THE BURNING QUESTIONS ABOUT HLUHLUWE:

CAUSES AND CONSEQUENCES OF A SEVERE WILDFIRE

(Photograph taken by Dirk Swart)

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ABSTRACT

The biophysical drivers of fire; ignition, fire weather conditions, fuel biomass, and flammability, differ in varying ecosystems. The rates of occurrence of these factors influence fire regimes. This study investigated the causes and consequences of a severe wildfire that swept through the Hluhluwe Game Reserve, KwaZulu-Natal South Africa in September 2008. This fire was an extreme event that seems only to have been possible due to the combination of circumstances that occurred in the days prior to and during the 14th/15th September 2008. The event was considered extreme because it burnt from savanna into thicket and forest patches, which is atypical of fires. The fire caused large structural change in tree demography, however, not much change in densities.

The results of this study indicate that coupled weather conditions conducive to fire; namely low relative humidity, high temperatures and high wind speeds, occurred at the time of the fire. The synergistic influences of fire weather conditions and the state of available fuel caused this severe fire. The fire continued to burn for 48 hours before weather conditions relaxed and became less dangerous. These data suggest extreme fires such as the September 2008 event may be exploited by managers to reclaim former grasslands and savannas that have suffered the effects of bush encroachment and/or create open areas allowing grasslands to develop. However, severe fires run the risk of leading to the loss of forests and the biodiversity that they support. This study has identified the conditions likely to promote such severe fires.

Key words: Bush encroachment, fire, biodiversity, Savanna, thicket, management, extreme events

INTRODUCTION

Mesic grasslands and savannas in South Africa are being invaded by thicket, a process termed 'bush encroachment' (Watson and MacDonald 1983; King 1987; Ward 2005; Wigley *et al.* 2009), and significant increases in woody cover have been reported for Africa (Higgins *et al.* 1999; Kraaij and Ward 2006; Britz and Ward 2007). Bush encroachment in savannas refers to two different processes: the substitution of savannas by a closed, broadleaf woody community with an understorey comprising of minimal to no grass, or an increase in savanna tree and shrub densities (Skowno *et al.* 1999). The fore mentioned process causes a change in vegetation form and composition, which ultimately results in an entire biome switch. In Hluhluwe Game Reserve most woody biomass increase is accounted for by the evergreen resprouting species *Euclea divinorum* and *Euclea racemosa* (Skowno *et al.* 1999). Analyses of aerial photographs of the reserve have shown rapid E*uclea* encroachment (Skowno *et al.* 1999, Wigley *et al.* 2009). Since the 1930's, tree cover, particularly in the northern region of the reserve, has increased dramatically.

This 'bush encroachment' has been attributed to diverse causes, including reduced frequency and/or intensity of fire or changes in herbivore pressures or herbivore type. Bush encroachment under three contrasting land use practices have been compared over a 60+ year period. Though large differences in woody increases were found and linked to land use (Wigley *et al.* 2009), all areas of their study showed major increases in trees. This suggests a global driver favouring the spread of thickets and forests at the expense of grasses. If elevated CO_2 enhances the respouting ability of thicket species, as hypothesised by Bond and Midgley (2000), then this would be a key global change driving the expansion of thicket and, one that requires directed conservation management.

Thicket and forest expansion may be seen as a threat to the future of natural grasslands however, forest ecologists are concerned about fire burning into forests and the threat of their replacement by grasslands. Though savannas in forest-savanna mosaics can burn very frequently, fires do not usually penetrate into forests because fire spread is linked to abundance of grassy fuel loads (Hennenberg *et al.* 2006). If the occurrence of grassland fires entering and burning forests becomes more frequent, then forests may be eliminated. Understanding the mechanisms driving the reduction in savanna in Hluhluwe is important in being able to manage a savanna ecosystem, and potentially reverse the effects, or reduce further impacts, of bush encroachment in the Reserve. Additionally, this substitution of grasslands by thicket reduces game viewing opportunities, potentially reducing revenue to our reserves, and therefore is of importance for park management.

