A Fire Management Environmental Decision Support System for the uKhahlamba Drakensberg Park World Heritage Site

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FRONTISPIECE

This is where fire and humanity first joined, and that fact makes Africa the same as everywhere, only different (Pyne 1995: 45).

DECLARATION

This study was undertaken in fulfilment of the academic requirements for the degree of Masters of Science in Applied Environmental Science. I declare that the work in this dissertation was carried out in accordance with Regulations of the University of KwaZulu-Natal and represents the original work of the author. Any work taken from other authors or organisations is duly acknowledged within the text and reference chapter.

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ABSTRACT

Fire is a major disturbance force that affects global ecosystems and associated biomes and plays a pivotal role in the determination of ecosystem structure, functionality and dynamics. Anthropogenic environmental disturbances have resulted in shifts in fire regimes and the biogeochemical processes of these ecosystems are thus unable to function as they have done in the past, impacting both floral and faunal species. Therefore there is a need for anthropogenic management. Prescribed burning is one of the few beneficial fire management options available to decrease the severity of wildfires, decrease the associated costs in suppressing these fires and restore fire-dominated ecosystems.

The uKhahlamba Drakensberg Park World Heritage Site (UDP-WHS) is predominantly managed for water resource and nature conservation, and fire hazard reduction. It is divided into management compartments in which prescribed management burns are conducted, (i.e. manager's burn by compartment). These compartments are subdivided by three altitudinal belts (alpine, sub-alpine and montane). Each of these belts contains different vegetation communities and therefore requires different fire regimes. However these compartments do not coincide with the natural contours and consequently, the altitudinal belts of the Park. This is problematic for management as a certain percentage per altitudinal belt is required to be burnt annually. When burning a compartment that falls within two or more belts, the total area of that compartment needs to be sub-divided into its respective altitudinal belts as a whole compartment can be prescribed to burn not a sub-division thereof.

A fire management environmental decision support system (EDSS) was developed to achieve prescribed burning objectives in the UDP-WHS. The system is based on ecologically ideal fire regimes and fire management objectives of the heritage site, using GIS and associated graphs to visually display the required fire regimes. The EDSS data preparation, statistical analysis and modelling was completed using ESRI ArcGIS suite (ArcMap, Scene and Catalog). Its main components are two models, an excel spreadsheet and an ArcMap document. The spreadsheet contains the historical burning data of the management compartments based on the compartment codes, with each compartment being not burnt or having a burning treatment. Years Since Last Burnt (YSLB) was calculated from these data and joined to the management compartments in the ArcMap document. The Intermediate output model was developed to create numerous temporary outputs allowing decision makers to decide which compartments to treat with prescribed burning by re-running the model with required alterations. The second model (Final Output model) is then run to export the selected burning treatment in table format to update the original historical data, and consequently YSLB, in the excel and ArcMap document. The ArcMap document contains the user interface housing the graphs for each altitudinal belt showing the percentage area selected to be burnt per YSLB compared to the minimal, maximum and ideal fire regimes. The fire management EDSS for the UDP-WHS consists of an ArcMap document, geodatabase, excel document and folders, which are all housed in one single folder. The use of GIS and EDSSs in environmental management improves the efficiency and accuracy of the decision making process and provides the ability to validate outputs.

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CHAPTER ONE

INTRODUCTION

1.1 Introduction

In a universe informed by fire, fire becomes a universal tool. To the prehominid fires of the earth, humans have added, subtracted, redistributed, and rearranged. Human societies have inserted fire into every conceivable place for every conceivable purpose, and they have done so for so long and so pervasively that it is impossible to disentangle fire from either human life or the biosphere (Pyne 1995: 299).

Fire is a major disturbance force that has affected global ecosystems for approximately 420 million years (Bowman and Murphy 2010; Parr and Chown 2003) with this force impacting upon many biomes across the world including forests, grasslands, savannas, heathlands and Mediterranean systems (Bond and Keeley 2005; Bowman and Murphy 2010; Brown 2000a; Parr and Chown 2003; Trabaud 1987). A diversity of flora and fauna species are dependent on fire for survival and therefore many ecosystems are fire-dependent in maintaining the biogeochemical processes. A natural complex fire regime creates habitat complexity by establishing a patch mosaic landscape comprising of vegetation patches in different regenerative stages. This complexity provides a diverse range of microclimates, resources and habitats, increasing both floral and faunal species richness (Bowman and Murphy 2010). Fire, being a multiscale process, has and continues to have, in an evolutionary sense, a pivotal role to play in the determination of the structure, functionality and dynamics of global ecosystems (Bond and Keeley 2005; Bowman and Murphy 2010; Parr and Andersen 2006; Parr and Chown 2003; Pyne 1984; Trabaud 1987). Therefore when managing ecosystems, especially for biodiversity, it is fundamentally important to be able to predict and understand individual species' and community response to fire (Parr and Chown 2003).

Humankind, through time, has exerted a major influence on fire over the landscape, becoming an integral component of global ecosystems. Due to this influence fire regimes have shifted, resulting in detrimental impacts upon numerous ecosystems (Brown 2000b). Anthropogenic loss and fragmentation of environments results in the ecological processes no longer being able to function as they did in the past (Chivian 2001) and the modification of biogeochemical cycles (Olff and Ritchie 2002), therefore anthropogenic intervention is required in the form of environmental management. Human-beings have interfered with the natural functioning to such an extent that these ecosystems can no longer function without them. This management was initially the anthropo- suppression of fire in areas where fire was historically an integral part of that system, resulting in accumulation of moribund biomass (fuel load). According to Keane and Karau (2010), this accumulation of fuel along with global warming has contributed to an increase in frequency, severity, intensity and size of wildfires (veldfires). This alteration of fire regimes has adverse affects on the ecology of landscapes. More recently, environmental managers have realised the importance of having fire management strategies that incorporate the ecological role of fire (Brown 2000b).

Prescribed burning is one of the beneficial fire management options available to decrease the severity of wildfires, decrease the associated costs in suppressing these fires, and restore fire-dominated ecosystems (Arkle and Pilliod 2010; Boer *et al.* 2009; Keane and Karau 2010). Prescribed burning consists of burning under controlled conditions to reduce surface fuel loads over relatively large areas (Arkle and Pilliod 2010; Boer *et al.* 2009; Keane and Karau 2010). This decreases the potential fire intensity and difficulty of temporarily suppressing fires when wild unplanned fires occur (Boer *et al.* 2009). Although there are critics of prescribed fires, perspectives on fire management are shifting due to a call for natural resource management to be more grounded in ecological principles (Boer *et al.* 2009). In this context, important management objectives include conservation or restoration of ecological processes and disturbance regimes. In fire-prone ecosystems, prescribed fire may be a management tool for sustainably re-introducing or maintaining significant aspects of the natural disturbance regime (Boer *et al.* 2009), which is required in natural resource management.

The consideration of all environmental and ecological aspects in natural resource management requires the development of appropriate tools for supporting management policy decision-making. The recognition of comprehensive linkages between ecological, economic and human systems in policy-making has resulted in a greater complexity of sustainable management of environmental systems and therefore tools such as decision support systems (DSSs) are required (Matthies *et al*. 2007).

Natural resource management has a range of issues often requiring large amounts of data, complex analysis and a user friendly method of explaining the results. Data (usually incomplete) and statistical analysis tools do exist, however the appropriateness or accessibility to decision makers is a limitation. These decision makers often have limited time to undertake or complete complex tasks (Walker and Johnson 1996). The development of DSSs allows the integration of a range of information technologies, analytical tools and data, which can improve data accessibility and make available rigorous analytical tools which are used to evaluate and justify the results of the decision making process more efficiently and effectively (Walker and Johnson 1996).

Developed originally to support business managers, decision support systems (DSS) have been increasingly utilised in the field of environmental management due to DSSs ability to simplify problems associated with the complex interactions between socio-cultural, economical and biophysical systems (Matthies *et al*. 2007). The use of geographical information systems (GIS) in conjunction with a DSS adds a spatial dimension to the support system which is required when working within the environment. GIS is increasingly becoming an integral component of natural resource management activities (Nath *et al.* 2000). An Environmental Decision Support System is an environmentally based DSS used by natural resource managers in the decision making process where there are various stakeholders (i.e. managers) and data that require an efficient and accurate tool to be used to complete the decision making process (Matthies *et al*. 2007).

All anthropogenically protected areas, including within South Africa require some degree of management and consequently a decision making process to conserve their natural resources. There is also a need to evaluate and validate decisions made during a decision making process. The uKhahlamba Drakensberg Park World Heritage Site (UDP-WHS) is a protected area forming part of the eastern escarpment of the KwaZulu-Natal Province, South Africa. It contains a high flora and fauna species richness, including high levels of endemicity. Due to numerous main rivers' headwaters originating in the park, it is a vital water source for a water scarce country (Briggs 2006; Matthews and Bredenkamp 1999; van Wilgen *et al*. 1990). The prescribed burning of the region is undertaken by Ezemvelo KwaZulu-Natal (KZN) Wildlife, the provincial custodians of biodiversity. According to Everson et *al.* (2004), burning biennially would maintain the level of abundance of the most important species in the park. The park is divided into management compartments by which prescribed burns are implemented (Priday 1989; van Wilgen *et al.* 1990), with certain compartments needing to be burnt each burning season to maintain the desired fire regime while at the same time maintaining a patch mosaic of the landscape.

This research examines the development a fire management decision support system for prescribed burns in the uKhahlamba Drakensberg Park World Heritage Site. To determine, at the start of each burning season, which compartments should be burnt, and to accommodate unplanned fires. The system is based on the ecologically ideal fire regimes of individual altitudinal belts demarcated within the heritage site and the surrounding areas.

1.2 Aim and Objectives

1.2.1 Aim

To develop a fire management environmental decision support system for the uKhahlamba Drakensberg Park World Heritage Site based on ecologically ideal fire regimes and fire management objectives.

1.2.2 Objectives

To meet the aim of this study, the following objectives were set:

- Identify the uKhahlamba Drakensberg Park World Heritage Site (UDP- WHS) boundaries and altitudinal zonation.
- Create a template and Triangulated Irregular Network (TIN), containing the management polygons (compartments) and compartment identification number.
- Determine fire management objectives of the UDP- WHS.
- Gather information of various aspects of the UDP-WHS: historical fire data and sensitive areas within the UDP- WHS (i.e. campsites, rock art, forests, etc.).
- Consultations and workshops with Ezemvelo KZN Wildlife
- Develop environmental decision support models
- Create a geodatabase housing the fire management decision support system.

1.3 Structure of Dissertation

The introductory chapter provides a brief background to the dissertation and its main components. The aim and objectives of the research are presented. Chapter two examines the literature on fire, decision support systems and the Drakensberg Mountain Range. Chapter three details the methodology used in the collection and analysis of the data including the description of the study site, with chapter four presenting and describing the results. Chapter five is a detailed discussion of the results along with the limitations of the study, linking the results back to the literature in chapter two. The concluding chapter, six, consolidates the findings of the research and outlines the objectives achieved during the research and how these objectives were achieved.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

"Fire is the most widespread ecological disturbance in the world" (Pyne *et al*. 2004: 5).

The emergence of terrestrial vegetation saw fire become nature's 'scavenger' by removing accumulated dead vegetation biomass, and recycling nutrients back to the earth (Bowman and Murphy 2010; Brown 2000a; Brown 2000b; de Ronde *et al.* 2004a). The majority of terrestrial ecosystems have annual vegetative growth which senesce resulting in moribund material accumulating. The build-up of this dead biomass (fuel) may shade and suppress the living plant and become a fire hazard (de Ronde *et al.* 2004a). There are variations, in fuel accumulation amounts across the landscape due to several factors (i.e. time since last fire, rainfall, herbivory levels and vegetative patchiness). These variations along with shifts in weather and changes in topography, result in fluctuations in the intensity of fire and other factors including fire severity and frequency, during wildfire and prescribed burning, promoting biodiversity of the landscape (de Ronde *et al*. 2004a; Stocks *et al*. 1997).

Fuel is the accumulated dry combustible plant material which is based on its tendency to ignite, i.e. wet plant material will not ignite therefore is not considered fuel (de Ronde *et al*. 2004a). Fuel accumulation indicates an increasing potential for fire to ignite, spread, and intensify as the time since the last fire occurred increases. Total vegetative biomass increases where annual biomass increment exceeds decay due to photosynthesis with the biomass (fuel) accumulation not necessarily being uniform over time (Brown 2000b). In forested areas, the annual biomass increment is unavailable for combustion due to being tied up in live tree biomass. Grasslands have short fire intervals resulting in the regular increase in fuel until it is removed or reduced, usually by fire, especially in grassland areas (Brown 2000b).

Due to the expansion of urban areas and habitat alteration/destruction placing greater pressure on the natural environment, the ecological processes can no longer be left to function as they did in the past (Chivian 2001; Driver *et al.* 2005; SEF 2002). Hence the formation of protected areas (such as the uKhahlamba Drakensberg Park World Heritage Site) where biodiversity and natural processes can be managed, including fire management which forms a major component of the ecological functioning of ecosystems.

This review is divided into three sections, namely Fire (2.2), Decision Support System (2.3) and the Drakensberg Mountain Range (2.4). Fire covers fire behaviour and management including different fire types and prescribed burning techniques. Fire management problems in terms of conflict between built assets and biodiversity are highlighted. The Decision Support System section consists of the two components making up a support system, namely Geographical Information Systems (GIS) and decision support tools. The Drakensberg Mountain Range includes the physical, ecological and cultural aspects of the area, present fire management techniques and optimal prescribed burning techniques in terms of vegetation requirements. Conservation and management constraints preventing the achievement of management objectives are reviewed. This section is placed in the literature review as opposed to the study site description as the study site forms part of the larger Drakensberg range.

2.2 Fire

"Fire is a bad master but a good servant" (Phillips 1965).

Fire is an ecologically important and integral force that has shaped many of the global plant communities and probably has been doing so since the arrival of terrestrial vegetation on the Earth's surface, in particular in Africa (Flannigan and Wotton 2001; Davis 1979, Harris 1958, Komarek 1973, Smith *et al*. 1973 cited in Trabaud 1987). Africa is considered to be the 'Fire Continent' (Komarek 1965) due to the widespread occurrence of biomass being burnt (de Ronde *et al*. 2004a). Africa's high volumes of lightning storms and ideal fire climate of wet and dry periods facilitates the ability of Africa to support this high level of fire. Annually, there are approximately 168 million hectares of land burned south of the equator, equating to 17% of the land (total of 1 014 million hectares) and accounting for 37% of the global dry matter burnt (Pyne *et al*. 2004).

Fire flourishes due to the majority of sub-Saharan Africa having an environment to sustain it, with continual wetting and drying of the land and minimal fluctuations in temperature compared to the northern hemisphere. This results in the wet seasons increasing fuel loads and dry seasons desiccating the biomass, which is then ready to be burnt. Adding to this ideal climate is the irregular drought and torrential rain events. The onset of rain will characteristically bring thunderstorms along with their associated dry lightning (Pyne *et al*. 2004).

Fire, in most African ecosystems is a natural and beneficial disturbance of vegetation, in terms of both structure and composition and nutrient recycling and distribution. However, there are still substantial unwarranted and uncontrolled fires occurring, therefore effective actions are required to limit unneeded direct damages to life, infrastructure and fire-sensitive natural resources and indirect damages in the form of atmospheric emissions which have adverse effects on the global climate system and human health (Pyne *et al*. 2004). The most sensitive problem areas are at the interface between fire savannas/ grasslands, residential areas, agricultural systems and fire sensitive forests. Even though the total economic estimates of damages caused by African fires is unavailable, ecologically and economically important resources are steadily being destroyed by fires crossing the boundaries between fire-adapted and fire-sensitive environments. These fires are also responsible for widespread deforestation in numerous southern African countries (Pyne *et al*. 2004).

Fire plays an important ecological role in many environments and it is therefore imperative to have informed fire management to effectively conserve biodiversity. Ecologists and scientists alike need to ensure that the best scientific advice is made available for fire managers (Parr and Andersen 2006). Even with the best scientifically based practices being advised there are constraints on the management of prescribed fire that make it difficult for resource goals to be achieved, while the protection against veldfires permits the development of undesirable ecological consequences (Brown 2000b). To overcome this quandary, land managers and the public need to take cognisance of the ecological role of fire in the natural functioning of ecosystems when meeting varied resource objectives (Brown 2000b). Regardless of the fact that fire management for biodiversity conservation is limited by inadequate knowledge (Parr and Chown 2003), fire as a management tool is being used in protected areas (see Biggs and Potgieter 1999; Russell-Smith 1995; Stander *et al.* 1993), more out of necessity than choice. If the resources are available then information on the effects of different fire management policies on all facets of diversity should be considered, such as the effects fire has on a broad range of taxa at the species, population and community levels (Parr and Chown 2003).

Not much has changed, according to Driscoll *et al.* (2010), with little systematic research or monitoring being completed to assemble adequate data, resulting in the limitation of available evidence that can be used to effectively evaluate management policy outcomes. The absence of these evaluations may result in the implementation of management practices that are harmful to biodiversity, even with the lack of knowledge of the effectiveness of these practices on protecting assets such as biodiversity (see Fernandes and Botelho 2003; Backer *et al.* 2004; Bradstock *et al.* 2005; Cary *et al.* 2009).

2.2.1 Fire Behaviour

"Fire behaviour is the general term used to refer to the release of heat energy during combustion as described by the rate of spread of the fire front, fire intensity, flame characteristics and other related phenomena such as crowning, spotting, fire whirlwinds and fire storms. The manner in which, and the factors that influence, the release of heat energy, involves the study of fire behaviour" (Trollope *et al*. 2004: 27).

Fire behaviour defines what fires do during its phases of existence, i.e. ignition, build-up, propagation and decline (Stocks *et al*. 1997), which are dependent on environmental aspects such as fuels, weather, topography, and past and present fire regimes (Pyne 1984). The understanding of fire behaviour is ecologically important as behavioural factors, i.e. fire intensity and rate of spread, influence species distribution and abundance. The intensity of the fire will determine the scorch height, thus determining the level of consumption, mortality or areas of the plant canopies that are untouched by the fire. The fire front rate of spread determines residence time for lethal fire temperatures at a specific point, which has relevance for both floral and faunal species. Flame front continuity determines the probability of an animal species reaching relative safety (escaping back through the flames to recently burnt ground). While the fire patchiness (mosaic of local variations in fire intensity) in resource availability determines if viable sources of recolonisation remain located within the boundaries of the fire, which is optimally desired for conservation of biodiversity (de Ronde *et al*. 2004b; Huston 1994; Whelan 1995). Combustion completeness determines the quantity of remaining biomass, which is used by species for cover in addition to an erosion barrier (Whelan 1995). Environmental and biotic factors influence various fire regime characteristics which consequently determines the behaviour of specific fires (Table 2.1).

Table 2.1: Summary of the main environmental and biotic factors affecting fire behaviour

Factor	Effect
Fuel Load	Determines maximum energy available to a fire. Fuel arrangement affects aeration (i.e. tightly packed fuels, vertical and horizontal spread: into canopy and patchy ground fuel respectively). Fuel size distribution can affect probability of initial ignition. Flammability can be increased (resins and oils) or decreased (mineral content) dependent on fuel chemistry of parent plant species.
Overall Climate	Determines vegetation productivity and composition and therefore rate of fuel accumulation and species organic chemistry.
Rainfall and Humidity	Probability of ignition, rate of combustion and rate of spread are decreased with an increase in fuel moisture and a high relative humidity.
Wind	Desiccates fuel. Oxygen availability for combustion is increased. Pre-heats and ignites fuel in advance of the front, can result in ignition far ahead of front. Changes in wind direction can increase fire front.
Topography	Creates local climate variations (i.e. fuel moisture, relative humidity, wind interaction). Allows for pre-heating and ignition for fires burning uphill. May provide natural fire breaks (i.e. cliff faces). Partially determines distribution of plant communities of different flammability's, may allow for landscape spatial heterogeneity.

(Adapted from Whelan 1995)

2.2.1.1 Fire Regimes

"Individual fires are to regimes as storms are to climate" (Pyne *et al*. 2004: 2).

The realisation that ecological systems experience recurrent phenomenon in the form of natural disturbances resulted in investigations into the link between wildfires and ecosystems. This is due to the need to understand the effects these disturbances have on ecosystem structure and function (Johnson and Miyanishi 2001). As with most recurring disturbances, fire is able to be classified by a regime with the most important fire regime aspects/facets being interval, area, intensity and season. Due to the possibility of fire having a positive or negative effect on plant species and overall community diversity the four facets of a fire regime interact with the components of ecological resilience (elasticity, amplitude, malleability and damping). These interactions determine the species composition of communities within a specific area (Malanson 1987).

The term fire regime is increasingly been used in the field of fire ecology however there seems to be two different meanings developing. First, it has been utilised for describing a particular fire or a certain prescribed fire to be applied to an area. Second, the more common use, is the summary of the typical fire characteristics ((e.g. combination of frequency, season, intensity and fire type (van Wilgen and Scholes 1997)) experienced at a certain area (Whelan 1995). A fire regime is a statistical concept which refers to the nature of fire occurrence over long periods of time, in addition to the prominent immediate effects that usually characterize an ecosystem (Brown 2000a; Pyne *et al*. 2004). Due to the large variability of fires over space and time, fire regime descriptions are generally broad resulting in difficulties in classifying regimes into distinct categories. One difficulty is that placing distinct boundaries around continuously varying biological processes involves some degree of chance. The classification dilemma is to make the classification useful and practical (to managers) without undue complexity. However, to accurately represent the nature of biological processes, such as response to fire, complexity of interacting variables has to be accounted for. There is a requirement for a trade-off between either practicality and accuracy or simplicity and complexity (Brown 2000a).

The concept of 'fire regime' brings about a certain level of order to a complicated body of fire behaviour and fire ecology knowledge, providing a simplified way of communicating to both specialists and general public regarding the role of fire. Fire regimes can be classified according to fire characteristics or on the effects produced by the fire (Brown 2000a; Whelan 1995). The four broad fire regimes are understory, stand-replacement, mixed severity and non-fire. Understory and mixed severity are applicable to forests and woodlands, while non-fire is where minimal or no natural fires occur. Stand-replacement is applicable to forests, woodlands, shrublands and grasslands with the occurrence of fire resulting in substantial changes in the aboveground structure of the dominant vegetation. Approximately 80% or greater of the dominant vegetation is consumed or dies (Brown 2000a). The stand-replacement fire regime is the appropriate regime for many African and South African grasslands and shrublands such as those found in the Drakensberg Mountain Range. All fire regimes have been described by factors such as fire frequency, fire periodicity, fire intensity and severity, fire size, fire spread patterns/ patchiness, seasonality, fuel consumption, and depth of burn (Bond and Keeley 2005; Brown 2000a; Pyne 1984; van Wilgen and Scholes 1997) (Table 2.2).

Table 2.2: Main fire regime characteristics

Characteristic	Description
Intensity	Refers to energy release or to other direct measures of intensity such as flame height, extent of the fire front and rate of spread. Fire intensity, after ignition, will be influenced by the range of factors found in Table 2.1, with the fire history of a particular area having a significant effect on intensity, via availability of fuel. There is a strong correlation between fire intensity and fire frequency, i.e. a recently burnt area will not have had adequate time for fuel accumulation that supports intense fires. Despite the fact that fire intensity is a vital measurement, ecologists prefer fire severity which is a measurement of fire impact on an ecosystem (i.e. mortality).
Frequency	Fire occurrence per area within a desired time period. Two factors determine the potential fire frequency of a specific area, first, fuel productivity (time taken to build up available fuel) and second, frequency of ignitions. These factors are affected by variability in climate each year, i.e. during ignition season; therefore a high fuel load and lightning strikes will not necessarily result in fire that year. Components of frequency include fire interval and fire period. Fire interval is the time taken between a fire and the preceding fire, whereas fire period or average fire interval is the interval averages taken over numerous fires.
Extent/Patchiness	Following ignition, a fires' patchiness or extent will be affected by numerous factors of fire behaviour. Principally, vegetation and landscape heterogeneity, whereby some plant communities (associated with soils and topography) and natural topographical features, i.e. ridges, gullies, water bodies, can serve as natural fire breaks. Consequently spatial patterns (varying fuel loads) created across the landscape by past fires and/or herbivory will be influential in terms of extent and patchiness of the subsequent fire.
Season	The principal factor of fire season is climate due to the natural ignition season (i.e. lightning) being determined by the climate of the area. It is dictated by the coincidence of natural ignitions and low moisture fuel. By measuring lightning strikes and relating it back to periods of plant growth and senescence, the natural fire season of a given area can be defined, usually around the driest time of the year. However, due to human influence fire seasons are altered by the provision of ignitions outside the period of natural lightning storms.

(Summarised from Bond 1997; Bond and Keeley 2005; Tainton and Mentis 1984 and Whelan 1995)

Numerous factors mentioned above have a climatic element, i.e. under optimum conditions landscapes can be burnt under virtually any climate regime. However the probability of the fire (and subsequent behaviour if ignited) is dependent on the current meteorological conditions (van Wilgen and Scholes 1997). The majority of a region burnt would only have occurred over a few days of a year that experienced the required severe fire weather (dry, hot and windy) (Flannigan and Wotton 2001). Dead dry fuels are required for the occurrence of fire with the moisture level being dependent on antecedent and present rainfall, temperature, humidity and radiation. The moisture content must be low enough to permit ignition and to sustain combustion (van Wilgen and Scholes 1997). The fire frequency and extent are therefore dependent on availability of dry combustible fuels which is determined by mean annual rainfall. Climate also affects, both directly and indirectly, fire frequency, intensity and severity through air temperature and wind speed and its manipulation of fuel accumulation (van Wilgen and Scholes 1997; Whelan 1995). The ultimate factor determining a fire regime is climate with past climatic conditions determining plant communities' characteristics and distributions, and current climate being the determinant of natural ignitions (i.e. lightning) and fire behaviour following ignition (Whelan 1995). Hence, "climate is the single most important factor that ultimately decides whether a species can survive in a habitat or not" (Joubert 2006: 42).

When assessing some of these factors such as fire frequency there may be some complications. For example, fire frequency may involve complex fire behaviour at different spatial scales with different limitations. Natural fire season is controlled by the coincidence of ignitions and level of moisture in fuel, hence it is usually during the driest periods of the year. However, human beings have significantly altered fire season through providing artificial ignitions when they would not occur naturally (Bond and Keeley 2005).

2.2.2 Fire Management

"Fire… is one of the first tools that humans used to re-shape their world" (Bond and Keeley 2005: 387).

The use of fire as a land management tool has been and is still extensive, with evidence of past and current use by indigenous peoples (van Wilgen and Scholes 1997). Fires were deliberately ignited for clearance of dense vegetation (easier for travel and to flush game), nutritional regrowth attracted game (hunters) and provided a nutritional supplement (pastoralists), regeneration of desired plant species i.e. food species and for protection (firebreaks around campsites) (van Wilgen and Scholes 1997; Whelan 1995). Currently, approximately 2 700 - 6 800 million tons of plant carbon is released annually by burning of savanna vegetation and through its use in shifting agriculture. The use of fire by human beings in Africa for over a million years has resulted in the loss of evergreen forests due to the extension of grasslands and savannas. This is evidence that strengthens the fundamental conclusion that "fire is a general and influential ecological phenomenon throughout the world and cannot be ignored when considering the management of rangeland ecosystems for both domestic livestock and wildlife purposes" (Pyne *et al*. 2004: 6). Societies confronted with destructive wildfires developed fire management which includes activities concerned with the modification of the impact of wildfires on property, people and ecologically sensitive areas which they were concerned with and the use of prescribed burning to achieve fire management objectives, all conducted with the consideration of environmental, social and economic criteria (Martell 2001). The level of achievability is dependent upon several factors: i) the degree of understanding of fire and ecosystem processes and the fire management impacts on the ecosystem, ii) how well are the impacts, social and economic, understood, iii) the availability of technology and resources given to fire management organisations' by society, iv) organisations' knowledge, skills and experience and v) environmental challenges of the ecosystem (Martell 2001).

The utilisation of fire has been practised in a four-part strategy, namely: to prevent undesirable ignitions, to modify the environment (where there will be a potential for fire) to alter the effects and behaviour of a fire, to suppress wildfire and last to exploit the use of controlled fire (Pyne 1984). At the foundation of any fire management plans and objectives is the notion that humans can control the stopping and starting of fires (Pyne 1984). "Any statement of goals or theory about the adequacy of fire management must originate with the techniques by which accidental ignition can be prevented, wildfire suppressed, and prescribed fire substituted for wildfire" (Pyne et. *al* 1996: 309). If these techniques were not achievable, fire management or protection would merely be a program of prediction and defence resembling that of a flood control or tornado warning system. Instead, the various techniques allow for a level of control over how fires start, spread, and how they can be utilised to achieve desired human objectives (Pyne 1984; Pyne et. *al* 1996). Fire management has moved away from the traditional prevention and suppression to more of an ecological and economic concern using the fire management techniques to understand and mimic the fire regime of a given area (Johnson and Miyanishi 2001).

Fire management typically aims to achieve objectives, using an understanding of fire to formulate actions that would achieve those objectives. These actions would be intended to control the frequency, area, intensity or impact of a fire event. The different contexts and scales under which these objectives are taken include institutional, economic, social, environmental and geographical, ranging from local to national (Flasse *et al*. 2004). The variation in range of fire management objectives is dependent on the management issues in addition to available resources (means and capacity). Regardless of the level, reliable information and scientific knowledge (such as fire impact on ecosystem components, i.e. soil and vegetation) upon which suitable decisions and actions are based, is essential for effective fire management (Flasse *et al*. 2004). Fire management objectives are generally restricted to a geographical area such as watersheds or protected areas. These areas are large and to efficiently manage these areas they can be subdivided into smaller manageable parcels or compartments. Each of these compartments may have different fire management objectives derived from the broader objectives of the geographical area. According to Pyne *et al.* (2004), most fires are initiated for prescribed burning programmes that have been created to meet both range and wildlife management objectives.

The requirements of fire management in sub-Saharan Africa are unique, being hindered by specific ecological needs, anthropogenic problems, land-use or a combination of these. Fire managers have to overcome many obstacles when trying to achieve site-specific objectives, including satisfying conflicting requirements for biodiversity conservation, rock-art protection and safety. Besides the above mentioned obstacles there are regional problems and demands influencing the decision-making process, such as population pressure, industrialisation and grazing requirements, water availability and heritage artefact protection (Everson *et al.* 2004)

2.2.2.1 Prescribed burning

"Prescribed burning is both a science and an art requiring a background in weather, fire behaviour, fuels, and plant ecology along with the courage to conduct burns, good judgement, and experience to integrate all aspects of weather and fire behaviour to achieve planned objectives safely and effectively" (Wright and Bailey 1982: 387).

Prescribed fires form an integral component of the fire management concept, and any fire that achieves desired management objectives is deemed a prescribed fire. Ignitions maybe planned or unplanned, providing that the fire is contained within the predetermined area and required behavioural properties, it will be allowed to burn. The difference between a prescribed fire and wildfire is that prescribed fires promote the management objectives while a wildfire does not (Pyne 1984). Environmental managers have to recognise that there is always going to be fire (in historically fire prone areas), either as prescribed or wildfires and by using fire as an ecological management tool, vegetation can potentially be manipulated favouring desired objectives of that area (de Ronde *et al*. 2004a). There are three forms of control when it comes to prescribed burning: first, fire spread control, achieved through establishing natural and/or unnatural firebreaks; second, fire intensity control, through the use of a prescribed burning plan; and last, frequency control, through the ability of igniting and suppressing desired and unwanted fires respectively. This manipulation of time, place and intensity of fires allows fire management organisations to control the effects of the fire. The criteria needed for a prescribed burning will originate from various sources: goals from the land management plan put together by the appropriate administration unit, conditions from the fire management plan, and the control methods from a burning plan (Pyne *et al*. 1984).

Prescribed burning reduces fuel loads that have accumulated since the last time an area was burnt and allows managers to attain planned management objectives under specific environmental conditions (Bond and Keeley 2005). Prescribed burning as a fuel management tool, directly (type and intensity of fire) and indirectly (fire size and extent) influences aspects of fire regime (Martell 2001). Fire rotation interval is “the time required to burn the equivalent of a specified area, whereas fire return interval is the time interval between fires at any one site” (Bond and Keeley 2005: 390). The frequency or intervals between these burns have to be considered carefully as widespread burning which leads to short inter-fire intervals may result in some species declining in numbers and dependent on the size of the region, may threaten those species with extinction. The level of risk depends on the species’ distributions compared to the extent of burning (Driscoll *et al.* 2010). Therefore having different objectives for smaller compartments instead of wide-spread burning across large areas, allows for the counteraction of this risk.

Land management organisations deliberately ignite fires for various reasons, usually following a prescription drafted before burning. Reasons for these prescribed burns include hazard-reduction which are fires that are controlled and conducted in the annual cool season (Table 2.3). High-intensity fires (hot and dry conditions) may be prescribed to remove certain undesirable species (alien invasive) or maintain a vegetation type which requires high-intensity fires (Whelan 1995). Controlled prescribed fires are utilised for species maintenance, elimination and biodiversity in addition to maximising water runoff (Table 2.3).

Prescribed burning is recognised as a vital ecological factor in African grasslands and savannas (de Ronde *et al*. 2004a). There is a general understanding of the effects of fire regimes (fire type, intensity, season and frequency) on the components of the plant community, i.e. grasses and trees, due to research into this field of study dating back to the early 20th century. This, sequentially, supported the use of fire as a management tool.

Prescribed burning plans have been developed for various African and South African grassland and savanna ecosystems under various land use management objectives such as wildlife and livestock production (de Ronde *et al*. 2004a).

2.2.2.2 Prescribed burning Techniques

There are various prescribed burning techniques used by fire management agencies depending on the type of burn desired, meteorological conditions, vegetation characteristics, geographical location, along with numerous other reasons. Each technique has advantages and limitations and rationale for use (Appendix A).

Table 2.3: The use of prescription fire to achieve various desired management objectives.

Management Objective	Use of Fire in Achieving Objective
Forestry	Prevention of widespread crown fires with rotational hazard-reduction burning. Selection of species: Removal of species competing with desired timber species. Soil dwelling pathogens, disease and weed control and removal. Stimulation of regeneration of desired tree species by high-intensity, i.e. improvement of productivity.
Flower Harvesting	Maximising the production of woody perennial inflorescences, especially Proteaceae in Africa, i.e. improve productivity.
Water Resources/ Watershed Management	To maintain a sustained yield of good quality water, e.g. Drakensberg Mountain Range in southern Africa.
Urban	Low fuel loads around installations/ subdivisions, etc.
National Parks (Protected Areas)	Wildlife hazard reduction by reducing accumulated fuel. Maintenance of certain species/ communities that require a specific fire regime (including decision to allow wildfire burn out). Conserve and maximise biodiversity. Soil dwelling pathogens, disease and weed control and removal. Creation of wildflower displays. Maximise forage quality and quantity.
Rangeland	Removal of pathogens and parasites of livestock and wildlife. Maximise forage quality and quantity by removing moribund material. Specific-species selection. Bush encroachment control.
Security/ Hazard Reduction	Provide fuel (fire) breaks, protect infrastructure during wildfire as well as prescribed fires. Removal of biomass to decrease fire intensity of future fire.

(Compiled from Bailey *et al*. 1993; Bond 1997; de Ronde *et al*. 2004a; Edwards 1984; Whelan 1995; Trollope 1989)

2.2.2.3 Fire Breaks

To counteract increased fire frequency caused by anthropo-ignitions dissection or sub-dividing of the landscape is required in the form of fire breaks (Whelan 1995). Burning fire breaks is a form of security burning to restrict a fire to a particular location or property and to protect infrastructure (Table 2.3). They decrease the cost of trying to prevent fires entering neighbouring land and reduce the probability of fires leaving the designated area, which is more cost-effective than having to compensate for damages to property (de Ronde *et al*. 2004a; Edwards 1984). Various fire breaks, natural and unnatural, are used by land managers to decrease the probability of a given fire spreading from one area to an undesirable other (Whelan 1995) (Table 2.4), in addition to limiting unwanted social, economic and biological impacts (Martell 2001).

