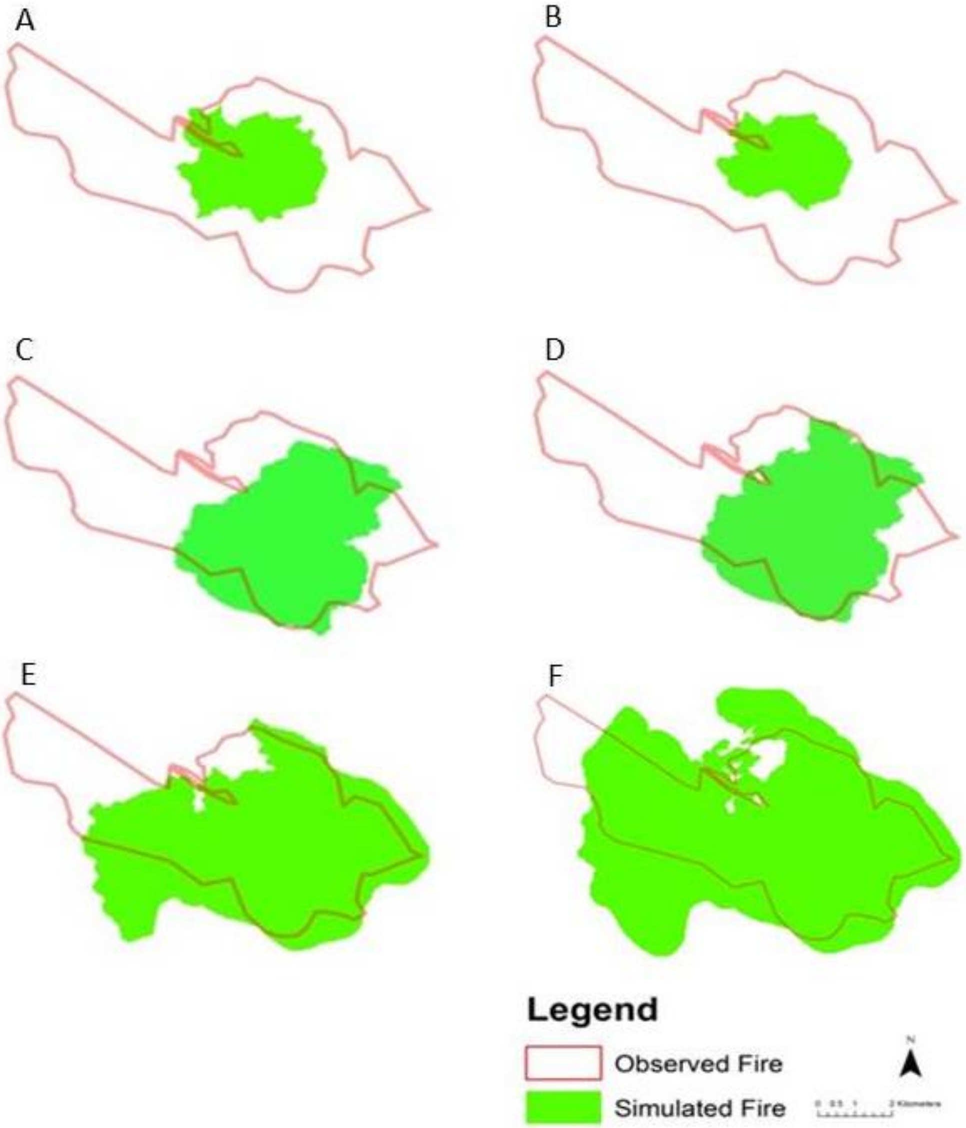

Figure 6: Fire spread perimeters of the different FARSITE simulations (green) overlaid with observed fire perimeter (red). The different models are a) FMF1 b) FMF2 c) FMC1 d) FMC2 e) FMC3 f) FMC4 (See Table 4 for Fuel explanation of model codes)

Table 4: Statistical evaluation of the FARSITE simulation performance of custom and standard fuel models. The Sorensen's coefficient (SC) derived from the error matrix. Additional models representing decreased fuel moisture values are included for visual comparison only.

