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THE IMPACT OF CLIMATE CHANGE ON WILDFIRE

WORKSTREAM 4: RESEARCH REPORT

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TABLE OF CONTENTS

TABLE OF FIGURES

LIST OF TABLES

1 INTRODUCTION

Most of the natural vegetation in South Africa is adapted to fires and requires fires to maintain ecosystem function and biodiversity (Bond, 1997; Van Wilgen et al., 1990). At the same time fires are a threat to human lives, livelihoods and assets and large losses are incurred in fires every year[1] by both the public and private sector. This tension – that fires are necessary but fires are a hazard – is behind the approach taken to fires in natural vegetation in policy and legislation, which supports the formation of Fire Protection Associations to manage fires and prevent veldfires[2]. Climate change is projected to increase air temperatures, and increase the periods between rainfall events, which are likely to increase the periods of high to extreme fire-danger days and, thus, the risk of veldfires.

However, climate change will also alter vegetation productivity and, possibly structure, and thus fuel dynamics which may influence the fire behaviour as well (Archibald et al., 2018; Bond and Scott, 2010). The current study has not attempted to assess the impacts of climate change on fuel dynamics because the development of suitable models for doing this for southern African conditions is still an emerging field of research, so fuel dynamics are assumed to be similar to what they are now.

Fire risk has been assessed at a national level for South Africa using information on the fire hazards related to the fire regimes in different vegetation fire ecology types and the consequences for human lives, livelihoods and assets (Forsyth et al., 2010). The 2010 assessment followed the well-established approach of dividing risk assessments into the hazards and the consequences of exposure to those hazards, also termed the hazard and the vulnerability. This assessment builds on and updates the 2010 assessment, focusing on fire risk at the local authority, settlement and within settlement levels.

[1] http://www.fpasa.co.za/journals/sa-national-fire-statistics
[2] A wildfire is a fire burning in natural vegetation or veld or modified vegetation and could be a managed or unmanaged (wild) fire.

There is evidence that communities living in the wildland-urban interface of South African towns are becoming increasingly exposed to wildfires due to, for example, expanding town boundaries (Holloway et al., 2010; Nel et al., 2014; Syphard et al., 2013). Under conditions of climate change it is predicted that the frequency and severity of high and extreme fire-danger events and, thus, the risks will increase, at least in the Fynbos Biome (Le Maitre et al., 2015; Midgley et al., 2005). Investments in protecting settlements need to prioritise those identified as having the greatest risk. Therefore the objective of this study was to determine the level of risk prevailing in the wildland-urban interfaces of the settlements of South Africa. A secondary objective was to determine how the current number of high and extreme fire-danger days that these settlements experience is likely to change under different climate change scenarios.

2 BACKGROUND

The following sections describe the overall approach and the details of the final methodology are given under Methodology (section 3).

2.1 Fire hazard

Fire hazard depends on the nature of the fuels available to burn and the typical weather conditions during which fires occur, especially wild fires. As data on the fuel loads in natural vegetation types were only available for a very limited set of sites and fire ecology types, a different approach was adopted (Forsyth et al., 2010; Le Maitre et al., 2014b). South Africa has a long history of fire ecological research which has resulted in a large body of data and information on the fire ecology, behaviour and fire regimes in the major vegetation types of South Africa, notably grasslands, savanna-woodlands and fynbos (e.g. Bond, 1997; Goldammer and de Ronde, 2004; Kraaij and Wilgen, 2014; Tainton, 1999; Teie, 2009; Van Wilgen and Scholes, 1997). The available information was synthesised to identify 13 fire ecology types and the fire regimes and behaviour were described for each of these types (Forsyth et al., 2010; Le Maitre et al., 2014b). Each of the 430 different vegetation types in the national vegetation map (Mucina and Rutherford, 2006) were assigned to one of these 13 fire ecology types, resulting in a map of South Africa showing the distribution of the fire ecology types (Figure 1).

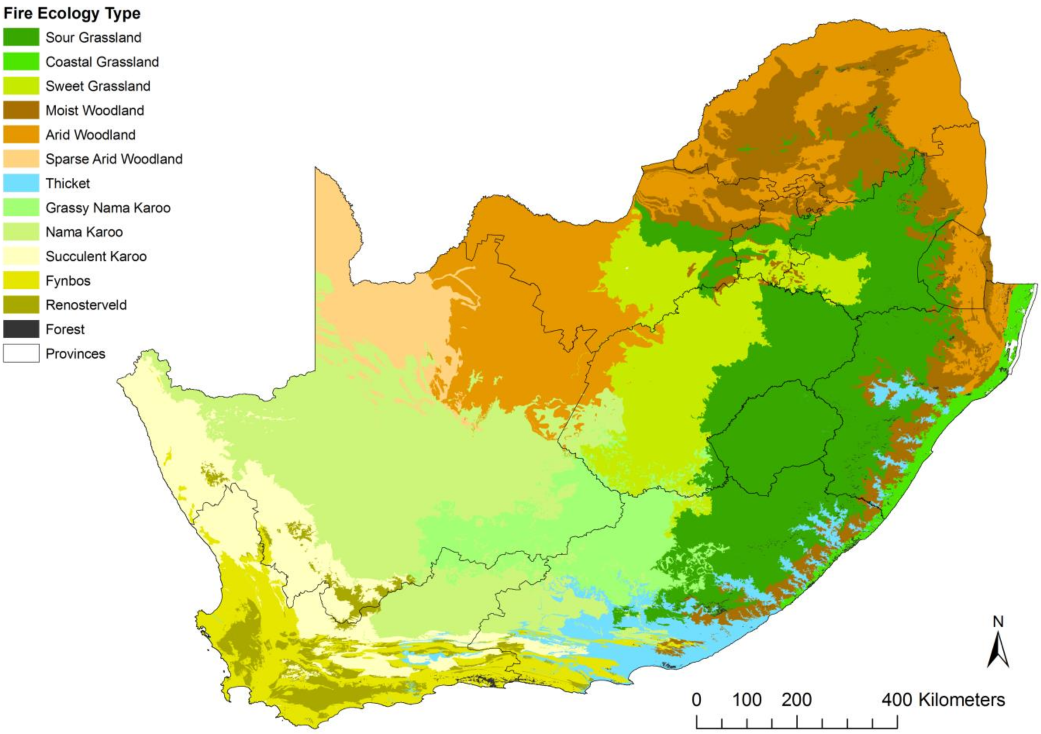

Figure 1: Fire ecology types and their distribution in South Africa, Lesotho and Swaziland (Bond, 1997; Forsyth et al., 2010; Le Maitre et al., 2014b).

The 13 fire ecology types can be arranged into three main groups (Forsyth et al., 2010; Le Maitre et al., 2014b):

- Fire-dependent ones which require fires at the right intervals to regenerate the vegetation
- Fire-independent ones which may burn but do not require fire for regeneration
- Fire-sensitive ones which are adversely affected by fires and can take many years to recover

Fire hazard will not be an issue for settlements in fire ecology types where fire hazard is low or fires occur only rarely because there generally is insufficient fuel. These include the Nama Karoo, Succulent Karoo and some forms of Thicket. Indigenous Forests only occupy very limited areas so there are unlikely to be many, if any, settlements which are located in Forest areas but if they did the fire hazard would be low. In Sparse Arid Woodland and in low rainfall areas of Sweet Grassland, the hazard will vary depending on the rainfall and grass production during the growing season (Table 1).

Table 1: Summary of the fire ecology types, the role of fire in ecosystem regeneration and the fire characteristics (after Le Maitre et al., 2014b). The threshold of 650 mm of mean annual rainfall (MAP) is based on studies summarised by Bond (1997) but this value is a guide rather than being precise with low rainfall being associated with a low occurrence of fires (Archibald et al., 2009) even in vegetation with grass fuels.

Fire ecology type	Role of fire	MAP (mm/year)	Fire characteristics
Moist Woodland	Fire-dependent	>650	Sufficient fuel for fires every year; in dense woodlands there may be too little grass to sustain fires; woody overstorey can carry fire; fire hazard can be high to extreme
Arid Woodland	Fire-dependent	400-650	Sufficient fuel for fires in high rainfall years; woody overstorey plants rarely burn; fire hazard can be high
Sparse Arid Woodland	Fire-independent	<400	Sufficient fuel for fires only after exceptional rains; sparse woody overstorey which does not carry fire; fire hazard can be high
Sour Grassland	Fire-dependent,	>650	Sufficient fuel for fires every year; fire hazard can be high to extreme
Sweet Grassland	Fire-dependent	<650	Sufficient fuel for fires in high to exceptional rainfall years; fire hazard can be high
Coastal Grassland	Fire-dependent	>650	Sufficient fuel for fires every year ; mixed woodland and grassland, all carry fire; fire hazard can be high to extreme
Fynbos	Fire-dependent		Fine fuel and litter accumulates over time; can burn after 4-8 years; fire hazard can be high to extreme
Renosterveld	Fire-dependent		Fine fuel and litter accumulates over time; can burn after 3-4 years; fire hazard can be high to extreme
Thicket	Fire-independent		Fuel loads low, does not normally burn; some grassy forms burn periodically; fire hazard can be high
Nama Karoo	Fire-independent		Insufficient fuel; some forms with high sweet grass cover can burn after exceptional rainfall years; fire hazard can be moderate to high
Grassy Nama Karoo	Fire-sensitive		Accumulates sufficient fuel in high rainfall years; fire hazard can be high
Succulent Karoo	Fire-independent		Insufficient fuel; very rarely burns; fire hazard low
Natural Forest	Fire-sensitive		Fuel properties limit fires; can burn in exceptionally hot and dry conditions; fire hazard low to moderate

2.2 Changes in land-cover and fire hazard

The fire ecology types described above are all classified as natural vegetation in the land-cover data (GTI, 2015). In many areas the land-cover has been converted from natural vegetation to other land use and land-cover types and some of these land-cover types modify the fuel loads. The most obvious one is the establishment of forest plantations of introduced tree species, notably pines, eucalypts and wattles. Plantations of these species have high fuel loads and considerable resources are invested in attempting to ensure that such plantations areas are protected from fire (Van Wilgen and Richardson, 2014, 2012). Since the trees require 5-30 years to reach a harvestable size this requires substantial investments in fire protection and exclusion every year. When fires burn plantations they can present substantial fire hazards to infrastructure and any settlements adjacent to or within plantation areas (Goldammer and de Ronde, 2004; Teie, 2009). Fires in plantations can be particularly damaging if they occur in areas that have recently been clear-felled and there are lots of debris (slash) and other large woody material left behind. Fires under these conditions can be severe, with large woody debris burning intensely and for long periods of time (hours to days) (Keeley, 2009), doing considerable damage to soils by consuming the organic matter that binds the soil particles, and generating water-repellent conditions (Le Maitre et al., 2014a; Scott, 2000, 1997, 1993; Shakesby and Doerr, 2006; Shakesby, 2011). These conditions can alter a catchment's hydrological responsiveness and lead to unexpected flooding.

A range of crops are grown in South Africa but only some produce large quantities of fuel and can become a fire hazard. The annual crops generally produce little if any fuel except for maize but even in the case of maize, the residue ranges from 2.8-5.8 tons/ha (Batidzirai et al., 2016). This is comparable with, and even higher, than the dry biomass reported for high-rainfall, sourveld grassland at 3.4 tons/ha but closer to the total grassland biomass of 5.6 tons/ha (Everson et al., 1988), suggesting that burning maize lands can result in a high to extreme fire hazard. Compared with grassland, sugar cane is another crop which can generate large amounts of fuels but it is generally harvested at a stage where much of the crop is still green. This still leaves a residue but the biomass is relatively low. Orchards and vineyards can burn in fires but generally where there is sufficient fuel in the weedy growth or cover crop underneath the vines or trees. The biomass of this secondary vegetation is generally low so that the fire hazard is low. An inspection of the areas regularly burnt in fires shows that fires in agricultural lands are a regular occurrence. If these fires spread into the adjacent natural vegetation they could results in hazards like those estimated in this study (Table 1).

A wide range of introduced (alien) plant species have also become significant invaders of natural vegetation in South Africa. Many of these species grow taller, larger, or become denser than the natural vegetation and thus increase fuel loads (Jayiya et al., 2004; Van Wilgen and Richardson, 1985). The greater fuel loads can increase the fire hazard by increasing fire intensity as well as increasing fire severity and the damage done to seed banks and soils (Bond et al., 1999; Le Maitre et al., 2014a; Van Wilgen and Scott, 2001). There are data available on density and species composition of invasions but these are mapped in a generalised way (Kotzé et al., 2010). This means that the data are suitable for a general overview of the invasions in an area but cannot give accurate data on invasions in specific locations. In this study we have used the land-cover classes to infer the density of woody plants, including invading alien shrub and tree species, and increase the fuel load and fire hazard because the land-cover includes such invasions (without explicitly identifying them) and provides greater spatial accuracy.