Table 2.4: Natural and Unnatural Fire Breaks

Natural	Unnatural
***Evergreen Indigenous Forests*: closed canopies, free of continuous combustible ground fuel layer**	*Power lines*: required servitude results in application of continual fuel management
***Rivers*: with riverine forests also free of continuous combustible ground fuel layer**	*Railway lines*: with added fire breaks on each side (widening)
***Swamps and Wetlands*: latter with no burnable fuel or fuel burned prior to fire season**	*Ploughed land and Vineyards*: no fire hazard, usually fuel-free. Damage to vineyards possible.
***Rock sheets*: rocky outcrops or shallow soil areas and/or steep slopes/ cliff faces where no continuous combustible fuel layer is found**	*Agricultural*: Maize or other grains most times unburnable, but short periods after harvesting, residual moribund biomass highly flammable.
***Over-grazed grasslands*: grazing applied so extensively that grass will not even burn properly under extreme weather conditions.**	*Roads*: public, rural and agricultural roads create strip with no continuous combustible ground fuel layer. May need strengthening by widening.

(Summarised from de Ronde *et al*. 2004a)

2.2.2.4 Biodiversity

"Pyrodiversity promotes biodiversity" (Martin and Sapsis 1992: 150).

The biodiversity of many ecosystems can be increased by the inclusion of fire and reduced by the exclusion. The most diverse complexes of species are created by variations of fire regimes in time and space. Hence, an area with a high variability in timing of fire, intensity, frequency and fire spread patterns are inclined towards greater biological diversity in ecosystem components (Brown 2000b; Tainton and Mentis 1984). However, there can be too much fire which will have the opposite effect, with a decrease in biodiversity when fire frequency is greater than what would have occurred under the natural fire regime. The underlying relationships need to be understood to provide a basis for fire management to meet biodiversity conservation goals (Brown 2000b).

Techniques used to determine natural or historical fire regimes of an area include fire scar sampling of tree growth rings to find evidence of sequential burns, lake and dam sediment sampling for evidence of extreme or unusual past runoff events, recorded fire events (oral and written), extrapolation from present meteorological conditions and, vegetation characteristics (morphology, life-cycles, fuel build-up) and responses to various fire regimes (ESA 2002). In the absence of definitive knowledge of the historical fire regimes of an ecosystem, vital attributes of plants and animals and post-fire seral stages are utilised in predicting the responses of individual species and communities to various disturbances, fire included. These responses are used in the development and implementation of ecologically acceptable fire regimes (e.g. Bradstock *et al*. 1998; Bradstock and Kenny 2003; Burrows 2008; Franklin *et al*. 2001; Tolhurst 1999; van Wilgen and Forsyth 1992). The determination of the natural fire regime of an area should result in the development of appropriate fire management policies. The variety of different ecosystems and vegetation communities is evidence of the presence of different regimes and therefore the need for a variety of prescribed fire techniques and practices in any landscape management policy (ESA 2002).

Fire survival of individual organisms', found within communities and ecosystems, is dependent on numerous life-history, anatomical, physiological and behavioural characteristics (Whelan 1995). Changes in response to a specific fire regime by species' populations and community assemblages, are largely dependent on individual organisms' traits. Plant and animal species have fundamentally different adaptations to deal with fire, this is due to the relative immobility of plants in addition to plants being able to endure serious injury to certain components without facing mortality as many animal species would most certainly face with the same level of injury (Whelan 1995).

Species' fire tolerances vary and certain fire regimes will promote the growth and spread of certain species while eliminating or restricting other species in that community (Geldenhuys *et al*. 2004). Therefore, according to Miller (2000), it is vital for flora management that the factors controlling the initial vegetation response to fire is understood. The effect fire has on plant communities can have significant variations both among different fires and having a mosaic effect within the individual fire. "Fire behaviour, fire duration, the pattern of fuel consumption, and the amount of subsurface heating all influence injury and mortality of plants, and their subsequent recovery" (Miller 2000: 9).

Fire-prone landscapes support species that are not only fire tolerant but also fire-dependent. These species require fire to complete their life-cycles and/or to maintain their competitive advantage. The post-fire environmental benefits include increased availability of resources, removal of moribund material, nutrient-rich ash and increased levels of sun incidence (Bowman and Murphy 2010). Within these fire-prone ecosystems there are plant species and communities that are fire-sensitive. They survive, usually, in areas that have low fire frequency and severity (i.e. maybe due to topography). For instance, forests which are fire-sensitive are found within grasslands that require periodic burns. The forests are usually found in rocky gorges, incised gullies (forest refugia) and waterways. This is due to forest species being able to reach maturity (or fire resistant size) between fires because intensity of fires are higher moving up hill, rocks decrease levels of fuel, gorges have higher humidity (therefore flammability of fuels is less), and a high soil moisture content leading to a higher growth rate (Bowman and Murphy 2010; Frost 1984; Irwin and Irwin 1992).

Surface fires, either head or back fires, are the dominant fire type in grassland and savanna ecosystems. Occasionally crown fires occur under very intense fire conditions, usually in the form of 'torching'. The type of fire determines at which vertical level heat energy is released compared to where the meristematic sites of the bud tissue are located from which plants recover after burning (de Ronde *et al*. 2004b). Trollope (1978) cited in de Ronde *et al*. (2004b), found that when it comes to grasslands in South Africa, a surface back fire significantly depressed the re-growth of grass swards compared to surface head fires due to longer exposure to heat and at which level the heat was released. The more heat released at ground level from back fires and the longer exposure to critical threshold temperatures associated with back fires adversely affected the shoot apices of the grass plants. According to de Ronde *et al*. (2004b), there is no significant effect of fire intensity on the recovery of grass swards after a series of fires ranging from cool to extreme intensities. A controversial issue with fire being used as a management tool is that of seasonality of burning, due to very little quantitative information on the effects on productivity of grass swards in terms of season of burning. There are contrasting ideas when burning should occur, for example West (1965) believed that it is vital to burn during dormancy, advocating burning prior to spring rains (end of winter) to insure a high-intensity fire to control bush encroachment. In contrast, Scott (1971), stressed that burning at this time of year will damage the grass sward, burning rather after the first spring rains (de Ronde *et al*. 2004b). Although there are different ideologies, more recent research concludes that burning in late winter or after the first rains have no significant difference in the effect on the grass sward (Dillion 1980; Tainton *et al.* 1977; Trollop 1987 cited in de Ronde *et al*. 2004b).

In the moist grasslands of KwaZulu-Natal Province in South Africa, burning in autumn instead of late winter/ early spring declines the climax species, *Themeda triandra*, while increasing the less desirable species of *Tristachya leucothrix* (de Ronde *et al*. 2004b). The species that are commonly found in pristine grasslands, increase with regular burning but decrease with over- and under-utilisation, are termed 'Decreaser' species, such as the palatable *T. triandra*. Conversely, 'Increaser' species (e.g. *T. leucothrix*) are favoured by an infrequent fire regime and are unpalatable (Everson *et al.* 2004). The low mortality and high initiation of tillers in Decreaser species associated with frequent winter/spring burns is due to the close proximity of the shoot apices to the surface at this time of the year (Kruger 1984). Whereas, in summer burns when the shoots are elevated off the surface the survival of the tillers is less than six (Everson *et al.* 2004) or eight percent (van Wilgen *et al*. 1990) attributed to the destruction of the meristematic tissue. The lateral tillers produced by *T. triandra* is due to dormant season defoliation indicating that *T. triandra* is naturally adapted to fire defoliation and moderately adapted to herbivory (Everson *et al.* 2004).

One of the biggest hindrances to prescribed burning of areas where a grass sward dominates, such as the grasslands of the KwaZulu-Natal Drakensberg Mountain Range, is overgrazing (Brown 2000b). Bunchgrass species, i.e. *T. triandra*, are more affected than rhizomatous grasses. Plant diversity can be decreased by excessive grazing, without fire and following fire where desirable vegetation is reduced or removed completely. In grasslands, woody plants out-compete grasses with overgrazing, which could defeat the purpose of burning to stop and decrease bush encroachment (Arnott 2006; Brown 2000b).

Favourable sites for invasive non-indigenous (alien) plant species can be created by fire, allowing them to become established. There is a potential problem, if there are alien species already growing in areas (i.e large seedbank) that receive prescribed burning due to aggressive alien species being able to out-compete and exclude indigenous vegetation. Exposure of soil by severe fires most likely will result in that area becoming invaded, especially if a population of exotic species are already established resulting in acceleration of their dominance (Brown 2000b). The connection between fire regime and exotic bush encroachment is well documented, especially in southern Africa with Australian *Acacia* species and pines (especially *Pinus patula*) (Bond 1997; Whelan 1995). In the Drakensberg

Mountains, the Australian *Acacia mearnsii* (black wattle) and *A.dealbata* (silver wattle) respectively, are establishing and displacing indigenous *Themeda*-dominated grasslands. This is especially prolific along riverine areas, which is problematic due to these species utilising large quantities of water and South Africa being a water scarce country. Therefore according to Scott (1993), all catchments still consisting of natural indigenous vegetation communities are subject to management by regular burning to prevent the further spread of these alien invasive species.

Fires in indigenous forests are not regular occurrences and are only experienced under certain conditions such as after long periods of extreme droughts. This is not usually on a large scale, in most cases it is only the forest edges that are exposed to the threat of fire due to the type of adjoining biome, i.e. grasslands. The understory vegetation species are relatively unaffected by fire, due to a high moisture retention which is suited for protection against fire damage (de Ronde *et al*. 2004b).

Both the abiotic and biotic components within an ecosystem are affected by fire. Even though the vegetation receives the primary impact, it is vital to consider the effects of fire on fauna, especially if the aim of management is to conserve biodiversity. Faunal species that are adapted to survive in fire-prone areas have developed responses to fire and includes avoidance, and active use of fire and burnt areas for feeding or as cues for breeding. Therefore fire has direct and indirect effects on fauna (Bigalke and Willan 1984; de Ronde *et al*. 2004b; Whelan 1995). Direct effects include mortality which is usually low due to avoidance responses (dispersal), with high levels being in flightless arthropods and insects in vulnerable development stages. Indirect effects of fire relate to the changes in the physical environment and vegetative structure and composition. This potentially could lead to changes in food quantity and quality, vegetative cover and micro-site characteristics such as ground temperature and soil moisture (Bigalke and Willan 1984; de Ronde *et al*. 2004b). Faunal species' populations are then in turn affected by the changes in the environment. Burns can favour certain species over others. Some species may utilise open areas created by burns for greater visibility, decreasing predation, whereas others may become more vulnerable to predation due to less cover (de Ronde *et al*. 2004b). However, according to de Ronde *et al*. (2004b), there are many deficiencies in the understanding of the effects of fire on fauna.

A useful simplification is that herbivores are either food quality or food quantity limited. Food quality is measured primarily by the level of nitrogen (protein) in the food (vegetation). In the first growing season post-fire, the primary productivity of the herbaceous layer is improved due to moribund material (fuel load) being removed by the fire and the stimulus received by the young tillers. This keeps grass species in a more productive and palatable growth phase. Post-fire tiller regrowth is more attractive to grazers, both livestock and wildlife, due to the higher levels of nitrogen and less structural carbohydrates/ fibre compared to unburned vegetation (de Ronde *et al*. 2004a; de Ronde *et al*. 2004b). These changes in food quality may have a cascade effect resulting in changes in population sizes and composition along with temporal and spatial redistribution of animals as they are deterred by, or attracted to, burned areas. These changes may occur over a few days, weeks or months. These movements are not only determined by burnt or not burnt but other functions, including; type of habitat burned including the surroundings, season and fire size. Food quality is the limiting factor in moist-fertile grasslands and savannas therefore herbivore use is affected by fires, exhibiting a range of responses, in time, to fire. Species can be classified into different groups based on post-fire grazing-recolonisation succession (Table 2.5) (de Ronde *et al*. 2004b). Species that make use of the immediate post-fire conditions, exploit the post-fire re-growth and use the habitat only after adequate re-growth has occurred such as oribi and mountain reedbuck. Browsers have a tendency to avoid burnt areas until sufficient browse re-growth has occurred. Despite the obvious advantages of recently burned area, which a large number of species prefer, there is still a need for unburned areas in the landscape due to the requirement of cover which is vital for species such as grey rhebuck, mountain reedbuck and oribi, due to the behavioural practice of lying-out, which lasts for at least six weeks after birth (de Ronde *et al*. 2004b).

Burrow-dwelling species such as the pygmy mouse (*Mus minutoides*), the multimammate mouse (*Mastomys natalensis*) and the forest shrew (*Myosorex varius*) are able to survive not only the fire but also the subsequent increase in the risk of predation and exposure before the vegetative cover is re-established. In the KwaZulu-Natal Drakensberg, burning decreased the abundance of small mammals, with only the presence of the forest shrew until re-growth allowed for the recolonisation of the area. However, long periods without burning also resulted in a decline in the number of species present (de Ronde *et al*. 2004b).

Bird species seem to be positively affected by fires in terms of the provision of food during or immediately after the fire. Species flock to fire fronts to feed on insects dispersing ahead of the fire front (e.g. Fork-tailed drongos, *Dicrurus adsimilis*), others feed on dead insects after the fire has past (cattle egrets, *Bubulcus ibis*) and some feed on recently burned ground (southern bald ibis, *Geronticus calvus*) (de Ronde *et al*. 2004b; Engstrom 2010). As with mammals, burnt areas have positive and negative repercussions when it comes to nesting with some species favouring burnt areas due to better predation detection, while for others, fire means the removal of habitat cover and potential destruction of nesting grounds (de Ronde *et al*. 2004b).

The mortality levels of insects after fires is high compared to other taxa but this is not the primary negative effect fire has on insects. Fire alters vegetation structure, food availability and microclimate. Numerous species respond to higher surface temperatures, caused by removal of vegetation, by moving their nests further underground. Most species in fire-prone areas can fly therefore potentially can escape the fire and repopulate at a later stage (de Ronde *et al*. 2004b; Engstrom 2010).

The main strategies reptiles and amphibians use are evasion and avoidance. Tortoises either shelter in crevices or behind rocks in rocky-areas or, in open less rocky areas they escape by moving to bare patches of ground. Other reptilian and amphibian species avoid fire by habitat selection (damp sites) or by moving underground into holes, beneath rocks, into trees or water sources such as wetlands (de Ronde *et al*. 2004b; Russell *et al.* 1999).

Table 2.5: Large mammal utilisation of post-fire areas in the Drakensberg Mountain Range of KwaZulu-Natal Province.

Species	▼ ● ■	Reference	Comment
Black wildebeest (*Connochaetes gnou*)	● ■	Brooks & Berry (1980); Gandar (1982); Wilsey (1996)	Area selective, prefers short grass, avoids grass when long.
Blesbuck (D*amaliscus dorcas phillipsi*)	●	Du Plessis (1972); Novellie (1978); Brooks & Berry (1980)	Feeds on short grass, prefers young growth after defoliation.
Grey rhebuck (*Pelea capreolus*)	● ■	Rowe-Rowe (1982); Oliver *et al.* (1978)	Favour grasslands: short, burnt for feeding and long grass for cover.
Mountain reedbuck (*Redunca falvorufula*)	● ■	Rowe-Rowe (1982); Oliver *et al.* (1978)	Feeds on short recently burnt grass, long grass for cover.
Reedbuck *(Redunca arundinum*)	● ■	Venter (1979)	Favours grasses when green and nutritious and recently burnt areas.
Oribi (*Ourebia ourebi*)	● ■	Everett *et al*. (1991); Rowe-Rowe (1982, 1983)	Requires short (feeding) and long grass (cover) during same year.
Red hartebeest (*Alcelaphus buselaphus*)	●	Gureja & Owen-Smith (2002); (Mills and Hes 1997)	Prefers medium height grasses, sprouting grasses after fires
Eland (*Tragelaphus oryx*)	● ■	Rowe-Rowe 1983; Rowe-Rowe and Scotcher 1986; Scotcher 1982; Frost & Robertson 1985	Mixed feeder, avoids burnt areas returns when green and nutritious.

Species that: ▼ exploit immediate post-fire conditions, ● utilise post-fire regrowth, ■ require sufficient post-fire regrowth

(Adapted from de Ronde *et al*. 2004b)

2.2.2.5 Limitations

"... [land] managers often need some immediate answers, while scientists often are unwilling or unable to provide complete answers without a lengthy study. A central problem here is the difficultly in dealing with scientific uncertainty. Often scientists are unwilling to provide scientific advice on a problem unless there is a very high degree of scientific certainty about the solutions being offered. On the other hand, a manager may use scientific advice and knowledge as if it were the final solution, and be unwilling to alter management practices and regulations in light of changing conditions and revised scientific ideas" (McAninch and Strayer 1989: 203).

The problems between the interface of ecological theory and land management highlighted above by McAninch and Strayer (1989) include; i) lack of appropriate scientific training whereby even if the land managers possess it, there is insufficient time for interpretation of available data and translation into practice, ii) Many researchers put forward theories without the under standing of the complication of the application of that theory in addition to determining the most relevant management data, iii) Ecological theories are sometimes poorly developed, most still being debated amongst ecologists, they are general ideas and predictions which are not tailored for certain situations, and iv) Knowledge of applying site-specific fire regimes resides with a small number of people, and when trying to achieve certain management aims and objectives, there are limited reliable data on the effectiveness of prescribed burning in doing so (Whelan 1995). Another problem is that conventionally scientists have been more concerned with understanding the workings of a system while land managers are predominately interested in behaviour prediction or control of a system (McAninch and Strayer 1989).

Besides the problems between theory and management, there is the simple but difficult task of prescribed burning at the ecologically correct time of the year. van Wilgen *et al*. (1990) highlight the difficulties in enforcing specific fire regimes due to time availability between high fire danger months and months where it is unacceptable to burn in ecological terms. A management program may require large areas of land to be burnt but there may be only a few weeks annually that are viable to do so (Fig. 2.1) (Whelan 1995). To compound matters further the acceptable time of year to burn coincides with the season with the highest fire danger (Whelan 1995). To deal with this problem many environmental managers burn rangelands out of season to stimulate a 'green bite' for grazing by wildlife and livestock. This is ecologically damaging and unacceptable as: the vigour of the grass sward is reduced, basal and canopy cover is reduced and an increase in runoff of rainwater could potentially result in accelerated soil erosion (de Ronde *et al.* 2004a).

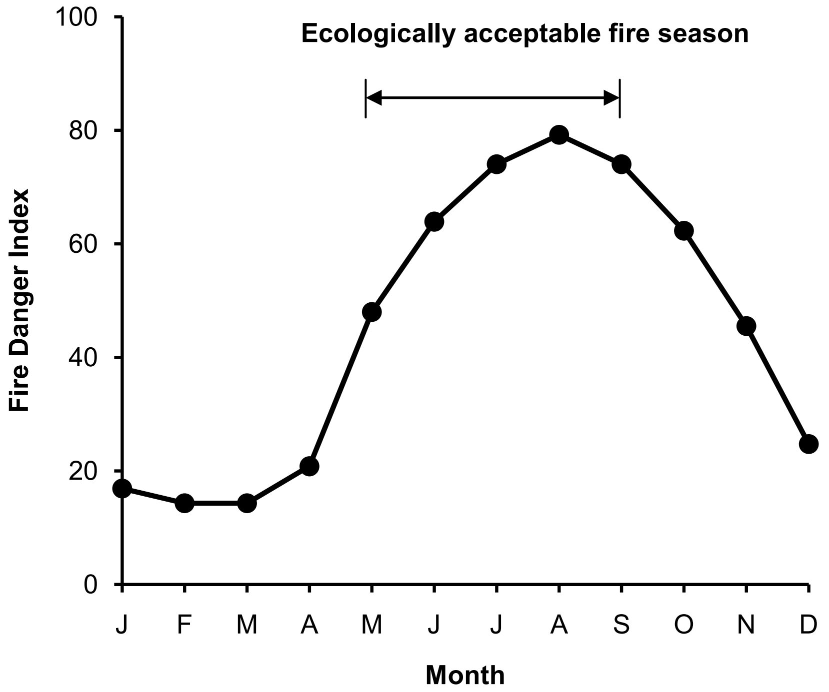


Figure 2.1: The annual cycle of fire danger at a typical KwaZulu-Natal Drakensberg site. The ecologically acceptable burning season runs from early winter (May) to early spring (late August). Burning operations are feasible for this entire period, however this coincides with the highest fire danger indices (van Wilgen *et al.* 1990).

The prescription of fire has a number of problems which have to be dealt with quickly to prevent unnecessary burning or loss of property from runaway fires. Embers are a major problem in the burning of prescribed fires and extinguishing of wildfires. Burning vegetative materials, such as leaves, are lofted into the air by convection caused by rising hot air. These embers may be carried by prevailing winds to new areas, even jumping fire breaks propagating fire ahead of the burning front (Zedler 2007).

Due to an increase in ignition rates and an expanding interface between the natural environment and urban infrastructure, fire management is receiving increasing attention. Fire management is controversial due to conflicts in objectives. Some objectives and policies are driven by protection of built-assets, with little thought to conservation of biodiversity. Failure to correct this approach and the resultant conflicting objectives, could result in significant environmental degradation and loss of species (Driscoll *et al.* 2010).

Prescribed fires, with the objective of asset protection may involve large scale burning through regions containing predominately indigenous vegetation. Short fire return intervals (1 to 4 years) are required to reduce fuel build up, minimising the risk to assets. The effectiveness of these prescribed burns to protect against wildfires is reduced under severe fire weather. The effectiveness is dependent on the distance between the asset and a rea burnt, with closer proximity burns offering higher risk reduction then dispersed burns (Driscoll *et al.* 2010). This risk reduction only takes the asset into consideration, ecological impact of these prescribed fires and management objectives are secondary.

2.2.2.6 Fire Management in the future

"Global change, the combined effect of human activity on atmospheric and landscape processes, affects all aspects of fire management" (Ryan 2000: 175).

According to Houghton *et al*. (1996) and Watson *et al*. (1996 cited in Ryan 2000) there has been an increase in atmospheric carbon dioxide causing changes in the global carbon cycle, increased levels of nutrient deposition (e.g. nitrogen) resulting in the modification of the biogeochemical cycling and land use and cover transformations. The above unnatural trends are set to continue into the future. The combustion of biomass (e.g. wood, fossil fuels) and industrial processes are the cause of the changes in the atmospheric chemistry, which in turn will significantly impact on the biogeochemical processes in addition to the changes in radiation levels, well known as the greenhouse effect (Ryan 2000). The modification of the atmosphere's composition and radiation balance will have a cascading effect on environmental aspects such as precipitation, temperature, humidity and vegetative development, thus affecting ecological and fire management. These meteorological alterations together with changes in land use (i.e. roads, subdivisions, farming, plantations) will further alter vegetation and fuels (Ryan 2000). The potential increase in the incidence of extreme fires, brought on by climate change, has resulted in concern of increases in frequency, intensity and extent of wildfires (Bowman and Murphy 2010), ultimately resulting in changes to fire regime characteristics (Ryan 2000). Further complications for prescribed fire management come from continual movement of the urban fringe into wildlands (Ryan 2000).

The increase of carbon dioxide concentrations potentially increases the plant productivity (especially C_3 species), hence fuel load abundance which affects fire frequency and intensity. Nitrogen levels in foliage may decrease with the increase in carbon dioxide, resulting in larger fuel loads due to slower decomposition (Bowman and Murphy 2010). However, the effects of climate change on fire frequency and intensity will vary significantly between biomes. Woody plants may be favoured by increases in carbon dioxide in environments with both trees and grasses meaning a decrease in grass species composition and abundance. A decrease in these highly flammable grass species will result in a decrease in fire frequency and intensity, further promoting this shift from grass to woody species dominated landscape (Bowman and Murphy 2010).

Complications in fire management will increase given that fire risk, ecosystem functioning and habitat template will change for many species, invasive species included (Bowman and Murphy 2010). Due to the complexity of climate change, it is difficult for accurate estimations regarding rate and direction of change creating a growing interest in the consequence of landscape-level fires on the distribution of vegetation in a changing environment (Bond 1997). However, what is clear from the current perspective is that future changes will increase the pressure placed on fire management organisations to meet their desired objectives (Ryan 2000). According to Dunlop and Brown (2008), trying to maintain current fire regimes through prescribed burning will become resource intensive with restricted success resulting in a negative impact on biodiversity compared to the effects of the natural regime changes. Therefore it will potentially be more efficient to allow change and manage the outcomes; with the challenge of doing so while still protecting habitat suitable for sensitive species, in addition to managing threats to infrastructure and urban areas.

2.3 Environmental Decision Support System (EDSS)

Science is increasingly being called upon to provide information for complex environmental decision making (Liu *et al*. 2008: 846).

The appeal for effectively integrating science and decision making is ever-present in environmental management. Scientists are frustrated with decision makers ignoring their inputs while the decision makers are disgruntled as vital information required for their decision making is frequently not accessible or not presented in useable formats (Liu *et al*. 2008). The result of this is large gaps in knowledge between science and decision making, affecting the information flow across the knowledge and applied boundary. The suggestion put forward is that scientist need to provide information that is compatible with decision makers' requirements and to enhance the information's credibility, legitimacy, and saliency which will increase the probability of the research results being adopted (Liu *et al*. 2008).

One approach could be though the use of Decision Support Systems (DSSs) which will aid managers in making vital decisions in circumstances where human judgement is recognised as an important factor in the problem solving process, however ' human information processing' limitations impede this decision making process (Rauscher 1999). They add value, when introduced into the decision making process, by making scientific knowledge available to the decision makers (van Delden *et al.* 2011) by making use of models, analytical techniques and information retrieval to develop and evaluate alternatives (Sojda 2007). A DSS is generally defined, by Matthies *et al*. (2007: 123), as an "interactive, flexible, and adaptable computer based information system especially developed for supporting the recognition and solution of a complex, poorly structured or unstructured, strategic management problem for improved decision-making. It uses data and models, provides an easy, user-friendly interface, and can incorporate the decision-makers own insights." The ideal aim is to intensify the decision makers' power without compromising their right to utilise human judgement and choice making. They attempt to combine the human intellectual flexibility and imagination with the speed and accuracy of the computer (Rauscher 1999). According to Bui (2000), the development process of decisions support system consists of five building blocks (Table 2.6).

Table 2.6: Development building blocks for Decision Support Systems.

Building Blocks	Description
Information resource management	Input data required for decision analysis and resolution; output data generated and presented to decision makers for policy making. Effective management of these data constitutes a major task of any decision support tool.
Model Management	A model is a reality abstraction created to aid decision makers focus on main elements of a problem. Multiple objective optimisation under constraints. Given a decision problem, the challenge faced by a DSS is finding the best decision method/s able to suggest a satisfying solution to policy makers.
Interactive problem solving	Direct interaction between the DSS and its users allows for a more responsive and user-centred view of the problem. Good DSSs provides the correct information to the right person at the right time with full transparency. Should also provide cognitive feedback to decision makers by helping in the comprehension of dynamic changes in the underlying assumptions.
Communications and teamwork support	Usually the decision making process involves more than one decision maker and support for communication and coordination is an important dimension of DSS. Support for information exchange, federated organisational memory, group decision and negotiation is an integral component of organisational decision support.
DSS as non-human co-workers	In a tightly connected networked world, we postulate a working scenario in which humans will team up with computers as co-workers to optimise execution of management decisions (Negroponte 1995). In the multi-dimensional context of management, various DSS could serve as task-specific aids to policy makers.

(Summarised from Bui 2000)

2.3.1 EDSS in Natural Resource Management

The survival and quality of life of the human species is dependent on the ability to manage earth's natural resources (Rizzoli and Young 1997). The sustainable natural resource management is complex, relying on informed actions of both individual users and managers of these resources. There is greater complexity, however, in sustainable management of both on- and off-site natural resources than exclusively for economic efficiency or ecological conservation. In addition features of the resource base need to be monitored, evaluated and managed and a more holistic view of potential and cumulative impacts, is required (Walker and Johnson 1996). Adding to the complexity is legislative, economic and societal demands, conflicts and expectations, meaning decision makers must have the ability to prove that any decisions made were scientifically based and accurate (Liu and Stewart 2004; Walker and Johnson 1996). When it comes to natural resource management, EDSSs have a strong role to play in the facilitation of improved decision making by allowing the effective use of current scientific data and understanding of decisions that are increasing in complexity but are usually poorly structured (Sojda 2007; Walker and Johnson 1996).

The sustainable management of ecosystems and their resources (both terrestrial and aquatic) requires the inclusion of environmental and ecological factors in policy-making. There needs to be the development of a suitable instrument or tool to allow the policy-makers to take these factors into consideration (Matthies *et al*. 2007; Sojda 2007). Although this is possible without a support tool, other factors complicate the decision-making process such as the interactions between the natural, economic and social systems and the poorly-structured nature of environmental decision-making (Matthies *et al*. 2007; Reitsma 1996). Therefore the application of an environmentally based decision support system is vital (Matthies *et al*. 2007). "An environmental decision support system (EDSS) often consists of various coupled environmental models, databases and assessment tools, which are integrated under a graphical user interface (GUI), often realized by using spatial data management functionalities provided by geographical information systems (GIS)" (Matthies et al. 2007: 123). According to Bui (2000), certain factors should be taken into consideration when designing environmentally based decision support systems for natural resource management (Table 2.7).

Table 2.7: Factors involved in designing environmental decision support systems

Design Factors	Description
Decision makers	Decision makers should be solicited beyond the reliance of public authorities. All stakeholders should democratically and pro-actively assume their decision-making responsibilities in taking charge of their fate and that of future generations- in spite of a decision environment prone to faulty assumptions and lacking of incentives for personal integrity.
Decisions	Decision making in natural resource management should embrace all economic, social, political and environmental components to maximise productivity while assuring the long-term viability of natural systems.
DSS modelling approach	Modelling environmental management problems requires research and gathering of economic and ecological information, comprehensive goal formulation and constraints, and context-dependent knowledge and heuristics for problem solving. Modelling implies management of interdependencies between multiple and conflicting goals, a search for solutions that are equitable to current and future generations, and assessment of potential and chronic threats and protection from counterproductive disruptions.
Database requirements	Quality data are required for successfully putting modelling into practice. Research into database design often cautions the difficulty in setting up data for DSS. Data needed for DSS are typically historical data with extrapolation potential. The data are typically retrieved and combined from multiple sources, characterised by a varying degree of detail and accuracy. Conventional database management systems are not designed to handle these types of requirements effectively.
Visualisation and interface requirements	Decision algorithms should be transparent to policy makers. Interface controls should be designed to allow DSS users to "navigate" the problems at hand through time (e.g. past experience, current impacts, and future consequences), space, problem determinants, and perspectives.

(adapted from Bui 2000)

The complexities in decision problems and EDSSs can be managed by modelling. The attempt to understand the various aspects of a decision problem and the decision making process is pointless if attempting to efficiently and effectively implement an EDSS in the absence of a form of framework or models (Liu and Stewart 2004). The application of modelling during the decision making process can model the EDSSs while reducing the artistic skills required in modelling EDSSs. The introduction of modelling can bridge the space between scientists and decision makers as the EDSS design, implementation and evaluation processes are made understandable to both parties (Liu and Stewart 2004).

Wildland fire management is affected by various sources of uncertainty. Besides the natural unpredictability associated with fire behaviour, uncertainty sources include: missing or incorrect data, incomplete scientific understanding of ecological response to fire and fire behaviour response to management treatments (fire suppression, fuel reduction, etc.) and limited measurements of resource value to guide prioritisation across fires and resources that are at risk (Thompson and Calkin 2011). The addition of spatio-temporal dynamics associated with climate change, vegetative succession, species migration and disturbance regimes add further uncertainty and complexity to strategic management. The recognition of these various uncertainties resulted in decision makers and scientists developing numerous decision support tools and systems to aid in the decision making process (Thompson and Calkin 2011). According to Sojda (2007: 269), "decision support systems should contribute to reducing the uncertainty faced by managers when they need to make decisions regarding future options".

2.3.2 Geographical Information Systems (GIS)

Decision support systems are utilised during strategic planning, in particular where scenario analysis and simulation models are needed in policy-making. Due to the spatial element of natural resource management, DSSs are integrated into GIS tools, providing spatial functionality (Matthies *et al*. 2007). According to Matthies *et al*. (2007), Environmental Decision Support Systems EDSS's are rapidly developing as: spatial databases (geodatabases) improve, increase in availability of long-term data sets and computing techniques and modelling advance.

According to Nath *et al*. (2000), a geographical information system (GIS) is an assemblage of hardware, software and data (geographic) with the purpose of acquiring, manipulating, retrieving, analysing, reporting and displaying geographical information in an efficient manner to achieve specific objectives. Major reasons why the utilisation of GIS as a powerful analytical tool has increased in natural resource management is its statistical capabilities (calculations of area and perimeter, variance reports, coverage comparisons) and its ability to visually represent outcomes (2D and 3D maps). For example, national parks or watersheds can be viewed in three dimensions, useful in total area calculations and decision impact evaluation (Matthies *et al*. 2007; Nath *et al*. 2000). GIS provides the ability to merge natural resource data with fire management data. Therefore fire management data can be statistically and visually analysed efficiently at a landscape-scale which, with the absence of a GIS, would not be possible (Caprio *et al*. 1997). Thus, GIS can aid resource management decision making and underpins many of the decision support technologies (Walker *et al.* 2001). The functionality of GIS and their associated tools can be applied at various stages of the decision making and planning process (Fig. 2.2).

The use of GIS and their associated decision-making tools in natural resource management is constrained due to numerous factors, including: lack of appreciation of the GIS technological capabilities, inadequacy in principle and methodology understanding, lack of administrative commitment in ensuring continuity of GIS and associated spatial decision support tools and limited communication between GIS analysts, specialists and end-users (Nath *et al*. 2000).

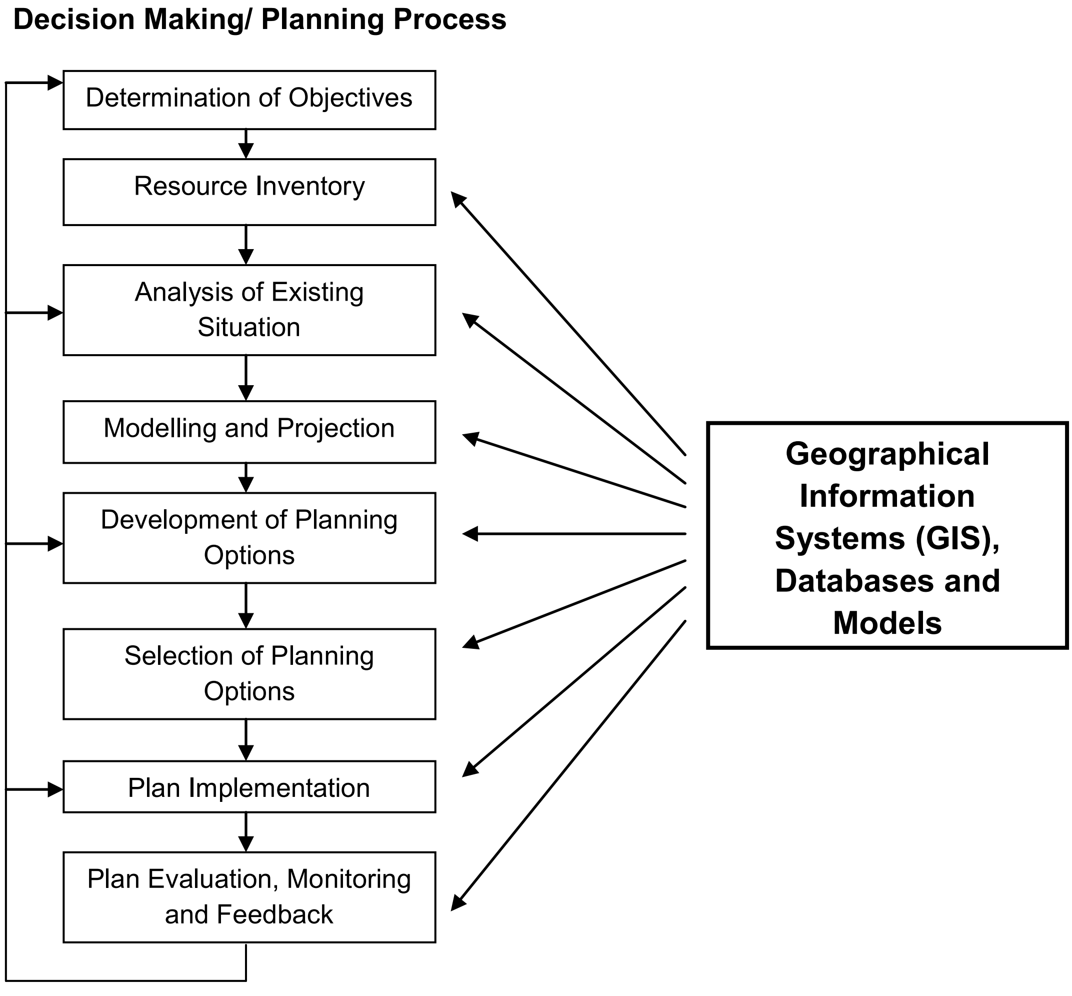


Figure 2.2: Integration of GIS, databases and models into the planning process of natural resource management (adapted from Gar-On Yeh 2000)

2.3.3 Use of EDSS in Fire Management

According to Bonazountas *et al.* (2007), there have been numerous efforts to develop EDSSs for fire management by utilising technologies such as GIS, however no integrated system exists. There have been a plethora of software programs created to predict where fires may occur or behave for fire prevention and fighting, but not in determining which areas require prescribed burning to satisfy a specific fire regime (e.g. Bonazountas *et al.* 2007; Iliadis 2005; Keramitsoglou *et al*. 2004; Lee *et al.* 2002; Wybo 1998).