Simulation type	Fuel model code	SC	% correct	% under estimated	% over estimated
FARSITE standard model					
a. Stream wind	FMF1	0.34	21	78	0
b. Gridded wind	FMF2	0.28	17	83	0
Custom Fynbos model					
c. Stream wind	FMC1	0.579	43	57	6
d. Gridded wind	FMC2	0.60	46	54	6
Drier vegetation - based on simulation d*					
e. Custom dry (100 100)	FMC3	0.73	70	30	22
f. Custom dry (70 100)	FMC4	0.76	86	14	45

*indicates models where live herbaceous and live woody biomass was artificially dried out based on the values indicated.

3.2 Daily fire scar comparison - Fire simulation accuracy

Further analysis was carried out to determine how well FARSITE was able to simulate the pattern of spread on each day of the fire. This was done using the Custom Fynbos Model with the gridded wind input (i.e. similar to B in Figure 6) which was set so that end of the simulation period coincided with the daily fire scars. This model was chosen to represent daily fire scars as the input data are representative of the fynbos vegetation despite this model not performing the best. The daily perimeters of the dry fuel model (simulation F) can be found in the Appendix 8.2. The simulated fire areas were compared with the observed daily fire scars for each of the days (Figure 7). The SC values ranged between 0.01 and 0.60 (Table 5), with the first day having very little overlap at all between actual fire perimeter and simulated fire perimeter. The accuracy of the simulation improved over the duration of the fire resulting in the final SC score of 0.6.

Table 5: Results of analysis daily analysis.

Daily Fire Scar	SC
Day 1 - 1900	0.01
Day2 - 0900	0.09
Day2 - 1300	0.18
Day3 - 1500	0.56
Day3 - 2400	0.60

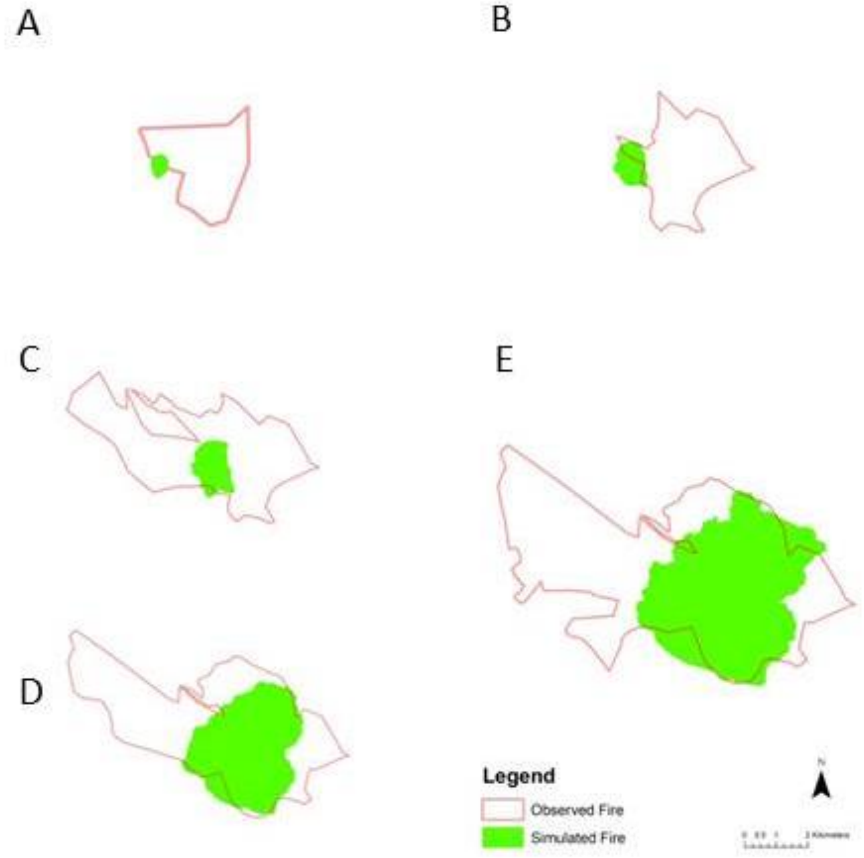

Figure 7: Daily fire spread perimeters (red) and FARSITE simulations (green) indicating the accuracy of the custom fuel model. The model used was the Custom Fynbos model run using the stream wind input data. The time steps are as follows: A) 9th March 19h00 B) 10th March 09h00 C) 10th March 13h00, D) 11th March 15h00 and E) 11 March 24h00.