2.3 Fire vulnerability

Assessing fire vulnerability involved (Forsyth et al., 2010):

- Identifying the conditions that increase the likelihood of loss for particular elements-at-risk including: environmental (e.g. ecologically sensitive ecosystems), social (e.g. human lives, livelihoods) and economic (e.g. infrastructure, built structures, agricultural crops) elements that are exposed to a hazard, and are at risk of loss.
- Determining the vulnerability level for different situations and conditions.

This study has focused on the social and economic risks. Forest plantations can be environmentally sensitive because they can experience severe fires at times when high ground fuel loadings (e.g. slash from thinning or felling) is present. These conditions result in increases in storm runoff and soil erosion and changes in catchment properties (Scott et al., 1998). Such changes were not included in this assessment.

Social impacts were assessed as those that directly affected life expectations and human health and directly related to the ability of those social systems to recover (Forsyth et al., 2010). A key factor in this is the financial reserves (e.g. savings) and the skills and equipment required to protect against fires. This is directly related to financial income so areas with low income were assessed as being the most vulnerable. Suitable income data are available for ±7 x 7 km spatial analysis units known as mesozones (Naudé et al., 2007; Van Huyssteen et al., 2009) and the settlement typologies developed for this study. Social impacts can also be inferred from the land-cover classes for urban settlements. Informal settlements around towns and dense rural settlements are typically the most vulnerable because the entire settlement, and all the household possessions, can be destroyed by a fire (a social and an economic loss).

Annual dryland crops were excluded from the economic impact assessment as they rarely burn before harvest while irrigated crops generally do not burn (Forsyth et al., 2010). Perennial crops, such as orchards, and forest plantations were included because re-establishment and recovery after a fire may take a number of years. Harvestable natural products are difficult to quantify and there are no maps so, although they are critical for many rural communities, they could not be included. Livestock losses are often incurred during fires and should be accounted for as well, with non-commercial farmers often being the most vulnerable, but suitable datasets are lacking. Other economic losses would include those involving infrastructure (e.g. power lines) and structures and facilities (e.g. houses, barns, factories, clinics) which were included.

2.4 Fire risk

The potential for economic and social losses was rated based on a plausible wildfire scenarios developed for each fire-ecotype (Forsyth et al., 2010). The fire scenarios were used to evaluate the fire hazard and determine the likelihood and consequences of (i.e. vulnerability to) such a fire in workshops with stakeholders. The combinations of likelihood – rated from ‘rare’ to ‘almost certain’ - and fire consequences – rated from ‘insignificant’ to ‘catastrophic’ – were used to arrive at a level of fire risk from ‘low’ to ‘extreme’. In the 2010 study, the outcome of the analysis was an assessment of the economic and social fire risk in each spatial unit (mesozone) which was then aggregated to the level of the local authority to identify those most at risk from fires. In this analysis the overall assessment was for all selected settlements in a local authority, individual settlements and within individual settlements. Changes in the fire risk in future can be accommodated by adjusting either the fire scenarios or the likelihood or both. We do not plan to run stakeholder workshops to redo the fire risk assessment process and, so, will rely on the findings of the 2010 assessment for the actual ratings of fire risk.

2.5 Modelling fire danger

The fire ecology types can be divided into groups based on the likelihood of the occurrence of a wildfire (Table 1). The Succulent Karoo, Nama Karoo and Thicket rarely burn because they have little or no fuel except for some grassy forms of Thicket and thicket-grassland transitions with higher grass cover. Sparse Arid woodland and Sweet Grassland will burn only after exceptionally high rainfall years result in sufficient grass fuels. Fires in Fynbos and Renosterveld occur regularly with their occurrence determined by cumulative fuel loads, which usually take 4-6 years to be sufficient to carry a fire. The other savanna and grassland types can accumulate sufficient fuel burn every year but mostly burn every two years (Le Maitre et al., 2014b). The Forest rarely burns and can be considered a low fire hazard for this analysis. This means that the focus needs to be on modelling the fire hazard in two groups of fire ecology types:

- Fynbos and Renosterveld with a mix of woody and herbaceous fuels
- Moist and Arid Woodland and Sweet, Sour and Coastal Grassland where grass fuels are dominant

2.5.1 Fynbos and Renosterveld

Fynbos and Renosterveld occur primarily in the winter rainfall region and the dry summers result in dry fuels and ideal conditions for fires, but both Fynbos and Renosterveld extend eastwards to near Port Elizabeth and grassy forms of Fynbos occur in the Zuurberg and the Kaprivierberge east of Grahamstown. Here the rainfall is bimodal with a mixture of summer and winter and the dry conditions and fires can occur throughout the year (Kraaij et al., 2013). For the Fynbos the fuels comprise a mixture of fine-leaved shrub and grass like fuels such as restios, sedges and grasses, except where there are dense stands of Proteaceae (Le Maitre, 2015). Decomposition rates are slow so that fine dead fuels accumulate and play an important role in fire ignition and propagation. Renosterveld lacks the Proteaceae, restios are rare or absent and some forms have abundant geophytes and annuals during the winter which add to dry fuel load in the summer.

Fire danger in these fire ecology types is well captured by the McArthur forest Fire Danger Index (FDI) and less well by the Lowveld FDI (Willis et al., 2001). Algorithms were developed for calculating these indexes from the climate data outputs from the CSIR global climate modelling system (Forsyth et al., 2015). The algorithms were used to calculate the values of the FDIs for both current and future climates. The McArthur forest FDI can also be applied to the rest of the country but is not best suited to grass-dominated fuels as discussed below.

2.5.2 Woodland and Grassland

The onset of grass growth is triggered by the increase in soil moisture following the onset of the rainy seasons in the summer rainfall region (Archibald and Scholes, 2007; Parrini and Erasmus, 2009; Whitecross et al., 2017). In the fire ecology types with grass dominated fuels, the seasonality of the grasses is important. In the high altitude and Highveld grasslands the seasonality is determined by minimum temperatures which determine when grasses begin growing and very low temperatures, especially frosts which kill the grass above the soil (Ellery et al., 1995). In the drier areas the grass growth is regulated primarily by moisture availability which determines the onset of the growing season, and moisture stress linked to the onset of the dry season. Here the amount of rainfall during the rainy season plays two roles, regulating the amount of growth (Deshmukh, 1984; Govender et al., 2006; Hély et al., 2003; Snyman and Fouché, 1991) and the onset of moisture stress in conjunction with temperature (Ellery et al., 1995).

The process of grass die-back is known as curing. Curing is important because it determines the amount of live versus dry fuel and thus the fuel mix and load and conjunction with rainfall, and thus the resulting fire behaviour under a given set of conditions (Archibald et al., 2010a; Govender et al., 2006). The dynamics of grass fuels play an important role in the extent of fires (e.g. burned area) and the seasonality of fires, with Sour Grasslands in the interior of KwaZulu-Natal burning far more extensively and frequently than the coastal belt grasslands and the valley Bushveld (Buthelezi et al., 2016) (Figure 2). The interior grasslands also have a more strongly defined burning season than the coastal grassland and Valley Bushveld (Figure 2). Given that the curing is dynamic and driven by temperature or moisture availability, it would be ideal to be able to simulate it for future climates from data on the key variables rather than have a static start and end date. Although there have been studies of the phenology of the grasses-fuelled biomes (savanna, grasslands) in South Africa and how that phenology varies with annual rainfall, these models focused on the timing rather than the cues.

The following rules were suggested for modelling the phenology of Highland Sourveld which is found in the Drakensberg and its foothills (Everson et al., 1985): Curing was initiated by the following conditions, a minimum temperature of 0°C for 5 successive days or 1 day of -4°C. All live fuel would then be moved to dead fuel. New growth or greening up would take about

14 days and have a high moisture content (250%) before decreasing to 120% in mature foliage (equations provided). The same rules could probably be applied to KwaZulu-Natal Sandstone Sourveld, possibly to Ngongoni Veld but not to the coastal grasslands. The phenology of South African vegetation has been studied and divided into biome related groups (Hoare and Frost, 2004; Wessels et al., 2011). The moister savannas were found to be distinct from the arid savannas, mainly because the arid savannas respond to inter-annual rainfall variations and lack the clear peaks of the moister savannas. The Indian Ocean Coastal belt was separated from the remaining grasslands but displays a similar winter dormancy period to the grassland and savanna biomes (Wessels et al., 2011) which fit with the seasonality of fires (Figure 3).

For practical reasons the McArthur Forest FDI was used in this study for all the fire ecology types.

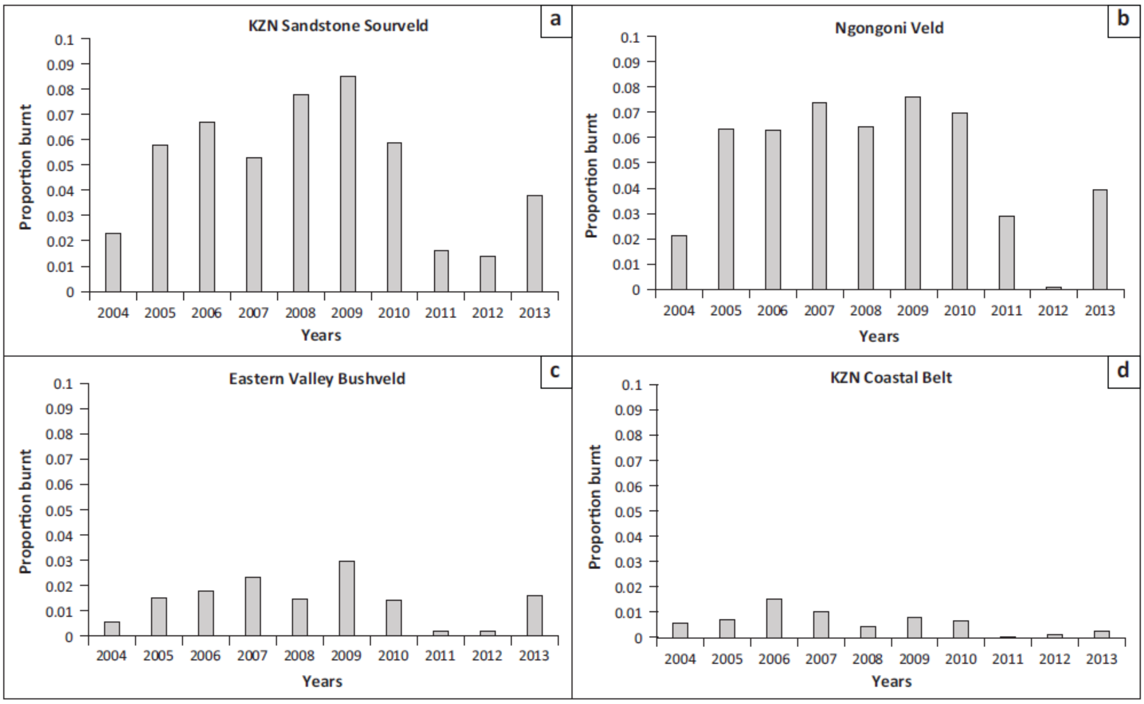

Figure 2: Total burnt area (expressed as proportion of total area within each vegetation type) in the (a) KZN Sandstone Sourveld, (b) Ngongoni Veld, (c) Eastern Valley Bushveld and (d) KZN Coastal Belt over a 10-year period (from Buthelezi et al., 2016).

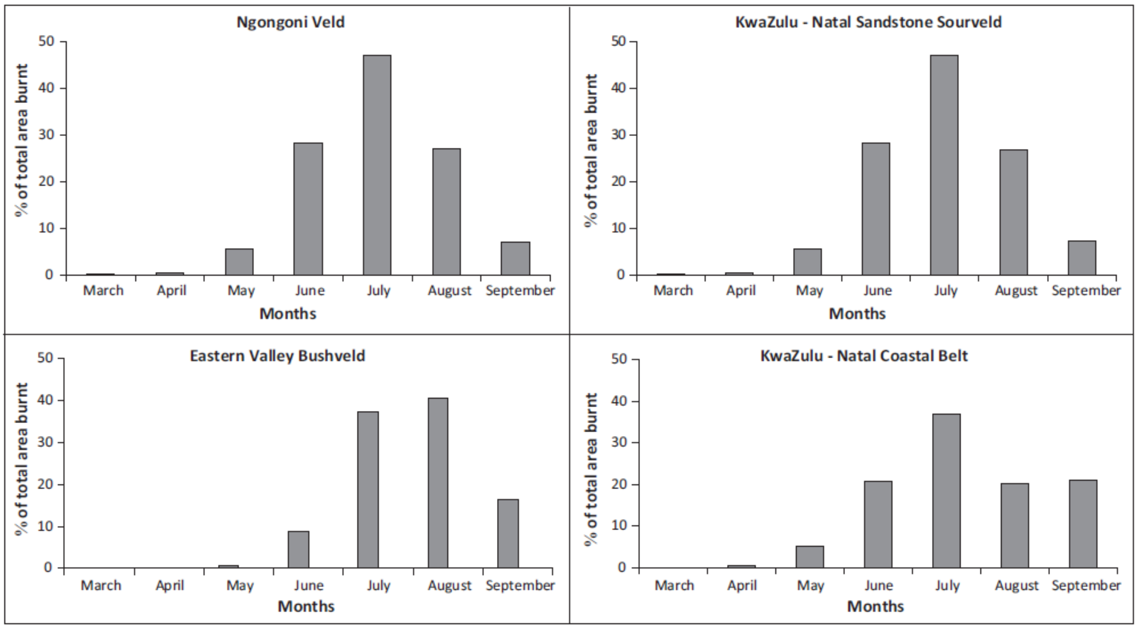

Figure 3: Percentage of the KwaZulu-Natal Sandstone Sourveld, Ngongoni Veld, Eastern Valley Bushveld and KwaZulu-Natal Coastal Belt that burnt in each month (March to September) (from Buthelezi et al., 2016).