2.3.4 Conclusion

Environmental DSSs are intelligent information systems with the aim of time reduction of decision making in an environmental domain and improvement of those decisions, both in consistency and quality. Due to the implication that to make decisions means that there is a problem awareness, means that it must be based upon information, experience and knowledge of that process (Poch *et al.* 2004). EDSS are built to incorporate artificial intelligence methods, geographical information systems, statistical analysis techniques and environmental ontologies (Fig. 2.3) (Poch *et al.* 2004).

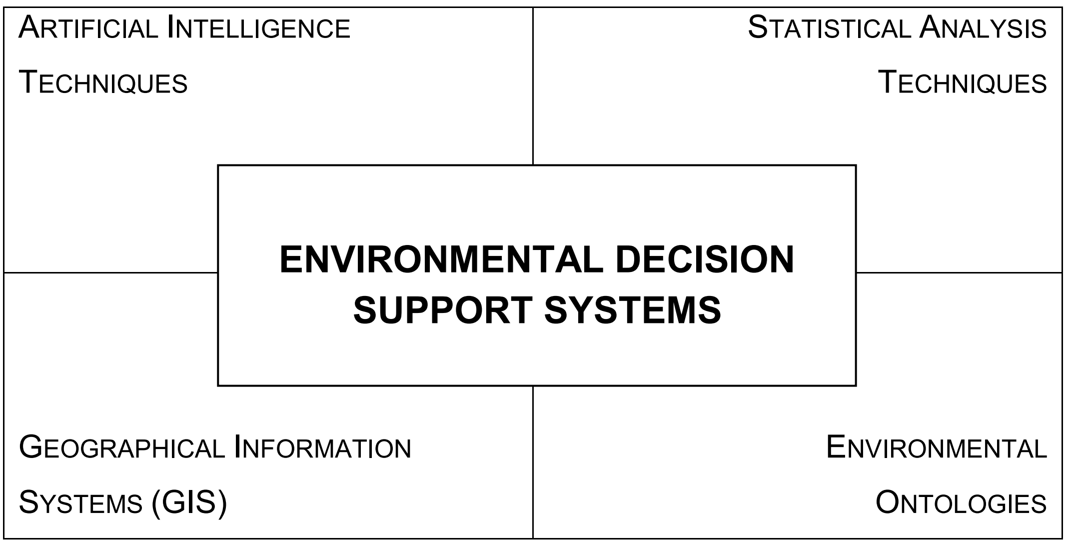


Figure 2.3: Components of a conceptual EDSS.

2.4 The Drakensberg Mountain Range

The Drakensberg Mountain Range forms the most southern point of the African archipelago mountain system (White 1978), forming part of the Great Escarpment of South Africa, separating the interior high-altitude plateau from the thin coastal belt. It ranges almost the entire country, spanning more than 1 000 kilometres, from the town of Elliot in the south to Tzaneen in the north-eastern part of South Africa (Carbutt and Edwards 2004). The major regions of the Drakensberg are located in KwaZulu-Natal and Eastern Cape provinces. Cliffs, grasslands, indigenous forest patches, mist, high levels of summer rainfall, frost and snow characterise this unique landscape (Matthews and Bredenkamp 1999).

Werger's (1978) phytosociological study of Africa describes two, out of seven, floristic regions that are represented in the Drakensberg Mountain Range, namely the Afro-alpine and Afromontane Regions (see Killick 1978 and White 1978). According to Acocks (1988) the vegetation complex of the park consists of three of the 70 South African Veld Types, namely *Themeda – Festuca* Alpine Veld (no. 58), Highland Sourveld (no. 44a) and a small area of Southern Tall Grassveld (no. 65). The majority of the area consists of grasslands, along with small patches of wooded areas that are restricted to lower altitudes and moist south-facing slopes. There are high levels of variation in the topography from extremely exposed basalt cliffs to more sheltered sandstone formations and from undulating hill slopes to river valleys, including rocky gorges and pristine steep-sided valleys (van As and du Preez 2006). Harboured within this basalt and sandstone escarpments are caves and rock shelters containing the largest concentration of early San rock art in sub-Saharan Africa, depicting the Khoisan peoples' beliefs and way of life over four thousand years ago (KNCS 1999).

Conservation is required due to the level of biodiversity of endemic and threatened floral and faunal species supported by the Drakensberg. The only community of afro-alpine vegetation found in southern Africa is located between Lesotho, Eastern Cape and KwaZulu-Natal. One of the main features of this vegetation is the extremely rare (due to limited range on the subcontinent) extensive network of wetlands (Johnson *et al.* 1998; Killick 1978). The region's ecological heterogeneity is a result of a high geological and geomorphic diversity, altitudinal range, extremes in temperature, high rainfall and a variety of high altitude wetlands (i.e. springs, tarns, peatlands and streams). Ten rivers or major streams have their origin in the Park which includes the Boesmans, Mkhomaasi and Mzimkhulu rivers and Tugela tributaries, making the Park one of the country's major water catchments (Irwin and Irwin 1992; KNCS 1999).

2.4.1 Physical Features

The Drakensberg Mountains runs along the border of the Kingdom of Lesotho, forming a double rampart of escarpments on the edge of the plateau. This escarpment is, according to Matthews and Bredenkamp (1999), the most important geomorphic feature in southern Africa. It contains several peaks reaching over 3 000 metres above sea level (a.s.l.) forming part of a barrier of jagged basalt-capped peaks containing an array of summits and plateaus, cliffs, buttresses and deep valleys amid high spurs (KNCS 1999). Between this and a second escarpment, at 1 000 metres below, are high-altitude grass-covered slopes banded with basalt. The second escarpment referred to as the Little Berg comprising of fine-grained sandstone which falls away into steep-sided river valleys and rocky gorges containing patches of various vegetation types (forests, thickets and grassland) in addition to waterfalls, cascades and rock pools (KNCS 1999).

2.4.1.1 Geology

Geologically, the Drakensberg Mountains consists of sedimentary rocks, namely sandstone and mudstone (Stormberg Group). An accumulation of basalts (igneous lava rock formations) cap this sedimentary layer in the KwaZulu-Natal Drakensberg areas, forming the peaks and cliffs (Drakensberg Group) (Matthews and Bredenkamp 1999; Sycholt 2002; van Wyk and Smith 2001). The Amphitheatre located at the Royal Natal National Park contains high basalt cliffs that form a crescent over 600 metres high and runs a length of 5 kilometres (KNCS 1999). The KwaZulu-Natal Drakensberg contains the highest peaks of the escarpment, with the highest being Thabana-Ntlenyana peaking at 3 483 metres a.s.l. (Matthews and Bredenkamp 1999; van As and du Preez 2006; van Wyk and Smith 2001).

The sedimentary rocks that underlie these cliffs were formed with numerous depositions in a basin that was developed through compressional tectonics in the Cape Fold belt to the south and south-east. This sandstone succession reaches up to 150 metres in thickness that accumulated as desert dunes and wadi systems during the dry Late Jurassic epoch, with its most distinctive feature being the sandstone high cliffs of the Clarens Formation (KNCS 1999; Sycholt 2002; van Wyk and Smith 2001). The resultant soils are largely acidic lithosols (KNCS 1999). Footprints of quadrupedal and bipedal dinosaurs are preserved in the lacustrine and interdune sediments, which are exposed in caves and overhangs roofs (KNCS 1999).

2.4.1.2 Climate

The climate is broadly classified as temperate with summer rainfall (van Wyk and Smith 2001). The subtropical anticyclones have a significant influence on the climate of the Drakensberg mountain range, resulting in high volumes of water leading to precipitation levels exceeding evaporation levels. There is a distinct dry season due to subsidence of cold air causing atmospheric stability. In summer, this subsidence inversion layer will ascend above the escarpment allowing the influx of humid air from the Indian Ocean. The humid air is a prerequisite for the formation of rain-bearing clouds, with precipitation predominantly being in the form of thunderstorms (KNCS 1999). There are large variations in mean annual rainfall, from 635 mm to over 2 000 mm on the main escarpment, mostly received (70%) between November and March (KNCS 1999; van Wyk and Smith 2001).

The annual mean temperature is ± 16 degrees Celsius however considerable altitudinal variations both seasonally and diurnally occur. During summer, the north-facing slope at lower altitudes receive the highest temperatures reaching 35 °C, with the plateau, during winter, receiving the lowest temperatures of -20°C (Irwin and Irwin 1992; KNCS 1999; van Wyk and Smith 2001). Snow and frost are common occurrences in winter between April and October at higher elevations and lower altitudes when there is cold air draining into the valleys from the plateau, with mist occurring almost daily year-round. The topography however controls their distribution and severity (KNCS 1999).

2.4.2 Ecology and Biological Diversity

2.4.2.1 Flora

The present vegetation assemblage is a consequence of the effects of climate and fire along with the complexities of geology, topography (slope and aspect), elevation, soils and drainage (Matthews and Bredenkamp 1999). The vegetation of the Drakensberg is predominately grasslands and characterised by altitudinal belts that follow the physiographic features. These three belts are the: montane belt (1280- 1830 metres a.s.l.), the sub-alpine (1830- 2865 metres a.s.l.), and the alpine belt (2865- 3500 metres a.s.l.) (Hill 1996; Johnson *et al.* 1998; Killick 1963, 1978, 1990; Matthews and Bredenkamp 1999; Sycholt 2002; van Wyk and Smith 2001) (Fig. 2.4 and 3.2). The montane zone ranges from the base of the basalt cliffs to the valley floors below (Johnson *et al.* 1998), dominated by *Themeda triandra*, which rapidly disappears with the exclusion of fire (Killick 1963; Whelan 1995). The majority of spurs contain *Protea* savanna (composed of *Protea caffra* and *P. roupelliae*), with

Podocarpus latifolius (Real Yellowwood) mountain forests being found in moist valleys sheltered from fire. The sub-alpine zone contains *Themeda-Festuca* grasslands dominating lower altitudes and *Passerina-Philippia-Widdringtonia* fynbos scrubland becoming the climax community in the higher altitudes (Hill 1996; Johnson *et al.* 1998; Matthews and Bredenkamp 1999). A climax heath is found in the alpine zone, dominated by species from the *Erica* genus such as *E. dominans* and *E. algida* and several *Helichrysum* species, with extensive alpine grasslands (dominated by *Festuca caprina*, *Merxmuellera disticha* and *Pentaschistis oreodoxa*) being interspersed amongst the *Erica-Helichrysum* alpine fynbos (heath). Woody plant communities are found in rocky enclaves throughout the three belts, dominated by species such as *Cliffortia linearifolia*, *Leucosidea sericea* and *Buddleja salviifolia* (Hill 1996; Johnson *et al.* 1998; van Wyk and Smith 2001) (Fig. 2.4). Grasslands, the major vegetation type of the Drakensberg, constitute 19 % of the Plant Diversity Centres, 11% Endemic Bird Areas and 29% of ecoregions (outstanding in terms of biological distinctiveness (Arnott 2006). The high-altitude wetlands or tarns are very diverse with 36 endemic species and a high diversity of restricted species (KNCS 1999). Connected wetlands systems stretch across the entire altitudinal gradient with the alpine and sub-alpine belts containing wetland meadows (high and low-altitude vlei's respectively) dominated by *Merxmuellera*, *Rhodohypoxis* and *Crassula* species. *Festuca caprina* is the major grass species in the sedge-grass meadows and marshes containing predominantly *Carex acutiformis, Isolepis fluitans* or Cyperaceae and Juncaceae families (Hill 1996; Johnson *et al.* 1998). The waterlogged areas of the montane belt are usually *Miscanthus capensis* meadows (Johnson *et al.* 1998). The floral assemblage found in the highest altitude areas of the Drakensberg has been compared to the alpine tundra of northern Europe, with the highest level of endemism been recorded on the highest peaks (Briggs 2006; van As and du Preez 2006).

The montane grasslands of the escarpment were thought to have originally been covered by a forest climax community and through frequent anthropogenic burning, the forest species were reduced to refugia areas and replaced with subclimax grassland communities (Acocks 1975). However, recent evidence indicates that the grasslands were originally the dominant climax community of that region. Due to grasslands being adapted to fire, occurring annually or biennially, indicates the presence of natural fires in these montane systems before the arrival of humans, making these grasslands a fire climax community (O'Connor and Bredenkamp 1997) (Fig. 2.5). Further evidence, is the high biodiversity and subsequent levels of endemism which is an indicator of age of these species-rich systems, while conversely, forests are relatively homogenous in terms of species not only in the Drakensberg but throughout there African range (Matthews and Bredenkamp 1999).

According to Acocks (1988), the Drakensberg consists of three veld/ vegetation types. The dominant type is the Highland Sourveld, which consists predominately of *T. triandra, Tristachya leucothrix* and *Alloteropsis semialata*. The *Themeda- Festuca* veld type found between 1 850- 2 150 m.a.s.l. is dominated by *T. triandra*, along with a high proportion of species that usually do not occur so prominently, such as several species from the *Festuca* genus. The small area of Southern Tall Grassveld is found up to 1 350 m.a.s.l. and is dominated by *T. triandra, Hyparrhenia hirta* and *T. leucothrix* (Acocks 1975). Along with Acocks (1975); Hill (1996), Johnson *et al*. (1998), Killick (1963), Phillips (1973) and Werger (1978) have made the use of altitudinal zonation to classify vegetation. In terms management of the Drakensberg, it is imperative that there is a conscious realisation of the variations in vegetation patterns that results from changes in altitude (Priday 1989).

2.4.2.2 Fauna

*"the [Drakensberg] plains for miles around had somewhat the appearance of a living ocean, the tumultuous waves being formed by the various herds crossing and re-crossing each other in every direction" (*Chapman 1868: 6)

The faunal species richness is not as renowned as its flora counterpart, however the vast range of niches created by this high floral richness results in a unique faunal diversity. There are numerous mammal, bird, reptile, frog and fish species with a high proportion being endemic or endangered. Their numbers were significantly higher in the past but due to past anthropogenic forces, a number of species have declined dramatically in number (in some cases becoming locally extinct) requiring repopulation from other regions or resulting in a total loss of species (Barnes 2003; Sycholt 2002).

The mammal species include the Chacma baboon *Papio cynocephalus ursinus*, brown hyena *Hyaena brunnea*, blackbacked jackal *Canis mesomelas*, aardwolf *Proteles cristatus*, serval *Felis serval*, small grey mongoose *Galerella pulverulentus* in addition to the largest populations of the clawless otter *Aonyx capensis* and spotted-necked otter *Lutra maculicollis* found in the KwaZulu-Natal and possibly South Africa (Briggs 2006; KNCS 1999; Sycholt 2002). Eleven out of the 16 rodent species are endemic to South Africa. There are large populations of antelope, 11 species in total including estimated populations of 1 500- 2 000 of the endemic grey rhebok *Pelea capreolus*, 2 000 el and *Taurotragus oryx* and 1 000 reedbuck *Redunca arundinum* in addition to bushbuck *Tragelaphus scriptus*, blue duiker *Cephalophus monticola*, klipspringer *Oreotragus oreotragus* and oribi *Ourebia ourebi* (KNCS 1999; van As and du Preez 2006).

There are approximately 300 recorded bird species which comprise 37% of the South African non-marine bird species. From these species 10 are internationally threatened and 18 are found in the Red Data Book for South Africa (Brooke 1984; KNCS 1999; Sycholt 2002; van As and du Preez 2006). The Drakensberg mountains contains an Endemic Bird Area of the world with 43 endemic species (including species with restricted range): the whitewinged flufftail or crake *Sarothrura ayresi*, Cape eagle-owl *Bubo capensis*, ground woodpecker *Geocolaptes olivaceus*, buffstreaked chat *Saxicola bifasciata*, yellowtufted pipit *Anthus crenatus*, Cape rock thrush *Monticola rupestris*, sentinel rock thrush *Monticola explorator*, and Drakensberg prinia *Prinia hypoxantha*. The woodland areas include the Gurney's sugarbird *Promerops gurneyi* and the high altitude species comprise of the yellowbreasted pipit *Anthus chloris*, mountain pipit *Anthus hoeschi*, drakensberg rockjumper *Chaetops auranticus*, and drakensberg siskin *Serinus symonsi* (which have restricted distribution to the escarpment) (KNCS 1999; Matthews and Bredenkamp 1999). The alpine heath species are the grey tit *Parus afer*, sicklewing chat *Cercomela sinuata* and Layard's warbler *Sylvia layardi* and the cliff dwelling species of the Cape vulture *Gyps coprotheres* (globally threatened), Bearded vulture (lammergeyer) *Gypaetus barbatus* (highly restricted range), lanner falcon *Falco biarmicus*, jackal buzzard *Buteo rufofuscus* and black stork *Ciconia nigra* (10-15 pairs). Grasslands (marshes included) support the black-headed heron *Ardea melanocephala*, blue crane *Grus paradisea*, wattled crane *Grus carunculata* (threatened), southern bald ibis *Geronticus calvus* (globally threatened), Stanley's bustard *Neotis denhami*, black harrier *Circus maurus*, African marsh harrier *Circus ranivorus*, lesser kestrel *Falco naumanni* (globally threatened), white stork *Ciconia ciconia* and corncrake *Crex crex*. Finally, the forest and thicket species are the chorister robin-chat *Cossypha dichroa*, black bushcap *Lioptilus nigricapillus*, African scrub warbler *Bradypterus barretti* and forest canary *Serinus scotops* (KNCS 1999; van As and du Preez 2006).

There are eight fish species which includes two introduced salmonidae species in addition to the rare endemic Drakensberg minnow *Oreodaimon zuathlambae*, rock catfish *Austroglanis sclateri* and the Maloti minnow *Pseudobarbus quahlambae* which was previously thought to be extinct (Briggs 2006; Sycholt 2002; KNCS 1999; van As and du Preez 2006). According to Matthews and Bredenkamp (1999), the rare endemic Treur River barb *Barbus treurensis*, is heavily restricted to a small area in the upper reaches of the Treur River. This river (narrow stream at this stage) is dissected by an impassable waterfall which is the only reason this species is not extinct due to an introduced predator, the trout (salmonidae), being unable to move upstream.

Of the 124 species and subspecies of amphibians found in South Africa, 21% (26 species) are found in the Drakensberg, including rare endemic species: longtoed tree frog *Leptopelus xenodactylus*, Natal chirping frog *Arthroleptella hewitti* and Natal and Hewitt's ghost frogs *Heleophryne hewitti* and *H. natalensis.* There are several species that are limited to a small range at very high altitude and low temperatures: water rana *Rana vertebralis*, Drakensberg frog *R. dracomantana*, Drakensberg stream frog *Strongylopus hymenopus*, Drakensberg toad *Bufo gariepensis nubicolus* and dwarf dainty frog *Cacosternum nanum parvum* (Johnson *et al*. 1998; KNCS 1999; van As and du Preez 2006). The reptilian species comprise of 23 lizard species including three endemic species namely Lang's crag lizard *Pseudocordylus langi* (listed in the South African Red Data Book and only found in isolated areas above 3 000 m), *Tropdosaura cottrelli* and *T. essexi* and the water monitor *Varanus niloticus*, the spiny crag lizard *P. spinosus* and Drakensberg dwarf chameleon *Bradypodium dracomontana*; two near endemic geckos; and 25 snake species, with the cream-spotted mountain snake *Montaspis gilvomaculata* (monotypic genus) being the only endemic (KNCS 1999; Branch 1988; van As and du Preez 2006). Some of the lizard species contain *Plasmodium* blood parasites (malaria) with high infection levels been found in high-altitude species (van As and du Preez 2006). The Eastwood's long-tailed seps (*Tetradactylus eastwoodae*) is a small snake-like plated lizard that has not been recorded since it was scientifically described in 1913. This is due to the complete habitat destruction of where this rare seps was originally located (Matthews and Bredenkamp 1999). Less known is the invertebrate fauna however the region does contain numerous endemic species, having 28% of the countries dragonfly species and approximately 12% of the country's butterfly species (KNCS 1999), this includes the extremely rare and poorly known Mokhotlong Blue *Lepidochrysops loewensteini*, the widespread, however restricted by habitat, Sylph *Mertisella syrinx* (Johnson *et al*. 1998); and the obscure *Charaxis marieps* (Matthews and Bredenkamp 1999).

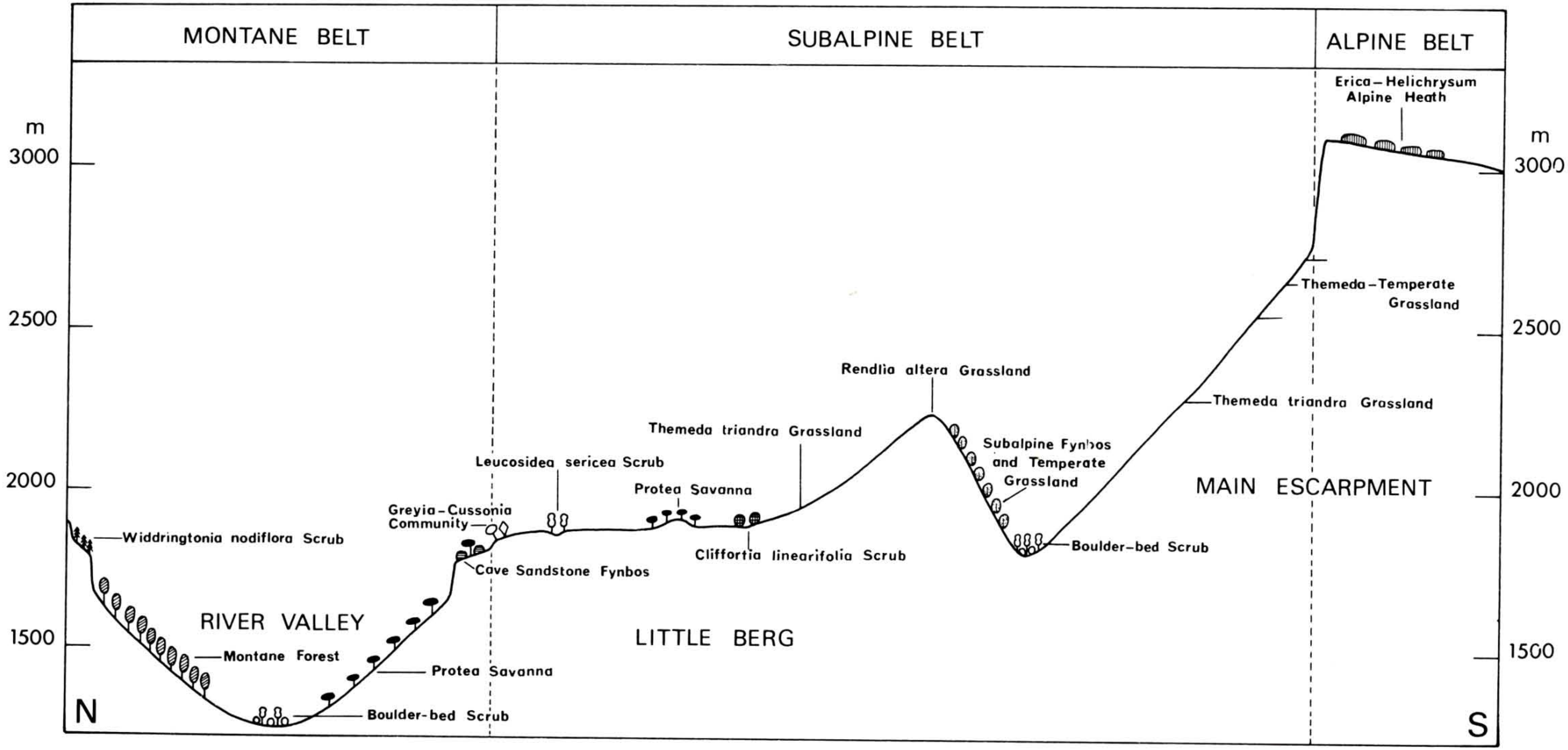


Figure 2.4: Cross-sectional profile through the KwaZulu-Natal Drakensberg showing the three altitudinal belts and their associated vegetation communities (from Killick, 1978).

2.4.2.3 Water and Wetlands

South Africa can be regarded as an arid country making water a major limiting factor in terms of economic development and growth. The mountain catchment areas are vital as the source of the country's rivers and consequently the country's water supply (Scott 1993).

The Drakensberg mountain range is South Africa's most important catchment area due to the quality and quantity of water. Numerous major southern African rivers and their associated tributaries have their sources in the Drakensberg, such as the Tugela and Orange Rivers. The Tugela flows over the Tugela Falls dropping a total of 850 metres in five drops (the highest waterfall in South Africa, one of the highest in the world) against the Amphitheatre (Briggs 2006; Matthews and Bredenkamp 1999; van As and du Preez 2006). The longest river in southern Africa, the Orange, originates in the Lesotho Highlands and meanders westward into the Atlantic Ocean. The topography does not generally favour large wetland development however a diverse range of wetland communities are present due to wetlands being able to develop under a range of physical conditions (van As and du Preez 2006).

The Drakensberg catchment area contains a high frequency of complex interconnected wetland systems, stretching across the altitudinal gradient consisting of tarns (open waterbodies), vleis, marshes and, a stream and river network. The wetlands play a vital role in the hydrological cycle of South Africa that the Drakensberg were declared a Ramsar Site (Ramsar: Convention on Wetlands of International Importance Especially as Water Fowl Habitat, 1971) in 1997 (Johnson *et al*. 1998).

2.4.3 Cultural Heritage

Archaeologically, the Drakensberg is one of the most significant regions in South Africa. It may have been occupied by human beings over the last million years, but it was the Khoisan people (inhabiting the area from 8 000 years ago until the late 19th century) who left behind some of the most renowned archaeological relicts (KNCS 1999; Matthews and Bredenkamp 1999). The Khoisan were artists leaving behind 35 000 paintings in 600 sites, the youngest being 150 years old and the oldest dating back several thousands of years (Briggs 2006; van As and du Preez 2006). They were hunter-gathers who often lived in caves and overhangs which are evident from the thousands of rock paintings which cover the walls and ceilings of these dwellings. Caves such as Battle Cave, Main Caves, Game Pass Cave 1 and Kanti Cave 1 are all declared National Monuments due to their collection of rock art. The rise of the Zulu military power and the arrival of the voortrekkers (dutch settlers) resulted in the destruction of the Khoisan and the extinction of a human civilisation (KNCS 1999). This extreme richness in rock art and other archaeological findings means that the Drakensberg is distinctly significant as a cultural heritage site (Johnson *et al.* 1998).

2.4.4 Fire in the Drakensberg

"Fire has an important, and usually beneficial role in maintaining the biodiversity, structure and function of African ecosystems" (Frost 1984, 1985 cited in van Wilgen and Scholes 1997).

In the Drakensberg, fire (natural and anthropogenic) is a vital environmental factor. Naturally fires can be ignited by lightning, usually occurring in early spring (high fuel load and lightning associated with thunderstorms) (Killick 1978), with figures of up to 17 % of South African fires being ignited in this manner (Killick 1963, 1978). This, along with fires being ignited by boulders rolling down slopes (rock falls) producing sparks on collision with other stationary boulders, is indicative that natural fires have been part of the Drakensberg environment since the inclusion of a dry season. Therefore grasslands not forests (under present climatic conditions) as argued by Acocks (1975), have predominated the landscape below the escarpment (Killick 1978; Tainton and Mentis 1984).

The grasslands of the Drakensberg Mountains are the dominant vegetation type (85%) with a mosaic of small patches of forests and heaths nestled within them (Irwin and Irwin 1992; Priday 1989). The forest communities are not adapted to fire and fire is not required in maintaining their condition, while the grasslands are, resulting in the majority of prescribed burns being performed in and tailored for the grassland regions of the Drakensberg. A generalised map of the fire regimes in South Africa was produced by Bond (1997) from a diverse group of sources (e.g. Trollope 1980, Edwards 1984, van Wilgen and van Hensbergen 1991). The map is not based on the extent of the general biomes, but rather on the fire sensitivity of the vegetation (Figure 2.5). The Drakensberg Mountains clearly is dominated by fire-prone mesic grassland with intermittent patches of fire-sensitive forest mosaic.

Grasses have adapted to be burnt. The organic material/elements making up the fuel are finely divided, with the spaces between them being spaced at a distance allowing good aeration and heat transfer between the elements. A dead grass leaf has a high surface to volume ratio, allowing it to dry to ignition point in a few hours of sun and wind after being soaked through by rain (Zedler 2007). Grasses in the Drakensberg have a seasonal cycle marked with a dry, cold dormant season. The probability of the grassland carrying a fire, natural or anthropogenic, is dependent on the amount of dead biomass (fuel) collected over this period after the warm wet growing period. Therefore the most probable time for the occurrence of fires is during the dormant season or the earliest and latest period of the growth season (Zedler 2007). The absence of this burning due to fire suppression management is detrimental to grasslands as moribund vegetation accumulates, smothering the grass species, consequently reducing habitat suitability for faunal species. When fires eventually do occur, they are very intense and damage the grass species, resulting in degradation or even mortality (Everson *et al.* 2004). Frequent fires favour the dominant grass of the Drakensberg and the rest of southern African grasslands, *T. triandra*, which is highly palatable and productive (Dillon 1980; Forbes and Trollope 1991; Scott 1971 cited in de Ronde *et al*. 2004a).

Fire is a natural disturbance that has a major role in the maintenance of grasslands. This includes the restriction of tree and shrub species that would, in the absence of fire, have a competitive advantage, resulting in bush encroachment and therefore a loss of grasslands (Huston 1994; Meadows and Linder 1993; Tainton and Mentis 1984).

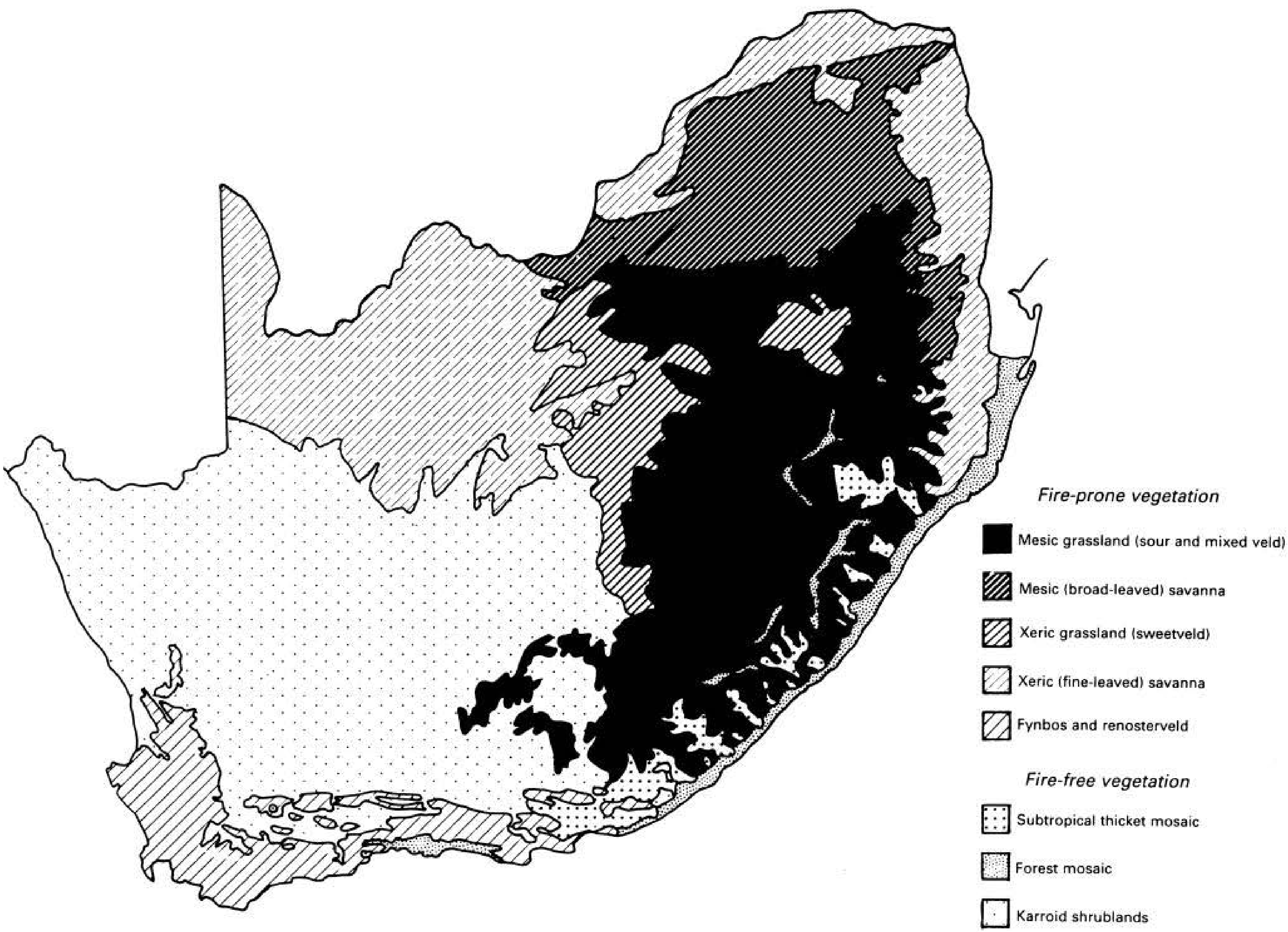


Figure 2.5: Generalised fire regimes of South Africa, the illustrating fire-prone and fire-sensitive areas according to vegetation communities (from, Bond 1997).

2.4.4.1 Fire Regimes and Management

The biological response to a fire can vary widely. It will depend, first, on the physical properties of the fire- its intensity, size, frequency and time of occurrence- all of which influence the chemical potential for combustion and determine the nature of the chemicals liberated by combustion. It will depend, too, on the genetic potential stored within biota, which may also be released by a fire, and on the mechanisms or relationships for exploiting a fire that may exist within the biota (Pyne 1982: 38).

According to Hall (1984) and Tainton and Mentis (1984), the present floral communities of the Drakensberg have been significantly shaped by fire, both natural and anthropogenic. Forms of conscious management are evident from the Stone Age where nomads manipulated the landscape with the use of fire to maintain grasslands in a palatable state for game herds. The seasonal vegetative and climatic variation resulted in these early inhabitants following game migratory movements with a degree of regularity (Priday 1989). This would imply that there was, although very simplistic, an application of a system of rotational burning during spring (Priday 1989). Present management is carried out by fire management organisations, mainly in conservation areas such as in the fire-prone grasslands of the KwaZulu-Natal Drakensberg where prescribed fires are essential in managing these areas. Managers require fire danger ratings that are precise and consistent to safely burn and predict the occurrence of wildfires (Everson *et al.* 2004).

The montane grassland catchments of the Drakensberg are primarily managed to protect and conserve the water resources, biodiversity and preserve the soil layer. The management objectives are to keep the ecosystems functioning naturally and conserving genetic resource and diversity (Everson *et al.* 2004; Irwin and Irwin 1992; Sycholt 2002). Due to this type of grassland (sourveld) not supporting large herds of grazers naturally, the removal of the moribund material by grazers is not sufficient, (different in reserves due to introduction of animals). Therefore, the only available method of managing this excess fuel is fire, and consequently fire is widely used in achieving the fire management aims and objectives of the Drakensberg protected areas (Everson *et al.* 2004).