4 DISCUSSION

The FARSITE simulations did not result in a high congruency between the actual fire and predicted fire scars although a range of values for various variables was tested and different fuel models were applied. Overall the accuracy was not as a high as those reported in the published literature where Sorenson Coefficient values as high as 0.92 were obtained (Jahdi et al., 2014). Previous non-spatial tests of fire behaviour models in the fynbos have indicated that observed rates of spread correlated well with modelled ones (Van Wilgen et al. 1985). However, predictions of "real-time" fire spread may not be as robust due to the highly variable nature of fynbos fuels (Le Maitre and Marais 1995; Van Wilgen, 1984). FARSITE assumes a homogeneous vegetation structure within a fuel type which is used to approximate fire behaviour and cannot account for structural variation in the characteristics of fuels. For example, it is well known that finer fuels such as grasses or ericaceous shrubs have higher rates of spread compared to more forest or woodland vegetation types (Jahdi et al., 2014; Philips et al., 2006) and the distrbution of these vegetation might not be captured within the fuel models. This may have contributed to low accuracy values because fynbos is heterogeneous and biomass can vary over short distances or within stands (Le Maitre and Marais 1995; Van Wilgen 1984). Other reasons for the inaccurately simulated spread include the poorly understood interactions between irregular topography and wind fields which could affect the growth rates and rate of spread of fires (Linn et al. 2007; Weise et al., 2006). The rugged topography of the Jonkershoek Valley (Figure 1), and the highly variable wind speed and direction during the fire (Figures 2 and 4), create conditions where such factors could well have had an important influence on model performance.

One of the known modelling issues in FARSITE, as in most models of complex phenomena, is that there is a tendency to compound errors over time (Finney, 2000; Finney et al. 2013). This could result in progressive deviations in the spread, as the later starting conditions and locations are based on incorrect data, the result being visually inaccurate patterns of spread. However, our observations of daily fire scars indicate that as the fire becomes larger, there is more agreement between the simulation and actual fire scar. This too, is a possible outcome because some errors may be in one direction and others in the opposite direction, leading to a progressive cancelling out as the burnt area increases and includes more variation in fuels and wind conditions and, thus, spread rates (Finney 2000). The fire growth model is particularly sensitive to small scale variability in the starting conditions which exert less influence as the fire increases in size (Finney, 2000).

We tested the effects of changes to the input values for both the wind data and fuel models. In particular, changing the weather input data has been shown to increase the accuracy of model simulations (Weise et al., 2006). The Wind Ninja wind simulation creates a uniform flow over the terrain which increases the resolution of wind data. While this did improve the accuracy of the fire simulation, the difference was marginal and the simulated fire did not spread far enough down the valley, despite the strong south-easterly winds during the evening and night of the 10th (contrary to observations of the actual fire) (see Figure 3).

Changing the fuel models also had large impacts on how the simulated fires spread. The standard FARSITE fuel models were tested and were found to under-represent the fuel characteristics, resulting in low rates of spread. The custom fynbos models as derived from Van Wilgen (1984) and Le Maitre and Marais (1995), performed better as has been found by Arca et al. (2007) and Iliopoulos et al. (2013) in Mediterranean shrublands. However, the default generic fuel moisture content values (Table 2) contributed to the underestimation of the fire simulation and may have been too high given the hot and dry conditions that were experienced in the week prior to the fire. There had also not been any rain since about the middle of February 2015. After adjusting the fuel moisture values, the overall fire spread appeared to adequately represent the fire behaviour. However, these simulations tended to overestimate the area burned. Active suppression was not incorporated into this modelling approach because of the complications it would introduce, and that did affect the accuracy of the simulated fire perimeter versus the observed one.