3 METHODOLOGY

In this study we adapted the process we followed in the 2010 study (Forsyth et al., 2010), which used the mesozones (irregular polygons about 50 km^2 in area) as the basic assessment unit to use the settlement boundaries as the assessment unit. We added two components to this assessment, namely fire occurrence information supplied by the CSIR's Meraka Institute and based on MODIS data, and the projected changes in the occurrence of fire-danger days generated by the Green Book project.

3.1 Defining the area for assessing the hazard

The settlement boundaries or footprints were supplied by the Green Book project as a set of named polygons to which a number of attributes were linked. We focused on the outer boundaries of these settlements as defining the centre of the Wildland-Urban Interface (WUI) where urban or other infrastructural development borders on and intermingles with flammable natural vegetation, called wildlands in the United States of America (Theobald and Romme 2007). The WUI is the area where residents and their assets are exposed to death or injury and damage from wildland fires. Assets are things that society values and fire-sensitive assets can be social, economic and environmental in nature (Gill et al., 2013). Examples of social assets include human lives and homes, businesses, houses, schools and sheds, while environmental assets could include wetlands or biodiversity.

There is no universal standard for the dimensions of the WUI and different studies have adopted a variety of approaches including set widths and densities of structures (Conedera et al., 2015; Ghermandi et al., 2016; Herrero-Corral et al., 2012; Lampin-Maillet et al., 2010; Whitman et al., 2013), often depending on the purpose and spatial resolution of the study. For a very detailed, aerial photograph-based assessment of the WUI in two areas of South Africa we chose to use a width of 100 m on either side of the wildland-urban boundary for the risk assessment (Forsyth and Le Maitre, 2015). For this national level assessment we chose the commonly used width of 1 km. This is appropriate given that our primary concern was the impact on infrastructure, particularly houses which are susceptible to being set on fire during high fire danger conditions by wind-borne embers carried for at least 1 km by wind before they land in gutters, enter roof eaves or open windows and ignite fires (Alexandre et al., 2016; Blanchi et al., 2006).

A number of the settlements comprised a number of sub-units which adjoined each other on one or more sides, so the first step was to dissolve them so that there was a single, continuous boundary to use in defining the inside and outside. That polygon boundary was then buffered using ArcGIS to a width of 1 km on both the inside and the outside. The outside or exterior buffer was used to analyse the land-cover classes to estimate the fuel load and fire danger (likelihood) and the inside or interior buffer to assess the consequences of, or vulnerability to, a wildfire. So, the WUI was defined as a 2 km wide strip with its centre defined by the boundary of the settlement provided by Workstream #3. We know from inspection of the land-cover data that there can be natural vegetation on the inside and/or infrastructure on the outside of the centre line, but using this boundary would make the findings comparable across all the different studies in this project and for all settlements. In many cases the centre of the settlement is less than 1 km from the edge so the entire settlement is in the inner buffer.

3.2 Characterising fuels and fire hazard

There are various ways of estimating the fuel loads, ranging from vegetation or land-cover classifications to field sampling. From previous studies we know that only certain vegetation types in South Africa burn regularly in fires and thus pose a hazard and these have been grouped into a set of fire ecology types (Le Maitre et al., 2014b). However, this only gives a broad distinction between fire ecology types that burn regularly and those that rarely burn or have never had a detectable fire (Archibald et al., 2010b, 2009; Le Maitre et al., 2014b). Finer resolution data are needed to provide information on the structure and other characteristics of the vegetation that influence fire behaviour and, thus, the fire hazard (Baeza et al., 2002; Everson et al., 1985; Van Wilgen, 1984).

The National Land-Cover of 2013-14 provides a number of classes of natural vegetation and transformed land-cover classes that can be used to infer the fuel structure and characteristics (GTI, 2015). The classification was automatically generated from remote sensing images using an algorithm which analysed changes over a time series of images which represented a full seasonal cycle. The data are available at a spatial resolution of 30x30 m. There are 72 classes in the land-cover dataset which can be divided into the following broad categories:

- 11 for natural or degraded natural land-cover types, which include one for permanent water bodies such as lakes and man-made dams
- 22 for cultivated land under various crops
- for commercial forest plantations and woodlots
- for mines and mine infrastructure
- 29 for urban areas which also include information on the vegetation within the urban matrix and indicate the size of the land holdings

The natural classes give an indication of the vegetation density and the structure and were used as the basis for assigning the Fire Hazard in the form of the 'Likelihood of a wildfire' (Forsyth et al., 2010).

Table 2: The eleven natural land-cover classes with a description of each class (GTI, 2015)

Class Name	Description
Water seasonal	Areas of open, surface water that is only detectable in certain seasons; typically vleis, pans or small dams that dry out; seasonal vegetation and reeds can fuel fires and be a fire hazard; often very limited in extent
Water permanent	Areas of open, surface water detectable all year round; includes both natural (e.g. lake) and man-made water features (e.g. dams); mapped extent represents the maximum detectable water extent during the 2013-14 assessment period
Wetlands	Wetland areas with a high vegetation cover seasonally or all year round; includes seeps/springs, marshes, floodplains, lakes / pans, swamps, estuaries, and some riparian areas and such area within areas under subsistence cultivation; typically have more biomass and, thus, potentially more fuel than adjacent vegetation and a fire hazard
Indigenous Forest	Natural or semi-natural forest, dominated by tall trees (>5 m), canopy cover >75%, often with understory vegetation canopies
Thicket /Dense bush	Natural or semi-natural tree and/or bush (shrub) dominated areas, canopy heights 2-5 m, and canopy cover >75%, can include localised lower cover areas (±60%); includes a range of woody vegetation types
Woodland/Open bush	Natural or semi-natural tree and/or bush (shrub) dominated areas, canopy heights 2-5 m and canopy density 40-75%, can include localised lower cover areas (15-20%); includes a wide range of bush and woodland vegetation types, often with a high ground cover of grasses
Grassland	Natural or semi-natural grass dominated areas, where woody plant cover is <20%, can include localised higher cover (<40%) such as bush clumps; may include planted dryland pastures
Shrubland fynbos	Natural or semi-natural shrub dominated areas, canopy height typically <2 m, mainly associated with the Fynbos Biome; canopy cover very variable from low to high; low cover is normal for a few year after fires and in very rocky areas
Low shrubland	Natural or semi-natural shrub dominated areas, canopy height typically <2 m; mainly in arid areas including the Karoo; canopy cover very variable from low to high; low cover is normal in very rocky areas and degraded areas
Erosion (donga)	Areas with dongas mapped in various studies by GTI and others; probably under-estimated in well vegetated areas

Class Name	Description
Bare none vegetated	Areas of bare ground (soil) or sparse to very sparse vegetation cover (<5-10%), either of natural origin or due to natural (e.g. soil slip) or man-induced processes (e.g. advanced vegetation degradation and erosion), bare rock, dry river beds, dry pans, coastal dunes and beaches; inland sand dune and sandy areas; may include recent fire scars in fynbos areas

There is a clear increase in biomass from low shrubland to woodland or thicket to forest but this does not directly translate into an increased fuel load, and thus fire hazard. In the case of forest the structure of the vegetation and the fuel characteristics tend to make forests fire-resistant (Van Wilgen et al., 1990). However during dry and warm to hot weather and strong winds, fires can burn and spread through forests (Geldenhuys, 1994; Phillips, 1931), especially the drier forms of forest (as seen in the recent Knysna fires). Nevertheless, the likelihood of fires in forests is considered 'Rare' (**Error! Reference source not found.**). The oody biomass in thicket and woodland does not necessarily contribute to fuel loads, especially in savanna, where the primary fuel is the grass layer. However, the grass layer in areas with a rainfall of at least 600-650 mm accumulates enough fuel to sustain fires every year and so the likelihood is assessed as 'Likely' (Bond, 1997; Bond et al., 2003; Le Maitre et al., 2014b). Many forms of thicket do not burn but some forms do, while shrubland fynbos does burn giving them both a likelihood of 'Possible'.

Table 3: The relationship between the natural land-cover classes (GTI, 2015) and the likelihood of a fire (after Forsyth et al., 2010)

Class Name	Likelihood	Description
Water seasonal	Possible	Likelihood of a fire is once in 10 years; might occur at some time; as likely as not
Water permanent	Rare	Likelihood of a fire is once in 100 years; may only occur in exceptional circumstances
Wetlands	Possible	Likelihood of a fire is once in 10 years; might occur at some time; as likely as not
Indigenous Forest	Rare	Likelihood of a fire is once in 100 years; may only occur in exceptional circumstances
Thicket /Dense bush	Possible	Likelihood of a fire is once in 10 years; might occur at some time; as likely as not
Woodland/Open bush	Likely	Likelihood of a fire is once in 5 years; will probably occur

Class Name	Likelihood	Description
Grassland	Likely	Likelihood of a fire is once in 5 years; will probably occur
Shrubland fynbos	Possible	Likelihood of a fire is once in 10 years; might occur at some time; as likely as not
Low shrubland	Rare	Likelihood of a fire is once in 100 years; may only occur in exceptional circumstances

This classification was then used to assess the likelihood of a fire in other land-cover classes, especially the urban classes which often included a vegetation component (Table 4). Commercial forest plantations can have high fuel loads and are often of inherently flammable species, notably eucalypts and pines with their high wax and resin contents which tend to lead to high intensity fires that are difficult to control (Gill and Zylstra, 2005; Schwilk, 2015). These species are well adapted to fires in their native habitats and fires trigger spread and seedling recruitment, increasing the density and this is also what makes the pines, in particular, very successful invaders in many parts of the world (McConnachie et al., 2015; Richardson et al., 2000; Richardson and Bond, 1985). The increased fuel loads in areas invaded by these same tree species, and many other tree and shrub species, result in fires that are difficult to control and they contribute to the fire hazard in South Africa. Invasions by these species are not shown in the land-cover as such, but can be inferred from information on the tree and shrub cover in the descriptions when compared with the natural vegetation for those areas. We have assumed that high woody plant cover is likely to reflect some degree of alien plant invasion in those areas and have allowed for that in this assessment. The land-cover classification currently recognises three stages of plantations and/or woodlots: mature trees, young trees and clearfelled. Since the stage of plantation areas varies over time as they grow, mature and are clearfelled, the characteristics will change over time and all plantation/woodlot areas could be treated as one likelihood. We decided to distinguish between the likelihoods in the different stages to illustrate the importance of periodic reassessments of the fire hazard as part of the ongoing fuel management. So, young and clearfelled plantations/woodlots with their relatively low fuel loads are given a likelihood of ‘Possible’ while mature plantations/woodlots with higher fuels are rated ‘Likely’. Clearfelled areas do have high fuel loads from the unharvested material, but this is typically close to the ground and this stage typically is only present for a short period while the plantation is re-established so we have not increased the likelihood.

The urban classes are divided into broad groups based on the density, the mix of building types and degree of formal planning and then also by the structure of the vegetation (Table

4). We have also used our experience based on an assessment of the fire hazard on the WUI in the Helderberg area near Cape Town (Forsyth and Le Maitre, 2015) and the impacts of a subsequent wildfire in this area (G. Forsyth unpublished data) to assess the likelihoods for different urban classes.

Table 4: The relationship between the urban cover classes (GTI, 2015) and the likelihood of a fire (after Forsyth et al., 2010).