"...man has decided he can do better than nature by managing fires – a complex issue because different plant communities require different types of burn. The unpredictability of natural fires was replaced about 50 years ago [in the Drakensberg] by controlled burning to 'aid the conservation of a healthy biodiversity and avoid damage to soil structure'"(Sycholt 2002: 15). The fire management of the Drakensberg Catchment Area (DCA) has had four distinct forms within a relatively short period of time. The DCA was managed from the beginning of the 20th century to the mid 1960s by the Department of Forestry, where the policy was to leave the environment to function naturally without any anthropogenic influences. The burning of fire breaks was the only prescribed burning permitted. There were still fires ignited by the local inhabitants, the San, to attract game. The next burning policy, from the mid 1960s to early 1970s, was one of burning large areas of approximately 2000 hectares following spring rains. Burning in smaller compartments (500 ha) after the spring rains continuing into October, replaced the above policy until the mid 1970s. Burn intensity was restricted and a categorisation of burns, hot (only in pure grasslands) or cool (grasslands with woody vegetation), was practiced (Priday 1989). The burning conditions, in terms of climate and vegetation, were determined by field managers which would ultimately determine what kind of burn it would be. The implementation of this policy was very difficult due to the small suitable burning season (first spring rains to October) (Priday 1989; van Wilgen *et al.* 1990). Experiments with different fire regimes in the Cathedral Peak region of the Drakensberg influenced the current fire management policy, with the recognition of three suitable burning periods: May-June, July and August-September. Each compartment is biennially burnt, alternatively in each above period. This resulted in fuel reduction throughout the dry season and has increased the number of suitable days for burning. However, there are no restrictions of fire intensity in this policy and the responsibility is placed on experienced field managers whether to burn or not (Priday 1989; van Wilgen *et al.* 1990). To overcome this, a fire rating system was developed using various environmental variables to aid in the decision making on whether to burn an area or not (Everson *et al.* 2004).

According Bond (1999: 630), “Past management of grassland and savanna areas was based on commercial rangeland principles and aimed at creating the most productive rangeland for animal production. Even the grasslands of the Drakensberg mountain catchment were burnt at seasons and frequencies to promote the optimum grass sward for beef production- in the absence of any beef herd”. The management aims have slowly shifted away from promoting animal production to the promotion of water production and subsequently to “perpetuate the native biota in abundance and variety” (Mentis and Rowe-Rowe 1979: 75), shifting to the present ideology of promotion of biodiversity (Arnott 2006).

The appropriate fire regime for grasslands is determined by climate and available fuel (Everson *et al.* 2004). Annual burns in the KwaZulu-Natal Drakensberg are required to maintain fire breaks, with the remaining grasslands being divided into compartments (sometimes greater than 400 ha). These are burnt primarily in a biennial pattern alternating between the three burning periods mentioned above (approximating to autumn, winter and spring), this method is called rotational block burning. The burning of areas after rain is often practiced to create more of a patch mosaic burn (Arnott 2006; Sycholt 2002). Annual burns are possible due to the rapid fuel accumulation in grasslands, however, this is not cost-effective (van Wilgen *et al.* 1990). According to Killick (1963) and van Wilgen *et al.* (1990), this biennial burning has been the primary management technique in the Drakensberg and has resulted in the fine sward of *T. triandra*, in addition to the promotion of species diversity. This biennial regime is favoured by the five most abundant antelope, namely, blesbok, grey rhebok, mountain reedbuck, oribi and eland (Rowe-Rowe 1982) (Table 2.5). It is not only beneficial for the larger antelope but also for the small mammals, this in turn supports populations of avian and terrestrial predators, increasing the biodiversity of the region (Rowe-Rowe and Lowry 1982). It was concluded, by Everson and Tainton (1984 cited in Arnott 2006) that annual and biennial burning over 30 years had no significant impact on grassland condition, however exclusion of fire for only 5 years resulted in changes in species composition.

Prescribed burning after the initial active growth (later spring early summer) is detrimental to *T. triandra* cover in the KZN Drakensberg Highland Sourveld. To maintain this *T. triandra* sward, burning is restricted from October until next burning season. Ideally prescribed burns should occur while the grasses are still in dormancy (late winter). Due to the size of some of the areas needed to be burnt and time required, burning has to occur earlier in winter. There is a high fire hazard at this time as a result of grasses being cured up to 95 % by June (Fig. 2.1) (Everson *et al.* 2004; van Wilgen *et al.* 1990). However opportunities for safely burning areas occur after light precipitation. It is not only about time of year when it comes to determine prescribed burns but also weather conditions within these burning periods. The atmospheric variables at the time of the burn determine whether the objectives of that burn are achievable. Typically conditions for safe burning are low wind speeds and temperatures and high relative humidity (Everson *et al.* 2004) (Fig. 2.1). These are important due to their independent effects on rate of spread. Fire danger rating models were created to integrate the variables, both atmospheric and plant (such as fuel loads and moisture content) into one practical burning index. When the burning index is within desired limits, prescribed burns can be applied (Everson *et al.* 2004).

Due to the Drakensberg being predominately covered by grasslands, the fire regimes are predominately based on burning this vegetation community correctly. However, within these grasslands there is a mosaic of forests, although small in comparison their conservation value is high (Fig 2.5). They are stable ecosystems on which prescribed fire do not have a huge influence, however the vegetation found along the forest edges is effected by fire. To protect these forests from unnatural fires, prescribed burns are burnt away from forest margins, minimizing any potential threat from high intensity fires (Priday 1989).

2.4.5 Conservation Management

Conservation in the Drakensberg Mountains commenced with the establishment of a game reserve near Giant's Castle in 1903 (KNCS 1999). Slowly the reserve grew after the procurement of farm land surrounding the reserve to the extent of just over 20 000 hectares by 1910 (Barnes 2003). The demarcation of a crown forest in 1905 saw the first real protection and conservation of the wild fauna (game) species. The demarcation meant faunal species were included in 'Forest Produce' and no permits were issued for hunting in demarcated crown forests, in addition to that, the land from then on was state owned. In 1973 the KwaZulu-Natal Drakensberg was declared a Wilderness Area, and since then there has been a positive progression in conservation resulting in the area being declared a World Heritage Site in 2000, due to its ecological and physical uniqueness (Barnes 2003; Sycholt 2002; van Wyk and Smith 2001). This makes the Drakensberg one of the few dual (both natural and cultural) heritages sites in the world (Everson and Morris 2006). By 1992, according to Irwin and Irwin (1992), the World Conservation Strategy identified the area as a priority biogeographical region. In additional, in 2001/2 the park's biodiversity received further protection resulting from an initiative between South Africa and its neighbouring country, Lesotho. This was called the Maloti-Drakensberg Transfontier Conservation and Development Area, protecting against large scale destruction of the landscape (e.g. afforestation) in the South African Drakensberg Park and the Sehlabathebe National Park in the Lesotho Maloti Highlands (KNCS 1999). Therefore the important managed conservation regions are the: uKhahlamba/Drakensberg Park which is 243 000 hectares and consists of the Giant's Castle Game Reserve, Kamberg Nature Reserve, Lotheni Nature Reserve, Royal Natal National Park, Rugged Glen Nature Reserve, Vergelegen Nature Reserve, Cathedral Peak State Forest, Cobham State Forest, Garden Castle State Forest, Highmoor State Forest, Mkomazi State Forest, Monk's Cowl State Forest; and the Sehlabathebe National Park in Lesotho (6 500 ha) (van Wyk and Smith 2001). Effective management of these large grasslands is required in the form of an appropriate fire regime, conserving vital biodiversity components (Arnott 2006). Progression of the Drakensberg protection and management from the establishment of the first reserve until present has been shaped by important events in the parks' history (Fig. 2.6).

The legislation under which the park is considered a conservation area include: the amended KwaZulu-Natal Nature Conservation Management Act 9 of 1997 and the National Forest Act 84 of 1998. Components within the park are also protected by numerous other legislation: the amended Water Act 54 of 1956, National Water Act 36 of 1998, the National Monuments Act 28 of 1969, the amended Environment Conservation Act 73 of 1989, the

KwaZulu-Natal Heritage Act 10 of 1997, National Environmental Management: Biodiversity Act 10 of 2004, and the National Environmental Management Act 107 of 1998 (Irwin and Irwin 1992; KNCS 1999).

The management of parts of the park was assigned to the Natal Parks Board when it was formed in 1947 (Barnes 2003) from the Department of Forestry (and its successors until the 1980s), which was then amalgamated with the KwaZulu-Natal Department of Nature Conservation to form the KwaZulu-Natal Nature Conservation Service (KNNCS) in 1997. The KNNCS was officially renamed to the current provincial conservation body managing the Drakensberg, Ezemvelo KZN Wildlife, in 2002 (see Fig. 2.6) (KNCS 1999; Singh 2002). KZN Wildlife is responsible for the implementation of the above legislation and the development of management objectives of the KwaZulu-Natal province including the Drakensberg. The KNNCS founded a comprehensive community conservation program for the Park, with partnership forums being established involving all communities and interested and affected parties (KNCS 1999). The Partners in Mountain Conservation (a conservation and development program) was developed for sustainable use of certain products within the park, including: certain grass and sedge harvesting for building, thatching and handicrafts; medicinal plant seed collection; removal and translocation of surplus faunal species; scientific research data collection; recreational activities (fishing, fly fishing for trout) and timber removal of alien invasive species (KNCS 1999).

2.4.5.1 Management Constraints

Along the international boundary and bisecting the Drakensberg are communal tenure populations whose livelihoods are dependent on the mountain resources. This increasingly places the biodiversity, cultural and other features under threat from development, unsustainable rangeland management, and invasion by alien plant species. Management of these catchments is therefore complex involving environmental issues, social dynamics and land tenure (Everson and Morris 2006). Secondary constraints include soil erosion and the impact tourism has on alpine trails (walking and mountain biking), caves and rock art (KNCS 1999; Sycholt 2002).

The invasion of exotic species has consumed 1.4 percent (approx. 3 500 ha) of the natural vegetation of the park by 1999, and has continued to do so (KNCS 1999; Sycholt 2002). The timing or seasonality of fire is highly stressed by managers in fire management plans. Out-of-season arson and fires lead to ecological degradation in the form of change in species composition and soil erosion (KNCS 1999). The border between South Africa and neighbouring Lesotho is a zone of continual problems for South African land managers due to trans-border poaching and hunting dogs, drug and firearm trafficking and cattle rustling. This is exacerbated by the lack of management of the Lesotho Highlands, with tourists being attacked while hiking along the border (KNCS 1999).

Alien invasive flora is a significant threat due to these species high volume of water consumption and invasive properties. The most damaging species are the black wattle *Acacia mearnsii*, silver wattle *A. dealbata*, pine *Pinus patula*, American bramble *Rubus cuneifolus*, grey poplar *Populus canescens* and *Cotoneaster* spp. (Briggs 2006; KNCS 1999). Over the past century invasive species has decreased the national water flow by seven per cent (Briggs 2006). To decrease the abundance of species, the South African Working for Water campaign hires local residents to clear alien tree infestations in the park, which they can utilise (i.e. firewood). Controlled burning is also used to maintain the natural vegetation preventing the influx of alien species (KNCS 1999).

The rock art is under constant threat by the deterioration caused by both natural forces (weathering of rock and paint) and anthropogenic forces (vandalism). Vandalism forms include smoke from campers blackening the rock, tourists wetting paint to bring out colours plus writing or drawing over the paintings. To combat this, sites of the majority of paintings have been removed from public maps with region access and camping in painted caves controlled strictly, with access only with the presence of a guide (KNCS 1999; Sycholt 2002).

2.5 Conclusion

This literature review provides an indepth overview of the natural role of fire in global and local ecosystems over time. It is evident that mankind has influenced the natural process of fire in most eco systems to such an extent where these systems can no longer function correctly without continued human intervention or management. Therefore to keep these ecosystems, e. g. the uKhahlamba Drakensberg Park World Heritage Site (UDP-WHS), functioning optimally natural resource management is required in the form of prescribed burning. The use of GIS and EDSS's in natural resource management, due to their efficiency and accuracy has been highlighted. The UDP-WHS was reviewed to provide an understanding of the importance and environmental uniqueness of the bioregion. Achieving the correct fire regime for different altitudinal belts of the UDP-WHS to maintain the area in a pristine state, through the use of an EDSS and periodic prescribed burning, will be the core focus of this research.

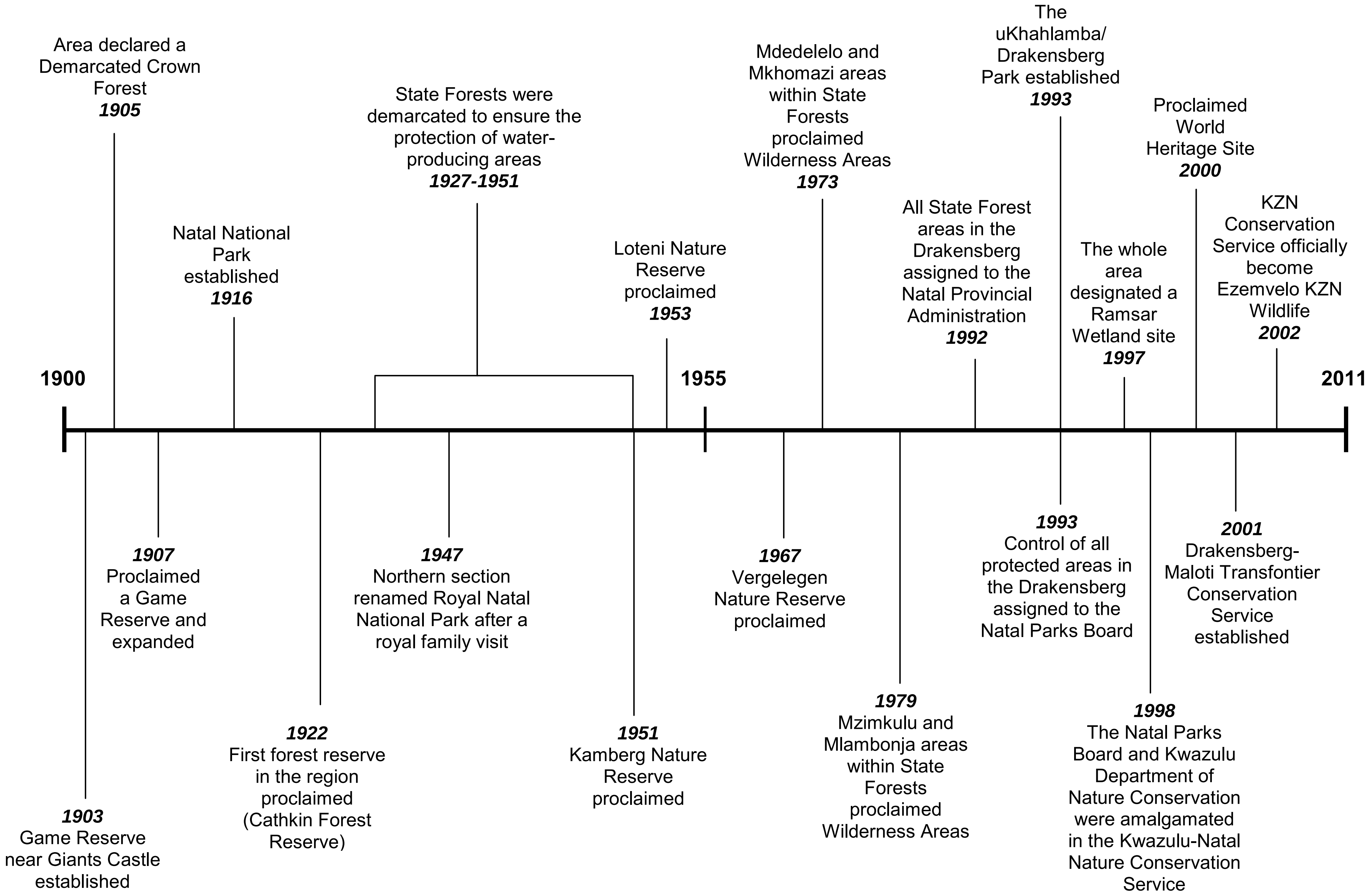


Figure 2.6: History of the Establishment of the uKhahlamba Drakensberg World Heritage Site

CHAPTER THREE

METHODS

3.1 Introduction

This chapter outlines the methodology developed to produce the fire management environmental decision support system (EDSS) for the uKhahlamba Drakensberg Park World Heritage Site (UDP-WHS). Due to the nature of EDSSs the research is strongly methodology driven. It contains analyses that require inputs that are the resultant outputs of previous methodical steps. Therefore intermediate results have to be displayed in this section instead of the results chapter as they are required for subsequent steps in the methodology, making the methods themselves an integral component of the results. The chapter details of the initial data collection and preparation to the final decision support system consisting of layouts and graphs of each altitudinal belt (Fig. 3.1).

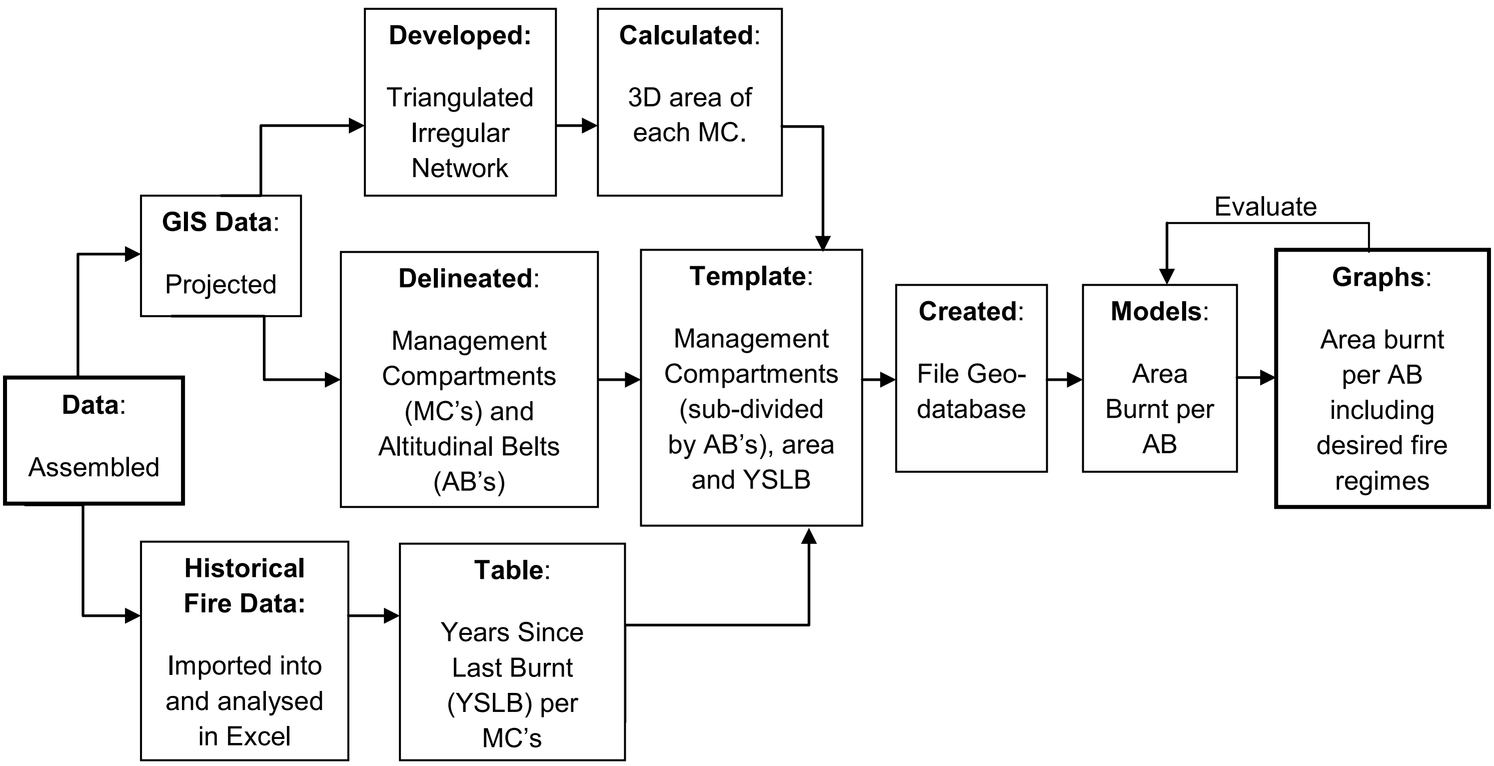


Figure 3.1: Schematic flow diagram representing the methodology process, producing a fire management decision support system for the uKhahlamba Drakensberg World Heritage Site. Each step will be discussed in more detail in section 3.3.

3.2 Study Site Description

This section provides an overview of the Park. The physical features, ecology, biodiversity, fire regimes and conservation management of the Park are discussed in section 2.4 of the literature review due to the park forming part of the larger Drakensberg Mountain Range (section 2.4).

3.2.1 Introduction

The uKhahlamba Drakensberg Park extends 200 kilometres along the KwaZulu-Natal Drakensberg mountain range, giving rise to the eastern escarpment of southern Africa (Fig. 3.2), lying between 28° 55' to 29° 55'S and 29° 05' to 29° 45'E, with Royal Natal National Park (a northern outlier), between 28°38' to 28°46'S and 28°52' to 29°00'E. The altitudinal range is between 1 280 and 3 446 metres. It contains a high diversity of flora and fauna, resulting in the Park being a major centre of plant, bird, amphibian and reptile endemism (KNCS 1999; van As and du Preez 2006).

The upper escarpment contains a diverse selection of summits and spurs (over 3 000 m), cliffs, ramparts and deep valleys. Undulating grassland slopes containing basalt bands are found a thousand metres below making up the second escarpment, the Little Berg. Descending further down presents steep-sided river valleys and rocky gorges hosting patches of forest, thickets and grassland, waterfalls, cascades and rock pools (KNCS 1999). The ecological heterogeneity is attributed to the geologic/geomorphologic diversity, range in altitudes and temperatures, high levels of precipitation and the numerous high altitude water networks comprising of springs, wetlands, tarns, bogs, marshes and streams. The origins of ten major rivers or streams are found within the Park including the Boesman's, Mkhomaasi and Mzimkhulu rivers and tributaries of the Tugela, making the park one of the major water catchments of the country (Briggs 2006; KNCS 1999; van As and du Preez 2006).

The World Heritage Site (WHS) is located inside a centre of plant diversity, the Drakensberg Centre of Endemism. The high species richness is due to the convergence of the Cape and subtropical biota, resulting in 247 endemic plant species. An extensive diversity of habitats is attributed to past speciation, major erosion and uplift, and dispersal and establishment events (KNCS 1999; van As and du Preez 2006; White 1978). These habitats include the summit plateaus and spurs, mid-altitude steep slopes and valleys below. These habitats make respective hosts to the unique alpine tundra and *Erica-Helichrysum* heath; diverse fynbos scrub, grasslands and woodland communities and; various grassland and forest communities (Hill 1996; KNCS 1999).

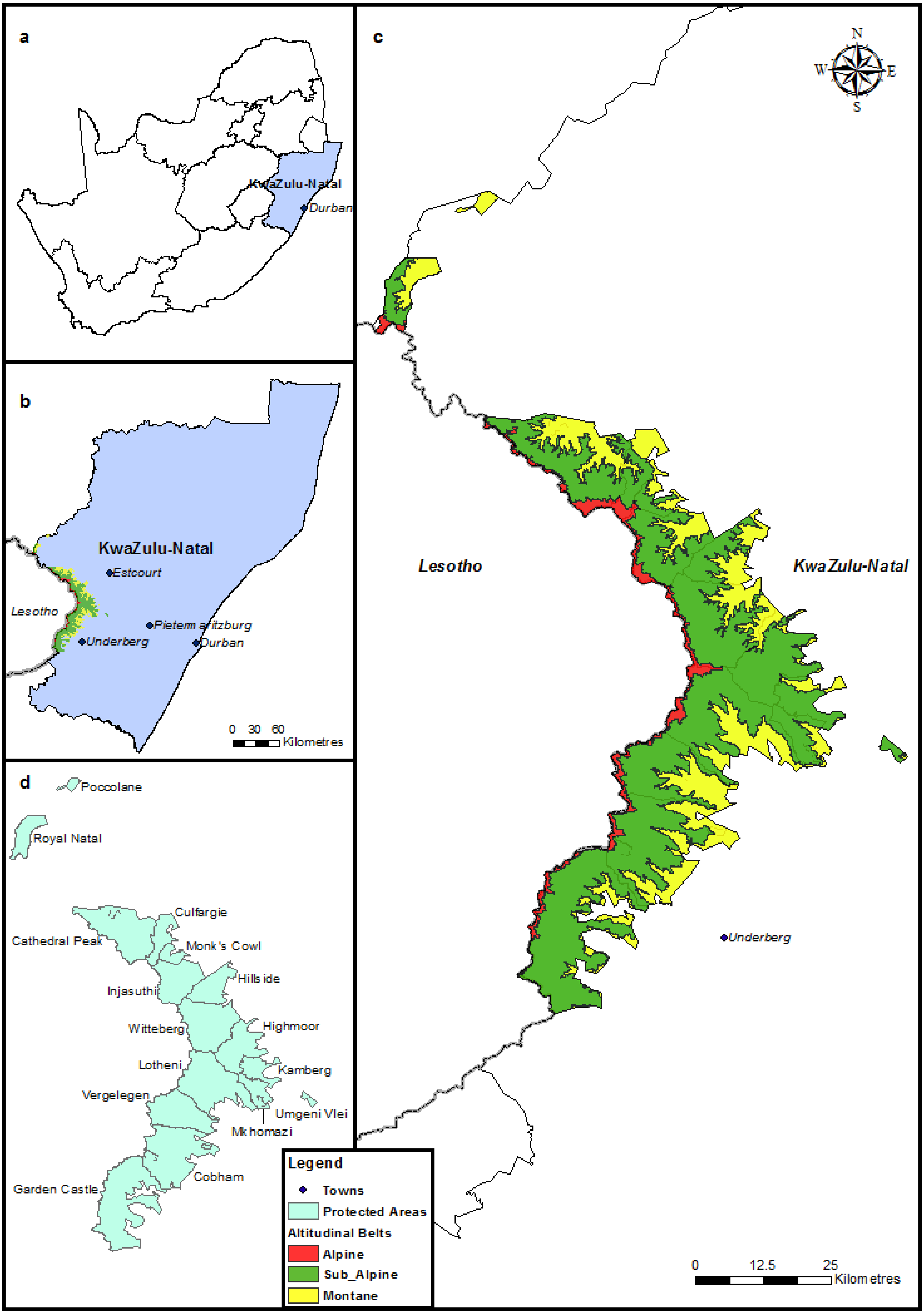


Figure 3.2: uKhahlamba Drakensberg World Heritage Site (c) with associated protected areas (d) in relation to the KwaZulu-Natal Province, its associated towns (b) and the Republic of South Africa (a).

3.2.2 Flora

The uKhahlamba Drakensberg Park (KwaZulu-Natal) contains 2 153 known plant species consisting of angiosperms (1 993 species), gymnosperms (5 species), pteridophytes (70 species) and 85 species of bryophytes. Two features that stand out are the high percentages of Compositae and monocotyledons, 285 species and five families respectively, comprising 55% of the flora (Briggs 2006; Everson and Morris 2006; KNCS 1999; Sycholt 2002). Among these species there are 109 internationally threatened and 109 nationally threatened. The total endemism percentage of the entire floral community is 29.5% ((39% of the Asteraceae family are local endemics (Briggs 2006; Matthews and Bredenkamp 1999; van Wilgen *et al*. 1990)), meaning there is a large number of endemic species which include the *Protea nubigena* and the Drakensberg Cycad *Encephalartos ghellinckii*. (Johnson *et al*. 1998; KNCS 1999; van Wilgen *et al*. 1990), and the only species of indigenous bamboo *Thamnocalamus tessellatus* (Briggs 2006; Matthews and Bredenkamp 1999). The highly endemic *Protea nubigena* (cloud protea) is considered to be the world's rarest protea species, with a range of less than one hectare consisting of no more than a hundred healthy individuals found above 2 400 m, on a single steep slope (Briggs 2006). The genus *Helichrysum* is the most prolific producer of floral endemics in the northern regions of the Drakensberg (Matthews and Bredenkamp 1999). In the entire Drakensberg Afro-alpine zone, at least 247 of the 394 species occur in the park of which there are 98 endemic or near-endemic species (KNCS 1999). The Drakensberg Mountain range with its treeless steep alpine slopes is the southernmost point of the afromontane regional centre of endemism, which is considered as one of the oldest centres of plant endemism in the world (van As and du Preez 2006; White 1978).

3.2.3 Fauna

The number of fauna species of the uKhahlamba Drakensberg Park is not as abundant as the floral species however the vast range of vegetation communities gives rise to a diverse set of faunal niches and consequently a high faunal species richness. There is a total of 48 mammal species, 299 bird, 48 reptile, 26 frog and 8 fish species. Many of which are rare, endemic or restricted in their distributions (KNCS 1999; van As and du Preez 2006; van Wilgen *et al*. 1990), for example, the park hosts the only known populations within a protected area of the Sclater's golden mole *Chlorotalpa sclateri*, Cape mole rat *Georychus capensis*, ice rat *Otomys sloggetti* and whitetailed mouse *Mystromys albicaudatus* (Briggs 2006; KNCS 1999; Sycholt 2002). Ancient invertebrate lineages have originated in the region explaining the presence of relict palaeogenic invertebrate taxa (KNCS 1999). None of the mammals are on the internationally threatened species list however 11 and seven are found in the Red Data Book for South Africa and CITES Appendices, respectively (Smithers 1986; KNCS 1999). The common, rare and endemic species are listed in chapter two (section 2.4.2.2).

3.2.4 Heritage

The largest, most diverse concentration of early rock art in sub-Saharan Africa are located in the parks numerous caves and rock shelters (Briggs 2006; KNCS 1999; Matthews and Bredenkamp 1999; van As and du Preez 2006). The Park falls within a Conservation International-designated Conservation Hotspot, a WWF Global 200 Eco-region, forms one of the world's Endemic Bird Areas, is designated a Ramsar wetland site and has been designated a World Heritage Site (KNCS 1999).

3.3 Data Preparation

3.3.1 Assemblage

The data collected were both quantitative (GIS compatibility format) and qualitative (workshop). Most data were acquired from the cartographic unit at the University of KwaZulu-Natal (UKZN) and Ezemvelo KZN Wildlife (Table 3.1). The data from UKZN were in a format (.shp) that is compatible with Geographical Information Systems (GIS) software. The data from Ezemvelo KZN Wildlife, provincial custodians of biodiversity, were in various formats (.shp, workshop outcomes, .xlsx) and needed to be reformatted depending on the requirements from each individual datum (Table 3.1).

Table 3.1: Data source, type, format and required format

Source	Data	Format	Required Format
University of KwaZulu-Natal, Pietermaritzburg (Cartographic Unit)	KwaZulu-Natal Provincial Boundary	.shp	.shp
	Digital Terrain Model (DTM)	DTM	TIN
	River System	.shp	.shp
	Forests	.shp	.shp
	Place Names	.shp	.shp
	Contour Lines	.shp	.shp
Ezemvelo KwaZulu-Natal Wildlife	Study Area Boundary	.shp	.shp
	Historical Fire Data	.shp	.xlsx
	Sensitive Areas	Workshops	.shp
	Ideal Fire Regimes	.xlsx	.shp
Literature Review	Altitudinal Belt Divisions	Literature	.shp

3.3.2 Projections and Programs

All raw data are required to be in the same coordinate system (map projection and datum) to run analyses. The data that had an unknown or incorrect coordinate system had to be defined using the *Define Projection* tool within the ArcMap program. When running this tool, certain parameters were set, determined by geographic locality and user requirements (Table 3.2). Once all the data were defined, they were projected to the same coordinate system, using the *Project* tool. The projection is Universal Transverse Mercator 36 South (UTM Zone 36S) World Geodetic System (WGS) 1984 as the extent of KwaZulu-Natal falls within this zone (Table 3.2).

Table 3.2: Parameters for the *Define Projection* and *Project* tools.

Define Projection	
New Projected Coordinate System	
Name	LO29
Projection	Transverse Mercator
Central Meridian	29
Geographic Coordinate System	Cape.prj
Project	
Output Coordinate System	
Select	Projected
Projected Coordinate System	WGS 1984 UTM Zone 36S.prj

All data preparation, statistical analysis and modelling were completed using the ESRI ArcGIS suite (version 9.3.1 initially) containing several different Geographical Information System (GIS) software products (programs), i.e. ArcMap, ArcCatalog and ArcScene. ArcMap was used for the preparation, editing, statistical analysis and modelling of the data. The preparation, editing and data management were achieved using ArcCatalog and ArcScene was required to develop a 3D model of the study site to determine the 3D area. This was made available for use by the University of KwaZulu-Natal. A new version of the ArcGIS suite (version 10) became available close to completion of the research and therefore although the new version was required due to added features that were vital for completion of the project, time restrictions resulted in the full abilities of the new version not being explored or utilised.

3.3.3 Altitudinal Belts and Management Compartments

The historic prescribed fire data for the UDP_WHS were obtained from the Ezemvelo KZN Wildlife for a 10 year period (2001 – 2010). There were variations amongst the years in number and position of management compartments with some compartments being overlapped, duplicated, combined, and /or sub-divided within and between the years. To develop a study area template, the management compartments were correctly digitised by displaying the years simultaneously to view common occurrences and variations. Where there were discrepancies between the years a common dominator was sort by visually comparing all the years usually resulting in only one of the years being incorrect (Fig 3.3). There were similar problems with variations in the labelling of the compartments, however there was also common labelling amongst the compartments that were automatically assigned as compartment codes. The code assigned to each compartment was dependent on the previously developed template. Each year needed to be corrected and assigned the appropriate code to comply with the base template to determine the prescribed burning characteristics of each compartment for each year. Some compartments had two different codes, meaning they would be considered twice in any analysis, which was corrected.

The number of compartments varied between the years (Table 3.3), with the template total being 489 management compartments. Therefore each year had to be corrected for: number of compartments, compartment code and prescribed burning characteristics (burnt/not burnt, type of burn, etc.); i.e. if a compartment was required to be sub-divided (Fig 3.3c) then the burning characteristics data of that large compartment determined the data of the smaller sub-divided compartments (Fig 3.3a). The original EKZNW digitising process was incorrect resulting in overlaps of neighbouring compartments. This was only realised further along in the process when it became problematic during statistical analysis and these problems were corrected for and discussed in the following section.

Table 3.3: Number of compartments into which the park was divided in different years

Year	Number of Compartments
2001	586
2002	554
2003	585
2004	603
2005	574
2006	560
2007	606
2008	424
2009	614
2010	536

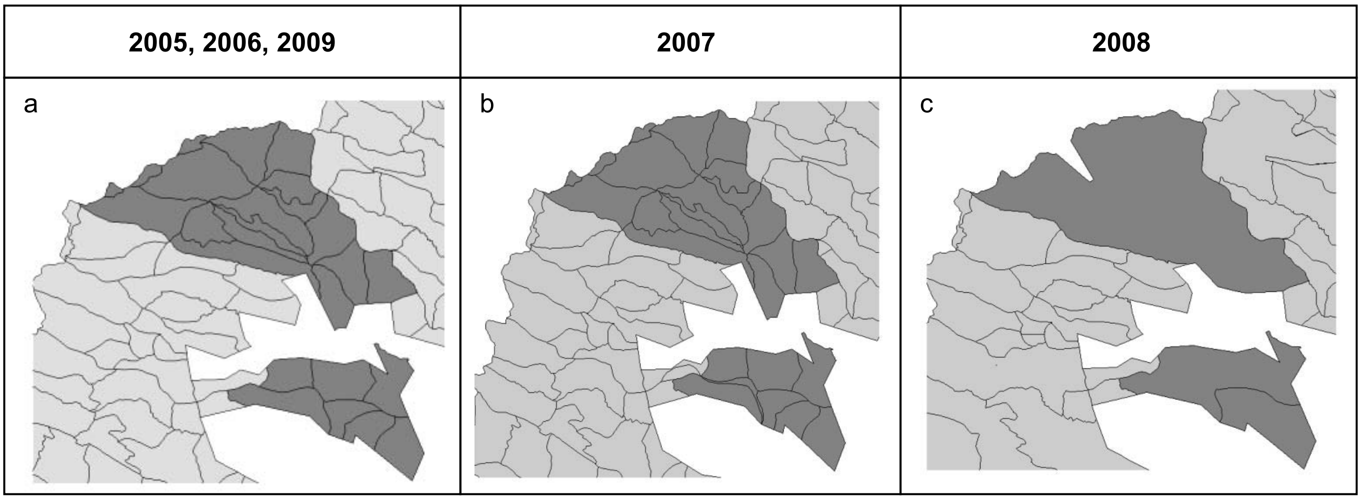


Figure 3.3: Variations in management compartment boundaries between different years. Inconsistencies in management compartment boundaries between the years (dark grey) were corrected using common dominators found within the other years (2005 – 07, 09).