My intention was to determine the causes of the September 2008 Hluhluwe fire and to assess whether we can better predict and control such wildfires. I also wished to explain the consequences of this event for both thicket and forest patches, and if fire could be a potential tool for trying to restore grasslands invaded by thicket in Hluhluwe since the 1950s, as well as to evaluate the potential threat to tall forest of recurrent severe fires. The results should also facilitate disaster management in similar bioclimatic regions elsewhere in South Africa.

To achieve these ends the immediate aims were:
1) To describe the fire event
2) To determine what the weather and fuel conditions were prior to and at the time of the fire
3) To assess the frequency of these conditions so as to assess the frequency of similar extreme fire events in the past and possible changes in the future
4) To investigate the impact of the fire (tree mortality and aerial extent)
5) To evaluate the use of extreme fire events as a management option for reversing thicket expansion or as a threat to forest conservation.

MATERIALS AND METHODS

This study consisted of four parts. Firstly I assembled data on this fire event including when and where the fire burnt, using interviews, ground surveys and satellite mapping. Secondly I collected climatic and weather data to establish the fire weather conditions and how unusual these were on different temporal scales (hourly, daily, monthly, and over long term records). Thirdly I wished to determine the likely reoccurrence intervals of such a fire event from the available data having established the weather conditions during the fire. Fourthly, the severity of the fire could be attributed to *Chromolaena odorata,* an invasive weed, and changes in the fuel load due to *Chromolaena* or clearing operations. To establish whether *Chromolaena* fuel helped promote fire spread into thickets and forests I obtained maps of *Chromolaena* density and analysed their influence on fire patterns. Firstly I determined the impacts of this fire on thicket and forest vegetation composition and structure. I used the response data to measure the amount of vegetation change following this severe fire event. I was also able to quantify post-burn regrowth and so to evaluate whether grass fuel loads would be sufficient to allow a follow-up burn to convert invasive thickets back to savanna.

Study area

This study was carried out within the Hluhluwe-iMfolozi Park (28°11'5''S 32°0'59''E). The reserve, situated in central Zululand, South Africa, is characterized by hilly topography and covers approximately 96 000 ha, supporting a rich diversity of flora and fauna. The reserve is divided into Hluhluwe in the north, iMfolozi in the south and the corridor in the middle. This study was restricted to the northern Hluhluwe region of the park. Hot, wet summers and cold dry winters characterise the reserve. Rainfall is closely linked to elevation within the park (Balfour and Howison 2001), producing a rainfall gradient from ~1000 mm per annum at higher elevations in Hluhluwe Game Reserve, to ~600 mm per annum at lower elevations in iMfolozi Game Reserve. The rainy season peaks between October and March. In South Africa, grassy biomes receiving >650 mm mean annual precipitation are thought to have the potential to develop into forest (Bond *et al.* 2003). The mean minimum temperature is 13°C and the mean maximum temperature is 35°C (Greyling and Huntley 1984 in Balfour and Howison 2001). Frost is very rare in the region. Thunderstorms are common during the summer rainfall season. Altitude ranges from 580 m above sea level in the north east of the reserve, to 90 m above sea level.

Most of the reserve is covered by *Acacia* savannas, *Euclea* thickets, and patches of *Celtis-Harpephyllum* forests (Whateley and Porter 1983). The study area falls primarily into Northern Zululand Sourveld (Mucina and Rutherford 2006; veld type SVI 22), with some Zululand Lowveld