The use of reduced fuel moisture models in this study was the result of continued experimentation with parameters. This approach indicates that there are many options for the modeller to use which is likely to have large impacts on the FARSITE simulation. Similarly, the low accuracy of the custom fynbos models indicates the need to improve the confidence in the data especially under different weather conditions. These changes greatly affected the rate of spread of the simulated fire.

Varying the input parameters provided an opportunity to assess the sensitivity of the FARSITE fire simulator to changes in biomass, fuel moistures and wind data inputs. Accuracy of FARSITE simulations depends on appropriate calibration and should be seen as an important component of the modelling procedure aimed at obtaining sound input settings. Given that the standard fuel models are not appropriate for this region, sufficient time should be invested to increase the level of confidence in the data inputs (Arca et al., 2007; Jahdi et al., 2014). The FARSITE fire simulator has been widely used but most authors recommend that sufficient effort be placed on developing and testing fuel models that better represent local conditions (Arca et al. 2007; Philips et al., 2006; Pierce et al. 2014).

4.1 Limitations of this study:

Familiarising ourselves with the FARSITE model and developing an understanding of its requirements and the effects of different configurations and parameter settings was time consuming. This had a number of knock on effects. The fire suppression module of FARSITE was not used in this initial assessment of the fire model but is an additional complication. It requires estimates of fireline production rates in local fuel types for actual crews and crew types, as well as knowledge of the capabilities of the available aerial firefighting resources. While data on suppression activities for Jonkershoek fire were available, there was insufficient time to adequately explore the functionality of this module. The same applies to the back-burn lit on the 11th. FARSITE can simulate multiple ignition points, unlike most fire behaviour models (Papadopoulos and Pavlidou 2011) but it would have made the simulations even more complicated.

The FARSITE model can output other fire behaviour data such as the rate of spread, fireline intensity and flame length in different locations. These data could be compared with the experience and observations of the fire-fighters but time constraints, partly due to the late start, meant that we could not examine these data in sufficient detail.

The assessment of the accuracy of the simulations was affected by spatial errors in the recording of the daily fire scars by the various observers. Such inaccuracies are understandable because the boundaries have to be recorded while in the midst of co-ordinating the logistics of the various teams and planning their deployment. For the firefighters a general idea of the fire front location is good enough but was not accurate enough for the purposes of this assessment. This is why we used the boundary of the fire based on Landsat 8 images dating from after the fire, rather than the firefighter's Google Earth based polygons[2] which we found to be too inaccurate. While these inaccuracies have affected our evaluation of the accuracy of the simulation it is clear that the focus should be on improving the modelling input data rather than seeking more accurate representations of the fire scar.

4.2 Recommendations

This section outlines the potential use of the FARSITE simulation modelling package and highlights the ease of use in doing so.

- Our experience with FARSITE shows that it does have potential for fire simulation in fynbos, a finding corroborated by studies in other countries which have shown it to be a useful tool. We

[2] Google Earth images use a quick 3-D image rendering system which means that the locations of features are not precise and can move between images. This also can result in inaccurate polygon boundaries.

found that once we had got the model configuration we were able to improve the simulations rapidly, partly because the developers of FARSITE have made every effort to provide detailed documentation and examples to improve the use of the modelling package. Despite the potential ease of use, sufficient time should be invested to fully understand and utilise the modelling package. We recommend investing in proper training so that the users (e.g. FPA members and staff) are able use and apply the model effectively and learn from its outputs. As far as we are aware this is the first attempt at using the FARSITE model in the fynbos. We are aware that a M.Sc. student is attempting to use FASITE to simulate the February 2015 fire on the cape Peninsula but her study is still underway.