Prescribed burning is carried out per management compartment, (i.e. managers burn by compartment). However these compartments do not coincide with the natural contours and consequently, the altitudinal belts of the Park. This is problematic for management as a certain percentage per altitudinal belt is required to be burnt per year. There are three altitudinal belts, namely montane, sub-alpine and alpine which were determined using contour line data and belt ranges (m.a.s.l.). When burning a compartment that falls within two or more belts, the total area of that compartment needs to be sub-divided into its respective altitudinal belts as a whole compartment can be prescribed to burn not a sub-division thereof.

The *Union* tool in ArcMap was utilised to compute a geometric intersection between datasets from multiple sources into a single output feature class preserving the attribute data from all the overlapping input features. This tool was preferred over the *Merge* tool, which is similar in function, however the *Merge* tool will not planarize (combine) feature geometries from the input feature classes. However, for both the *Union* and *Merge* tool the input data sets have to be of the same type (i.e. multiple point feature classes, multiple tables, but line feature classes cannot be merged with a polygon feature class), with the *Union* input features being limited to only polygon geometry.

The input datasets are the altitudinal belts and management compartments and the output feature class is a base map containing the three altitudinal belts (montane, sub-alpine and alpine). The issue being that the altitudinal belts are a polyline feature while the management compartments have a polygon geometry (Fig 3.5a). Therefore the belts have to be converted to a polygon feature. The alpine and montane belts were converted using the downloaded *ET Geowizards* tool (Fig. 3.4). Closed polylines were created of the two belts (Fig. 3.5b). The *Geowizard* only converts one closed polyline feature at a time. The reason for having more than one polyline per altitudinal belt is because the alpine and montane belts are intersected by the sub-alpine belt, which is continuous (Fig. 3.5c). When creating closed polylines it is vital that the *snapping* and *finish sketch* functions are utilised as they will not be converted to polygons if the polylines are not closed.

These individual polygons are merged and *dissolved* into their respective altitudinal belts, resulting in two feature classes (montane and alpine) (Fig. 3.5d). The two belts were *clipped* to the boundary of the UDP_WHS (study site) (Fig. 3.5e). The sub-alpine belt was created using the *Erase* tool, removing the montane and alpine belt from the study site, the remaining section was the sub-alpine belt (Fig. 3.5f; Fig. 3.4). These three altitudinal belts are used individually and they are merged together to create one belt base template (Fig 3.5g). The *union* tool was then run using the altitudinal belts and management compartments, both with polygon geometries.

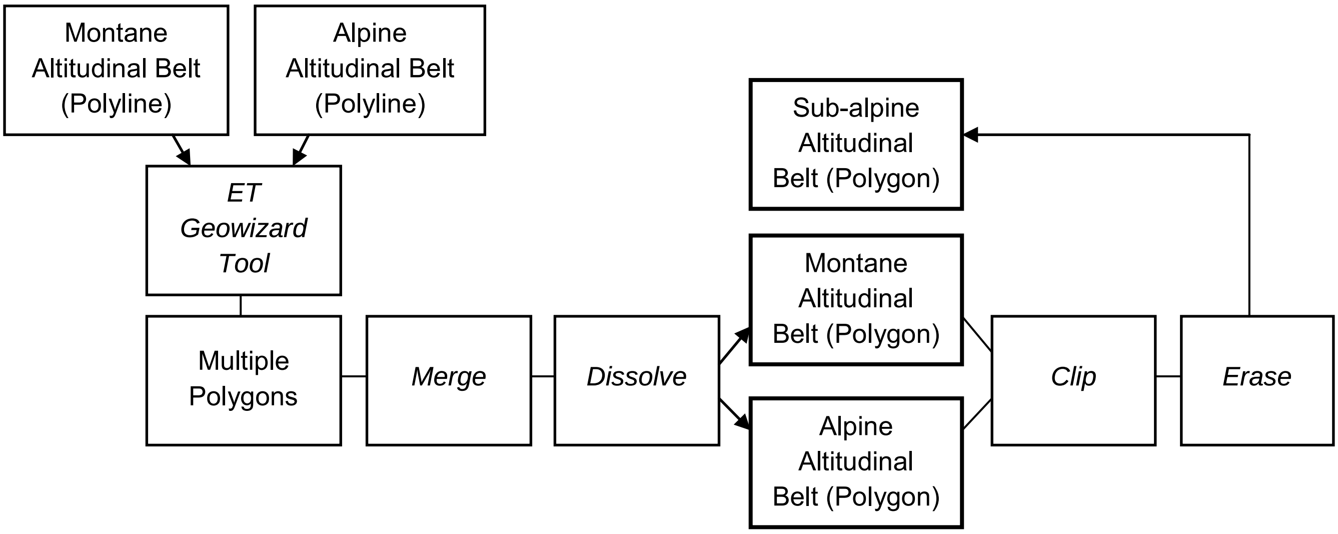


Figure 3.4: The development of the altitudinal belt polygon feature class (consisting of the alpine, sub-alpine and montane belts) from polyline feature classes using the ET Geowizard Tool.

Due to the compartments not coinciding with the altitudinal belts, the compartments were sub-divided after the union (Fig 3.6). The sub-divided compartments have the same compartment code as the parent compartment however they differ in surface area and altitudinal belt into which they belong. The total area burnt for each altitudinal belt is required and therefore when burning the compartment (e.g. fig 3.6a) which falls in all three belts (e.g. Fig 3.6b), the total area has to be sub-divided and added to the total area burnt of each belt.

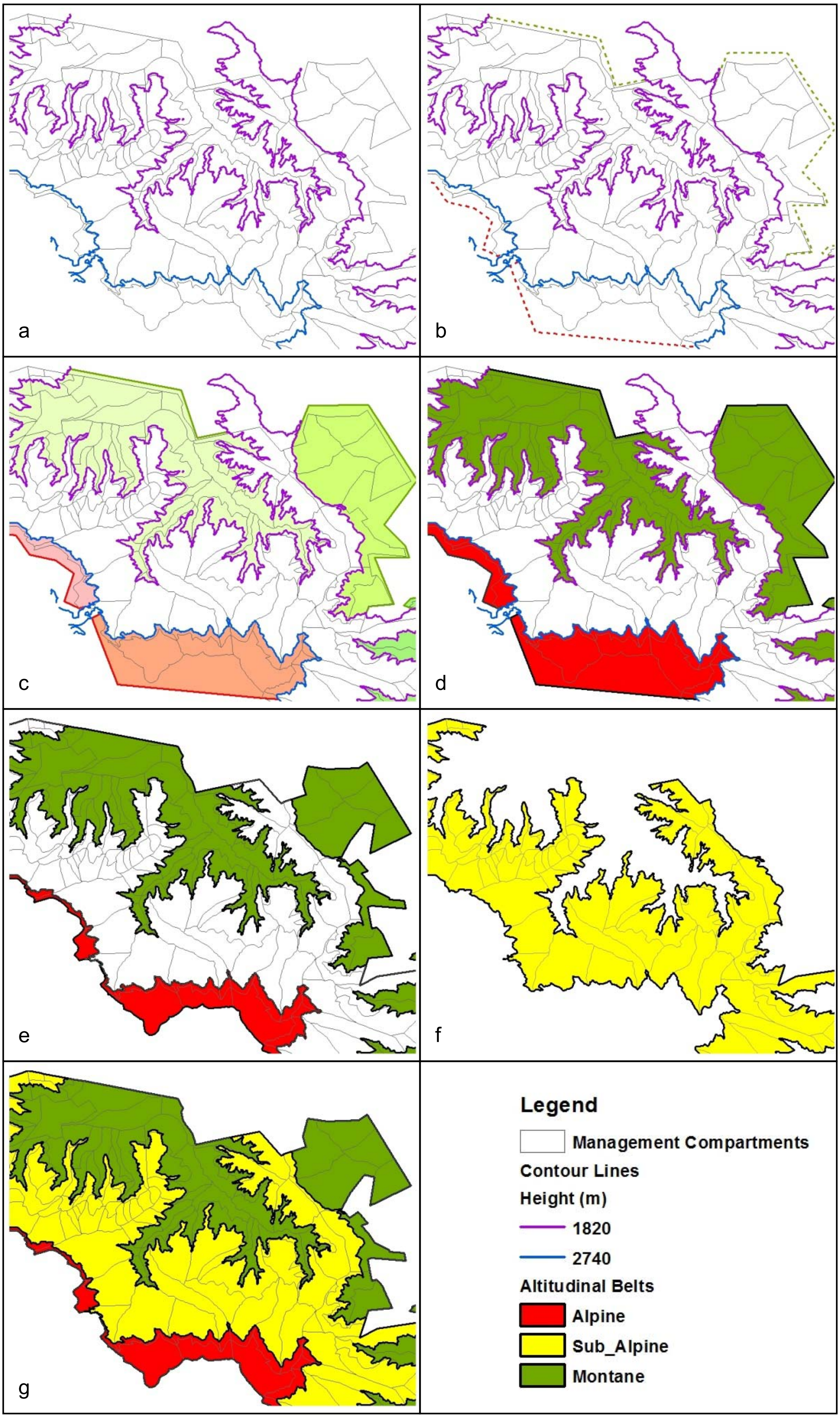


Figure 3.5: Process for developing the t hree altitudinal belts of the Drakensberg Park; a) management compartment with contour lines, b) closed polylines, c) several different polygons, d) different polygons merged to create individual belts, e) alpine and montane belt polygons clipped to UDP_WHS boundary, f) clipped sub-alpine belt, g) three altitudinal belts.

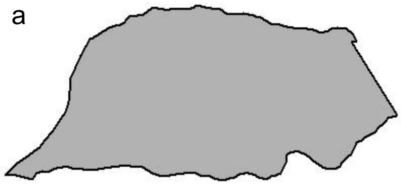
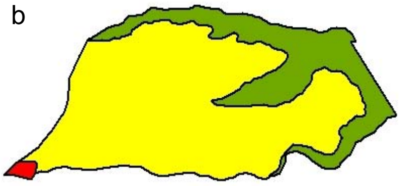
Management Compartment	Management Compartment sub-divided
a 	b 

Figure 3.6: A management compartment; a) before union; b) after the union subdividing the compartment into various belts.

3.3.4 Triangulated Irregular Network (TIN)

The precise area of each polygon is required to accurately determine total area burnt per altitudinal belt. To achieve this, the total area of each compartment could not be determined from the two-dimensional template map, due to the topography of the study site. Therefore a 3D version of the map and individual compartments was required. The Digital Terrain Model (DTM) and relief data (contour lines) of the study site were used to create a Triangulated Irregular Network (TIN) which was used to create the 3D model of the study site (Fig. 3.7c). The area of the study site was determined from the TIN however the area of the specific polygons could not be calculated because the DTM and relief data are not subdivided. Therefore the management compartments were converted to 3D with the *3D Analyst* toolbar (not toolbox) in ArcMap, using the DTM as the source heights and compartment code as the tag value field (Fig. 3.7b). The result is the shape changing from polygon to Polygon ZM (added z-coordinate) for each compartment (Fig. 3.7a). The 3D template with the ZM polygons was converted to a TIN (*3D Analyst* toolbar) which is subsequently used in the *TIN Volume Polygon* tool (*TIN Surface* toolset, *3D Analyst* toolbox) to determine the 3D surface area of each individual compartment (Fig. 3.7c). The *input TIN* is the one created previous, *Input Feature Class* is the 3D template and its reference plane is 'above plane height'. All the features involved must be in the same projection. Thereafter the surface area and perimeter of each compartment is calculated, from which percentage area was determined.

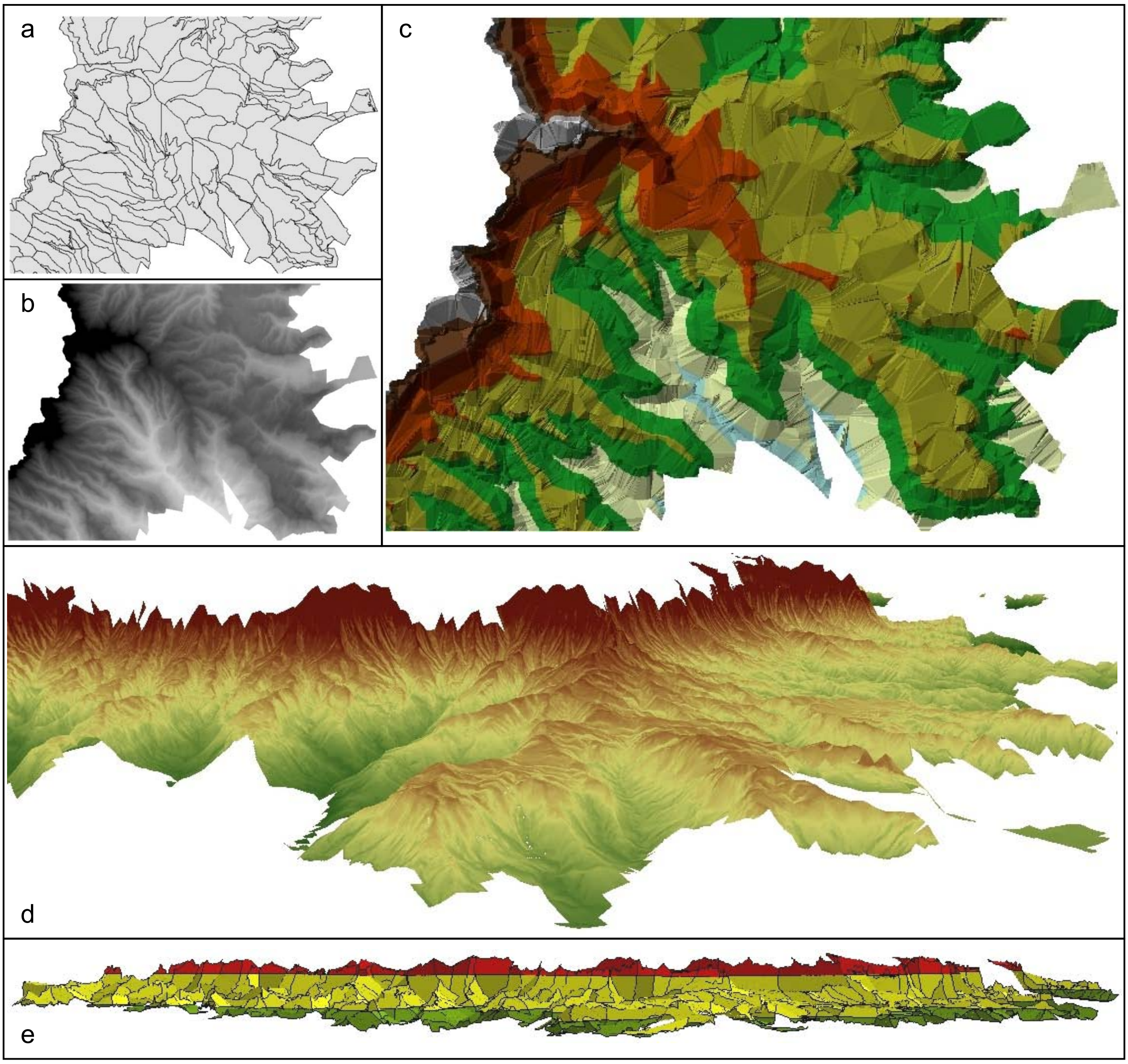


Figure 3.7: The use of the 3D template (a) and Digital Terrain Model (DTM) (b) of the UDP-WHS to create a Triangulated Irregular Network (TIN) (c), and a three-dimensional representation of the UDP-WHS (d) illustrating the altitudinal belts (e).

After this process, compartments had to be digitally rectified. A number of new polygons (after the union in the previous step) had exactly the same area (overlap), no area (neighbouring compartments not sharing common boundaries) or had a value or FID (feature arcmap identification number) of -1. A value of -1 means they fall outside the study area and a -1 value for FID indicates incorrect digitizing. This correction could not be done before the union due to the need for these values. The -1 values were deleted from the original base map. The overlapping occurs when the compartments are split by the altitudinal belts and the same section being counted in two different belts, i.e. in the montane and sub-alpine or sub-alpine and alpine. Therefore by looking at the 3D surface area and FID the polygons could be digitized correctly by deleting the incorrect overlapping polygons that were created. This digitising process is repeated until there are no outliers remaining. The number of compartments produced was 957 after the first run to 884 correctly digitised, no overlapping compartments after the 14th run. This problem was predominately due to incorrect digitising of the original data, where neighbouring compartments did not share boundaries, instead new polygons (with no area or minute areas) were created between them when the template was converted into a 3D template.

The three-dimensional representation of the UDP-WHS and the altitudinal belts was created in ArcScene (Fig. 3.7d, 3.7e). The base heights were determined from the z value created in the 3D conversion. A conversion exaggeration factor of 3 was used for visualisation purposes.

3.3.5 Historical Data

The historical fire data were collated and corrected due to each year varying in number of compartments and different compartment codes. Each compartment was either burnt or not burnt, with burnt being further divided into different burn treatments, i.e. scheduled, lightning, arson, invasive, accidental/runaway and unknown. A number of compartments in the various years had to be subdivided or grouped to comply with the base map. When subdivided, the new compartments data were determined by the original compartment. The data from all years were summarised into an excel spreadsheet based on the compartment codes, with each compartment being not burnt or having one of the burning treatments (Fig. 3.8).

An excel spreadsheet was utilised for its complex formula abilities and user friendly interface. The Years Since Last Burnt (YSLB) was determined using the array formula: {=LOOKUP(100,FREQUENCY(IF(*cell range*="Not_Burnt",COLUMN (D2:J2)),IF(*cell range* <>"",IF(*cell range*<>"Not Burnt",COLUMN(*cell range*)))))}, (using a consecutive combination of the CTRL,SHIFT,ENTER keys) (Fig. 3.8 column K). This formula was used to count the number of cells (years) a specific compartment has containing 'Not Burnt', until a year is reached containing a treatment (e.g. Fig. 3.8 row 4). A column is located at the end of the last year (Fig. 3.8 column J). This is used to add another year to the formula. A range of values is defined, called '*Treatment*' containing the different types of treatment options available. The entire dataset is selected and data validation is selected to allow the range of values located in the '*Treatment*' range. Therefore when updating the datasheet a dropdown list with available treatments is provided for each compartment. An error message is added if users enter an invalid value. This excel sheet is JOINED (using compartment codes) to the base map, therefore adding the dimension of having a complex formula which ArcMap 9.3.1 is unable to perform. The join must be validated to ensure all data are joined correctly. When the excel spreadsheet is updated, it is updated in the management compartment feature class within the ArcMap document. Therefore any analyses involving the feature class such as the creating of graphs will also be updated.

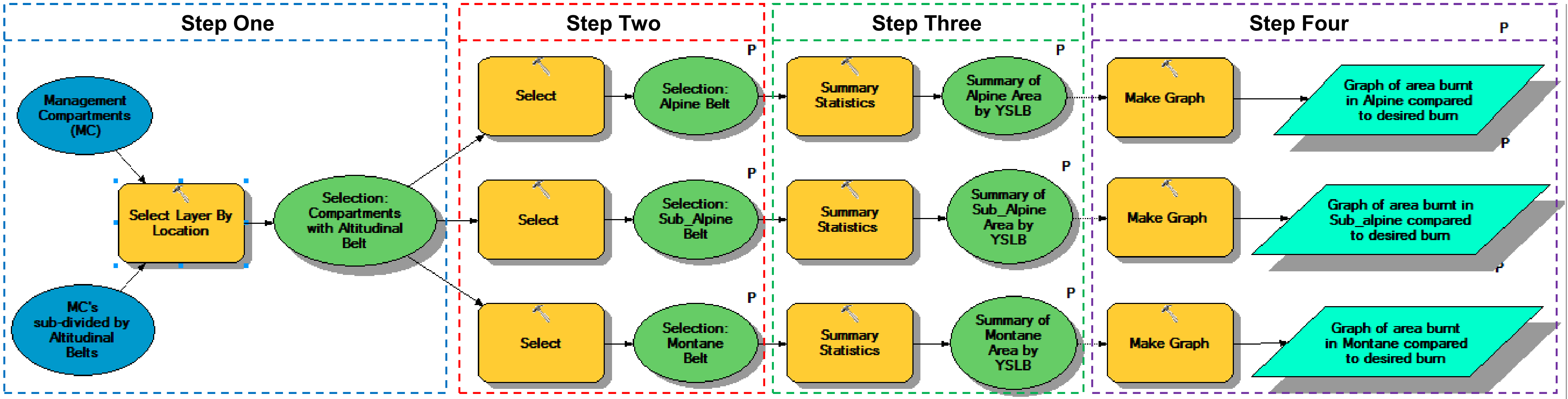
fx `=LOOKUP(100,FREQUENCY(IF(E2:J2="Not_Burnt",COLUMN(E2:J2)),IF(E2:J2<>"",IF(E2:J2<>"Not Burnt",COLUMN(E2:J2)))))`

	B	E	F	G	H	I	J	K
1	COMP_NAME	Treat_05	Treat_06	Treat_07	Treat_08	Treat_09		YSLB
2	CBHMA01	Not Burnt	Scheduled	Arson	Not Burnt	Not Burnt	Insert Next Year	2
3	CBHMA02	Not Burnt	Scheduled	Arson	Lightning	Not Burnt		1
4	CBHMA03	Not Burnt	Not Burnt	Scheduled	Not Burnt	Not Burnt		2
5	CBHMA04	Accidental/Runaway	Not Burnt	Arson	Not Burnt	Invasive		0
6	CBHMA05	Accidental/Runaway	Not Burnt	Arson	Not Burnt	Not Burnt		2
7	CBHMA06	Not Burnt	Not Burnt	Not Burnt	Not Burnt	Not Burnt		5
8	CBHMA07	Not Burnt	Not Burnt	Invasive	Not Burnt	Not Burnt		2
9	CBHMA08	Not Burnt	Not Burnt	Scheduled	Not Burnt	Not Burnt		2

Figure 3.8: Excel spreadsheet containing historical fire data used to determine the years since a management compartment was last burnt.

3.4 Model

The fire management environmental decision support system is based upon two models (i.e. Intermediate output and Final output model). These models were built in the *Macro Builder* of ArcMap 10. A new toolbox '*Fire_EDSS*' was created in the geodatabase to house the models, therefore the toolbox and models are not confined to a single computer. The *Intermediate output* model was developed to create numerous temporary outputs allowing decision makers to alter parameters then re-run the model (Fig. 3.9). Every output was overwritten by the following therefore preventing the accumulation of redundant data. This was achieved by changing the geoprocessing settings to allow the 'overwrite of outputs of geoprocessing operations' and retaining the same output names. There are instructions for the overwriting of the outputs in the model description of the model start up dialog box.



Step One

Selection of features in the Management Compartments (MC's) sub-divided by Altitudinal Belts layer from selections in the management compartment layer based on their spatial relationship.

Input Feature Layer: MC's sub-divided by Altitudinal Belts

Relationship: WITHIN

Selecting Features: Management Compartments (MC)

Selection Type: NEW_SELECTION

Step Two

The select tool extracts any required data (subset) from a feature class typically using a Structured Query Language (SQL) expression.

Input Features: Selection: Compartments with Altitudinal Belts

Output Feature Class: Selection: [*an altitudinal belt*] Layer symbology defined in properties

Expression (SQL): Specific altitudinal belt from Input feature, e.g. = Montane

Step Three

Summary statistics analyse the data and summarises field(s) into an output table.

Input Table: Selection: [*an altitudinal belt*]

Output Table: Summary of [*an altitudinal belt*] Area by Years Since Last Burnt (YSLB).

Statistics Field(s): Portion Area of Selection: Compartments with Altitudinal Belts (Type: SUM).

Case Field: (calculate statistics separately for each unique attribute value) YSLB from joined excel table.

Step Four

Creates a graph as a visual output from an input table/feature. **Input graph template or graph**: Graph of All compartments (must have 4 series)

Input Series: 1x Bar, 3x Line

Series Vertical Bar of type "bar:vertical"/ "line:vertical"

Dataset: Summary of [*an altitudinal belt*] Area by YSLB
X: YSLB
Y: Summary Area of [*an altitudinal belt*]
Sort Type: VALUE

Graph General Properties

Title: Total Area Burnt according to YSLB in [*an altitudinal belt*]

Output Graph Name: Total Area Burnt according to YSLB in [*an altitudinal belt*]

Figure 3.9: Model steps to create an Environmental Decision Support System (EDSS) for the fire management of the uKhahlamba Drakensberg Park World Heritage Site (UDP-WHS)

The select by location tool (step one) was used in the model to select features in the management compartments (MC's) sub-divided by altitudinal belts feature from selections in the management compartment layer based on their spatial relationship. The input feature layer (MC's sub-divided by altitudinal belts) is evaluated against the management compartments by which burns are conducted and therefore selections for burns are based. If the MC's sub-divided by altitudinal belts are WITHIN (relationship type) the selected management compartments then they are selected. The selection type is a NEW_SELECTION, meaning the resulting selection will replace any existing selection.

In step two the select tool extracts any required data from a feature class typically using a Structured Query Language (SQL) expression. This extracted data are stored in an output feature class. The input feature is the selected compartments in the Compartments with altitudinal belts feature from the previous step. The output feature class is stored in a temp folder and allocated a title according to which belt is been selected from, e. g. Selection_Montane. A SQL expression is used to select a subset of features, with differing syntax depending on the data source. The expression "*Compartments with Altitudinal Belts.Alt_belt*"= 'Montane' (for example) is used to select only the data pertaining to the compartments found in the montane altitudinal belt. The *Compartments with Altitudinal Belts.Alt_belt* indicates that input feature used in this expression is from the field 'Altitudinal belts' in the feature class "*Compartments with Altitudinal Belts*". A new feature for each altitudinal belt is added to the layout (add to display selected) based on the selected features from the previous step (step one).

The layer symbology in the properties of the resultant output feature allows for defining how it will be drawn when added to the layout. This is achieved by referencing a layer file that has the desired output design. Separate layers of each belt were designed and selected, according to what was required and then exported as a layer file to be the reference source for this step. These layers have to be in layer (.lyr) file format. The selection output used in the next step is made a model parameter.

Summary statistics analyse the data and summarises field(s) into an output table in the step three. The input is the feature created in the previous step and the output is a table with a suitable title. The statistical field that is required to be summarised is the area portion of the Compartments with altitudinal belts feature created by the TIN Volume Polygon in the area calculation section. The statistic type is SUM which adds the total value for the area portion field. The case field is the field in the Input Table used to calculate statistics separately for each unique attribute value. The case field used is the YSLB field from the excel table that was joined to the Compartments with altitudinal belts feature (Fig. 3.10). The output table is a model parameter.

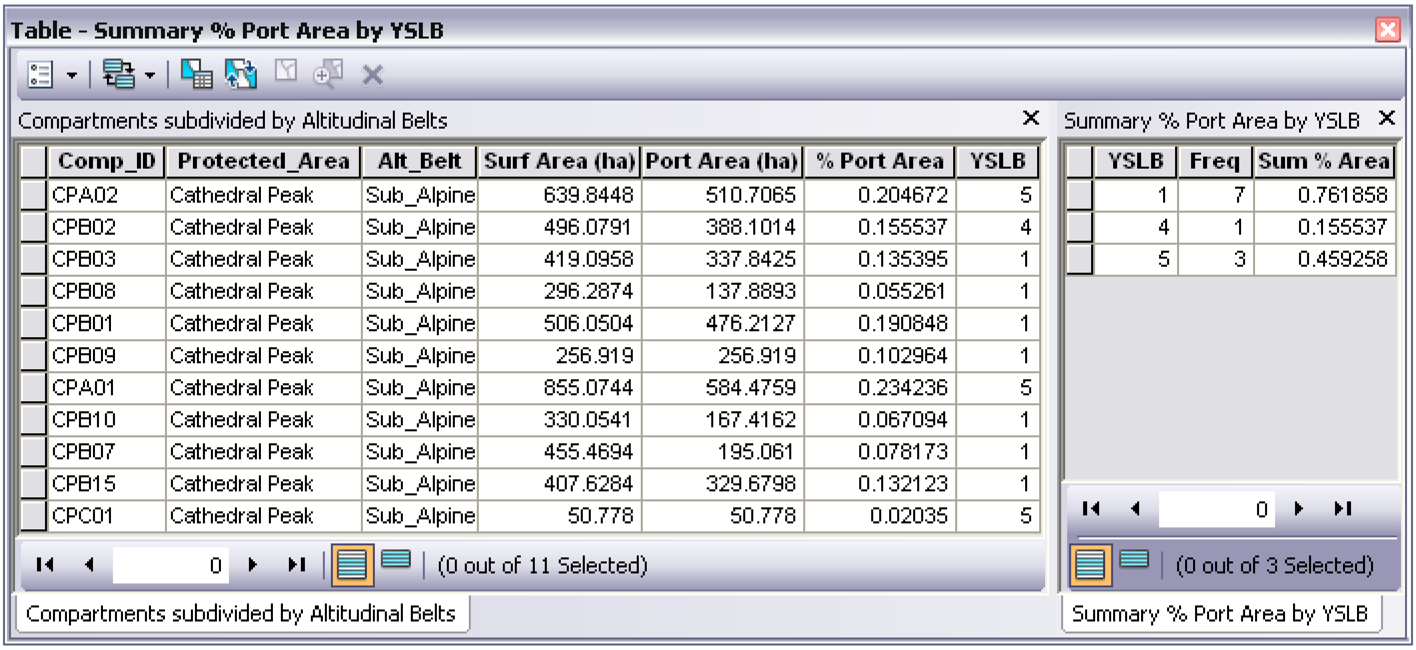


Table - Summary % Port Area by YSLB

Compartments subdivided by Altitudinal Belts

Comp_ID	Protected_Area	Alt_Belt	Surf Area (ha)	Port Area (ha)	% Port Area	YSLB
CPA02	Cathedral Peak	Sub_Alpine	639.8448	510.7065	0.204672	5
CPB02	Cathedral Peak	Sub_Alpine	496.0791	388.1014	0.155537	4
CPB03	Cathedral Peak	Sub_Alpine	419.0958	337.8425	0.135395	1
CPB08	Cathedral Peak	Sub_Alpine	296.2874	137.8893	0.055261	1
CPB01	Cathedral Peak	Sub_Alpine	506.0504	476.2127	0.190848	1
CPB09	Cathedral Peak	Sub_Alpine	256.919	256.919	0.102964	1
CPA01	Cathedral Peak	Sub_Alpine	855.0744	584.4759	0.234236	5
CPB10	Cathedral Peak	Sub_Alpine	330.0541	167.4162	0.067094	1
CPB07	Cathedral Peak	Sub_Alpine	455.4694	195.061	0.078173	1
CPB15	Cathedral Peak	Sub_Alpine	407.6284	329.6798	0.132123	1
CPC01	Cathedral Peak	Sub_Alpine	50.778	50.778	0.02035	5

(0 out of 11 Selected)

Summary % Port Area by YSLB

YSLB	Freq	Sum % Area
1	7	0.761858
4	1	0.155537
5	3	0.459258

(0 out of 3 Selected)

Figure 3.10: Summary statistics of the sum of percentage area burnt per year since last burnt (YSLB) per altitudinal belt. The table on the right is the summary of the table on the left for the sub-alpine altitudinal belt.

ArcMap 9. 3.1 was replaced with ArcMap 10 due to the need for the *make a graph* functionality in model builder that was only available in version 10 and necessary to complete step 4. One bar and three lines graph for the study site, using YSLB, portion area and ideal fire regimes, was created and exported. This served as the input graph template showing the selected features and the desired percentage burn for every YSLB. The four series have to be on one template graph. A limitation that was discovered was when adding another series to the template in the model, after creating the initial template, it causes the program to fail. Therefore four series have to be added to the original graph (one bar and three line) before exporting the template to prevent the program from 'crashing'. The input series for the bar series is the summarised table created in the previous step, making sure that the drive path to the summarised table not the existing table (i.e. the one that will continuously be updated). The data for the three line series are static tables located with the geodatabase. They have been created from the ideal fire regimes data and include the minimum, maximum and ideal percentage area burn per YSLB per altitudinal belt (see section 3.5.1), therefore providing an indication to the decision makers on how closely their selection aligns with the ideal regime.

The X series for all the series is the years since last burnt (YSLB) and the Y axis is the summary of the portion areas. The sort type is VALUE, however this has to be deselected for one of the other options then the model must be run then only select VALUE and it will function correctly. When selecting the x and y data the same classes must not both be in the x and y fields simultaneously, i.e. YSLB in both fields at any stage will result in the graph module not recognising the labels when changed. The title of the graph does not have to change, keeping it the same allows for overwriting and not a gathering of redundant data. Axes are labelled appropriately and the output is made a *model parameter* and *add to display* is selected.

3.4.1 Graph Template

To create the graph template, a graph containing the relevant data must be created. This graph must contain the one bar series and three line series. The bar series is based on the summary statistics of the park based on percentage area and YSLB. The three line series are based on nine tables (3 x 3 tables per altitudinal belt: Minimum, Maximum and Ideal). Once this graph is created, the properties are edited to ensure all data are correctly displayed and annotated (Fig. 3.11). The graph is then saved as a graph file.

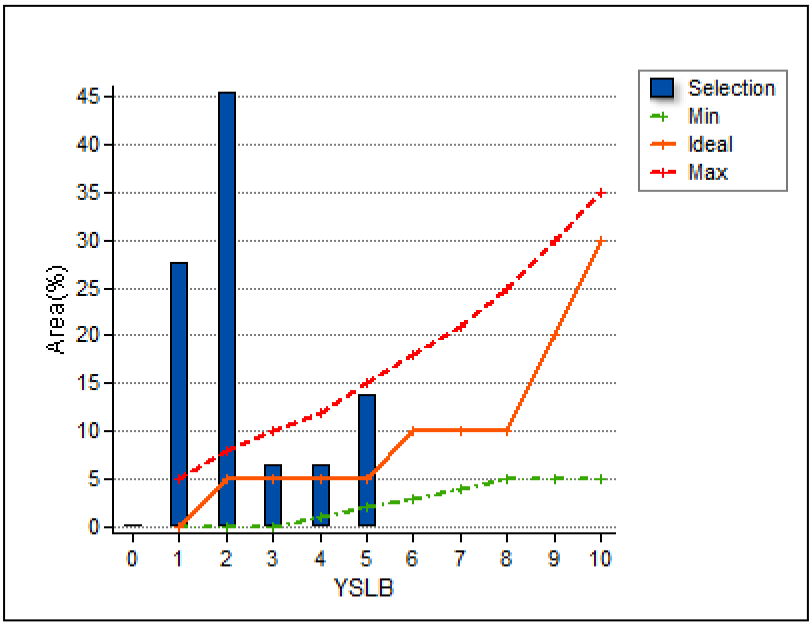


Figure 3.11: Graph Template used in the *Making a graph* step of the model of percentage area and years since last burnt (YSLB)

3.4.2 Final Output

When a final decision is reached, after numerous re-runs of the model, a final output is required. The second model (*final output* model) is run to export the selected burning treatment in table format to update the original historical data in the excel document (Fig. 3.12).

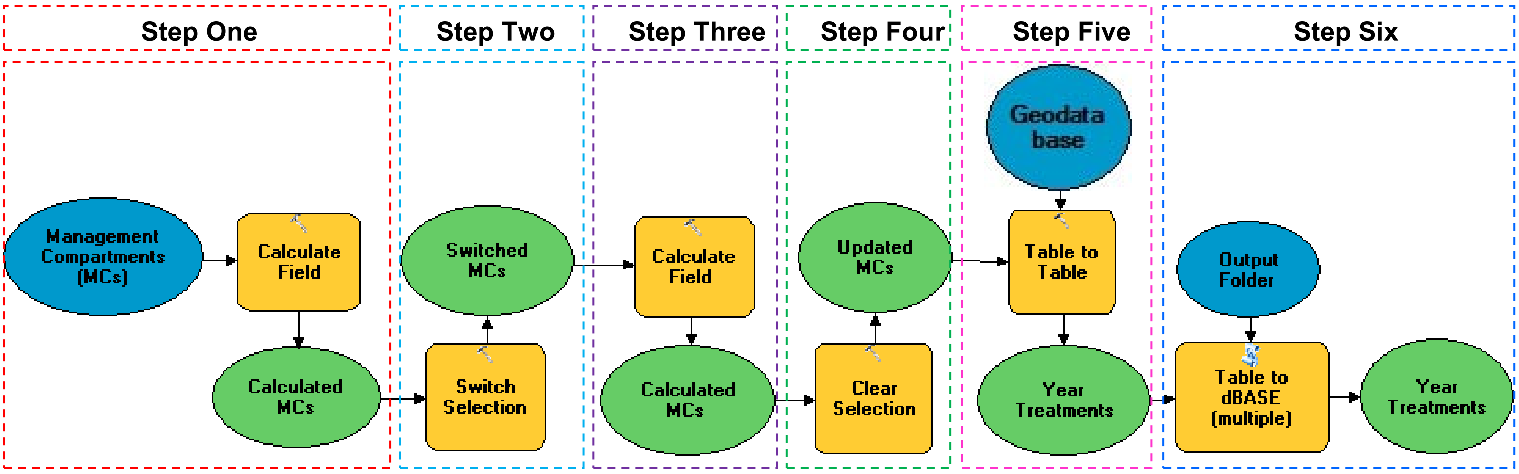


Figure 3.12: Model for Final Output of compartments management treatments to update the excel data.