(Mucina and Rutherford 2006; veld type SVI23) and patches of Scarp Forest (Mucina and Rutherford 2006; veld type FOz5). Northern Zululand Sourveld is dominated by wooded grassland, with areas of pure sour grasslands and infrequently also dense bushveld thickets. Most of Hluhluwe is covered by tall grassveld types with sparsely scattered solitary trees and shrubs forming a mosaic with typical savanna thornveld, bushveld and thicket patches of the Zululand Lowveld vegetation unit (Mucina and Rutherford 2006). Tall bunch grasslands dominate areas with higher rainfall and higher altitudinal ranges. These grasslands carry fire if sufficient fuel is left in the dry season. Grazing lawns cover a wide altitudinal range, are excluded from high rainfall areas and do not burn or only carry low intensity fires. This study was located in the higher rainfall region in tall bunch grasslands. The dominant vegetation is *Acacia* savanna forming mosaics with forest and *Euclea* thicket in the northern end of the Hluhluwe Game Reserve.

Fire attributes

To reconstruct the September fire event, including the spread, nature and extent of the burn, I interviewed Hluhluwe staff members who were present at the time of the fire. Ground-based mapping and satellite data was obtained to map the extent of the fire. Fire burning through grass areas typically stops at the edge of forests and/or thickets. The Hluhluwe 2008 fire was different in that it continued burning through entire areas of thicket and forest patches. In order to establish when and where thicket patches burnt, burn maps were drawn up by traveling the area after the fire (in June 2009) using a 2004 aerial photograph as a base. On this photograph we mapped areas of thicket and forest and identified those which had been burnt by the September 2008 fire. There is no recent vegetation map for the park (since Whately and Porter 1975) and therefore ground proofing was necessary. In addition, Landsat 7 raw reflectance satellite data was obtained from USGS, and SEVERI and Moderate Resolution Imaging Spectroradiometer (MODIS) products were also obtained in order to determine the areal extent and severity of the fire. The MODIS burnt area product is generated from time series of daily 500 m MODIS land surface data (methods described in Roy *et al.* 2005). Fire radiative power (FRP) is a measure of the radiant energy liberated per unit time from burning vegetation via the rapid oxidation of fuel carbon and is therefore related to fuel combustion. The SEVERI radiometer onboard the geostationary Meteosat 8 platform presents a unique opportunity to monitor FRP at 15 minute intervals, allowing analysis of the complete diurnal cycle of biomass burning and calculation of total fire radiative power (Roberts *et al.* 2005). The FRP graph was developed by taking 15 minute SEVERI FRP values and plotting them over time (hours). Unfortunately, while conceptually simple, the raw data obtainable from SEVERI is complex and difficult to assess. For this reason, the FRP graph was developed for use in this project by P. Freeborn (Kings College, London) and W. Marais (CSIR). The available Landsat data was unfortunately unable to be used to determine the burn scar of the September 2008 fire due to the spatial and temporal resolution of these products and the fact that these images are obscured by lines resulting from data errors on the sensor.

Causes of this extreme fire event and its severity: Weather conditions

To determine whether the September fire event was a result of unusual weather conditions, the variability in fire danger indices was explored. These analyses are based on weather stations located at Seme (28°10'5.952''S 31°58'7.284''E) and Egodeni (Hilltop) (28°4'15''S 32°2'25.7''E) for this fire. The Seme weather station is located approximately 9 km from the nearest burnt area. The Egodeni weather station is located near the Hluhluwe Research Centre; approximately 600 m away from the nearest burnt area. This was considered reasonable for use in analyses, as these are the nearest weather stations with the necessary data available to calculate fire danger indices. The weather records have gaps in the data and are therefore incomplete but the best available.

Weather records were obtained from the South African Weather Service (SAWS) and the Zululand Tree Project (ZLTP) database. Fire danger indices (FDIs) have been developed in various parts of the world to indicate the risks of high severity fires. I used the weather records to calculate FDIs using the most generally available FDIs. The Lowveld Fire Danger Index (FDI), also known as the SAFDI, is calculated taking into account temperature, relative humidity and wind (van Wilgen and Everson 1990, van Wilgen *et al.* 2000).