Class Name	Characteristics	Likelihood
Urban built-up: dense or open trees/bush	Well-established, usually planned, moderate density, mixed use; built-up with some natural vegetation: gardens and public open space; bush can be an important fuel and so can the ground layer	Likely
Urban informal: dense or open trees/bush	Unplanned, high density development interspersed with tree/bush cover; bush can be an important fuel and so can the ground layer	Likely
Urban residential: dense or open trees/bush	Well-established, usually planned, moderate density, residential; largely built-up with natural vegetation, gardens and public open space; bush can be an important fuel and so can the ground layer	Likely
Urban smallholding: dense or open trees/bush	Low density mix of buildings & other built-up structures, may include open and cultivated areas; formally declared agricultural holdings, and similar small holdings/small farms, typically located on the periphery of urban areas; extensive bush areas can be an important fuel bed and so can the ground layer	Likely
Urban sports and golf: dense or open trees/bush	Low density mix of buildings & other built-up structures associated with golf courses; typically represents the border extent of the entire estate or course; bush and less tended areas can accumulate fuels	Likely
Urban township: dense or open trees/bush	High density buildings and other built-up structures; formal, regulated, residential (RDP) housing; bush cover limited but usually untended and accumulates fuels	Likely

Class Name	Characteristics	Likelihood
Urban village: dense or open trees/bush	Variable density of structures; typically associated with rural villages, modern and traditional buildings; bush and less tended areas can accumulate fuels	Likely
Urban built-up: low vegetation/grass	As for built-up above, low fuel loads but grass fuels can accumulate potentially raising the Likelihood	Possible
Urban informal: low vegetation/grass	As for informal above, low fuel loads but grass fuels can accumulate potentially raising the Likelihood	Possible
Urban residential: low vegetation/grass	As for residential above, low fuel loads but grass fuels can accumulate potentially raising the Likelihood	Possible
Urban smallholding: low vegetation/grass	As for smallholding above, low fuel loads but grass fuels can accumulate potentially raising the Likelihood	Possible
Urban sports and golf: low vegetation/grass	As for sports and golf above, low fuel loads but grass fuels can accumulate potentially raising the Likelihood	Possible
Urban township: low vegetation/grass	As for township above, low fuel loads but grass fuels can accumulate potentially raising the Likelihood	Possible
Urban village: low vegetation/grass	As for village above, low fuel loads but grass fuels can accumulate potentially raising the Likelihood	Possible
Urban built-up (bare)	As for built-up above, little or no fuel	Rare
Urban informal (bare)	As for informal above, little or no fuel	Rare
Urban residential (bare)	As for residential above, little or no fuel	Rare
Urban smallholding (bare)	As for smallholding above, little or no fuel	Rare
Urban sports and golf (bare)	As for sports and golf above, little or no fuel	Rare
Urban township (bare)	As for township above, little or no fuel	Rare
Urban village (bare)	As for village above, little or no fuel	Rare
Urban school and sports ground	Open areas with mown grass cover, little or no fuel	Rare
Urban commercial	Formal, variable density and size of structures, often with extensive paved areas, little or no fuel	Rare
Urban industrial	Formal, variable density of generally large structures, often with extensive paved areas, little or no fuel	Rare

The next group was the cultivated land-cover classes where the primary distinction was between perennial crops (e.g. orchards) and annual crops (e.g. small grains, maize), and between irrigated crops and dryland crops (GTI, 2015) (Table 5). It is important to distinguish between commercial farming where the fields are interspersed with limited areas of natural, modified or degraded natural vegetation and subsistence cropping typically with small fields forming a mosaic with more extensive modified or degraded natural vegetation which would influence fire behaviour. For this assessment we have not increased the likelihood for subsistence cropping because the natural vegetation mosaic will have its own likelihood, but it could be considered in future. The land-cover also distinguished between crop vigour classes based on the Normalised Difference Vegetation Index with higher crop vigour indicating higher productivity and thus the potential for greater fuel load. We have not used this information to modify the likelihood class at this stage. For sugar cane, no distinction was made between commercial farming and emerging farmers because the crop is essentially the same.

Table 5: The relationship between the land-cover class for cultivated lands and the likelihood of a fire. See Table 9 for a description of the Likelihood. Low, Medium and High describe the vigour of the crop.

Class Name	Characteristics	Likelihood
Cultivated commercial fields (low, medium, high)	Annual crops, large fields and farms, little natural vegetation	Possible
Cultivated subsistence (low, medium, high)	Annual crops, small fields and farms, mosaic with natural vegetation	Possible
Cultivated commercial pivots (low, medium, high)	Annual crops, high intensity cropping of vegetables and other crops, little fuel	Unlikely
Cultivated cane commercial & emerging farmer's – crop fields or pivots	Perennial crop, cane can burn seasonally, commercial farmers have larger fields and farms than emerging farmers	Likely
Cultivated cane commercial & emerging farmers – fallow fields or pivots	Perennial crop, cane can burn seasonally, fuel load in fallow stage could be greater but fields on a cycle so the crop/fallow is not constant;	Possible
Cultivated vines (low, medium & high)	Perennial crop, vines and cover crops can burn	Possible
Cultivated orchards (low, medium, high)	Perennial crop, low fuel and green cover crops	Unlikely

The final step was to use the Zonal Statistics function in ArcGIS to calculate the area of each of the land-cover classes within the 1 km wide exterior buffer so that we could estimate the likelihood and, thus, the fire hazard in this portion of the WUI for each settlement.

3.3 Quantifying the fire hazard for each settlement

The output from the fire hazard (likelihood) assessment above was a GIS dataset with the area of the 1 km exterior buffer in each of the land-cover classes in that buffer. The land-cover class information was then joined to the corresponding likelihood class in the GIS to create a set of likelihoods matched to each land-cover class. The database was then exported to Excel as two datasets: settlements beginning with the letters A-L and those beginning with M-Z so that the numbers of records fitted within the limitation on the numbers of records that Excel can manage. A pivot table was then generated to calculate the areas in each likelihood class in each settlement and that was then used to calculate the proportion of each likelihood class in each settlement. Then the likelihood class with the highest proportion and >25% in each settlement was selected as the final class for each settlement. The rationale for using >25% was that there were four classes and a maximum of 25% would indicate an even split. If the split was even then the highest likelihood class would be chosen but in practice this did not happen. The final likelihood class was then joined to the settlement layer to create a spatial dataset with the likelihood and thus the fire hazard for each settlement.

3.4 Determining the consequences of a wildfire for each settlement

We followed essentially the same steps as we had with the fire hazard but this time with the land-cover classes present in the interior buffer. The first step in this process was to calculate the area in each land-cover class within the internal buffer as described above for the fire hazard.

In parallel, we used the characteristics of the land-cover in each settlement to generate ratings for social and economic consequences for each land-cover class in the event of a wildfire. The social consequences were assessed using a scale developed previously (Forsyth et al., 2010) which rates the impacts on the social assets of human life and health based on exposure to the hazard of wildfires (Table 6).

Table 6: Descriptions of the social and economic consequence classes used in this assessment (based on Forsyth et al., 2010).

Level of Consequence	Consequence end points	
	Social consequence criteria	**Economic consequence criteria**
Catastrophic	Death of one or more persons in the scenario, probable smoke inhalation and other health impacts; probably requiring emergency hospitalisation and affecting work capacity; or, evacuation required	Depressed municipal economy; extensive and widespread loss of assets; major impact across a large part of the community; long-term external assistance required to recover
Major	Extensive injuries to people in the scenario, probable smoke inhalation and other health impacts; probably requiring emergency hospitalisation and affecting work capacity; or, evacuation required	Serious financial loss, affecting a significant portion of the community; those affected require external funding (e.g. from Disaster Management funds) to recover
Moderate	Medical treatment required but full recovery possible, possible smoke inhalation and other health impacts; possibly requiring emergency hospitalisation	Localised damage to property and some financial loss; short-term external assistance required to recover
Minor	Minor injuries only, possible smoke inhalation and other health impacts, may require first aid treatment	Minor financial loss; short-term damage to individual assets; no external assistance required to recover
Insignificant	No injuries, no other health impacts, no first aid required	Inconsequential or no damage to property; negligible losses

Social vulnerability is generally directly related to people's wealth which, in turn can be linked to the kinds of housing they occupy and the services within their reach. Another dimension of the social consequences, which is also linked to the economic consequences, is the likelihood of the loss of dwellings and the insecurity that goes with being moved to, and having to live in temporary accommodation and the accompanying social disruptions and stresses (Edgeley and Paveglio, 2017; Holloway et al., 2010). Then there is also the potential for reduced health and disablement due to, for example burns or smoke inhalation, and even death and disruption of family life.

Table 7: The social and economic consequences based on the land-cover in the interior 1-km wide buffer of the settlements (see Table 12 for descriptions of the consequence classes).

Land-cover Class Name[1]	Social Consequences	Economic Consequences
Water seasonal	Minor	Insignificant
Water permanent	Insignificant	Insignificant
Wetlands	Minor	Minor
Indigenous Forest	Insignificant	Minor
Thicket /Dense bush	Major	Minor
Woodland/Open bush	Major	Moderate
Grassland	Minor	Moderate
Shrubland fynbos	Moderate	Moderate
Low shrubland	Minor	Minor
Cultivated commercial fields (low, medium, high)	Minor	Minor
Cultivated commercial pivots (low, medium, high)	Minor	Minor
Cultivated orchards (medium, high)	Minor	Moderate
Cultivated orchards (low)	Minor	Minor
Cultivated vines (low, medium, high)	Minor	Moderate
Cultivated permanent pineapple	Minor	Minor
Cultivated subsistence (low, medium, high)	Minor	Moderate
Cultivated cane pivot - crop	Minor	Moderate
Cultivated cane pivot - fallow	Minor	Minor
Cultivated cane commercial emerging – crop or fallow	Minor	Minor
Plantations / Woodlots mature	Moderate	Major
Plantation / Woodlots young	Minor	Moderate
Plantation / Woodlots clearfelled	Moderate	Minor
Mines bare, semi-bare, water seasonal or permanent	Insignificant	Insignificant
Mine buildings	Minor	Minor
Erosion (donga) or Bare none vegetated	Insignificant	Insignificant
Urban commercial or industrial	Minor	Major
Urban informal (dense trees / bush)	Major	Catastrophic
Urban informal (open trees / bush or low veg / grass)	Moderate	Major
Urban informal, residential or smallholding (bare)	Insignificant	Insignificant
Urban residential (dense trees / bush)	Moderate	Moderate
Urban residential (open trees / bush or low veg / grass)	Minor	Minor

Land-cover Class Name[1]	Social Consequences	Economic Consequences
Urban school and sports ground	Minor	Major
Urban smallholding (dense trees / bush)	Moderate	Major
Urban smallholding (open trees / bush or low veg / grass)	Minor	Moderate
Urban sports and golf (dense tree / bush)	Minor	Moderate
Urban sports and golf (open tree / bush or low veg / grass)	Insignificant	Minor
Urban sports and golf (bare)	Insignificant	Insignificant
Urban township (dense trees / bush)	Moderate	Major
Urban township (open trees / bush or low veg / grass)	Moderate	Moderate
Urban township (bare)	Insignificant	Insignificant
Urban village (dense trees / bush)	Moderate	Major
Urban village (open trees / bush or low veg / grass)	Moderate	Moderate
Urban village (bare)	Insignificant	Minor
Urban built-up (dense trees / bush)	Moderate	Major
Urban built-up (open trees / bush low veg / grass)	Minor	Moderate
Urban built-up (bare)	Insignificant	Insignificant

The economic effects of wildfires have generally not been thoroughly documented although there are some studies and data on particular sectors such as agriculture and forestry (Van Wilgen et al., 2010). For this assessment, the economic consequences were based on the degree or magnitude of the social and economic consequences for the community. These assets included infrastructure (such as power lines), industrial facilities (e.g. sawmills), fodder, livestock, homesteads, resorts, and plantation forests. Dryland crops, such as maize, were excluded since these seldom suffer significant losses due to wildfires. There may also be losses of harvestable natural resources, such as thatching-grass which could have detrimental impacts on local communities. In some areas, notably grasslands, there may be losses of the rangeland vegetation that would have provided fodder for livestock and may require short-term donations or subsidies but the focus here in on the settlements rather than the farms. However, in many rural areas, the people in the settlements are also the owners of the livestock and may experience economic losses or hardship.

3.5 Determining the final level of social and economic consequence for each settlement

The output from the social and economic consequence assessment above was a GIS dataset with the area in the 1 km interior buffer in each of the land-cover classes in that buffer. The land-cover class information was joined to the corresponding social and economic consequence class in the GIS to create a set of consequences matched to each land-cover class. The database was then exported to Excel as two datasets: settlements beginning with the letters A-L and those beginning with M-Z so that the numbers of records fitted within the limitation on the numbers of records that Excel can manage. A pivot table was then generated to calculate the areas in each social and economic consequence class in each settlement and the proportion of each consequence class in each settlement was calculated. The social and economic consequence class with the highest proportion and also >20% in each settlement was selected as the final class for each settlement. There were five consequence classes (Table 6) so a maximum of >20% rule was used because it indicates an even split across the five classes. If the split had been even then the highest likelihood class would have been chosen manually but in practice this did not happen. The final social and economic consequence class was then joined to the settlement layer to create a spatial dataset with the social and economic consequences for each settlement.

3.6 Using a risk matrix to assign a fire risk rating

The final step involved using a risk matrix or look-up table to assign a fire risk rating that took both the final fire danger (likelihood) and the final social and economic consequences for each town into account (Forsyth, Kruger & Le Maitre 2010) (Table 8).

Table 8: The full risk matrix for assessing the social and economic risk that each settlement is exposed to, (based on Forsyth, Kruger & Le Maitre 2010).