The model consists of six steps containing individual tools, inputs and outputs. Once the final selection on which management compartments to burn is decided, this model is run. Step one uses the '*calculate field*' tool to calculate the values of a desired field within the management compartments (MCs) feature class. The input table is the MCs feature class containing the selected compartments. The Structured Query Language (SQL) expression ((visual basic syntax (VB)) is *Treatment* (field name) = "Scheduled". The selected features are labelled *Scheduled* as during the decision making phase there can only be two options *Scheduled* and *Not Burnt*, with other treatments such as arson or accidental only occurring after the initial prescribed burning management plans have been completed. The second step switches the current selection of the compartments using the '*Select Layer by Attributes*' tool with the selection type, *Switch Selection*. This is necessary to select all the compartments that are not scheduled to be burnt that year. This switched selection is the input for step three which, using the '*calculate field*' tool, defines the selected features in the *Treatment* field as *Not Burnt*, using the SQL expression *Treatment* (field name) = "Not Burnt". At the completion of this step the *Treatment* field for all the compartments should be either *Scheduled* or *Not Burnt*. Step four uses the '*Select Layer by Attributes*' tool (selection type, *Clear Selection*), to clear all the selections on the management compartment feature class, required for the last two steps. Step five and six involve the export of the data. The '*Table to Table'* tool in step five creates a geodatabase table of the compartment codes and *Treatment* field, removing the remaining data. The *input rows* is the MCs feature class, *Output Location* is the EKZNW_Fire_DSS geodatabase, *Output Table*: Year Treatments and the *Field Map* is where the data that are not required is deleted. This results in a table making it easy to update the excel spreadsheet in the future. Step six utilises the '*Table to dBase*' tool to export the resultant geodatabase table (*Input Table*) from the previous step to a folder (*Output Folder*) containing the excel spreadsheet. The output is a dBase (.dbf) table, a format useable in excel.

The user can copy and paste the *Treatment* Field data into the specific *Year* column receiving that prescribed burning treatment in the excel spreadsheet. The *Scheduled* and *Not Burnt* entries will be recognised by the *Data Validation*, and the *Years Since Last Burnt* (YSLB) column will be updated. During the subsequent year, if there are unplanned fires due to arson, lightning, accidental/runaway or invasive then the User can open the excel document and change the affected compartments to the treatment that occurred. This will automatically update the YSLB and will reflect on the ArcMap document.

3.5 Geodatabase

A file geodatabase was created called 'EKZNW_Fire_DSS'. A file geodatabase was used as it can be utilised by several users simultaneously. However, only one user at a time can edit the same data. The geodatabase houses the feature classes, tables, relationship classes, toolboxes and other geodatabase components used in the development of the Fire Decision Support System (FDSS) (Table 3.4). When the geodatabase was completed it was compressed to delete all redundant data which if not removed will hinder the performance of the support system..

Table 3.4: Data types and description within the *EKZNW_Fire_DSS* geodatabase.

Feature Name	Type	Description
Management Compartments (MCs)	Feature Class	Study site divided into the UDP-WHS managerial compartments
MCs subdivided by Altitudinal Belts	Feature Class	UDP-WHS management compartments subdivided by the three altitudinal belt
Altitudinal Belts	Feature Class	The three altitudinal belts found in the study site, i.e. Alpine, Sub-Alpine and Montane
Management Compartments _Annotated	Annotation Feature Class	Annotated labels of each subdivided MC: percentage area.
Precautions	Feature Class, Table and Relationship Class	A feature class of precautions/ special attention found with UDP-WHS including images and fire treatment suggestions.
Fire_EDSS	Toolbox	Toolbox containing the two models required in the EDSS
Ideal, Min and Max (*Specific Altitudinal Belt*)	Tables	Three tables per altitudinal belt of ideal, minimum and maximum % area burnt per Years Since Last Burnt (YSLB)
Selection_ *Specific Altitudinal Belt*	Feature Classes	Temporary prescribed burning selection for each altitudinal belt (outputs of a model run)

3.5.1 Fire Regimes

The fire regimes for each altitudinal belt based on percentage area burnt and years since last burnt was determined by specialists and workshops with Ezemvelo KZN Wildlife (Fig. 3.13 and Table 3.5). There is the ecologically ideal, minimum and maximum percentage area burnt for each altitudinal belt in terms of how many years it has been since the compartments, found in each belt, have been burnt. This was based on the historical fire regime of the area, the ecological requirements of the flora and fauna communities and past scientific research conducted in the area (e.g. Everson and Tainton (1984); Killick (1963); Rowe-Rowe and Lowry (1982)).

Table 3.5: Fire regime parameters for each altitudinal belt in terms of percentage area burnt and years since last burnt (YSLB)

YSLB	Montane (%)			Sub-alpine (%)			Alpine (%)		
	Ideal	Min	Max	Ideal	Min	Max	Ideal	Min	Max
1	30	7	45	20	10	40	0	0	5
2	35	5	39	30	8	35	5	0	8
3	15	3	30	25	6	30	5	0	10
4	10	3	22	15	4	22	5	1	12
5	5	2	15	5	2	15	5	2	15
6	2	1	10	2	1	9	10	3	18
7	2	1	7	1	0	5	10	4	21
8	1	1	5	1	0	3	10	5	25
9	0	0	2	0.5	0	2	20	5	30
10	0	0	2	0.5	0	1	30	5	35

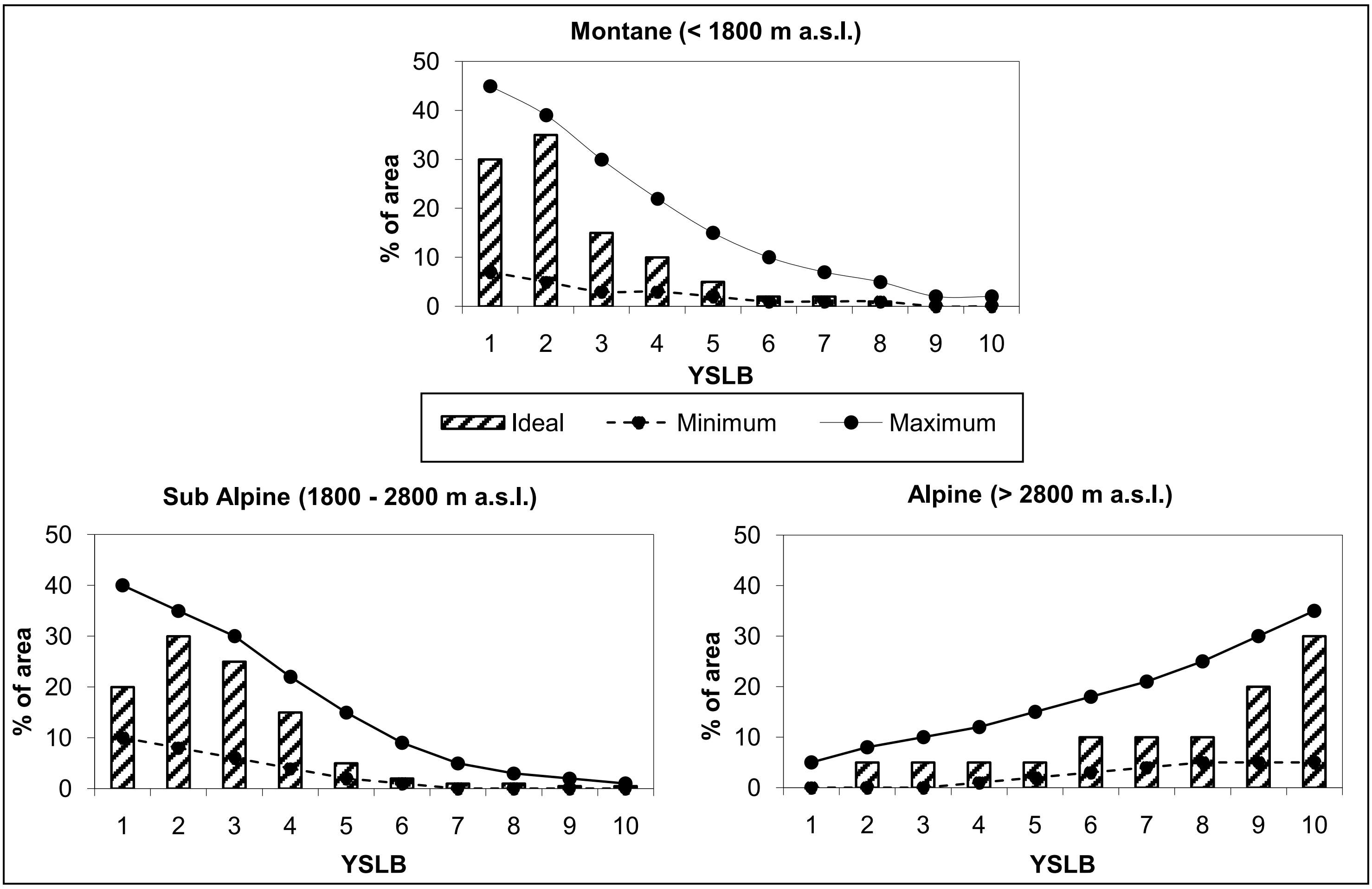


Figure 3.13: Fire regime parameters for each altitudinal belt in terms of percentage (%) area burnt and years since last burnt (YSLB) per burning period (per annum). The hatched bars are the ideal percentage area to be burnt per year since last burnt. The solid and dotted lines are the maximum and minimum percentage area.

3.5.2 Annotation

The percentage area and years since last burnt (YSLB) of each management compartment is required while making decisions regarding where to burn. Therefore these data needs to be visually represented on the layout. The management compartments are labelled with the expression [*Percentage_Area*] & " "& "%". These labels were converted to annotation with a reference scale of 1:100 000 and stored in the EKZNW_Fire_DSS geodatabase (Fig. 4.4).

The annotated labels are a separate feature related to the management compartment feature. Therefore the label expression can be changed to include more information. The other label is the YSLB, using the expression [*YSLB*] & " "& "YSLB" (Fig. 4.4). The scale range was set to not show labels when zoomed out beyond 1:150 000 to prevent dense clustering of labels at smaller scales.

3.5.3 Precautions

The uKhahlamba Drakensberg Park contains various elements resulting in World Heritage Site status, these elements include archaeological relicts, cultural significance and endemic and rare species. To maintain and conserve this unique region, special management objectives are required for various aspects associated with these elements (e.g. campsites, rock art sites, fire-sensitive species) to prevent damage and/or loss.

A feature class, '*Precautions*', was created containing these elements. This was created to alert the decision makers that there is a potential precaution within that management compartment. The element is displayed with a marker that the decision makers can select and display a window with all the required additional information of that specific element including an image, (Fig. 3.14) and a descriptive .pdf document. The exact location of Rock Art sites are not displayed in any of the decision support system images within this dissertation due to the sensitive nature of the data and to ensure the future archaeological integrity of the sites. Therefore depiction of sites and associated locations within this dissertation is purely fictional and are used for operational purposes.

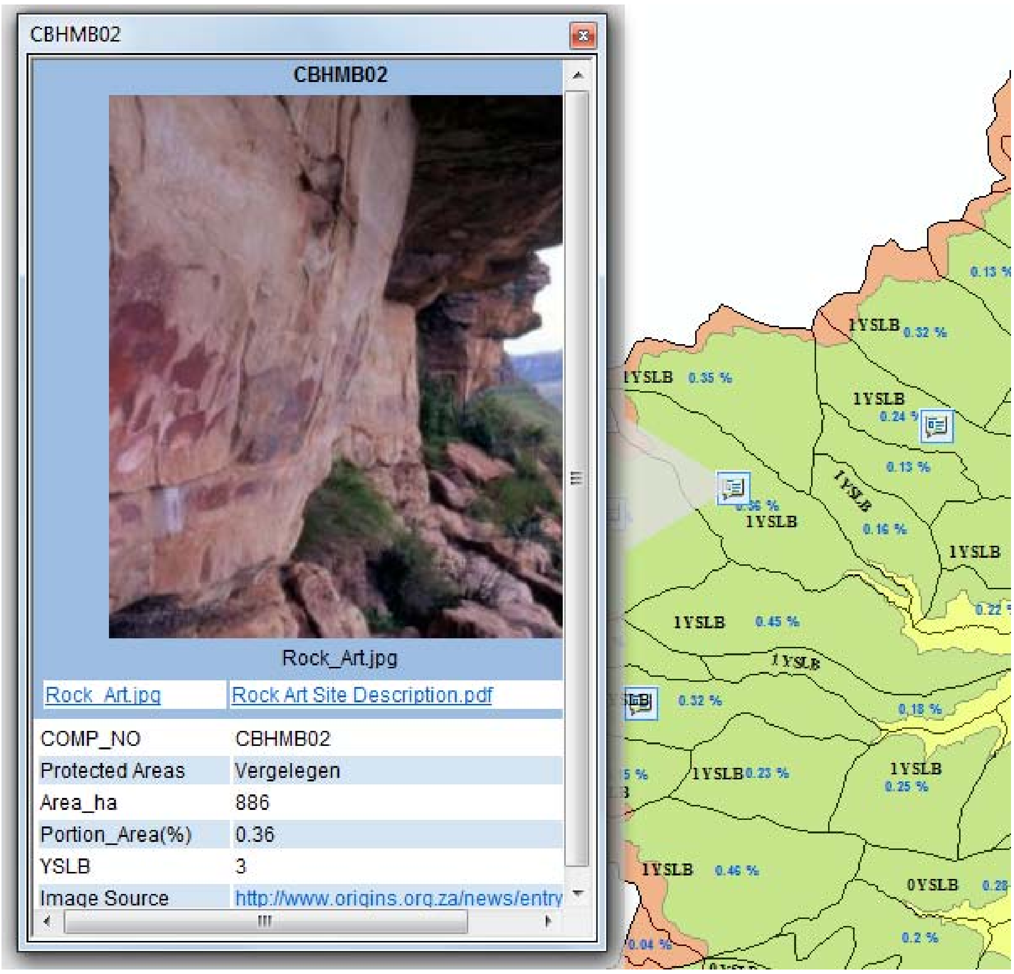


Figure 3.14: HTML popup display window showing precautions for sensitive area, i.e. rock art sites, within the uKhahlamba Drakensberg Park World Heritage Site

Additional information related to these specific elements is required to help decision makers in prescribed burning management decisions. Displaying this information is achieved through the use of '*Attachments*'. This allows for adding files to individual features in numerous formats (e.g. PDFs, images, documents). Attachments are similar to hyperlinks but allow the association of multiple files, storing of the attached files in a geodatabase and viewing of these files in numerous ways. The feature class has to be within an ArcGIS version 10 geodatabase, namely 'EKZNW_Fire_DSS'. The geodatabase was a 9.3.1 version and had to be upgraded by right clicking in the ArcCatalog tree under the general tab of properties and selecting '*Upgrade Geodatabase*'. To add information, the '*attachments*' had to be enabled on the feature class in the ArcCatalog. This enabling created a new table to contain attachment files and a new relationship class to relate the features to the attached files. The creation has to be done outside of an editing session, whilst adding attachments to the feature must be done during an editing season. Adding files has to be done during an editing session, found in the '*Attributes*' section (Editor toolbar). The feature must be selected, and the files added through the '*Attachment Manager*'. The data added can include an image of the precaution element, labels, area and suggested prescribed burning technique .pdf (Fig. 3.14). The attachments are stored in the geodatabase table and therefore do not have a link to the original source and can be used from different computers. To view this information on map layout, the HTML pop-up tool is used, which is found on the EKZNW FDSS toolbar.

3.5.4 Toolbar

A new toolbar '*EKZNW FDSS*' was created in the '*Customize Mode*' menu which opens the toolbar dialog box. It was developed to house all the tools that were required in selecting management compartments requiring prescribed burning (Fig. 3.15; Fig. 4.4).

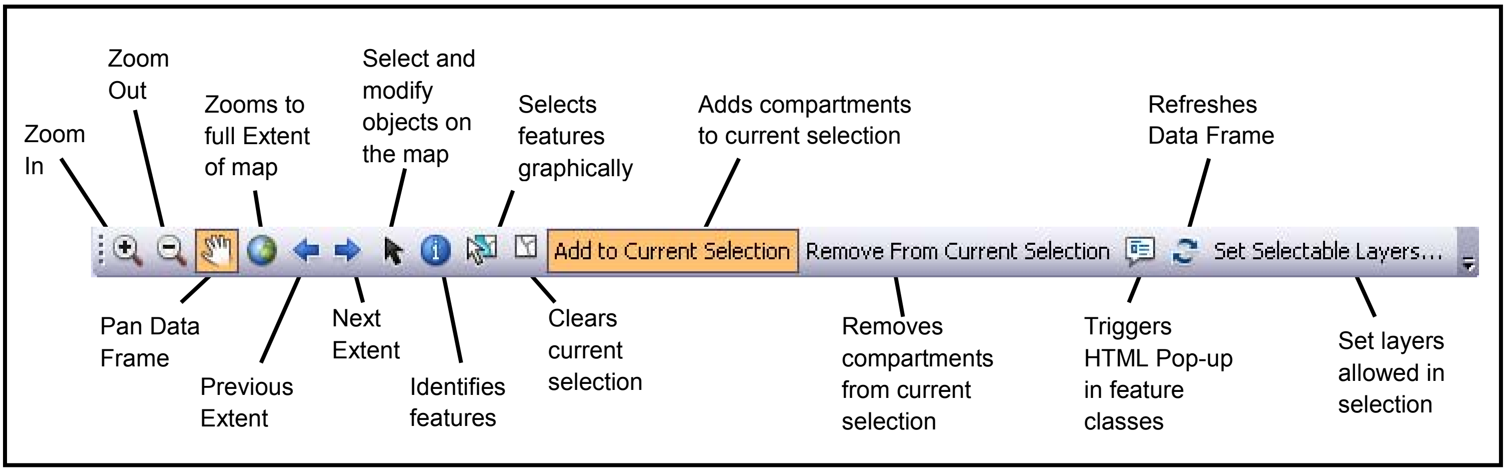


Figure 3.15: The 'EKZNW' toolbar in the uKhahlamba Drakensberg Park World Heritage Site (UDP-WHS) ArcMap document.

3.6 Ezemvelo KZN Wildlife (EKZNW) Workshops

A number of workshops were held with EKZNW during the research process. An initial workshop was held to determine the requirements and the viability of the project. Relevant data, EKZNW fire management objectives and the research framework were established during this initial workshop. Two subsequent workshops were held for updates and feedback to track the research progress and to gather additional data. The last workshop was for the final validation of the Environmental Decision Support System.

3.7 Conclusion

The research involved the collection, preparation, statistical analyses and modelling of large amounts of data using the ArcGIS software suite. This was required to develop an Environmental Decision Support System for the uKhahlamba Drakensberg Park World Heritage Site which is presented in the succeeding chapter.

CHAPTER FOUR

RESULTS

4.1 Introduction

The research aim was to develop an environmental decision support system for the uKhahlamba Drakensberg Park World Heritage Site (UDP-WHS). This chapter contains the final decision support system, layout interface (ArcMap document) and final export data. The previous chapter (chapter three: methodology) contains all the intermediate results that were required for the subsequent steps in the methodology to produce the final system. Thus chapter three and four need to be seen not as the more 'classical' individual methods and results chapters of a thesis but as an extension of each other. Hence the cross referencing between the two chapters.

4.2 Model Results

The results of the models (section 3.4) that form the foundation of the environmental decision support system, consists of intermediate and final outputs. These outputs are in the form of layouts, graphs and tables. Due to the size of the data set, a subset of the data will be used to visually display the results of these models.

4.2.1 Intermediate Model Outputs

The resultant output of the intermediate model (Fig. 3.8) includes the selected compartments (Fig. 4.1a) being divided into the three altitudinal belts. They are displayed with the unique colour palette that was determined from the layer file selected in the layer symbology in step two (Fig. 4.1b). These outputs are temporary and change with every run of the model. The selected data were summarised and displayed in individual bar graphs (Fig. 4.1c). The three line series in each graph provide the user with an indication of how closely the selected areas are in relation to the ideal fire regimes of each altitudinal belt (Fig. 4.1c).

4.2.2 Final Model Output

The management compartments that the decision makers have determined to require prescribed burning, from numerous runs of the intermediate model, are selected. The final model was run with this selection, with the final result being an exported .dbf table of all management compartments and associated treatment. The results of each step of the final model (fig. 3.11) are displayed and discussed (Fig. 4.2).

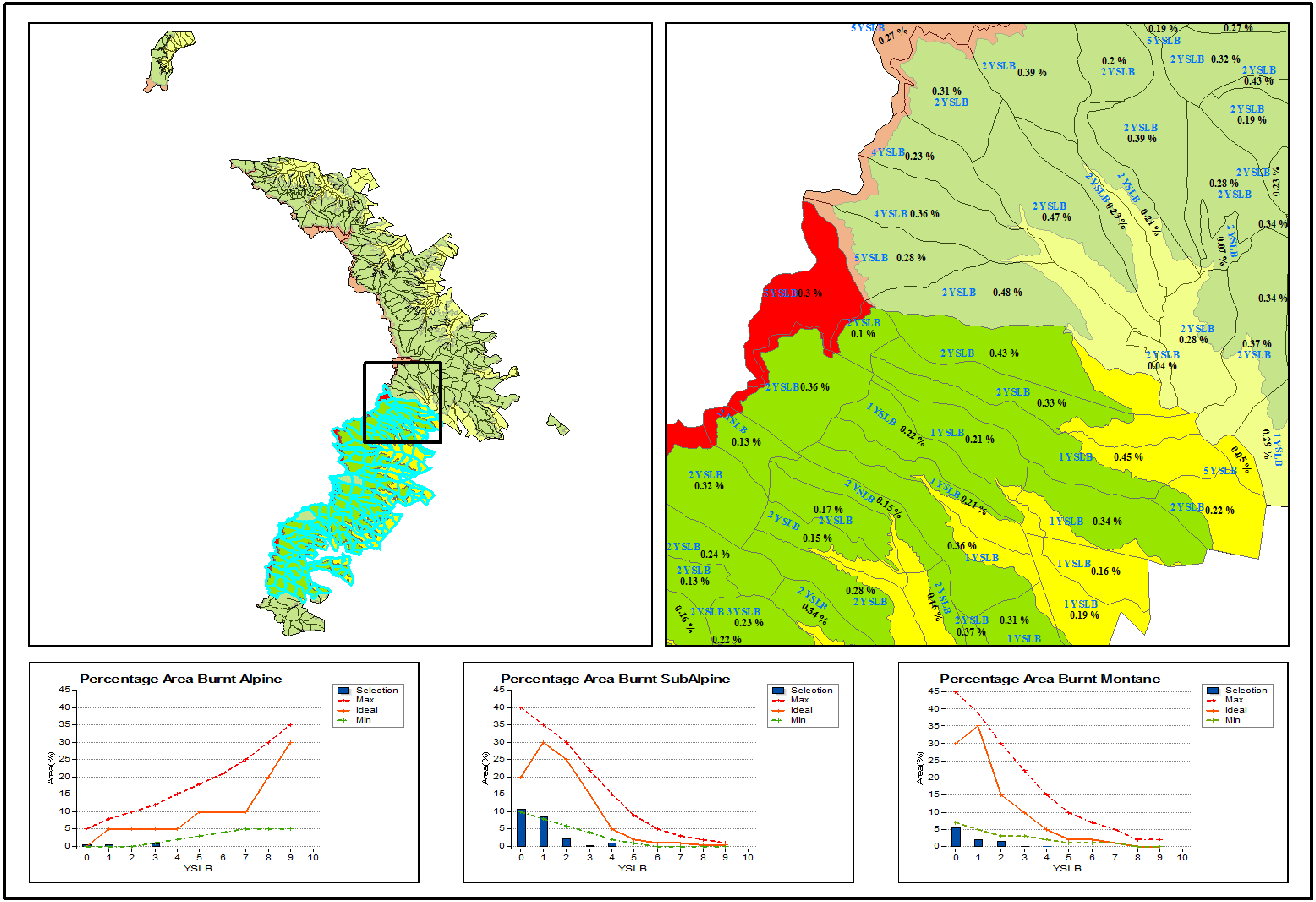


Figure 4.1: Temporary Model outputs of the uKhahlamba Drakensberg Park World Heritage Site (UDP-WHS) Environmental Decision Support System (EDSS), a) selected features in the UDP-WHS, b) selected features after the model has been run contain a specific colour palette and c) selected data was summarised and displayed in individual bar graphs with ideal fire regimes (line graphs).

Comp ID	Protected Area	Area (ha)	Area %	YSLB	Treatment
RNNPPRO	Royal Natal	2696	1.08	5	
WTBG01	Witteberg	1762	0.71	2	
WTBG02	Witteberg	2009	0.81	2	
WTBG18	Witteberg	469	0.74	2	
HLSD17	Hillside	2005	0.8	2	
CBHMB03	Vergelegen	1355	0.54	2	
IJST29	Injasuthi	1682	0.67	4	
WTBG05	Witteberg	1581	0.63	1	
WTBG06	Witteberg	1617	0.65	2	
HLSD29	Hillside	1516	0.61	2	

(5 out of 10 Selected)

Comp ID	Protected Area	Area (ha)	Area %	YSLB	Treatment
RNNPPRO	Royal Natal	2696	1.08	5	Scheduled
WTBG01	Witteberg	1762	0.71	2	Scheduled
WTBG02	Witteberg	2009	0.81	2	Scheduled
WTBG18	Witteberg	469	0.74	2	Scheduled
HLSD17	Hillside	2005	0.8	2	Scheduled
CBHMB03	Vergelegen	1355	0.54	2	
IJST29	Injasuthi	1682	0.67	4	
WTBG05	Witteberg	1581	0.63	1	
WTBG06	Witteberg	1617	0.65	2	
HLSD29	Hillside	1516	0.61	2	

(5 out of 10 Selected)

The compartments selected for prescribed burning in the management compartment feature class (left) was the input for step one (right). The selected features were labelled "*Scheduled*" in the treatment field using the field calculator.

Comp ID	Protected Area	Area (ha)	Area %	YSLB	Treatment
RNNPPRO	Royal Natal	2696	1.08	5	Scheduled
WTBG01	Witteberg	1762	0.71	2	Scheduled
WTBG02	Witteberg	2009	0.81	2	Scheduled
WTBG18	Witteberg	469	0.74	2	Scheduled
HLSD17	Hillside	2005	0.8	2	Scheduled
CBHMB03	Vergelegen	1355	0.54	2	
IJST29	Injasuthi	1682	0.67	4	
WTBG05	Witteberg	1581	0.63	1	
WTBG06	Witteberg	1617	0.65	2	
HLSD29	Hillside	1516	0.61	2	

(5 out of 10 Selected)

Comp ID	Protected Area	Area (ha)	Area %	YSLB	Treatment
RNNPPRO	Royal Natal	2696	1.08	5	Scheduled
WTBG01	Witteberg	1762	0.71	2	Scheduled
WTBG02	Witteberg	2009	0.81	2	Scheduled
WTBG18	Witteberg	469	0.74	2	Scheduled
HLSD17	Hillside	2005	0.8	2	Scheduled
CBHMB03	Vergelegen	1355	0.54	2	Not Burnt
IJST29	Injasuthi	1682	0.67	4	Not Burnt
WTBG05	Witteberg	1581	0.63	1	Not Burnt
WTBG06	Witteberg	1617	0.65	2	Not Burnt
HLSD29	Hillside	1516	0.61	2	Not Burnt

(5 out of 10 Selected)

The selection was switch (step two) as the field calculator will only calculate selected features. These features were calculated as "*Not Burnt*" in the treatment field (step three). Thus there were no blank records. Blank records are not registered by the *Years Since Last Burnt* (YSLB) formula in the excel spreadsheet, therefore will not be counted in the YSLB column.

Table — Management_Compartments

Comp ID	Protected Area	Area (ha)	Area %	YSLB	Treatment
RNNPPRO	Royal Natal	2696	1.08	5	Scheduled
WTBG01	Witteberg	1762	0.71	2	Scheduled
WTBG02	Witteberg	2009	0.81	2	Scheduled
WTBG18	Witteberg	469	0.74	2	Scheduled
HLSD17	Hillside	2005	0.8	2	Scheduled
CBHMB03	Vergelegen	1355	0.54	2	Not Burnt
IJST29	Injasuthi	1682	0.67	4	Not Burnt
WTBG05	Witteberg	1581	0.63	1	Not Burnt
WTBG06	Witteberg	1617	0.65	2	Not Burnt
HLSD29	Hillside	1516	0.61	2	Not Burnt

(0 out of 10 Selected)

Management_Compartments

Table — Management_Compartments

Comp ID	Treatment
RNNPPRO	Scheduled
WTBG01	Scheduled
WTBG02	Scheduled
WTBG18	Scheduled
HLSD17	Scheduled
CBHMB03	Not Burnt
IJST29	Not Burnt
WTBG05	Not Burnt
WTBG06	Not Burnt
HLSD29	Not Burnt

(0 out of 10 Selected)

Management_Compartments

The selection of a subset of the data is cleared, leaving no record selected (step four). This is because when exporting a table (step five) only the selected features are exported. The entire data set is required to update the dataset therefore by clearing the selection the entire attribute table is exported. Step five is necessary as it removes unnecessary fields.

Treatments

	A	B
1	Comp ID	Treatment
2	CBHMB03	Not Burnt
3	HLSD17	Scheduled
4	HLSD29	Not Burnt
5	IJST29	Not Burnt
6	RNNPPRO	Scheduled
7	WTBG01	Scheduled
8	WTBG02	Scheduled
9	WTBG05	Not Burnt
10	WTBG06	Not Burnt
11	WTBG18	Scheduled

Excel Datasheet — Historical Data

	A	B	C	D	E	F	G	H	I
1	Comp ID	Pre_2005	Treat_05	Treat_06	Treat_07	Treat_08	Treat_09	*Insert Year*	YSLB
2	CBHMB03	Burnt	Arson	Not Burnt	Arson	Not Burnt	Not Burnt		2
3	HLSD17	Burnt	Arson	Not Burnt	Runaway	Not Burnt	Not Burnt		2
4	HLSD29	Burnt	Not Burnt	Not Burnt	Invasive	Not Burnt	Not Burnt		2
5	IJST29	Burnt	Invasive	Not Burnt	Not Burnt	Not Burnt	Not Burnt		4
6	RNNPPRO	Burnt	Not Burnt	Not Burnt	Not Burnt	Not Burnt	Not Burnt		5
7	WTBG01	Burnt	Arson	Not Burnt	Arson	Not Burnt	Not Burnt		2
8	WTBG02	Burnt	Arson	Not Burnt	Invasive	Not Burnt	Not Burnt		2
9	WTBG05	Burnt	Runaway	Not Burnt	Arson	Arson	Not Burnt		1
10	WTBG06	Burnt	Runaway	Not Burnt	Arson	Not Burnt	Not Burnt		2
11	WTBG18	Burnt	Runaway	Not Burnt	Arson	Not Burnt	Not Burnt		2

The final step (six) is exporting the geodatabase table of step five into a .dbf table compatible with excel (left). The treatment field (in the left table) is copied and pasted into a new field created (under the *Insert Year* column) in the historical data set (right). Resulting in the data set and ArcMap document being updated. The excel document can be updated throughout the year with any treatment in the drop-down list.

Fig 4.2: Output tables for each step in the *Final Model* and the historical data excel spreadsheet.

4.2.3 Attribute Tables

The attribute table of the *management compartments* (MCs) and *MCs subdivided by the altitudinal belts* feature classes (created in section 3.2.3) contain the required data. The MCs feature contains 489 records with all the historical data from previous years. The MCs subdivided by altitudinal belts contains 884 features and which altitudinal belt each one is located in (Fig. 4.3). The 489 features are subdivided, using the altitudinal belts, into 884 features. Included in this division is area with the total area of a single compartment split into portions and assigned to one of the three altitudinal belts (Fig. 4.3 highlighted). The percentage area (per individual belt) of the portion area is calculated for use in the intermediate model.

Table - MCs_subdivided_Altitudinal_Belts

Management_Compartments_MCs

Comp_ID	Protected_Area	Area (ha)	Area (%)	Pre_2005	Treat_05	Treat_06	Treat_07	Treat_08	Treat_09	YSLB
CPF04	Cathedral Peak	629	0.25	Burnt	Not Burnt	Not Burnt	Arson	Not Burnt	Not Burnt	2
CPXIII	Cathedral Peak	50	0.02	Burnt	Not Burnt	Not Burnt	Not Burnt	Not Burnt	Not Burnt	5
CPXIV	Cathedral Peak	129	0.05	Burnt	Not Burnt	Not Burnt	Not Burnt	Not Burnt	Not Burnt	5
CPR103	Cathedral Peak	238	0.2	Burnt	Arson	Not Burnt	Arson	Not Burnt	Not Burnt	2
CPA02	Cathedral Peak	640	0.26	Burnt	Not Burnt	Not Burnt	Not Burnt	Not Burnt	Not Burnt	5
CPB02	Cathedral Peak	496	0.2	Burnt	Arson	Not Burnt	Not Burnt	Not Burnt	Not Burnt	4
CPB03	Cathedral Peak	419	0.17	Burnt	Not Burnt	Not Burnt	Not Burnt	Invasive	Not Burnt	1
CPB05	Cathedral Peak	177	0.07	Burnt	Not Burnt	Not Burnt	Scheduled	Not Burnt	Not Burnt	2
CPB06	Cathedral Peak	650	0.26	Burnt	Not Burnt	Not Burnt	Not Burnt	Not Burnt	Not Burnt	5
CPB08	Cathedral Peak	296	0.12	Burnt	Not Burnt	Not Burnt	Not Burnt	Invasive	Not Burnt	1

0 (1 out of 489 Selected)

Management_Compartments_MCs

MCs_subdivided_Altitudinal_Belts

Comp ID	Protected Area	Alt Belt	Total Area (ha)	Portion Area (ha)	Portion Area (%)	YSLB
CPF04	Cathedral Peak	Alpine	629	99.25	0.03978	2
CPF04	Cathedral Peak	Sub_Alpine	629	530.12	0.21245	2
CPXIII	Cathedral Peak	Sub_Alpine	50	50.46	0.02022	5
CPXIV	Cathedral Peak	Sub_Alpine	129	128.88	0.05165	5
CPR103	Cathedral Peak	Sub_Alpine	238	95.5	0.03827	2
CPR103	Cathedral Peak	Montane	238	142.32	0.05704	2
CPA02	Cathedral Peak	Alpine	640	129.14	0.05175	5
CPA02	Cathedral Peak	Sub_Alpine	640	510.71	0.20467	5
CPB02	Cathedral Peak	Alpine	496	107.98	0.04327	4
CPB02	Cathedral Peak	Sub_Alpine	496	388.1	0.15554	4

0 (2 out of 884 Selected)

MCs_subdivided_Altitudinal_Belts

Figure 4.3: The attribute tables of the *management compartments* (MCs) and *MCs subdivided by the altitudinal belts* feature classes. The highlighted features illustrate the subdivision of one compartment into two, with the total area being divided proportionally and each new portion assigned an altitudinal belt.

4.3 User Interface

The environmental decision support system is stored in the geodatabase (section 3.5) with the user interface set-up being stored in an ArcMap document (.mxd). This document contains the various feature classes (created in section 3.3), annotations (3.5.2), toolbox and toolbar (3.5.4) and the necessary changes in geoprocessing settings (Table 4.1).