- We are not convinced that FARSITE will be suitable for real-time simulations aimed at guiding management decisions while engaged in fighting a fire in the fynbos biome. The main reason for this is that its most important role would be to simulate scenarios of what would happen if this or that fire-fighting tactic was chosen. This requires, among others, the ability to generate weather conditions on demand. There is technology to do this but we believe it will be some time before we will have the human capacity and datasets required to do this in real-time. The simulations will also have to be more rigorously tested than we have done in this study (e.g. Filippi et al. 2014) to be defendable in legal actions.
- However, we believe that the ability to use FARSITE to test fire and weather scenarios makes it a valuable training tool for preparing managers and junior staff for planning suppression activities or develop response scenarios to changing weather conditions prior to a fire season. Success in fighting fires can often depend on having experienced people in the team who can use their experience and local knowledge to help them make tactical decisions. The use of FARSITE as a training tool to help build experience, albeit virtual experience much like flight simulators do for pilots, could prove invaluable if it leads to better decisions. These simulations also have potential to inform fuel management options and can point to areas which areas are likely to be at risk under certain weather or fuel load conditions.
- This study and others have identified the importance of developing custom fuel models for FARSITE (or other fire behaviour simulators) that are representative of the fuels in an area and based on adequately designed field sampling studies. There are a few studies that have been done in the fynbos, and in other major fuel types (e.g. grassland, savanna), but they are site specific. Fynbos, like many other shrubland fuels, is very variable structurally, both horizontally and vertically (see Van Wilgen et al. 1985) and we need a much greater understanding of how those characteristics influence fire behaviour. We know that invasions have significant impacts on fire behaviour but have very have limited data on how invasions alter fuel properties and thus fire behaviour (see Forsyth et al. 2015, chapter 4). This is an important issue which needs research. One of the options for better understanding the variability in fuels is to use remote sensing (e.g. Arroyo et al. 2008; Mallinis et al. 2008; McCaw et al. 2008), especially for mapping risk on the wildland-urban-interface but needs proper testing under local conditions.
- A number of studies have used FARSITE to test various options for fuel management with the objectives of reducing fire risks (Arroyo et al. 2008; Mallinis et al. 2008; Paz et al. 2014; Salis et al. 2013). The model has proven useful for suggesting ways of achieving these targets, especially in areas with a long history of fire behaviour modelling. This is a possibility that could be investigated by the Working for Fire Program or through National or Provincial Disaster Management structures.

- Prof. Milne is still keen to test the *Australis* model on the Jonkershoek fire and this opportunity could be investigated during the 2016/17 financial year.

5 CONCLUSIONS

Managers require models that are accurate in both time and space given certain inputs such as fuels, weather and topography. The FARSITE has the potential to assist in fire management by providing simulations that will test their fire planning skills and in tactical decision making for firefighting operations. The results of this study using FARSITE found that the fire spread simulations were not as accurate as we had anticipated given that others have experienced greater success. However, much of this seemed to be due to incorrect parameter values and settings. For example, where published fuel model data did not result in accurate simulations, varying parameters such as fuel moisture resulted in predicted fire scars that were much more similar to the actual fire scars. This finding highlights the need to better match fuel properties to fire conditions. Once the FARSITE model is sufficiently calibrated for the region and representative fuel models are developed, fire managers such as Working on Fire will be better prepared to use FARSITE at least as a training tool.

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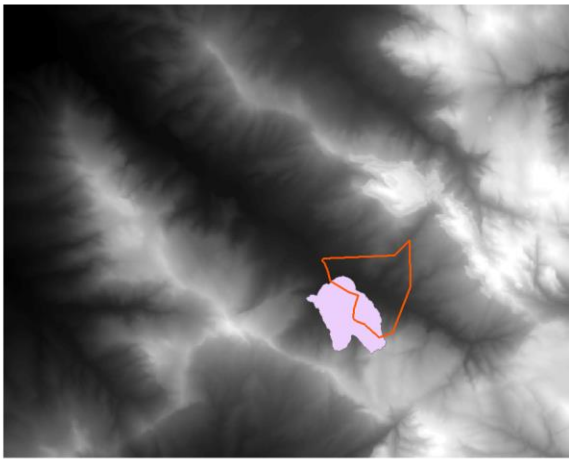
8 APPENDIX:

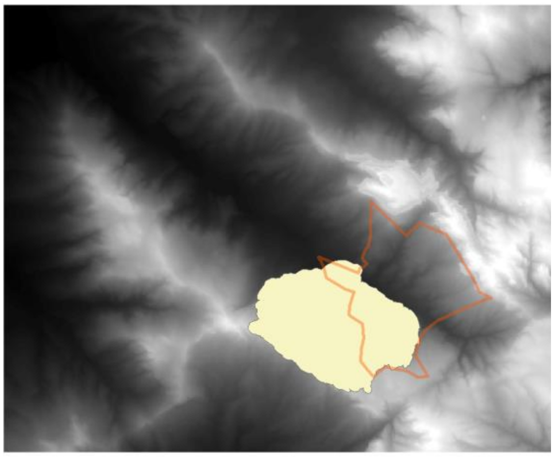
8.1 FARSITE input data

FARSITE files	FARSITE input	Description
Slope	Asci	DEM used to derive slope raster in degrees
Aspect	Asci	DEM used to derive aspect raster
Land cover	Asci	Raster coded with land coded with cover classes
Wind	.WND	Hourly data for speed, direction and time
Weather	.WTR	- Daily observation of temperature, - Hours at which minimum and maximum temp was recorded - Humidity - Precipitation
Fuel moisture	.FMS	The values indicate dead fuel moisture time lag
Adjustment factor:	(adj file)	Allows for use of estimated or observed data to tune the simulated fire rate for a specific fuel model.

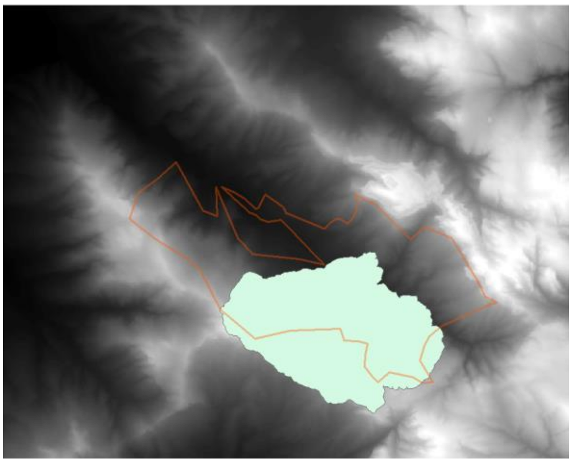
8.2 Daily fire spread perimeters of the dry fuel model



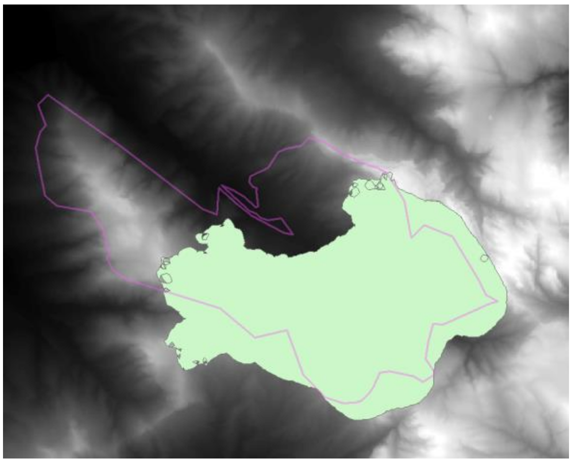
Day 1 - 1900



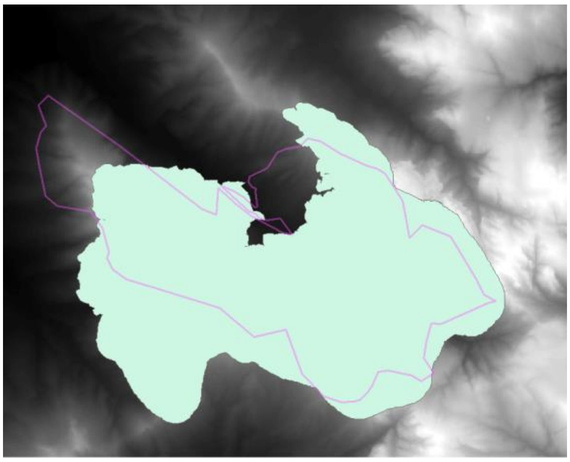
Day 2 - 0900



Day 2 - 1300



Day 3 - 1500



Day 3 - 2400

Figure 7: FARSITE fire behaviour fuel models – 8_70_70 (8 % dry, 70% moisture in wet and dry) without suppression