Likelihood Rating	Consequence Rating				
	Insignificant	Minor	Moderate	Major	Catastrophic
Almost certain	Medium	Medium	High	Extreme	Extreme
Likely	Low	Medium	High	Extreme	Extreme
Possible	Low	Medium	High	High	Extreme
Unlikely	Low	Low	Medium	High	Extreme
Rare	Low	Low	Low	Medium	High

The result of this process was an assessment of the fire risk for every one of the roughly 1600 settlements examined in this study.

3.7 Accounting for the effects of climate change on fire danger

As described in section 2.4, the occurrence of fire-danger days was calculated using the McArthur Forest fire danger index (FDI) which has been successfully tested in South Africa (Willis et al., 2001). We used the algorithms developed for calculating the FDI from the climate data outputs from the CSIR global climate modelling system (Forsyth et al., 2015) to calculate the daily values of the fire-danger indexes for both current and future climates. The data on fire-danger days were generated from the outputs of an ensemble of six global change models run with different greenhouse gas emission scenarios. In each case we used the worst case emission scenarios where there is little mitigation (RCP8.5). Each of the models was run for three climate change periods: baseline (1961 – 1990), near future (2021 - 2050) and far future (2070 -2099). The McArthur Forest Fire Danger Rating Model (Noble et al., 1980) algorithm was run on each of the three time period datasets to calculate the annual number of very high fire-danger days for an 8 x 8 kilometre grid covering southern Africa. The number of extreme and high fire-danger days was then extracted for each settlement polygon for the current, near and far future climates.

3.8 Using records for fire occurrence

In addition, we also used information on the occurrence of fires between 2001 and 2016 from the MODIS burnt-area product produced for the Advanced Fire Information System by the Meraka Institute. This summary gives the number of times a fire occurrence has been detected in each MODIS pixel (500 m x 500 m) during that period. The data are not perfect as they include both false detections or false positives (i.e. recording a fire where there wasn't one) and detection failures or false negatives (i.e. not detecting a fire) with an overall accuracy of about 75% (Archibald et al., 2010a; Roy and Boschetti, 2009; Tsela et al., 2014). This dataset was used to estimate the number of times a fire has occurred within the exterior buffer of each settlement. This provides a cross-check on the fire hazard and fire risk classification of each of the settlements.

4 RESULTS

4.1 Fire hazard or likelihood

Altogether, the likelihood and consequences of a wildfire occurring within the WUI has been examined for 1 596 settlements (Table 16). Each of these settlements is located within a particular fire ecology type, although some may be located on the boundary between one or more fire ecology types. These fire ecology types were the original vegetation in that area but, over time, parts or even all of the vegetation within the 1 km outside buffer have been modified and transformed, some potentially being a greater fire hazard. For example, invasion of fynbos or grassland by pines or eucalypts. However, for those that have some natural vegetation remaining, this gives an indication of the inherent fire-hazard also posed by natural vegetation outside that buffer. We analysed the relationship between the settlements and the original fire ecology types and found that 84% of all the settlements fell into a fire-dependent fire ecology type (Table 9). The sensitivity to fire indicates both that it would require fires to maintain ecosystem structure and function and that it burns naturally given the right conditions and a source of ignition (Le Maitre et al., 2014b) (Table 13). This also means that the local fire protection association or authorities would need to actively use fires to maintain the vegetation and manage fuel loads. About 48% of these settlements occur in Moist Woodland or Sour Grassland where fires can occur every year and the grass fuel layer requires fires every two to five years to rejuvenate it. About 14% of the settlements occur in 'Fire Independent' vegetation with most of them in the Nama Karoo, Thicket and Succulent Karoo fire ecology types where fires are rare or absent. Only 2% of the settlements are found in 'Fire Sensitive' vegetation and just over 80% of them are in the Grassy Nama Karoo fire ecology type which does occasionally burn, especially after high spring and summer rainfall. Sweet Grassland and Arid Woodland fire ecology types also require high rainfall to produce sufficient grass fuel for fires but when they do accumulate fuels, the fires can be very extensive and the authorities need to be prepared for such fires. The outside buffer of one settlement, not shown in Table 9, was dominated by a water body.

Table 9: The dominant fire ecology type and corresponding fire sensitivity of the original and remaining natural vegetation within the 1 km wide outside buffer on the WUI of each settlement. The values are the percentages of the totals in each column.

Fire ecology type	Fire sensitivity		
	Fire dependent	Fire independent	Fire sensitive
Arid Woodland	19.69	0.00	0.00
Coastal Grassland	4.46	0.00	0.00
Forest	0.00	0.00	19.23
Fynbos	11.14	0.00	0.00
Grassy Nama Karoo	0.00	0.00	80.77
Moist Woodland	20.21	0.00	0.00
Nama Karoo	0.00	37.22	0.00
Renosterveld	3.94	0.00	0.00
Sparse Arid Woodland	0.30	0.00	0.00
Sour Grassland	27.71	0.00	0.00
Succulent Karoo	0.00	27.35	0.00
Sweet Grassland	12.56	0.00	0.00
Thicket	0.00	35.43	0.00
Water bodies	0.00	0.00	0.00
Total number	**1346**	**223**	**26**

No settlements were given the highest overall fire likelihood of 'Almost certain' (Forsyth et al., 2010), but almost half of them fall into the 'Likely' and almost a third into the 'Possible' class. This indicates that management measures aimed at reducing the fire risks should be implemented in more than 80% of the settlements that were assessed. This is not particularly surprising given that most of the population and the settlements are located in the wetter eastern and southern parts of the country where the vegetation produces sufficient fuel for fires at quite short intervals.

Table 10: Towns categorised by the likelihood of a wildfire occurring within the Wildland-Urban Interface

Fire danger (likelihood of occurrence)	Fire return interval (years)	Number of settlements (% of total)
Likely	10	781 (48.9%)
Possible	15	528 (33.1%)
Unlikely	25	8 (0.5%)
Rare	100	279 (17.48%)
Total		**1 596**

Most settlements showed substantial variations in fire hazard (likelihood) within the outer buffer (Figure 4) suggesting that there is opportunity for vegetation management aimed at fuel reduction and fire protection. In this example, Clarens is clearly exposed to a much greater risk of fire than Bethlehem.

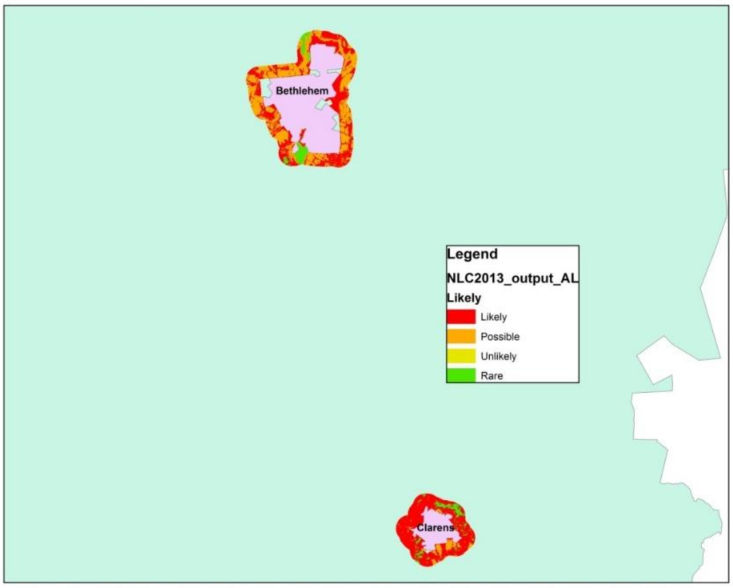

Figure 4: Spatial variations in the likelihood of wildfires occurring within the exterior 1 km buffer on WUI for Bethlehem and Clarens in the eastern Free State.

4.2 Economic and social consequences

The economic consequences of a wildfire occurring within the 1 km interior buffer of the Wildland-Urban Interface are generally classed as 'Moderate' with most of the rest being 'Minor' (Table 11). Only a few settlements had a rating of 'Major' and just one was 'Catastrophic' and these should be the focus of investments and actions aimed at reducing the consequences.

Table 11: Towns categorised by the economic consequences of a wildfire occurring within the outer 1 km buffer of the WUI. For descriptions of the consequence classes see Table 6

Economic consequence category	Number of settlements	Percent of total
Catastrophic	1	0.06%
Major	104	6.52%
Moderate	1 100	68.92%
Minor	344	21.55%
Insignificant	47	2.94%
Total	**1 596**	

The process of deriving the classification used in the interior 1 km wide buffer is best understood using a settlement as an example. An analysis of the land-cover classes within the buffer shows that there is a varied mix (**Error! Reference source not found.**5).

Figure 5: Land-cover classes present in the internal buffer of the Wildland-Urban Interface of a single South Africa settlement based on the 2013-14 national land-cover (GTI, 2015).

When these are regrouped into the economic consequence classes it is clear that most of the buffer comprises land-cover classes that fall into the ‘Insignificant’ to ‘Moderate’ economic consequence classes (**Error! Reference source not found.**6), and that the 'Major' class is resent but mainly confined to a few portions of the buffer. Overall, the 'Moderate' economic consequence class occupies the greatest proportion of the buffer and so the economic consequence of a wildfire in the interior buffer of the settlement WUI is characterised as 'Moderate' (**Error! Reference source not found.**).

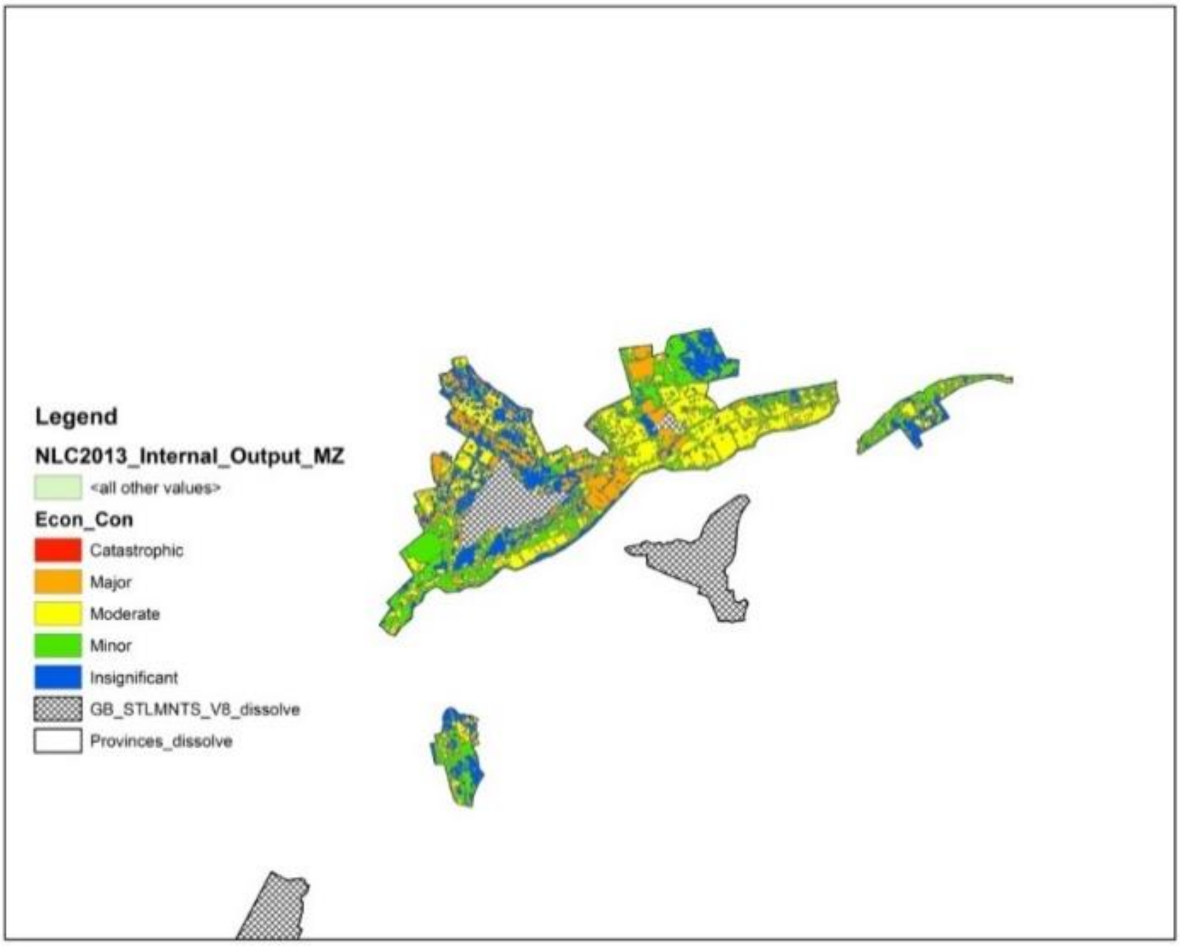

Figure 6: Land-cover classes for a single town categorised by levels of economic consequence present within the internal buffer of the Wildland-Urban Interface of a single South Africa settlement.