4.4 UDP-WHS Fire Management Environmental Decision Support System (EDSS)

The fire management EDSS for the uKhahlamba Drakensberg Park World Heritage Site (UDP-WHS) consists of an ArcMap document, geodatabase (3.5), excel document (3.3.5) and folders, which are all housed in one folder (Table 4.1)

Table 4.1: The various elements of the uKhahlamba Drakensberg Park World Heritage Site (UDP-WHS) fire Environmental Decision Support System (EDSS) and their location.

Folder Tree	Description
E:\University\2010\Ezemvelo_KZN_Wildlife	Host Folder
Table(dbf)_Exports	Folder containing dbf tables from the final model output used to update excel spreadsheet
EKZNW_Fire_DSS.gdb	EKZNW Fire EDSS File Geodatabase
Altitudinal_Belts	Altitudinal belts (ABs) feature class, housed in the GDB.
Management_Compartments_MCs	Management compartments feature class, housed in the GDB.
Management_Compartments_Labels	Management compartments annotated label feature class, housed in the GDB
MCs_subdivided_Altitudinal_Belts	MCs subdivided by ABs feature class, housed in the GDB.
Fire_EDSS 1_Temporary_Outputs 2_Final_Output	Fire EDSS toolbox containing the intermediate and final output models housed in the GDB.
Select_Alpine Select_Montane Select_SubAlpine	The selection features classes of each AB from the intermediate output model, housed in the GDB.
Alpine_Ideal Alpine_Max Alpine_Min	Ideal, maximum and minimum fire regimes for the Alpine altitudinal belt. Percentage area per Years Since Last Burnt (YSLB).
SubAlpine_Ideal SubAlpine_Max SubAlpine_Min	Ideal, maximum and minimum fire regimes for the Montane altitudinal belt. Percentage area per YSLB.
Montane_Ideal Montane_Max Montane_Min	Ideal, maximum and minimum fire regimes for the Montane altitudinal belt. Percentage area per YSLB.
EKZNW_Fire_DSS.mxd	EKZNW EDSS ArcMap Document
EKZNW_YSLB.xlsx	Excel document containing historical fire management data

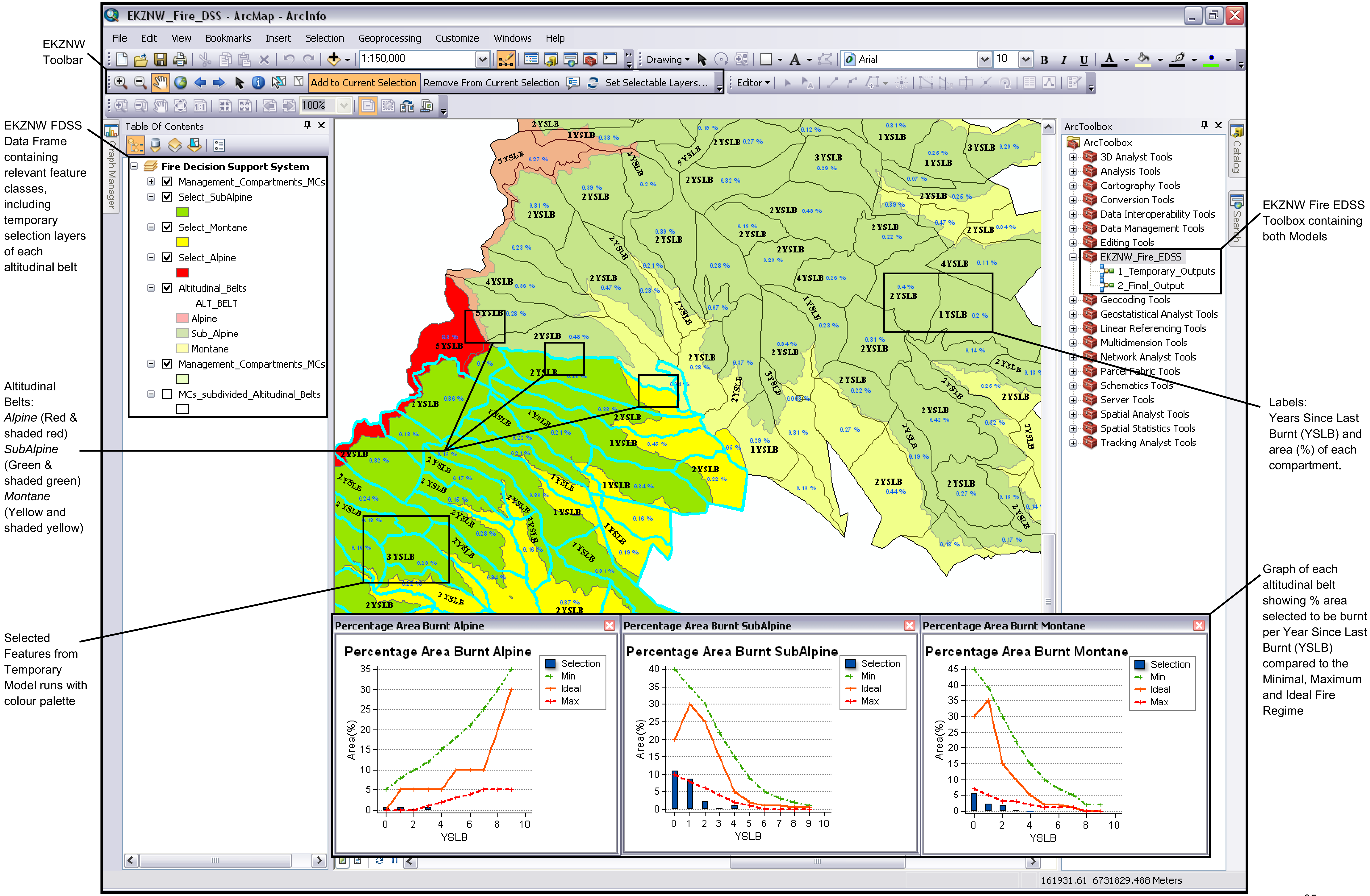


Figure 4.4: The user interface of the uKhahlamba Drakensberg Park World Heritage Site (UDP-WHS) Fire Management Environmental Decision Support System ArcMap document.

CHAPTER FIVE

DISCUSSION

5.1 Introduction

A fundamental property of planet Earth, fire persists as an evolutionary presence and ecological process of great import, and control over fire continues to be one of the foundations of human culture (Pyne 1984: vii).

Ecosystems, communities and species have evolved to be naturally self-sustaining ecological systems. The arrival of human into these ecosystems and the negative impact they have had is significant, altering this natural functioning. There is a need for these systems to function at their optimum level to avoid degradation and consequent loss of species, increase of undesirable species and a decline in natural resources. To keep these once vast landscape fragments functioning optimally human intervention is required in the form of natural resource management. This environmental management conserves the remaining species and their communities which benefits humans in terms of the resources available. According to Burrows (2008), there are numerous processes that affect natural resources, however, fire is an environmental factor that naturally can have a negative or positive effect on natural resources dependent on the prescribed fire regime and the presence of other interacting factors such as fragmentation and biological invaders.

The uKhahlamba Drakensberg Park World Heritage Site (UDP-WHS) is one of South Africa's main water sources and a region of high biologically diversity. To maintain the quality of this water source and species richness, suitable natural resource management objectives and decision support systems are required by the management custodians, Ezemvelo KZN Wildlife, involving scientific data and managerial decision makers, to keep this area in a pristine ecological state.

This chapter presents the results (chapter four) and intermediate results (chapter three) of the research. The use of GIS, a geodatabase and spreadsheets to develop an environmental decision support system, utilised in a provincial fire management plan, will be discussed. The advantages and limitations of the methodology developed in this study will be highlighted and the fire management EDSS linked to the theoretical framework of the research (chapter two).

5.2 Research Results

The raw data were collected and manipulated using ArcMap to develop required feature classes and two GIS models. These two models form the major components of the environmental decision support system for fire management in the UDP-WHS. A file geodatabase was created to host the EDSS and the developed feature classes. A spreadsheet was developed containing the historical fire data for each management compartment per year. This was created to determine the years since last burnt for each compartment. A user interface was developed in an ArcMap document, allowing the user interface to remain consistent. The final environmental decision support system developed for the UDP-WHS fire management consists of the geodatabase, historical data spreadsheet and ArcMap document.

5.3 Management Compartments

The UDP-WHS is divided into management compartments within which the environmental managers prescribe fire treatments. The ideal fire regimes are designed for each altitudinal belt which these management compartments boundaries do not conform to, therefore when burning a compartment this needs to be taken into consideration as the percentage area for the alpine altitudinal region is much lower than the neighbouring sub-alpine belt but one management compartment will be made up of both alpine and sub-alpine belts. This adds a level of complexity when burning compartments as prescribed burning takes place per compartment, affecting both altitudinal belts and, with the significant variations in percentage area needed to be burnt per belt, satisfying the requirements of neighbouring belts becomes difficult. Ideally the boundaries of the subdivided compartments should be altered to following the contour of the altitudinal belts. Therefore each belt could be managed as an individual entity with its own management objectives and not semi-dependent on what occurs in the neighbouring belts compartments.

A major factor is that these management compartments are anthropogenic-based. They were determined by pre-existing property boundaries, relief and ease of management. They are not based on the ecological requirements of the ecosystem. Therefore ideally burning should not be based on managerial designated areas but rather on the requirements of the landscape. There is the difficulty of control burning of large extents of land and consequently will require more resources, which are not always available.

The management compartments through subsequent years change in terms of boundaries, code and projection. Therefore to add data to the layout or to update the historical data, each year had to be standardised to avoid conflicting or incorrect information being used in the decision making process.

5.3.1 Fire Management Objectives

The ideal fire regimes developed from workshops with Ezemvelo KZN Wildlife (EKZNW) were determined and placed in the appropriate graphs (Fig. 4.4) to act as a guide for fire management decision makers. The regimes consider the main environmental and biotic factors affecting fire behaviour and characteristics which consequently affects the fire regime of an area. The prescribed burning of the UDP-WHS is to fulfil three management objectives, i.e. water resources/ watershed management, national parks (protected areas) and security/ hazard reduction. Ideally, after prolonged prescribed burning following these graphs using the EKZNW EDSS, will result in the fire regime of the UDP-WHS returning to an ecologically ideal regime.

5.4 Geographical Information Systems (GIS)

5.4.1 Use of Environmental Decision Support Systems

The use of EDSS in environmental management has improved the efficiency and accuracy of the decision making process (Matthies *et al.* 2007). Many EDSSs completely remove the human element of the process, however with the system designed for the UDP-WHS the human element was purposely kept intact. By allowing the inclusion of human decision making and coupling that with the efficient and accurate characteristics of an EDSS, prevents the complete rigidity of a computerised statistical system but reduces the level of human error and time involved in complex statistical analyses. Therefore combining a number of variables into one system, making rigid scientific information readily available but not compulsory in the decision making process.

In natural resource management there are complexities created by multiple environmental dynamics and different decision makers having conflicting objectives. This in turn makes environmental DSSs complex applications, requiring advanced technologies and high research and development efforts. They are also time consuming and expensive to develop and maintain (Liu and Stewart 2004). However, a well designed support system for natural resource management is an invaluable asset to decision makers, practitioners and stakeholders when faced with a decision problem (Liu and Stewart 2004). A EDSS also provides a means of evaluating and validating decisions made during a decision making process.

5.4.2 Geodatabase

Creating a geodatabase to host the fire management decision support system was accomplished however there were a few aspects that limited the full potential of a geodatabase.

The use of a geodatabase added functionalities that without, this EDSS would not have been possible. It allowed the housing of the newly created fire management toolbox which in turn housed the models required to run the support system. The storage of data in the geodatabase meant it could be tranferable between computers due to the data not being stored on individual computers but in the geodatabase itself. The compression functionality of the geodatabase is advantageous because as geodatabases are edited the delta tables increase in size and the number of states increase. Therefore the larger the tables and the more states mean more data ArcGIS must process each time one displays or runs analyses, slowing the performance of the support system.

However, there are a number of data that cannot be stored within a geodatabase because they will lose functionality. For example, the excel document can be imported into the geodatabase but then becomes a static table, defeating the purpose of having an excel spreadsheet. Therefore the portability function of the geodatabase becomes ineffective. There is a need for the user interface to be set-up in a particular way, therefore a ArcMap .mxd document was created that already has the study site template (containing the correct features with labels and correct settings), toolbox (containing the models), toolbar and graph templates located in the correct manner. The major concern with this is that every feature class and output has a path name to where they are found in the system. These data can still be portable by placing them in a folder that accompanies the geodatabase however the driver code changes from computer to computer. Therefore when loading the document, the drive letter must be kept constant between computers.

Nevertheless, the use of excel is based on the capacity of the end-users therefore allowing for a much higher number of users as excel is a common universal program with a simpler user interface compared to ArcGIS and associated geodatabases. Consequently more people will understand and have the ability to manage an excel document compared to updating and editing a geodatabase document.

5.4.3 Methodologies

The different methodologies (preceding the final methodology) utilised throughout the development of the decision support system to achieve the resultant EDSS in chapter four, were aborted for some reason are another. The use of models was the only viable option for this kind of system. However the older version of ArcGIS (9.3.1) had a significant flaw of not being able to create graphs in the macro model builder. To correct this problem a new version of the program, that had only recently become available, had to be explored. This version (10) had the required functionality, however due to its recent release required two service packs before the realisation that it had this capability. This version was only made available through a tertiary education institution that had the financial capacity to purchase the necessary licences. Due to the new version not being the common version, the number of people that can utilise this type of EDSS would be limited as a new version document cannot run all the processes in an older version of the program and the newer version will be financially available to limited number of users.

Besides the financial restraint, there are a number of other considerations in this type of environmental decision support system when using different programs and analytical tools. The updating of the graphs after selecting or deselecting management compartments for prescribed burning treatment only occurs after running the model. It is not completely interactive or autonomous, i.e. does not update automatically, making the process time consuming.

5.5 Prescribed Burning

The season in which prescribed burning takes place remains a controversial matter, predominately due to differences in objectives. According to Everson et *al.* (2004) the official consensus is that prescribed burning in the uKhahlamba Drakensberg Park region occurs during early winter, winter and early spring to remove accumulated fuel. Often burning is used in the stimulation of growth out of season and this is where the disputes occur. Surely if the only objective was to remove this residual plant material then the timing of burning should occur when the grass sward is able to develop a suitable canopy recovery within the shortest time possible. It is acknowledged that prescribing burns during the vegetative dormant period (winter) will not have a significant long-term effect on the sward's vigour, composition, cover and/or productivity (see Morris 1998 Everson et *al.* 2004). Therefore the suggestions of when to burn are based on the physiological state of the plant at the time of burn instead of time or season of the year. For that reason, prescribed burning should occur as close to the beginning of the first spring rains (start of growth season due to change in temperature) as possible, ensuring rapid vegetative growth to reduce the time the soil surface is exposed to wind and water erosive forces (Everson et *al.* 2004).

This is good in theory, however in practice it becomes more difficult. First, defining this optimum time of year to burn is complex as the first spring rains are preceded by smaller intermittent rainfalls (which may bring slight changes in temperature) which do not initiate the rapid spring growth associated with spring rains and major temperature changes but does however initiate some growth. Therefore when the first spring rains do occur, sward growth has already begun and the initial tillers can be fatally damage (Everson et *al.* 2004). Second, due to prescribed burning management plans being planned in advance, the size of the area requiring management and limited man power, it is not always possible to base burning on the unpredictable first spring rains or temperature change. The size of the UDP-WHS (approximately 243 000 ha) means that it is impossible to burn all the required area just before spring. Therefore even though it is optimal to burn in early spring (when there are changes in temperature which initiates growth), breaking it up into three periods during the dormant season mean managers can safely burn the required area before the start of the growing season.

To achieve the optimal fire regime certain management compartments have to be burnt each year within a given time period. Given unlimited resources this would be achievable, however due to limited resources including man power and a short burning season this becomes problematic. If the selected compartments are located within one area of the park then prescribing burns are feasible but if they are spread through the entire park the probability of burning the required compartments, within the set time period, decreases dramatically. This is due to distance between compartments requiring burns (resources and time) and a type of edge effect, where neighbouring compartments can be burnt as one large compartment where as separate compartments have a larger surface area to manage and control.

5.5.1 Precautions

The Drakensberg is known for its rich archaeological artefacts and unique sensitive areas, hence the reason for the precaution feature class in the decision support system. However with this awareness of these sensitive areas comes the increase in resources required to protect them. Specialised prescribed burning techniques and time are required to successfully burn that specific compartment without damaging the object contained within it. This, as mentioned above, is sometimes not feasible with the limited available resources/capacity (labour) and the extra time required to burn that compartment. This may potentially result in two things, avoidance of compartments with special precautions in them during the management planning stages, or during implementation on the ground, ignoring the need for special burn techniques (due to time and resources) and burning the compartment as normal, resulting in damage to that sensitive object/s.

Conversely, when prescribing special burning techniques for individual anthropo-objects the fire requirements of the vegetation are not considered. Therefore applying these techniques to parts of these management compartments may potentially result in changes in species and plant community composition, which goes against the objective of implementing prescribed burning.

However, there is a need for these sensitive areas in terms of cultural heritage and tourism and a need for prescribed burning. Therefore resources need to be made available to ensure these special prescribed burning techniques for these sensitive areas are implemented correctly with the least amount of damage to the vegetation to satisfy both management needs.

5.5.2 Unexpected burns

The presence of natural (lightning) and unnatural (arson, accidental, etc.) fire creates an uncertainty of which areas to burn. A certain set of compartments can be selected to be burnt for that year, however a natural fire could result in the burning of compartments not selected for that year due to lightning's high prevalence and unpredictability. The major problem faced by the Ezemvelo KZN Wildlife managers is the difficulty in applying suggested fire regimes is the transfrontier problems associated with the neighbouring country, Lesotho, which include trafficking of drugs and firearms over the international border, illegal hunting, stealing of commercial and subsistence farmer's stock and arson fires. The injudicious use of fire (arson fires) has a significant impact on fire management plans and achieving the required objectives (Krüger 2007). The Drakensberg grasslands are purposefully burnt in an attempt to divert attention and resources from main smuggling routes, in frustration/retaliation to successful enforcement of the law and, to hunt game attracted to burnt areas (Krüger 2007; Sycholt 2002). Many of these fires are not contained and can result in unprescribed runaway fires burning undesignated compartments, severely hindering management efforts to prescribe the ecologically correct fire regime.

Thus this requires that the decision support system needs to be able to receive unexpected updates and add them to the model all year round. This flexibility is vital for the managers to make adjustments to the fire management plans. They will be able to change which compartments to burn to continue to satisfy the fire regime requirements. The use of an excel spreadsheet and EDSS makes this achievable, instantaneous and user friendly.

5.5.3 Fire Breaks

To comply with South African legislation fire-breaks have to be burnt annually in the Drakensberg, affecting 5-10% of the landscape and creating an early season growth flush. This attracts herbivory and consequent defoliation having a potential effect on surface soil properties, species composition and diversity (O'Connor *et al.* 2004). This is a significant area percentage that needs to be taken into consideration when determining the annual percentage area required to burn. However fire breaks, do not have a significantly negative effect on the landscape and are seen as a sustainable management practice according to O'Connor *et al.* (2004).

5.6 Overgrazing

Vegetation pattern (and consequently faunal assemblages) in the world... is driven primarily by water availability and soil nutrients. Superimposed upon this, fire and grazing (by livestock and native herbivores) are major secondary drivers, and those most manipulated by human management (Kutt and Woinarski 2007: 95)

The lower elevations of the Drakensberg are under heavy pressure from overgrazing (KNCS 1999), combined with inappropriate fire management practices to promote out of season growth, results in land degradation. The inappropriate use of fire and overgrazing in the Drakensberg will result in reduced water quality, increased soil erosion, increased woody vegetation and decreased biodiversity (Blignaut *et al*. 2008; Kutt and Woinarski 2007). It has also directly been linked to a decline in bird and small-mammal population (Kutt and Woinarski 2007).

5.6.1 Carbon loss

Soil organic matter is the largest terrestrial organic carbon sink, with total carbon being three times higher than that of terrestrial vegetation. This is important in terms of climate change and carbon storage. The release of this CO_2 is due to land degradation, such as overgrazing and consequent soil erosion, causing an increase in the effects of climate change (Abril *et al.* 2005). According to Abril *et al.* (2005), burning of overgrazed areas results in a permanent tendency to carbon loss therefore the ideal fire regime for the Drakensberg may be ideal for the area but due to overgrazing may potentially be more detrimental to the landscape in terms of functionality and soil (and consequent carbon) loss.

5.7 Future Research

The development of Environmental Decision Support Systems (EDSSs) in natural resource management is progressing rapidly, resulting in a growing research focus as the complexities of socio-economic and biophysical interactions are increasingly acknowledged (Matthies et *al*. 2007). A significant factor in the increased utilisation of EDSSs is the advancements associated with Geographical Information Systems (GIS), i.e. the geographic and statistical analysis and visualisation tools (Matthies et *al*. 2007). This is evident in the increased analysis capabilities of ArcMap 10 from its predecessor ArcMap 9.3.1, which was pivotal for the completion of this research.

The fire management EDSS of the UDP-WHS has its limitations in that there is not an EDSS tool or model specifically designed for fire management. According to literature reviewed by Bonazountas *et al.* (2007), there have been efforts to create EDSSs for fire management by utilising technologies such as GIS, however no integrated system exists. There are numerous software programs to predict where fires may occur or behave for fire prevention and fighting, but not in determining which areas require prescribed burning to satisfy a specific fire regime (e.g. Bonazountas *et al.* 2007; Iliadis 2005; Keramitsoglou *et al.* 2004). Hence, the development of this fire management EDSS took a year with an understanding of GIS and EDSSs. Whereas with predesigned programs or tools which only require a few inputs; results can be obtained quicker with a minimal understanding of a GIS program. The lack of a suitable program/tool means that there are limitations in the methodology: the EDSS created in this research is not fully interactive, the data in the layout cannot be updated automatically, the EDSS is not fully portable and, requires an expert in the field of GIS to maintain the EDSS and to rectify any unforeseen problems. A specialised program will also decrease the amount of potential human error. There is a potential for human error, for example, when entering data into the excel spreadsheet or when compartments do not receive prescribed burning for an ecologically unacceptable period of time due to human decision making. Data may potentially be entered automatically and a rotational system in place to ensure that all compartments will receive prescribed burning when it is ecologically acceptable.

Further advancements in GIS will provide opportunities for further research into the development of management specific (i.e. fire management) decision support systems in natural resource management. EDSSs could potentially become more efficient and user friendly.

5.8 Conclusion

The conservation of biodiversity and protection of infrastructure and sensitive areas within the uKhahlamba Drakensberg Park World Heritage Site (UDP-WHS) was the driving force behind the development of the Fire Management Environmental Decision Support System (EDSS). The system was developed to aid decision makers in implementing annual prescribed burns in accordance to ideal fire regimes of the landscape. This chapter discussed the development of the EDSS, relating back to the theoretical framework in chapter two. The limitations of the methodology and the implementation of the system were examined.

CHAPTER SIX

CONCLUSION

6.1 Introduction

This chapter outlines the achievement of the research objectives, i.e. to identify the UDP-WHS boundaries and altitudinal zonation, create a template, determine fire management objectives, gather information of various aspects of the UDP-WHS, develop an environmental decision support model and, create a geodatabase housing the fire management decision support system; to achieve the overall aim of developing a fire management environmental decision support system for the uKhahlamba Drakensberg Park World Heritage Site based on the ecologically ideal fire regimes of individual altitudinal belts found within the heritage site and surrounding areas.

6.2 Objectives

6.2.1 Identify the uKhahlamba Drakensberg Park World Heritage Site (UDP- WHS) boundaries and altitudinal zonation and Create a template and Triangulated Irregular Network (TIN), containing the management polygons (compartments) and compartment identification number

Study site data, both quantitative and qualitative, were collected from various sources. The corrective digitising of each year (1991-2010) of the management compartments resulted in a base map containing 489 management compartments. Each compartment was assigned a unique identification code. The Digital Terrain Model (DTM) and relief data were utilised in the development of a Triangulated Irregular Network (TIN) of the UDP-WHS containing the management compartments. This was necessary in the determination of the three-dimensional area of the study site.

The altitudinal zonation was determined by creating three altitudinal belts (polygon feature) from the contour data (polyline feature). These three altitudinal belts were digitised and merged with the management compartments to create 884 sub-divided compartments. These sub-divided compartments do not receive unique codes as management decisions are made per management compartment and subsequently management decisions are applied to the sub-divided compartments. There were no limitations at the end of this process and therefore the objectives of 'identifying the uKhahlamba Drakensberg Park World

Heritage Site (UDP- WHS) boundaries and altitudinal zonation' and 'creating a template, containing the management polygons (compartments) and compartment identification number' were achieved.

6.2.2 Determine fire management objectives of the UDP- WHS, Gather information of various aspects of the UDP-WHS and Consultations and workshops with Ezemvelo KZN Wildlife

There were a number of consultations and workshops with Ezemvelo KZN Wildlife (EKZNW) personnel. The outcomes of these workshops were the theoretical ideal fire regimes and management objectives of each altitudinal belt found within the UDP-WHS. Due to the verbal format of these data it had to be converted to GIS format. This allowed for the visual display of minimal, maximum and ideal percentage area per year since last burnt for each altitudinal belt and the development of the precaution feature class. These workshops made available historical fire data for desired period and sensitive information on important areas such as rock art and infrastructure location. Therefore the objectives, 'Determine fire management objectives of the UDP- WHS', 'gather information of various aspects of the UDP-WHS' and consultations and workshops with Ezemvelo KZN Wildlife were achieved.

6.2.3 Development of environmental decision support models

The decision support system contains two models necessary to automatically display and update the required data. The two models are required to select management compartments requiring prescribed burning treatment and, after desired selections are made, to export the information to update the historical data consequently updating the years since last burnt. This is then continuously updated in the management compartment feature class in the ArcMap document. The functionality provided by the latest version of ArcMap made completing the models viable. These models were developed to required specifications thus allowing the objective, development of environmental decision support models, to be achieved.

6.2.4 Create a geodatabase housing the fire management decision support system

The development of a geodatabase was required to house the fire management decision support system, allowing the system to be a stand alone tool not dependent on a single computer. A geodatabase was developed, however the full capabilities of a geodatabase was not utilised due to the requirement of the excel spreadsheet which cannot be stored within a geodatabase. The storage of an excel document within a geodatabase results in the document losing its statistical functionality. Therefore the objective of 'creating a geodatabase housing the fire management decision support system' was achieved but with the limitation of not being fully functional. This was overcome by placing the geodatabase along with the excel document and other features within one folder. Therefore the one folder can be a stand alone tool with conserving the functionality of all the features within it.

6.3 Aim

All the objectives of this research were achieved and therefore the overall aim, of developing a fire management environmental decision support system for the uKhahlamba Drakensberg Park World Heritage Site based on the ecologically ideal fire regimes of individual altitudinal belts found within the heritage site and surrounding areas, was achieved.

6.4 Conclusion

Fire is an integral component of eco systems, affecting all aspects of resource and ecosystem management. Human influences have resulted in shifts in natural fire regimes resulting in management of fire-prone environments containing fire-maintained ecosystems needing to meet multiple objectives including protection of infrastructure and conservation of biodiversity. Planned burning is fundamental for managers to achieve fire and other landscape objectives to maintain the ecological functioning of the eco systems however, there is often difficulty in prescribing appropriate fire regimes. There is a need for decision support systems that integrate scientific data and management practices to be able to ecologically select areas to burn in keeping with the natural fire regime, while protecting infrastructure and sensitive areas. Decision support systems also make evaluating, justifying and validating decisions made during the decision making process, possible.

A fire management decision support system for the uKhahlamba Drakensberg Park World Heritage Site was developed. This system aids the custodians of the site, Ezemvelo KZN Wildlife management (decision makers), in developing the annual prescribed burning management plan to be applied to the management compartments of the park. The ideal fire regimes for each altitudinal belt were developed and utilised in the decision support system. This ensures that, ecologically, the correct fire regime would be applied to the landscape. Therefore conserving biodiversity, while infrastructure and sensitive areas are integrated in the support system allowing the decision makers to apply a burning regime that both conserves biodiversity and protects anthropogenic infrastructure and sensitive areas. The fire management environmental decision support system provides a means of evaluation, justification and validation of the decisions taken during the prescribed burning decision making process.

REFERENCES

Abril, A., Barttfeld, P. and Bucher, E. H. 2005. The effect of fire and overgrazing disturbs on soil carbon balance in the Dry Chaco forest. *Forest Ecology and Management*, 206, 399-405.

Acocks, J. P. H. 1975. Veld types of South Africa. *Memoirs of the Botanical Survey of South Africa,* No. 40. Botanical Research Institute. Department of Agricultural Technical Services, 40,1-128.

Arkle, R. S. and Pilliod, D. S. 2010. Prescribed fires as ecological surrogates for wildfires: a stream and riparian perspective. *Forest Ecology and Management*, 259, 893-903.

Arnott, W. L. 2006. *The effect of burning frequency on invertebrate and indigenous flowering forb diversity in a Drakensberg grassland ecosystem*. Unpublished Master of Science Thesis. University of Natal, Pietermaritzburg.

Backer, D. M., Jensen, S. E. and McPherson, G. R. 2004. Impacts of fire-suppression activities on natural communities. *Conservation Biology*, 18, 937-946.

Bailey, A. W., Brockett, B. H. and Mentis, M. T. 1993. Fire management in Pilanesberg National Park, Bophuthatswana, using expert systems as aids to decision making. *African Journal of Range and Forage Science*, 10, 25-30.

Barnes, B. 2003. *Giant's Castle: a personal history*. Privately Published, South Africa.

Bigalke, R. C. and Willan, K. 1984. *Effects of fire regime on faunal composition and dynamics*. In: Booysen, P. de V. and Tainton, N. M. (eds.). *Ecological effects of fire in South African ecosystems*. Springer-Verlag, Berlin.

Biggs, H. C. and Potgieter, A. L. F. 1999. Overview of the fire management policy of the Kruger National Park. *Koedoe*, 42, 101-110.

Blignaut, J., Aronson, J., Mander, M. and Marais, C. 2008. Investing in natural capital and economic development: South Africa's Drakensberg Mountains. *Ecological Restoration*, 26(2), 143-150.

Boer, M. M., Sadler, R. J., Wittkuhn, R. S., McCaw, L. and Grierson, P. F. 2009. Long-term impacts of prescribed burning on regional extent and incidence of wildfires: evidence from 50 years of active fire management in SW Australian forests. *Forest Ecology and Management*, 259, 132-142.

Bonazountas, M., Kallidromitou, D., Kassomenos, P. and Passas, N. 2007. A decision support system for managing forest fire casualties. *Journal of Environmental Management*, 84(4), 412-418.

Bond, W. J. 1997. *Fire*. In: Cowling, R. M., Richardson, D. M. and Pierce, S. M. (eds.) *Vegetation of southern Africa*. Cambridge University Press, Cape Town.

Bond, W. J. 1999. *Rangelands and biodiversity in southern Africa – impacts of contrasting management systems*. In: Eldridge, D. and Freudenberger, D. (eds.). *People and rangelands: building the future: proceedings of the 6th international rangeland congress 2*. International Rangeland Congress, Australia.

Bond, W. J., Geldenhuys, C. J., Everson, T. M., Everson, C. S. and Calvin, M. C. 2004. *Fire ecology: characteristics of some important biomes of sub-Sahara Africa*. In: Goldammer, J. G. and de Ronde, C. (eds.). *Wildland fire management handbook for sub-Sahara Africa*. Global Fire Monitoring Centre, Germany and Oneworldbooks, Cape Town.

Bond, W. J. and Keeley, J. E. 2005. Fire as a global 'herbivore': the ecology and evolution of flammable ecosystems. *Trends in Ecology and Evolution*, 20(7), 387-394.

Bowman, D. M. J. S. and Murphy, B. P. 2010. *Fire and biodiversity*. In: Sodhi, N. and Ehrlich, P. R. (eds.). *Conservation biology for all*. Oxford University Press, New York.

Bradstock, R. A. and Kenny, B. J. 2003. An application of plant functional types to fire management in a conservation reserve in southeastern Australia. *Journal of Vegetation Science*, 14, 345-354.

Bradstock, R. A., Bedward, M., Gill, A. M. and Cohn, J. S. 2005. Which mosaic? A landscape ecological approach for evaluating interactions between fire regimes, habitat and animals. *Wildlife Research*, 32(5), 409-423.

Bradstock, R. A., Bedward, M., Kenny, B. J. and Scott, J. 1998. Spatially-explicit simulation of the effects of prescribed burning on fire regimes and plant extinctions in shrublands typical of south-eastern Australia. *Biological Conservation*, 86, 83-95.

Branch, W. R. 1988. *South African red data book: reptiles and amphibians*. Council for Scientific and Industrial Research, Pretoria.

Briggs, P. 2006. *World Heritage Sites of South Africa: uKhahlamba Drakensberg Park*. 30° South Publishers, Johannesburg.

Brooke, R. K. 1984. *South African red data book: birds*. Council for Scientific and Industrial Research, Pretoria.

Brooks, P. M. and Berry, A. 1980. *The responses of 18 ungulate species to fire in the central complex, Zululand, between October 1975 and September 1977*. Unpublished report, Centre for Scientific and Industrial Research (CSIR).

Brown, J. K. 2000a. *Introduction and fire regimes*. In: Brown, J. K. and Smith, J. K. (eds.). *Wildland fire in ecosystems: effects of fire on flora*. General technical report RMRS-GTR-42 vol. 2. Rocky Mountain Research Station, Utah.

Brown, J. K. 2000b. *Ecological principles, shifting fire regimes and management considerations*. In: Brown, J. K. and Smith, J. K. (eds.). *Wildland fire in ecosystems: effects of fire on flora*. General technical report RMRS-GTR-42 vol. 2. Rocky Mountain Research Station, Utah.

Bui, T. X. 2000. *Decision support systems for sustainable development: an overview.* In: Kersten, G. E., Mikolajuk, Z. and Gar-On Yeh, A. (eds). *Decision support systems for sustainable development: a resource book for methods and applications*. Kluwer Academic Publishers, Boston.

Burrows, N. D. 2008. Linking fire ecology and fire management in south-west Australian forest landscapes. *Forest Ecology and Management*, 255, 2394-2406.

Caprio, A., Conover, C., Keifer, M. and Lineback, P. 1997. *Fire management and GIS: a framework for identifying and prioritizing fire planning needs*. Fire in California ecosystems:

integrating ecology, prevention and management: proceedings of the symposium. Association of Fire Ecology, California.

Carbutt, C. and Edwards, T. J. 2004. The flora of the Drakensberg Alpine Centre. *Edinburgh Journal of Botany*, 60(3), 581-607.

Cary, G., Flannigan, M., Keane, R., Bradstock, R., Davies, I., Li, C., Lenihan, J., Logan, K. and Parsons, R. 2009. Relative importance of fuel management, ignition management and weather for area burned: evidence from five landscape-fire-succession models. *International Journal of Wildland Fire,* 18, 147-156.

Chapman, J. 1868. *Travels in the interior of South Africa: comprising fifteen years' hunting and trading; with journeys across the continent from Natal to Walvis Bay, and visits to Lake Ngami and the Victoria Falls, Volume 1*. Bell and Daldy, London.

Chivian, E. 2001. Environment and health: 7. Species loss and ecosystem disruption- the implications for human health. *Canadian Medical Association Journal*, 164(1), 66-69.

Davis, A. M. 1979. Wetland succession, fire and the pollen record: a midwestern example. *The American Midland Naturalist*, 102, 86-94.

de Ronde, C., Trollope, W. S. W., Bailey, A. B., Brockett, B. H., Everson, T. M. and Everson, C. S. 2004a. *Application of prescribed burning*. In: Goldammer, J. G. and de Ronde, C. (eds.). *Wildland fire management handbook for sub-Sahara Africa*. Global Fire Monitoring Centre, Germany and Oneworldbooks, Cape Town.

de Ronde, C., Trollope, W. S. W., Parr, C. L., Brockett, B. And Geldenhuys, C. J. 2004b. *Fire effects on flora and fauna*. In: Goldammer, J. G. and de Ronde, C. (eds.). *Wildland fire management handbook for sub-Sahara Africa*. Global Fire Monitoring Centre, Germany and Oneworldbooks, Cape Town.

Dillon, R. F. 1980. *Some effects of fire in the Tall Grassveld of Natal*. Unpublished Master of Science Thesis. University of Natal, Pietermaritzburg.