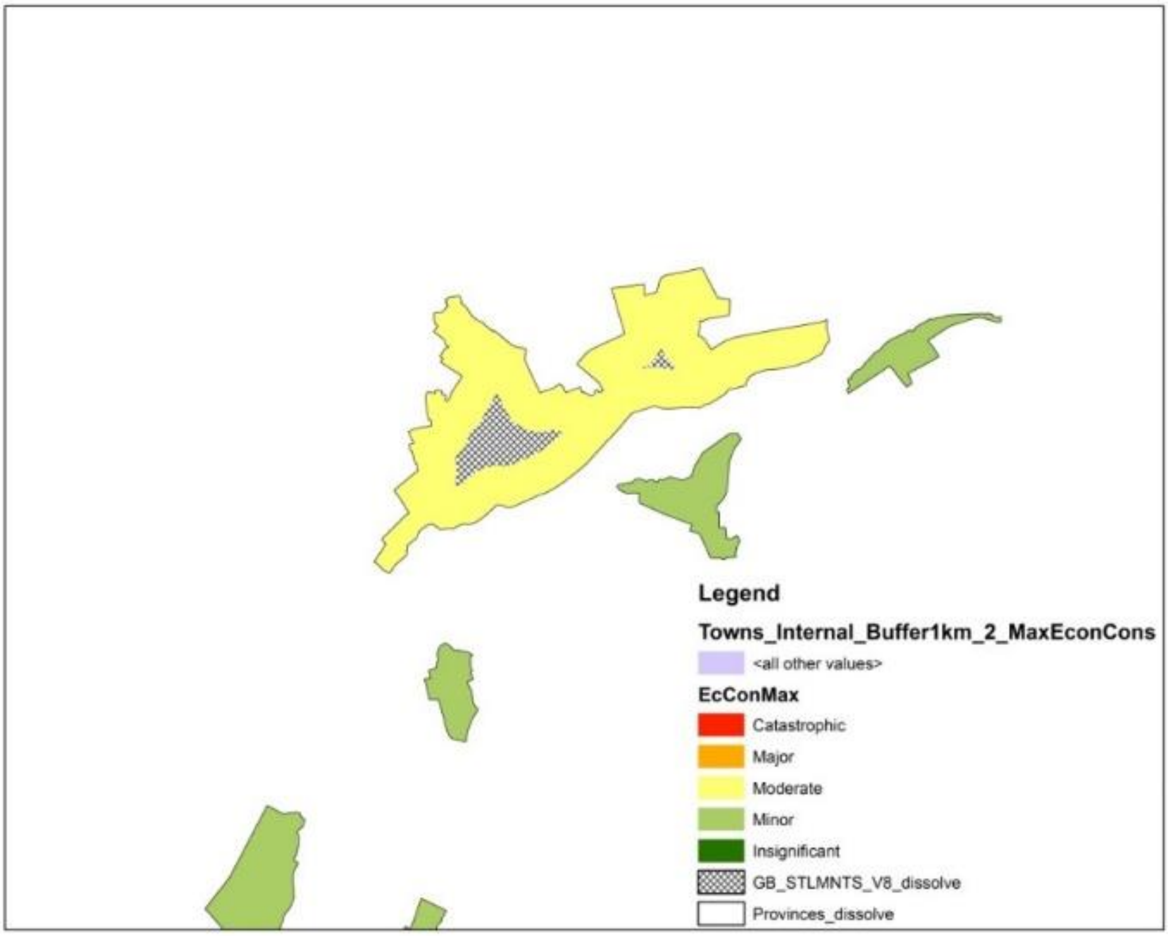

Figure 7: Economic risks aggregated to the dominant risk class occurring within the interior buffer of the Wildland-Urban Interface of a single town in South Africa.

4.3 Fire-danger days under current and future climates

The number of very high fire-danger days per year was calculated for 1 596 towns and for three time periods: baseline (1961 – 1990), near future (2021 - 2050) and far future (2070 - 2099). The outputs for the current climate or baseline (1961 – 1990) show that there is a high number of very high fire-danger days in the arid north-western and the western coastal parts of South Africa (**Error! Reference source not found.**), decreasing steeply to 0-25 days in uch of the southern part of the Western Cape, almost all of the Eastern Cape and KwaZulu-Natal and Mpumalanga and the western Free State. Most of the Northern Cape is Karoo shrublands which almost never experience fires (Archibald et al., 2010b; Le Maitre et al., 2014b), but a strip extending from the northern part of this province through Limpopo will experience 50-100 very high fire-danger days and is arid savanna and grassland. These vegetation types can experience fires after growing seasons with higher than normal rainfall (Archibald et al., 2010a; Le Maitre et al., 2014b).

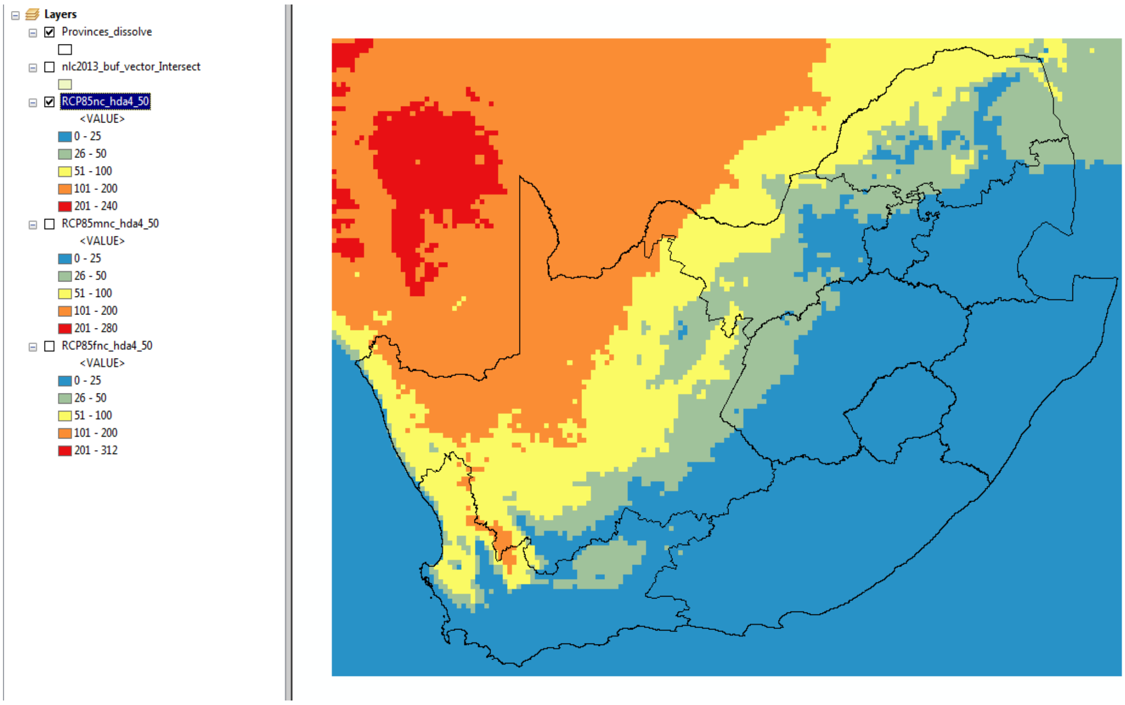

Figure 8: Classes of very high fire-danger days for southern Africa under the current climate (1961-1990).

The projections for both the near future and the far future show a southward and eastward expansion of the occurrence of >25 very high fire-danger days per year and a contraction in the areas experiencing 0-25 days per year. The most marked shifts are in the Free State, Western Cape, Eastern Cape, North West and Limpopo provinces.

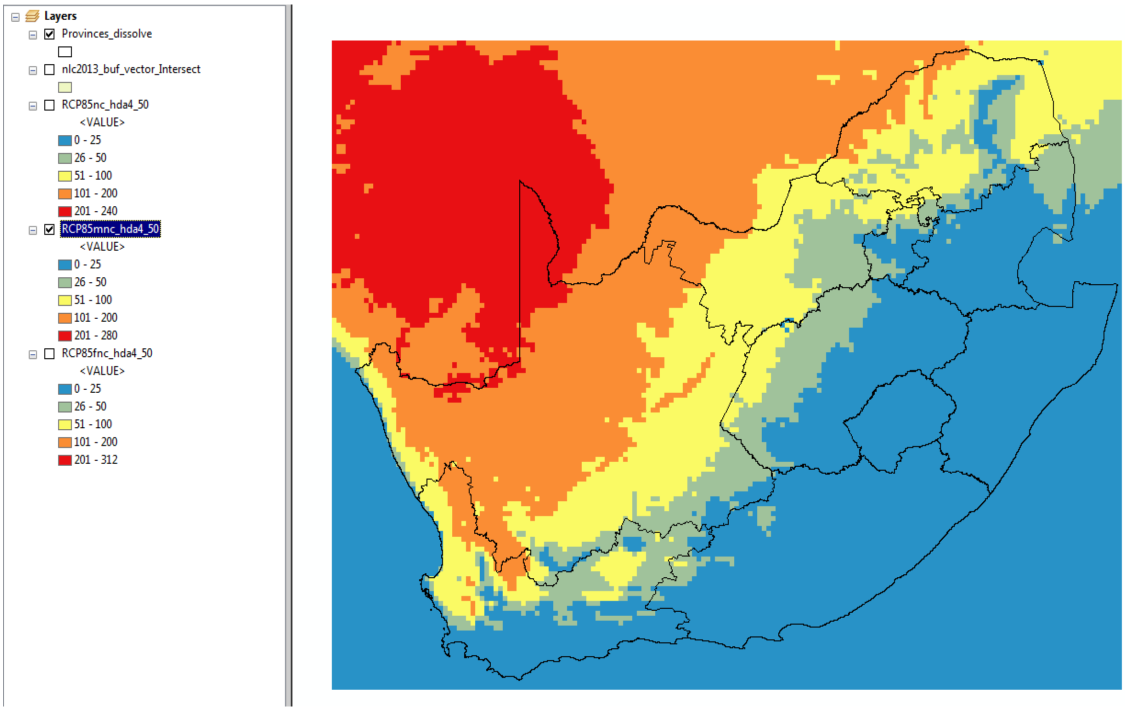

Figure 9: Classes of very high fire-danger days for southern Africa under the climate projects for the near future (2021-2050).

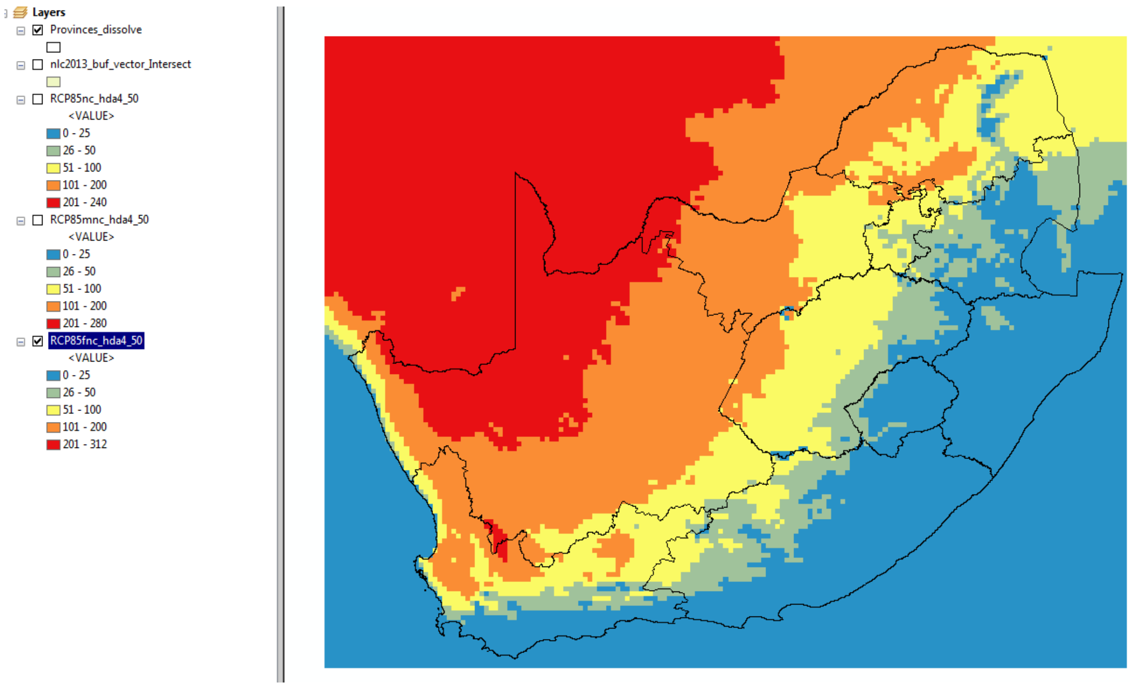

Figure 10: Classes of very high fire-danger days for southern Africa under the climate projects for the far future (2021-2050).