Driscoll, D. A., Lindenmayer, D. B., Bennet, A. F., Bode, M., Bradstock, R. A., Cary, G. J., Clarke, M. F., Dexter, N., Fensham, R., Friend, G., Gill, M., James, S., Kay, G., Keith, D. A., MacGregor, C., Possingham, H. P., Russel-Smith, J., Salt, D., Watson, J. E. M., Williams, D.

and York, A. 2010. Resolving conflicts in fire management using decision theory: asset-protection versus biodiversity conservation. *Conservation Letters*, 00, 1-9.

Driver, A., Maze, K. Rouget, M., Lombard, A. T., Nel, J., Turpie, J. K., Cowling, R. M., Desmet, P., Goodman, P., Harris, J., Jonas, Z., Reyers, B., Sink, K. and Strauss, T. 2005. *National Spatial Biodiversity Assessment 2004: priorities for biodiversity conservation in South Africa. Strelitzia 17*. South African National Biodiversity Insititute, Pretoria.

Du Plessis, S. S. 1972. Ecology of blesbok with special reference to productivity. *Wildlife Mongraphs*, 30, 1-70.

Dunlop, M. and Brown, P. R. 2008. *Implications of climate change for Australia's national reserve system: a preliminary assessment*. Department of Climate Change, Canberra.

Edwards, D. 1984. *Fire regimes in the biomes of South Africa*. In: Booysen, P. de V. and Tainton, N. M. (eds.). *Ecological effects of fire in South African ecosystems*. Springer-Verlag, Berlin.

Engstrom, R. T. 2010. First-order fire effects on animals: review and recommendations. *Fire Ecology*, 6(1), 115-130.

Everett, P. S., Perrin, M. R. and Rowe-Rowe, D. T. 1991. Responses of oribi to different range management practices in Natal. *South African Journal of Wildlife Research*, 21, 114-118.

Everson, T. M. and Morris, C. D. 2006. *Conservation of biodiversity in the Maloti-Drakensberg Mountain Range*. In: Spehn, E. M., Liberman, M. and Korner, C. (eds.). *Land use and mountain biodiversity*. CRC Press, New York.

Everson, C. S. and Tainton, N. M. 1984. The effect of thirty years of burning in the Highland Sourveld of Natal. *Journal of the Grassland Society of Southern Africa*, 1, 15-20.

Everson, T. M., Everson, C. S., de Ronde, C. and Trollope, W. S. W. 2004. *Regional fire management: objectives, practices and prescribed burning application*. In: Goldammer, J. G. and de Ronde, C. (eds.). *Wildland fire management handbook for sub-Sahara Africa*. Global Fire Monitoring Centre, Germany and Oneworldbooks, Cape Town.

Fernandes, P. M. and Botelho, H. S. 2003. A review of prescribed burning effectiveness in fire hazard reduction. *International Journal of Wildland Fire*, 12, 117-128.

Flannigan, M. D. and Wotton, B. M. 2001. *Climate, weather, and area burned*. In: Johnson, E. A. and Miyanishi, K. (eds.). *Forest fires: behaviour and ecological effects*. Academic Press, California.

Flasse, S. P., Trigg, S. N., Ceccato, P. N., Perryman, A. H., Hudak, A. T., Thompson, M. K., Brockett, B. H., Drame, M., Ntabeni, T., Frost, P. E., Landmann, T. and le Roux, J. L. 2004. *Remote sensing of vegetation fires and its contribution to a fire management information system*. In: Goldammer, J. G. and de Ronde, C. (eds.). *Wildland fire management handbook for sub-Sahara Africa*. Global Fire Monitoring Centre, Germany and Oneworldbooks, Cape Town.

Forbes, R. G. and Trollope, W. S. W. 1991. Veld management in the rural areas of Ciskei. *Journal of Grassland Society of South Africa*, 8(4), 147-152.

Franklin, J., Syphard, A. D., Mlandenoff, D. J., Hong, S. H., Simons, D. K., Martin, R. P., Deutschman, D. and O'Leary, J. F. 2001. Simulating the effects of different fire regimes on plant functional groups in southern California. *Ecological Modelling*, 142, 261-283.

Frost, P. G. H. 1984. *The responses and survival of organisms in fire-prone environments*. In: Booysen, P. de V. and Tainton, N. M. (eds.). *Ecological effects of fire in South African Ecosystems*. Springer-Verlag, Berlin.

Frost, P. G. H. 1985. *Responses of savanna organisms to fire*. In: Tothill, J. C. and Mott, J. J. (eds.). *Ecology and management of the world's savannas*. Australian Academy of Science, Sydney.

Frost, P. G. H. and Robertson, F. 1985. *The ecological effects of fire in savannas*. In: Walker, B. H. *Determinants of tropical savannas*. IRL Press, Oxford.

Gander, M. V. 1982. Description of a fire and its effect in the Nylsvley Nature Reserve, a synthesis report. *South Africa National Scientific Report Series*, 63, 1-39.

Gar-On Yeh, A. 2000. *Decision support with geographic information systems*. In: Kersten, G. E., Mikolajuk, Z. and Gar-On Yeh, A. (eds). *Decision support systems for sustainable* *development: a resource book for methods and applications*. Kluwer Academic Publishers, Boston.

Geldenhuys, C. J., van Wilgen, B. W., Bond, W. J., van de Vijver, C. A. D. M. and de Ronde C. 2004. *Fire effects on the maintenance of biodiversity, soil and nutrients*. In: Goldammer, J. G. and de Ronde, C. (eds.). *Wildland fire management handbook for sub-Sahara Africa*. Global Fire Monitoring Centre, Germany and Oneworldbooks, Cape Town.

Gureja, N. and Owen-Smith, N. 2002. Comparative use of burnt grassland by rare antelope species in a lowveld game ranch, South Africa. *South African Journal of Wildlife Research*, 32, 31-38.

Hall, M. 1984. *Man's historical and traditional use of fire in southern Africa*. In: Booysen, P. de V. and Tainton, N. M. (eds.). *Ecological effects of fire in South African Ecosystems*. Springer-Verlag, Berlin.

Harris, T. M. 1958. Forest fire in the Mesozoic. *Journal of Ecology*, 46, 447-453.

Hill, T. R. 1996. Description, classification and ordination of the dominant vegetation communities, Cathedral Peak, KwaZulu-Natal Drakensberg. *South African Journal of Botany*, 62(5), 263-269.

Houghton, J. T., Meira Filho, L. G., Callender, B. A., Harris, N., Kattenberg, A. and Maskell, K. (eds). 1996. *Climate Change 1995. The science of climate change. Contribution of Working Group I to the second assessment report of the intergovernmental panel on climate change* (IPCC). Cambridge University Press, Cambridge.

Huston, M. A. 1994. *Biological diversity: the coexistence of species on changing landscapes.* Cambridge University Press, Cambridge.

Iliadis, L. S. 2005. A decision support system applying an integrated fuzzy model for long-term forest fire risk estimation. *Environmental Modelling and Software*, 20(5), 613-621.

Irwin, D. and Irwin, P. 1992. *A field guide to the Natal Drakensberg. 2nd ed.* The Natal Witness Printing and Publishing Company, Pietermaritzburg.

Johnson, D. N., Barnes, K. N. and Taylor, B. 1998. *Important bird areas of KwaZulu-Natal*. In: Barnes, K .N. (ed.). *The important bird areas of southern Africa*. BirdLife, Johannesburg.

Johnson, E. A. and Miyanishi, K. 2001. *Strengthening fire ecology's roots*. In: Johnson, E. A. and Miyanishi, K. (eds.). *Forest fires: behaviour and ecological effects*. Academic Press, California.

Joubert, L .S. 2006. *Scorched: South Africa's changing climate*. Wits University Press, Johannesburg.

Keane, R. E. and Karau, E. 2010. Evaluating the ecological benefits of wildfire by integrating fire and ecosystem simulation models. *Ecological Modelling*, 221, 1162-1172.

Keramitsoglou, I., Kiranoudis, C. T., Sarimvels, H. and Sifakis, N. 2004. A multidisciplinary decision support system for forest fire crisis management. *Environmental Management*, 33(2), 212-225.

Killick, D. J. B. 1963. *An account of the plant ecology of the Cathedral Peak area of the Natal Drakensberg. Memoirs of the Botanical survey of South Africa Number 34*. Botanical Research Institute, Pretoria.

Killick, D. J. B. 1978. *The afro-alpine region*. In: Werger, M. J. A. (ed). *Biogeography and ecology of southern Africa. Vol 1*. Dr W. Junk bv Publishers, The Hague.

Killick, D. J. B. 1990. *A field guide to the flora of the Natal Drakensberg*. Jonathan Ball Publishers, Johannesburg.

Komarek, E. V. 1965. Fire ecology – grasslands and man. *Proceedings of the Tall Timbers Fire Ecology Conference*, 4, 169-220.

Komarek, E. V. 1973. Ancient fires. *Annual Tall Timbers Fire Ecology Conference*, 12, 219-240.

Kruger, F. J. 1984. *Effects of fire on vegetation structure and dynamics*. In: Booysen, P. de V. and Tainton, N. M. (eds.). *Ecological effects of fire in South African ecosystems*. Springer-Verlag, Berlin.

Krüger, S. 2007. Wilderness stewardship challenges in the uKhahlamba Drakensberg Park World Heritage Site. *USDA Forest Service Proceedings*, 49, 326-330.

Kutt, A. S. and Woinarski, J. C. Z. 2007. The effects of grazing and fire on vegetation and the vertebrate assemblage in a tropical savanna woodland in north-eastern Australia. *Journal of Tropical Ecology*, 23, 95-106.

KwaZulu-Natal Nature Conservation Service (KNCS). (1999). *Nomination proposal for the Drakensberg Park alternatively Known as uKhahlamba Park to be listed as a world heritage site*. Department of Environmental Affairs and Tourism, South Africa.

Lee, B. S., Alexander, M. E., Hawkes, B. C., Lynham, T. J., Stocks, B. J. and Englefield, P. 2002. Information systems in support of wildland fire management decision making in Canada. *Computers and Electronics in Agriculture*, 37(1-3), 185-198.

Liu, D. and Stewart, T. J. 2004. Object-oriented decision support system modelling for multicriteria decision making in natural resource management. *Computers and Operations Research*, 31, 985-999.

Liu, Y., Gupta, H., Springer, E. and Wagener, T. 2008. Linking science with environmental decision making: experiences from an integrated modeling approach to supporting sustainable water resource management. *Environmental Modelling and Software*, 23, 846-858.

Malanson, G. P. 1987. *Diversity, stability, and resilience: effects of fire regime*. In: Trabaud, L. (ed.). *The role of fire in ecological systems*. SPB Academic Publishing, The Hague.

Martell, D. L. 2001. *Forest fire management*. In: Johnson, E. A. and Miyanishi, K. (eds.). *Forest fires: behaviour and ecological effects*. Academic Press, California.

Martin, R. E., and Sapsis, D. B. 1992. *Fires as agents of biodiversity: pyrodiversity promotes biodiversity*. In: Harris, R. R., Erman, D. C. and Kerner, H. M. (eds.). *Proceedings of the symposium on biodiversity in northwestern California. Report 29*. Wildland Resources Centre, University of California, Berkeley.

Matthews, W. S. and Bredenkamp, G. J. 1999. *Great escarpment*. In: Knobel, J. (ed.). *The magnificent natural heritage of South Africa*. Sunbird Publishing, South Africa.

Matthies, M., Giupponi, C. and Ostendorf, B. 2007. Environmental decision support systems: current issues, methods and tools. *Environmental Modelling and Software*, 22, 123-127.

McAninch, J. B. and Strayer, D. L. 1989. *What are the tradeoffs between the immediacy of management needs and the longer process of scientific discovery?* In: Likens, G. E. (ed.). *Long-term studies in ecology: approaches and alternatives*. Springer-Verlag, New York.

Meadows, M. E. and Linder, H. P. 1993. A paleoecological perspective on the origin of afromontane grasslands. *Journal of Biogeography*, 20, 345-355.

Mentis, M. T. And Rowe-Rowe, D. T. 1979. Fire and faunal abundance and diversity in the Natal Drakensberg. *Proceedings of the Grassland Society of Southern Africa*, 14, 75-77.

Miller, M. 2000. *Fire autecology*. In: Brown, J. K. and Smith, J. K. (eds.). *Wildland fire in ecosystems: effects of fire on flora*. General technical report RMRS-GTR-42 vol. 2. Rocky Mountain Research Station, Utah.

Mills, M. G. L. and Hes, L. 1997. *The complete book of southern African mammals*. Struik, Cape Town.

Morris, C. D. 1998. *The current status of guidelines for burning and post-burn management of humid grassland in South Africa*. Agricultural Research Council, unpublished report.

Nath, S. S., Bolte, J. P., Ross, L. G. and Aguilar-Manjarrez, J. 2000. Applications of geographical information systems (GIS) for spatial decision support in aquaculture. *Aquacultural Engineering*, 23, 233-278.

Novellie, P. A. 1978. Comparison of feeding strategies of blesbok and springbok on the Transvaal Highveld. *South African Journal of Wildlife Research*, 8, 137-144.

O'Connor, T. G. and Bredenkamp, G. J. 1997. *Grassland*. In: Cowling, R. M., Richardson, D. M. and Pierce, S. M. (eds.) *Vegetation of southern Africa*. Cambridge University Press, Cape Town.

O'Connor, T. G., Uys, R. G. and Mills, A. J. 2004. Ecological effects of fire-breaks in the montane grasslands of the southern Drakensberg, South Africa. African *Journal of Range and Forage Science*, 21(1), 1-9.

Olff, H. and Ritchie, M. E. 2002. Fragmented nature: consequence for biodiversity. *Landscape and Urban Planning*, 58, 83-92.

Oliver, M. D. N., Short, N. R. M. and Hanks, J. 1978. Population ecology of oribi, grey rhebok and mountain reedbuck in Highmoor State Forest Land, Natal. *South African Journal of Wildlife Research*, 8, 95-105.

Parr, C. L. and Andersen, A. N. 2006. Patch mosaic burning for biodiversity conservation: a critique of the pyrodiversity paradigm. *Conservation Biology*, 20(6), 1610-1619.

Parr, C. L. and Chown, S. L. 2003. Burning issues for conservation: a critique of faunal fire research in southern Africa. *Austral Ecology*, 28, 384-395.

Phillips, J. 1965. Fire – as a master and servant: its influence in the bioclimatic regions of trans-Saharan Africa. *Proceedings of the Tall Timbers Fire Ecology Conference*, 4, 7-109.

Phillips, J. F. V. 1973. *The agricultural and related development of the Tugela basin and its influent surrounds*. Pietermaritzburg Town and Regional Planning Commission. Report Number 19.

Poch, M., Comas, J., Rodriguez-Roda, I., Sanchez-Marre, M. and Cortes, U. 2004. Designing and building real environmental decision support systems. *Environmental Modelling and Software*, 19, 857-873.

Priday, A. J. 1989. *Statistical modelling of fuel loads for development of a fire management strategy in the Natal Drakensberg*. Unpublished Master of Science Thesis. University of Natal, Pietermaritzburg.

Pyne, S. J. 1982. *Fire in America: a cultural history of wildland and rural fire*. Princeton University Press, Princeton.

Pyne, S. J. 1984. *Introduction to wildland fire: fire management in the United States*. John Wiley and Sons, New York.

Pyne, S. J. 1995. *World fire: the culture of fire on Earth*. University of Washington Press, Seattle.

Pyne, S. J., Andrews, P. L. and Laven, R. D. 1996. *Introduction to wildland fire*. (2nd ed.). John Wiley and Sons, United States of America.

Pyne, S. J., Goldammer, J. G., de Ronde, C., Geldenhuys, C. J., Bond, W. J. and Trollope, W. S. W. 2004. *Introduction*. In: Goldammer, J. G. and de Ronde, C. (eds.). *Wildland fire management handbook for sub-Sahara Africa*. Global Fire Monitoring Centre, Germany and Oneworldbooks, Cape Town.

Rauscher, H. M. 1999. Ecosystem management decision support for federal forests in the United States: a review. *Forest Ecology and Management*, 114, 173-197.

Reitsma, R. F. 1996. Structure and support of water-resources management and decision-making. *Journal of Hydrology*, 177, 253-268.

Rizzoli, A. E. and Young, W. J. 1997. Delivering environmental decision support systems: software tools and techniques. *Environmental Modelling and Software,* 12(2-3), 237-249.

Rowe-Rowe, D. T. 1982. Influence of fire on antelope distribution and abundance in the Natal Drakensberg. *South African Journal of Wildlife Research*, 2, 124-129.

Rowe-Rowe, D. T. 1983. Habitat preference of five Drakensberg antelopes. *South African Journal of Wildlife Research*, 13, 1-8.

Rowe-Rowe, D. T. and Lowry, P .B. 1982. Influence of fire on small mammal populations in the Natal Drakensberg. *South African Journal of Wildlife Research*, 12, 130-139.

Rowe-Rowe, D. T. and Scotcher, J. S. B. 1986. Ecological carrying capacity of the Natal Drakensberg for wild ungulates. *South African Journal of Wildlife Research*, 16, 12-16.

Russell, K. R., van Lear, D. H. and Guynn, Jr. D. C. 1999. Prescribed fire effects on herpetofauna: review and management implications. *Wildlife Society Bulletin*, 27(2), 374-384.

Russell-Smith, J. 1995. *Fire management*. In: Press, T., Lea, D., Webb, A. and Graham, A. (eds.). *Kakadu: natural and cultural heritage and management*. Australian National University, Canberra.

Ryan, K. C. 2000. *Global change and wildland fire*. In: Brown, J. K. and Smith, J. K. (eds.). *Wildland fire in ecosystems: effects of fire on flora*. General technical report RMRS-GTR-42 vol. 2. Rocky Mountain Research Station, Utah.

Scotcher, J. S. B. 1982. Interactions of vegetation and eland (*Taurotragus oryx* Pallas) in Giant's Castle Game Reserve. PhD thesis. University of Witwatersrand, Johannesburg.

Scott, D. F. 1993. The hydrological effects of fire in South African mountain catchments. *Journal of Hydrology*, 150, 409-432.

Scott, J. D. 1971. Veld burning in Natal. *Proceedings of the Tall Timbers Fire Ecology Conference*, 11, 33-51.

Singh, N. 2002. Speech by KwaZulu-Natal MEC of Agriculture and Environmental Affairs, at a dinner to officially launch Ezemvelo KZN Wildlife. Pietermaritzburg. www.info.gov.za/speeches/2002/0203111046a1001.htm accessed 20/05/11

Smith, D. M., Griffin, J. J. and Goldberg, E. D. 1973. Elemental carbon in marine sediments: a baseline for burning. *Nature*, 241, 268-270.

Smithers, R. H. N. 1986. *South African red data book: terrestrial mammals*. Council for Scientific and Industrial Research, Pretoria.

Sojda, R. 2007. Empirical evaluation of decision support systems: needs, definitions, potential methods, and an example pertaining to waterfowl management. *Environmental Modelling and Software*, 22, 269-277.

Stander, P. E., Nott, T. B. and Mentis, M. T. 1993. Proposed burning strategy for a semi-arid African savanna. *African Journal of Ecology*, 31, 282-289.

Stocks, B. J., van Wilgen, B. W. and Trollope, W. S. W. 1997. *Fire behaviour and the dynamics of convection columns in African savannas*. In: van Wilgen, B. W., Andreae, M. O., Goldammer, J. G. and Lindesay, J. A. (eds.). *Fire in southern African savannas: ecological and atmospheric perspectives*. Witwatersrand University Press, Johannesburg.

Strategic Environmental Focus (SEF). 2002. *Joburg Metropolitan Open Space System*. City of Joburg. South Africa

Sycholt, A. 2002. *A guide to the Drakensberg*. Struik Publishers, Cape Town.

Tainton, N. M., Groves, R. H. and Nash, R. C. 1977. Time of mowing and burning veld: short term effects on production and tiller development. *Proceedings of the Grassland Society of southern Africa*, 12, 59-64.

Tainton, N. M. and Mentis, M. T. 1984. *Fire in grassland*. In: Booysen, P. de V. and Tainton, N. M. (eds.). *Ecological effects of fire in South African ecosystems*. Springer-Verlag, Berlin.

Thompson, M. P. and Calkin, D. E. 2011. Uncertainty and risk in wildland fire management: a review. *Journal of Environmental Management*, 92, 1895-1909.

Tolhurst, K. G. 1999. *Towards the implementation of ecologically based fire regimes in the Grampians National Park*. In: Friend, G., Leonard, M., Maclean, A. and Sieler, I. (eds.). *Management of fire for the conservation of biodiversity*. Department of Natural Resources and Environment workshop proceedings, Australia.

Trabaud, L. 1987. *Fire and survival traits of plants*. In: Trabaud, L. (ed.). *The role of fire in ecological systems*. SPB Academic Publishing, The Hague.

Trollope, W. S. W. 1980. Controlling bush encroachment with fire in the savanna areas of South Africa. *Proceedings of the Grasslands Society of South Africa*, 15, 173-177.

Trollope, W. S. W. 1989. *Veld burning as a management practice in livestock production*. In: Danckwerts, J. E. and Teague, W. R. (eds.). *Veld management in the Eastern Cape*. Government Printer, Pretoria.

Trollope, W. S. W., de Ronde, C. and Geldenhuys, C. J. 2004. *Fire behaviour*. In: Goldammer, J. G. and de Ronde, C. (eds.). *Wildland fire management handbook for sub-Sahara Africa*. Global Fire Monitoring Centre, Germany and Oneworldbooks, Cape Town.

van As, J. and du Preez, M. 2006. *uKhahlamba/Drakensberg Park Barrier of Spears*. In: du Preez, M. (ed). *Essence of a land: South Africa and its World Heritage Sites*. Green Vision Foundation, South Africa.

van Delden, H., Seppelt, R., White, R. and Jakeman, A. J. 2011. A methodology for the design and development of integrated models for policy support. *Environmental Modelling and Software*, 26, 266-279.

van Wilgen, B. W. and Forsyth, G. G. 1992. *Regeneration strategies in fynbos plants and their influence on the stability of community boundaries after fire*. In: van Wilgen, B. W., Richardson, D. M., Kruger, F. J. and van Hensbergen, H. J. (eds.). *Fire in South African Mountain Fynbos*. Springer-Verlag, Berlin.

van Wilgen, B. W. and van Hensbergen, H. J. 1991. *Fuel properties of vegetation in Swartboskloof*. In: van Wilgen, B. W., Richardson, D. M., Kruger, F. J. and van Hensbergen, H. J. (eds.). *Fire in South African mountain fynbos*. Springer-Verlag, Berlin.

van Wilgen, B. W. and Scholes, R. J. 1997. *The vegetation and fire regimes of southern-hemisphere Africa*. In: van Wilgen, B. W., Andreae, M. O., Goldammer, J. G. and Lindesay, J. A. (eds.). *Fire in southern African savannas: ecological and atmospheric perspectives*. Witwatersrand University Press, Johannesburg.

van Wilgen, B. W., Everson, C. S. and Trollope, W. S. W. 1990. *Fire management in southern Africa: some examples of current objectives, practices and problems*. In: Goldammer, J. G. (ed.). *Fire in the tropical biota: ecosystem processes and global challenges*. Springer-Verlag, Berlin.

van Wyk, A. E. and Smith, G. F. 2001. *Regions of floristic endemism in southern Africa: a review with emphasis on succulents*. Umdaus Press, South Africa.

Venter, J. 1979. *Ecology of the southern reedbuck Redunca arundinum Boddaert 1785 on the eastern shores of Lake St Lucia*. Unpublished Master of Science Thesis. University of Natal, Pietermaritzburg.

Walker, D. H. and Johnson, A. K. L. 1996. NRM tools: a flexible decision support environment for integrated catchment management. *Environmental Software*, 11(1-3), 19-24.

Walker, D. H., Cowell, S. G. and Johnson, A. K. L. 2001. Integrating research results into decision making about natural resource management at a catchment scale. *Agricultural Systems*, 69, 85-98.

Watson, R. T., Zinyowera, M. C. and Moss, R. H. (eds).1996. *Climate Change 1995. Impacts, adaptations and mitigation of climate change: scientific technical analyses. Contribution of Working Group II to the second assessment report of the intergovernmental panel on climate change (IPCC)*. Cambridge University Press, Cambridge.

Werger, M. J. A. (ed). 1978. *Biogeography and ecology of southern Africa. Vol 1.* Dr W. Junk bv Publishers, The Hague.

West, O. 1965. *Fire in vegetation and its use in pasture management with special reference to tropical and subtropical Africa. Mimeographed publication number 1*. Commonwealth Agricultural Bureaux, England.

Whelan, R. J. 1995. *The ecology of fire*. Cambridge University Press, Cambridge.

White, F. A. 1978. *The afromontane region*. In: Werger, M. J. A. (ed). *Biogeography and ecology of southern Africa. Vol 1.* Dr W. Junk bv Publishers, The Hague.

Wilsey, B. J. 1996. Variation in the use of green flushes following burns among ungulate species: the importance of body size. *African Journal of Ecology*, 34, 32-38.

Wright, H. A. and Bailey, A. W. 1982. *Fire ecology: United States and southern Canada*. (2nd ed.). John Wiley and Sons, New York.

Wybo, J. L. 1998. FMIS: a decision support system for forest fire prevention and fighting. *Engineering Management*, 45(2), 127-131.

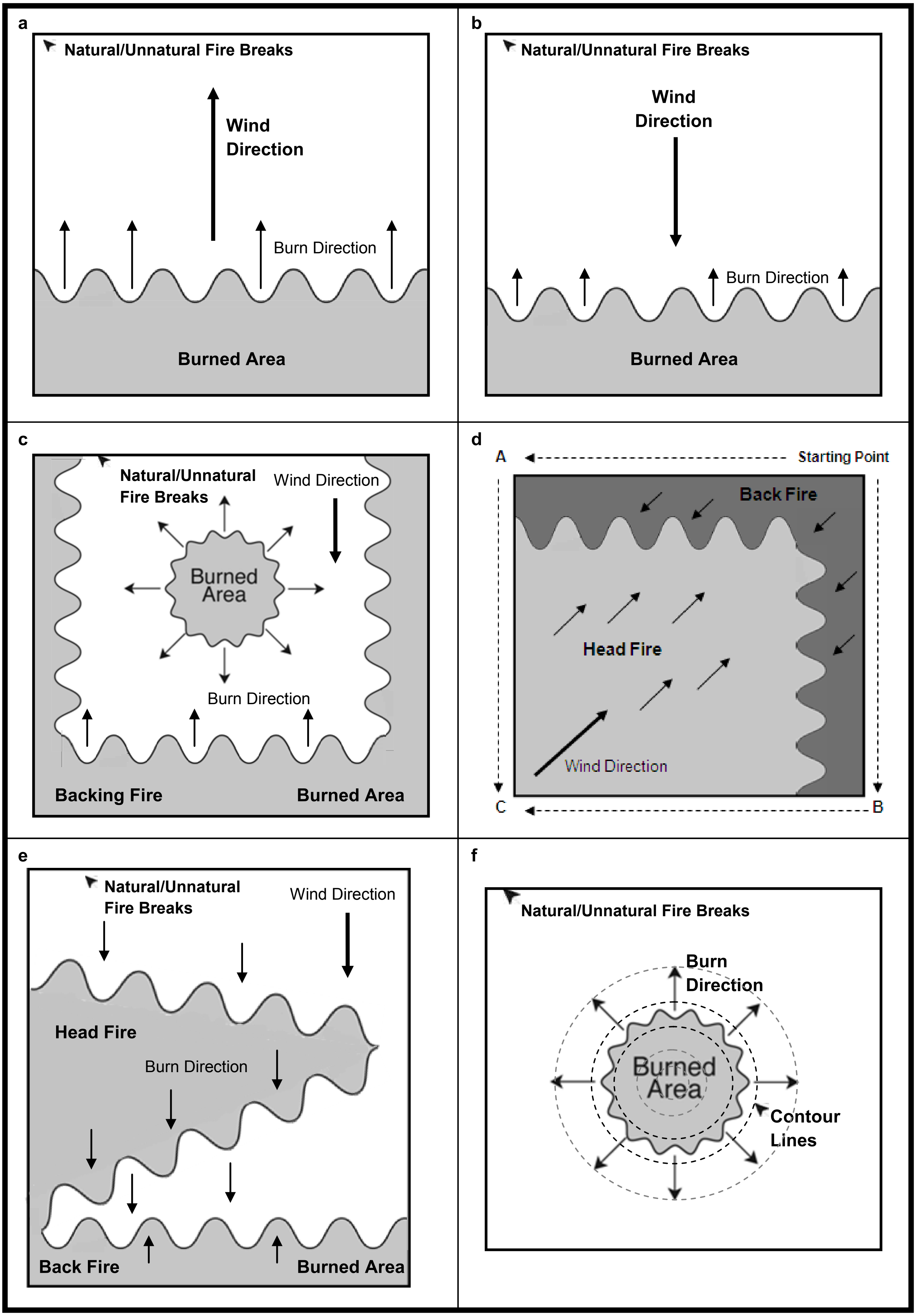
Zedler, P. H. 2007. *Fire effects on grasslands*. In: Johnson, E. A. and Miyanishi, K. (eds.). *Plant disturbance ecology: the process and the response*. Academic Press, California.

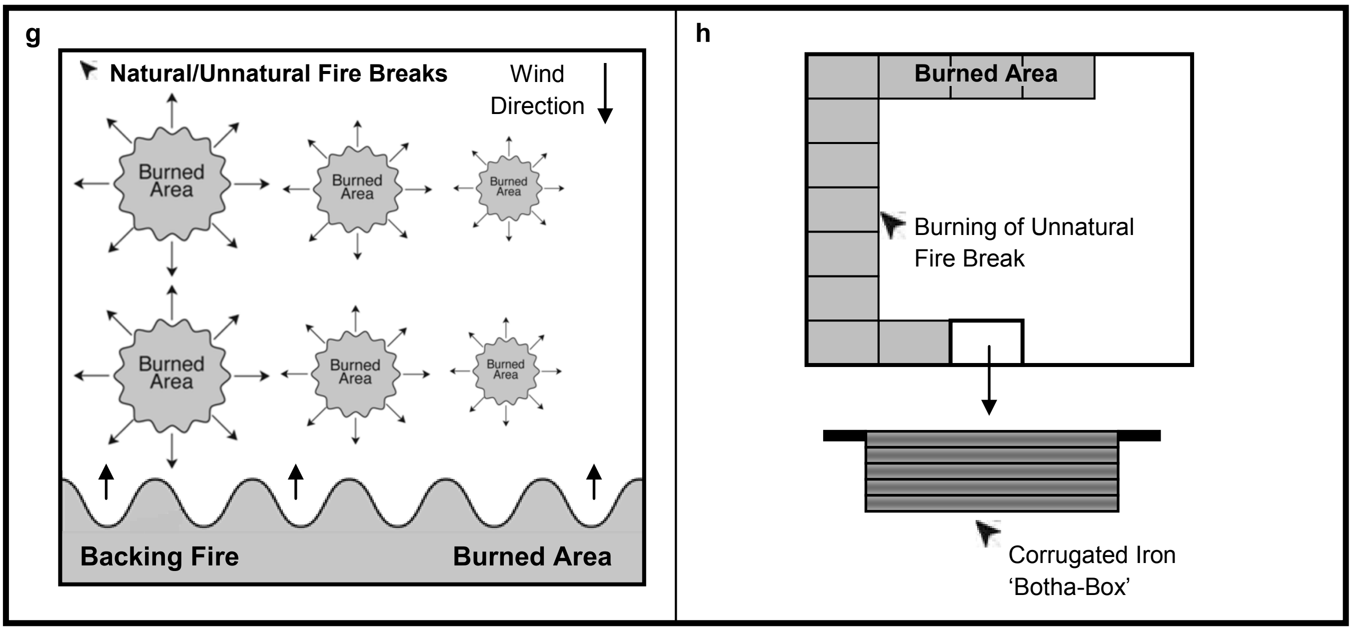
APPENDIX A

Different prescribed fire techniques for burning of fire management compartments or areas.

Technique	Where Used	Procedure	Advantages	Disadvantages	Figure
Head Fire	Large ar eas, br ush fields, clearcuts, under s tands w ith light fuels	Backfire downwind line until safe line created. Light Head Fire	Rapid, inexpensive, good smoke dispersal. C an b e us ed i n overgrazed grasslands.	High i ntensity, h igh s potting potential	2.1a
Back Firing	Under tree c anopy, heavy f uels near firelines	Backfire from downwind line; may build a dditional l ines an d bac kfire from each line	Slow, l ow i ntensity, low s corch, low spotting potential, e asiest and safest w ith s teady wind di rection. Can be used in grasslands.	Expensive, s moke s tays near ground, t he l ong t ime r equired may a llow wind s hift, C ant use in overgrazed grassland	2.1b
Centre and Circular Firing	Harvested/ clearcut areas inside industrial plantations; brush fields	Backfire downwind line until safe line created. F or c entre f iring, c entre i s lighted f irst. R ing t hen lighted al ong perimeter to draw to centre	Very r apid, best s moke di spersal, very h igh i ntensity, C onvection generated by these interior fires creates i n-drafts, dr aws f ire a way from surrounding vegetation	May de velop da ngerous convection currents; m ay develop l ong di stance spotting; may require large crew.	2.1c
	Method f or grasslands	Two perpendicular backfires burning downwind until s afe l ine c reated. Light head fire at opposite end	Greatly r educes t he r isk of l osing control of prescribed burns. Meeting of f lame fronts w ill prevent further spreading	Mostly h igh intensity, s potting potential. Wind shift may occur.	2.1d
Strip Head Fire	Large ar eas, br ush fields, clearcuts, partial cuts with light slash u nder tree canopies	Backfire f rom dow nwind line u ntil safe l ine c reated. Start head f ire at given distance up wind. C ontinue with s uccessive s trips of w idth t o give desired flames	Relatively rapid, intensity a djusted by s trip widths, f lexible, m oderate cost. Can be used in grasslands.	Need access within area; under stands having 3 or strips burning at one t ime may cause high intensity fire interaction	2.1e
Chevron Burning	Broken, s teep, topography, where a prominent r ound h ill (or"koppie") occurs.	Five to six burners with drip torches. Ignition i s s tarted simultaneously b y all the burners on the top of the hill, move i n a s tar-like pat tern do wnhill at equal speed	Very safe technique for this type of terrain, can be applied in all kinds of fuel, grassland, fynbos and inside i ndustrial p lantations, f ire intensity can be controlled	Need light or no wind conditions, l abour i ntensive, need t o c oordinate s peed moving downslope	2.1f
Spot H ead/ Point Source Fire	Large ar eas, clearcuts, p artial cuts w ith l ight s lash under tree canopies, mature, plantations	Backfire f rom dow nwind line u ntil safe l ine c reated. S tart s pots at given d istances up wind. A djust s pot to give desired flames.	Relatively rapid, intensity a djusted by s pot s pacing, c an g et variable effects from head and f lank fires, moderate costs	Need ac cess w ithin ar ea i f not done aerially.	2.1g
"Botha fire-box"	Burning firebreaks in grasslands/ savannas	Grass set al ight ar ound t he i nside perimeter of the open "box" structure. C ompletion of burn, m ove box along.	Safe bur ning under ex tremely windy conditions, l abour e fficient, suited to broken topography	Slow in comparison to the other burning techniques f or constructing fire breaks.	2.1h

(de Ronde et *al*. 2004a; Pyne 1984)


a
Natural/Unnatural Fire Breaks
Wind Direction
Burn Direction
Burned Area
b
Natural/Unnatural Fire Breaks
Wind Direction
Burn Direction
Burned Area
c
Natural/Unnatural Fire Breaks
Wind Direction
Burned Area
Burn Direction
Backing Fire
Burned Area
d
A
Starting Point
Back Fire
Head Fire
Wind Direction
C
B
e
Natural/Unnatural Fire Breaks
Wind Direction
Head Fire
Burn Direction
Back Fire
Burned Area
f
Natural/Unnatural Fire Breaks
Burn Direction
Burned Area
Contour Lines



Adapted from (de Ronde *et al*. 2004a; West 2005)

Prescribed burning techniques used in fire management, a) head fire; b) back firing; c) centre/circular firing; d) centre/circular firing method primarily used in burning grasslands; e) strip head fire; f) Chevron burning; g) spot head/ point source fire; and h) "Botha fire-box" used for constructing fire breaks.