4.4 Cederberg Local Municipality

The annual total of very high fire-danger days was then assessed for each of the 1 596 towns in the study using the settlement polygons. The outputs of this assessment can be illustrated for settlements in the Cederberg Municipality in the Western Cape (Figure 11) for both the current climate (Figure 12) and for the near (Figure 13) and far future (Figure 14).

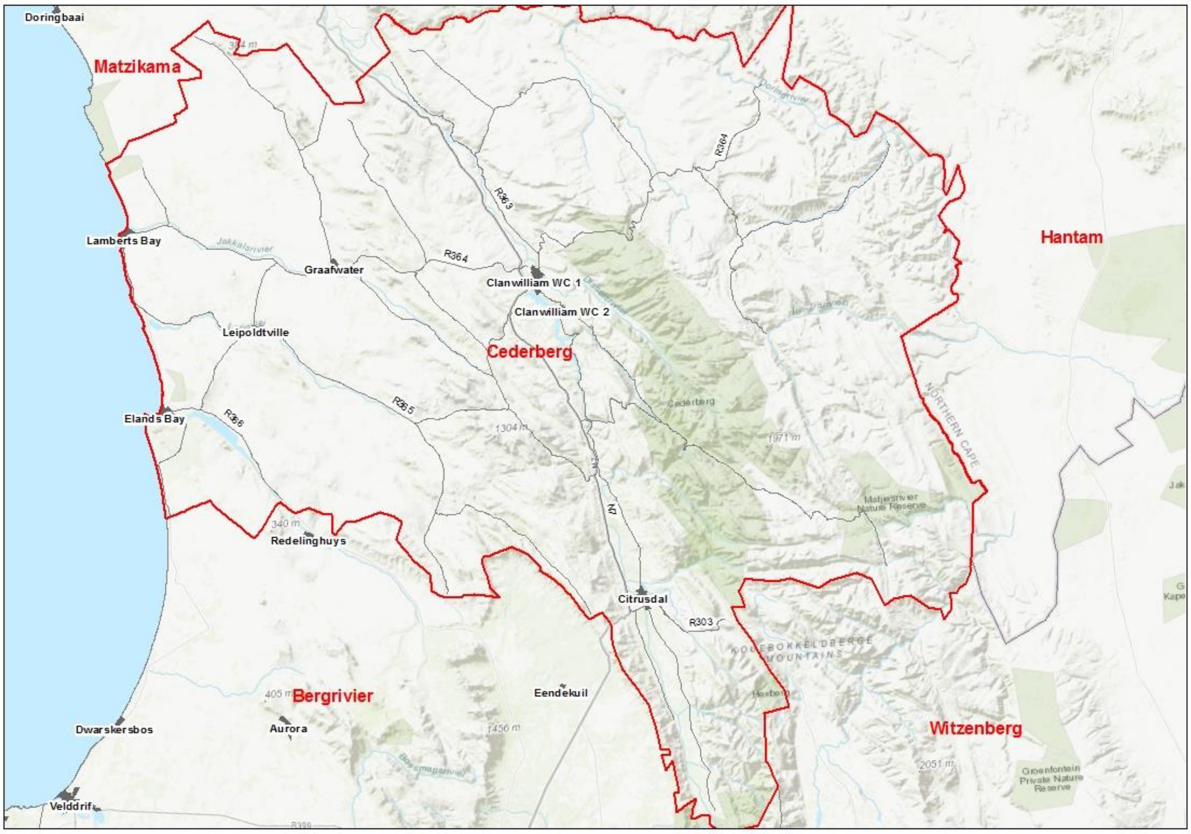

Figure 11: The Cederberg Local Municipality showing the location of the important settlements and the variable topography from the nearly flat West Coast lowlands to the rugged interior, particularly the Cederberg Mountains east of Clanwilliam.

The inland towns show a progressively worsening situation while the coastal towns remain in the same class throughout. For example, Clanwilliam currently experiences 81-140 very high fire-danger days a year, will experience about the same in the near future, but will experience an increase to 141-183 such days in the far future. This municipality is located in the area of relatively large numbers of very high fire-danger days in the hinterland of the West Coast in the Western Cape and towns in the southern part of the province (e.g. George) will experience much less change.

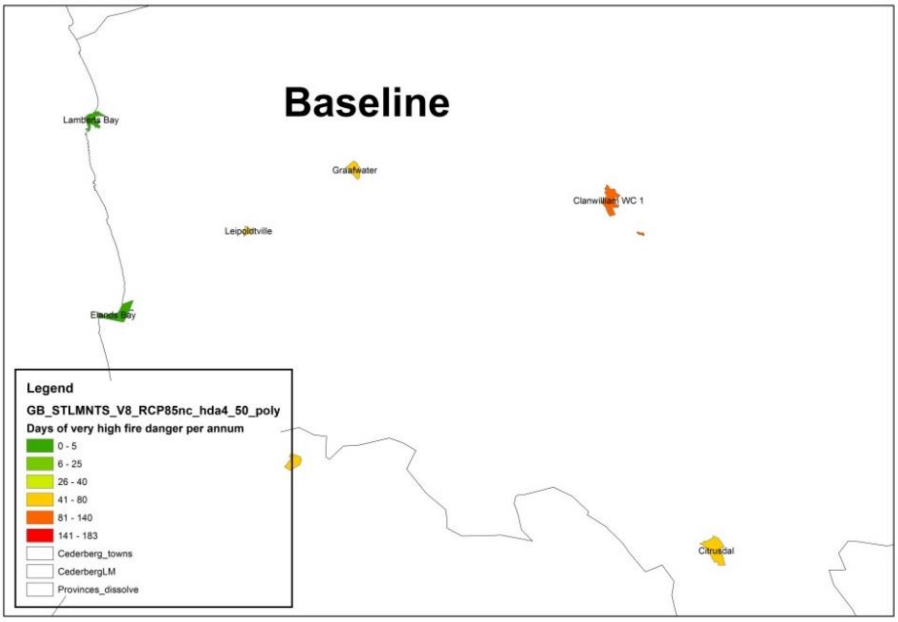

Figure 12: The number of very high fire-danger days for each the towns within the Cederberg Municipality under the current climate (1961 to 1990

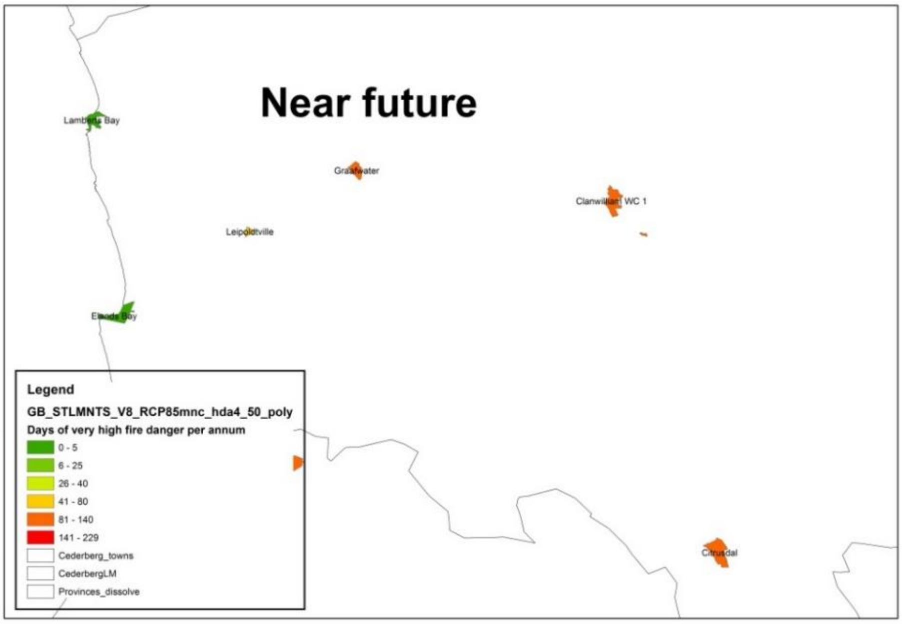

Figure 13: The number of very high fire-danger days predicted for the near future (2021 to 2050) for each of the towns within the Cederberg Municipality.

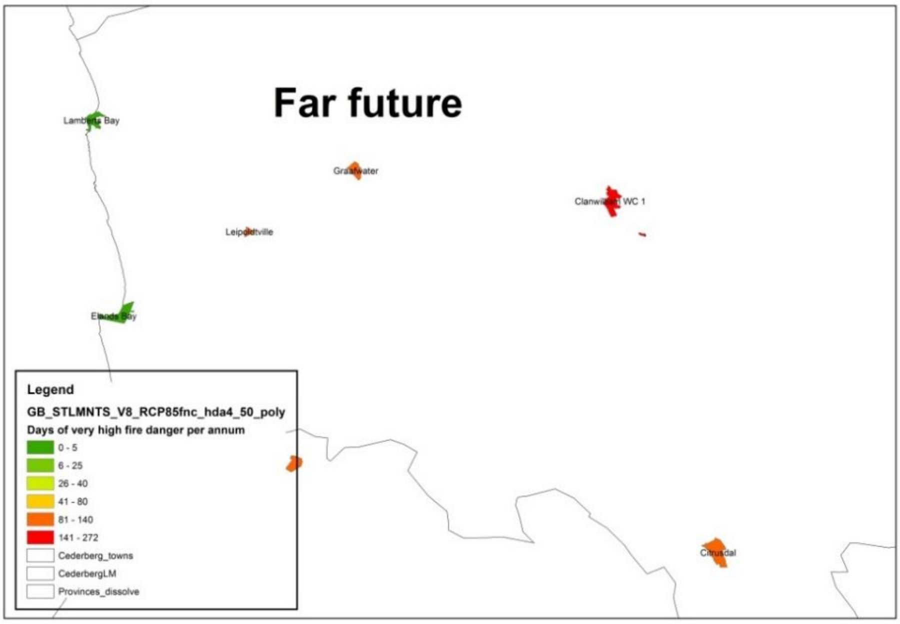

Figure 14: The number of very high fire-danger days predicted for the far future (2070 to 2099) for each the towns within the Cederberg Municipality.

4.5 Dihlabeng Local Municipality

Another example is the Dihlabeng Municipality in the eastern Free State which includes the town of Bethlehem (**Error! Reference source not found.**5).

Figure 15: Dihlabeng Municipality in the eastern Free State showing the main town of Bethlehem and the other small settlements. The southern boundary of the municipality is the border with Lesotho.

The fire-danger (likelihood of a fire) varies markedly between the different settlements, with Bethlehem and Rosendal classed as ‘Possible’ and the other settlements as ‘Likely’,(but the economic consequences (‘Moderate’) are the same for all of them (Figure 17).

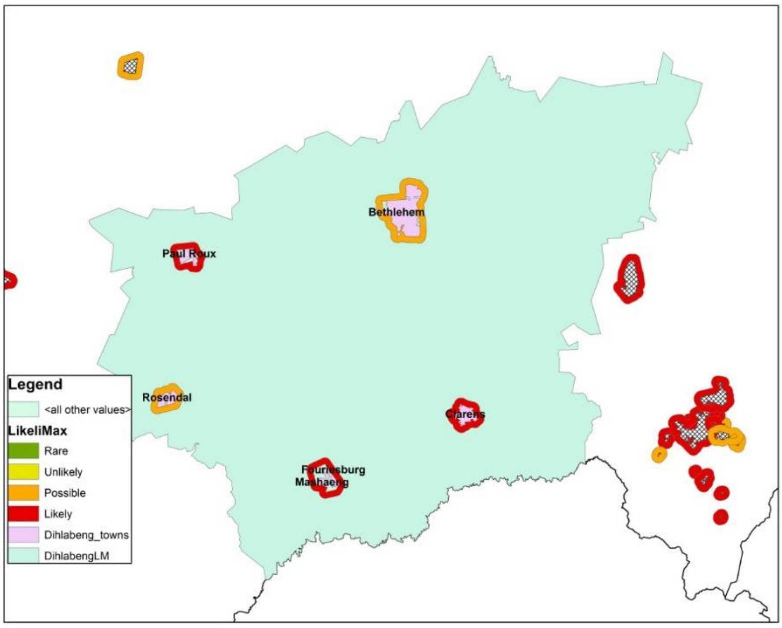

Figure 16: The fire hazard (likelihood) of the different settlements in the Dihlabeng Municipality in the eastern Free State.

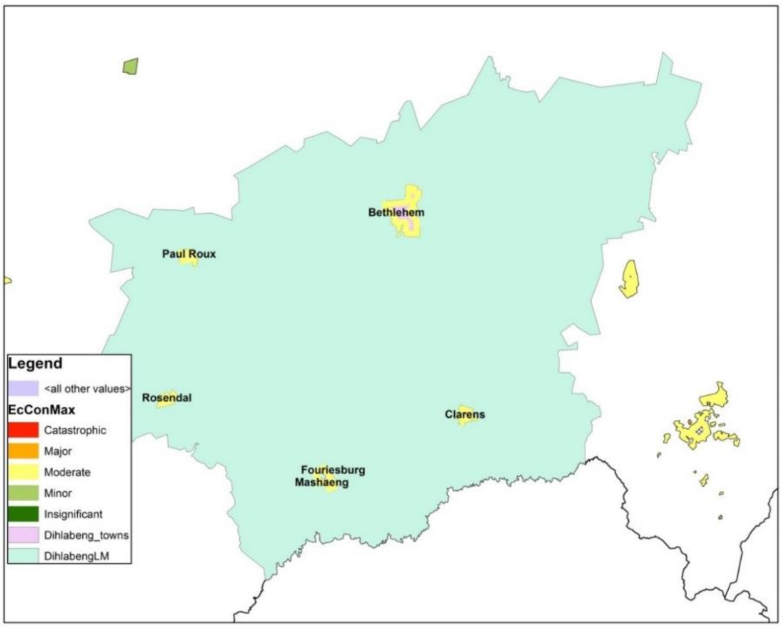

Figure 17: The economic consequences of wildfires in the settlements in the Dihlabeng Municipality in the eastern Free State.

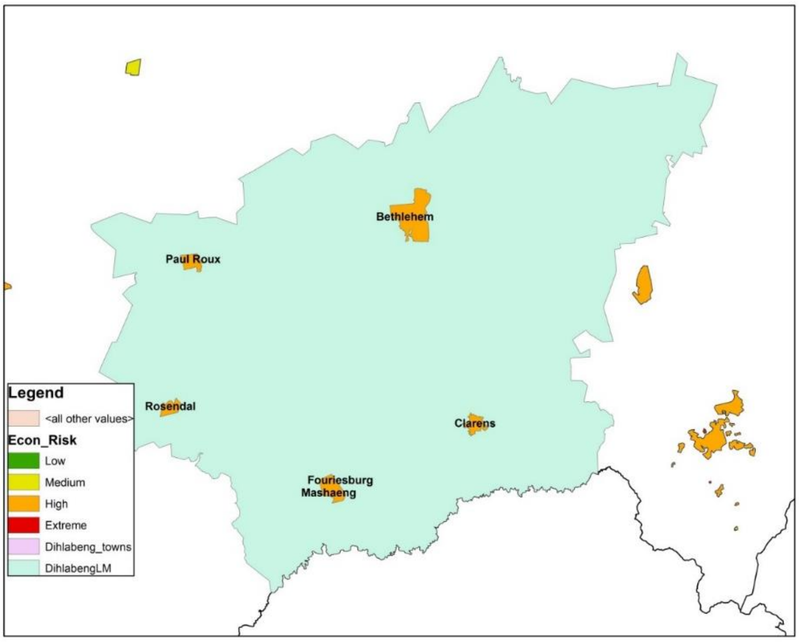

Figure 18: The economic risk associated with the occurrence of a wildfire in the settlements in the Dihlabeng Municipality in the eastern Free State.

Under the current climate the settlements within the Dihlabeng Municipality experience few very high fire-danger days per year (**Error! Reference source not found.**19) with Paul Roux nd Rosendal experiencing slightly more than the other settlements. In the near future Paul Roux shifts up one class to 11-25 days per year and in the far future all of the settlements shift up by one to two classes.

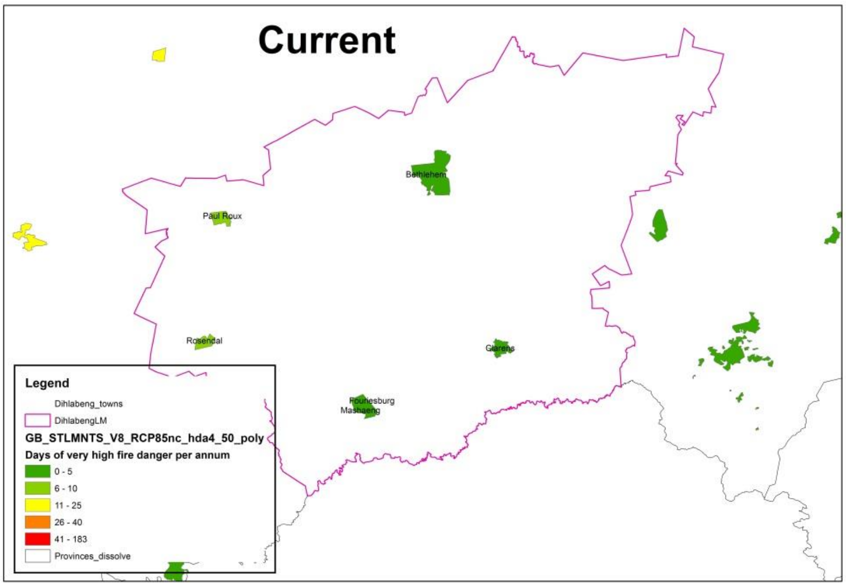

Figure 19: The number of very high fire-danger days for each of the towns within the Dihlabeng Municipality under the current climate (1961 to 1990).

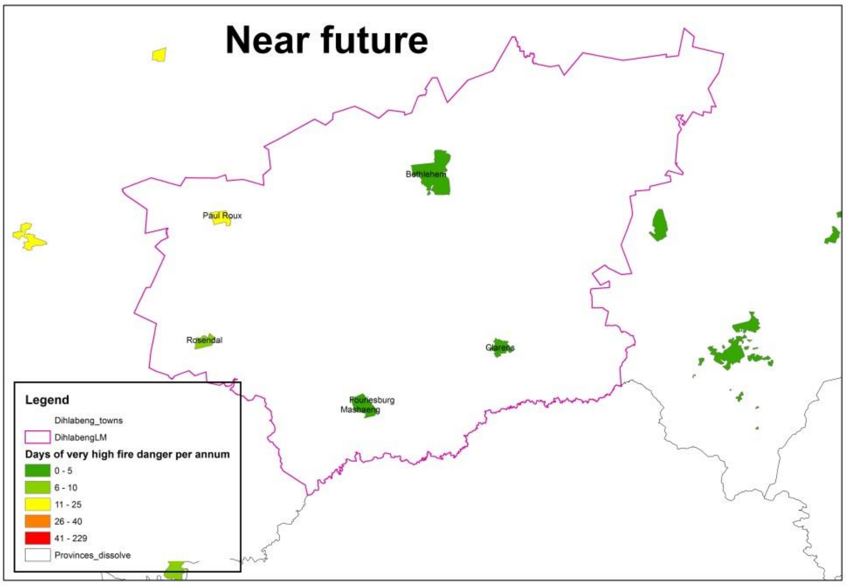

Figure 20: The number of very high fire-danger days for each of the towns within the Dihlabeng Municipality under the climate projected for the near future (2021 to 2050).

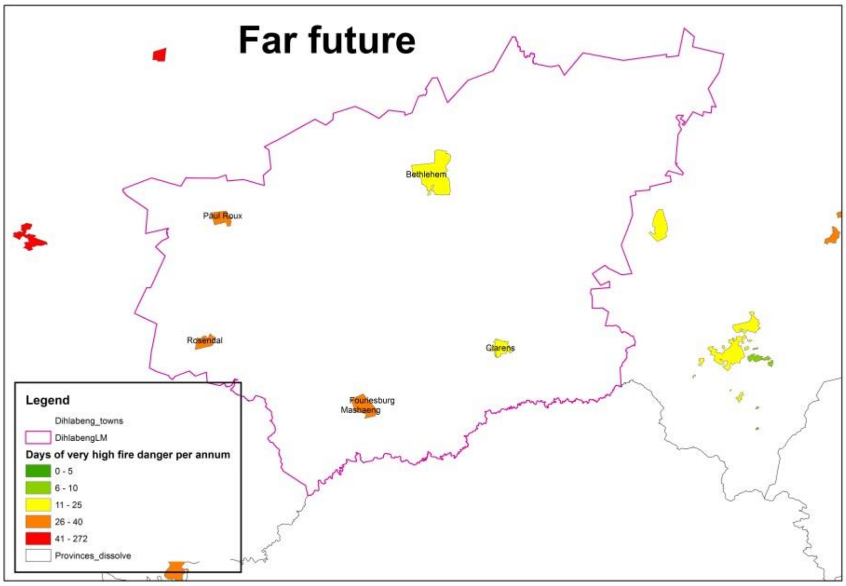

Figure 21: The number of very high fire-danger days for each of the towns within the Dihlabeng Municipality under the climate projected for the far future (2070 to 2099).

4.6 Fire occurrence

The analysis of fire occurrences in each settlement's 1 km wide outside buffer shows some interesting differences among the fire ecology types (**Error! Reference source not found.**2). lightly more than half the settlements have no recorded fires in their buffers. This does not mean that there have not been any fires because some fires, especially ones less than about 12 ha may not be detected and others, especially in Fynbos and Renosterveld, may not be detected at all (De Klerk et al., 2012; Le Maitre et al., 2014b).

Those with no fires include all those in the Succulent Karoo, Nama Karoo, Sparse Arid Woodland and Forest fire ecology types, which is what would be expected given that fires are expected to be rare (<1 in 100 years) in these fire ecology types. In contrast the settlements in the grassland and woodland fire ecology types are much more likely to have had fires, with more than 75% of those in the Sour Grassland, and nearly 60% of those in Moist Woodland, having had at least one fire. This is also in line with the expectations given that fires can occur every year in these fire ecology types. Slightly more than half of the settlements in Renosterveld have had more than one fire which differs from Fynbos where most have not had a fire.

Table 12: The numbers of fires recorded (i.e. the number of times a MODIS pixel was detected as burnt) in the outside buffer of each settlement.

Ecotypes	Maximum number of fires in pixel in			
	0	**1**	**2**	**≥3**
Arid Woodland	164	87	7	7
Coastal Grassland	39	17	3	1
Forest	5	0	0	0
Fynbos	95	52	1	2
Grassy Nama Karoo	19	1	1	0
Moist Woodland	109	107	33	22
Nama Karoo	79	3	1	0
Renosterveld	25	23	5	0
Sour Grassland	85	213	34	41
Sparse Arid Woodland	4	0	0	0
Succulent Karoo	61	0	0	0
Sweet Grassland	61	87	14	7
Thicket	71	6	2	0
Water bodies	1	0	0	0
Total number of towns	818	596	101	80

The percentage of the settlement buffer that has burnt over time shows a somewhat different picture. In the Sour Grassland and Moist Woodland, although the outside buffer may only have had one or two fires (**Error! Reference source not found.**2), those fires have cumulatively urnt quite a large proportion of that buffer and thus posed a greater fire hazard than is indicated by the occurrence alone. So, 17% of the settlements in the Sour Grassland and 9% of those in the Moist Woodland have has more than 50% of their buffer area burnt.

Table 13: The percentage of area of the outside buffer burnt over a 15 year time period for each settlement in each fire ecology type.

Fire ecology type	Percentage class				
	0	0.01 – 15.00	15.01 – 25.00	25.01 – 50.00	>50.00
Arid Woodland	164	56	16	26	3
Coastal Grassland	39	16	2	1	2
Forest	5	0	0	0	0
Fynbos	93	37	7	10	3
Grassy Nama Karoo	19	2	0	0	0
Moist Woodland	109	70	27	42	24
Nama Karoo	79	3	0	1	0
Renosterveld	25	17	5	5	1
Sour Grassland	187	58	16	26	60
Sparse Arid Woodland	4	0	0	0	0
Succulent Karoo	61	0	0	0	0
Sweet Grassland	62	39	23	28	17
Thicket	71	8	0	0	0
Water bodies	1	0	0	0	0
Total number of towns	818	341	128	200	110

5 CONCLUSION

This study extends beyond the 2010 assessment at the local authority level (Forsyth et al., 2010) because it explicitly assesses the fire hazard and the consequences or vulnerability at the WUI. The analysis shows that the majority of the settlements are located in fire ecology types that require fire and burn regularly. This means that the communities living in these settlements need to be adequately prepared to deal with such fires. This will involve a range of measures, including fuel reduction to reduce fire intensity and to exclude fires to protect vulnerable infrastructure. They also need to establish procedures to ensure that their level of preparedness to respond increases in line with increasing fire-danger ratings.

People living in settlements that do not have Fire Protection Associations should form them so that they can be better prepared to protect themselves from the negative impacts of unplanned fires. There is a lot of information available on the internet for people who are interested in reducing their fire risks, including:

- Firewise South Africa: www.firewisesa.org.za
- *Working on Fire:* https://workingonfire.org/
- *Fynbos Fire:* http://fynbosfire.org.za/
- *Kishugu:* http://kishugu.com/firescape-your-home-before-its-too-late/

This is only an initial assessment aimed at providing an overview of the relative fire hazard and fire risks for many settlements across the country. It needs to be supplemented with a more detailed local authority and settlement level assessment of the risk incorporating local knowledge and consultation with the affected communities (Holloway et al., 2010). We strongly recommend that local authorities which have settlements that are exposed to fire risks initiate and conduct such assessments in a participatory and consultative fashion.

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