> Lowveld FDI = -32.8937 + (1.07188* temperature) – (0.394077* relative humidity) + 1.1782 + (0.7212* wind)

The McArthur FDI also includes the influence of rainfall and incorporates the Keetch Byram Drought Index (KBDI). The drought factor (DF) is calculated from the Keetch Byram Drought Index (KBDI) as follows:

> DF = ((0.191* (KBDI$ since rain+ 1)^ 1.5) / (3.52* (KBDI$ since rain +1)^ 1.5 + (rain -1))

The McArthur FDI (McArthur 1966, van Wilgen *et al.* 2000) is then calculated as:

> McArthur FDI = 2* exp(-0.450+0.987 * log(DF) – 0.0345* relative humidity + 0.0338* temperature + 0.0234* wind)

We calculated FDIs using Seme weather records from 2001-2005 using the McArthur equation (McArthur 1966, van Wilgen *et al.* 2000). What is considered to be an extreme FDI was determined using the Department of Livestock and Pasture Science Fire Danger Rating System for Controlled Burning (Trollope, unpublished). The full series of days with FDIs exceeding an FDI of 50 was analysed. An FDI of 50+ is considered a "yellow day" and moderate risk of fire occurrence. An FDI of 50 or greater was used as a threshold value, to investigate whether there were days of continuously high FDIs that may have led to the September 2008 fire. The FDI days exceeding 50 were analysed to determine in which month they tended to occur. Daily SAFDIs for September 2008 were calculated and graphed to assess whether the 14th and 15th, the days when the fire occurred, had particularly high FDIs in relation to the rest of that month.

FDI is a compound index of several weather elements and may hide more than it reveals. Therefore available weather components were analysed separately and the windiest, hottest and lowest relative humidity days in the month of September 2008 were identified. Additionally the cumulative effect of weather conditions (wind run, low relative humidity and high temperatures) in September 2008 was evaluated. These cumulative measures were calculated similarly to how drought indices are determined. For example looking at wind, wind starts blowing and the longer and harder it blows, the worse the effect. When the wind stops, the cumulative measure drops to zero and is reset. Cumulative wind run was calculated as follows:

$$\text{Cumulative wind run (km)} = \sum_{i=1}^{n} V_i$$

where V_i = wind run (km) at interval i (hour), n = number of consecutive intervals where $V_i > 0$

For cumulative relative humidity, the threshold for reset was the cumulative value with 80% relative humidity. The following equation was used to calculate the cumulative relative humidity in September 2008:

$$\text{Cumulative low relative humidity} = \sum_{i=1}^{n} H_i$$

where H_i = low relative humidity at interval i (hour), n = number of consecutive intervals where $H_i < 80\%$

Cumulative high temperatures were calculated as follows:

$$\text{Cumulative high temperature} = \sum_{i=1}^{n} t_i$$

where t_i = maximum temperature (°C) at interval i (hour), n = number of consecutive intervals where $t_i > 20°C$

Frequency histograms were drawn up for the maximum cumulative wind run (km), maximum cumulative temperatures (>20°C) and maximum cumulative relative humidity (<80%) for the period 2001-2008. Only weather data over the Hluhluwe fire season (May to October) as defined by Balfour and Howison (2001), was used for this analyses. These frequency histograms were used to determine how extreme weather conditions were in September 2008 relative to the rest of the decade to evaluate whether this month was particularly unusual and/or extreme.

Long term frequency of high FDI days

In order to assess the frequency of extreme fire weather conditions, we analysed the cumulative FDIs for the period 1950-2008, as well as the frequency of cumulative FDIs over this period. Cumulative FDIs were calculated using the McArthur formula, such that:

$$\text{Cumulative high FDI} = \sum_{i=1}^{n} \mathrm{I}_i$$

where I_i = high McArthur FDI at interval i, n = number of consecutive intervals where $\mathrm{I}_i > 50$. The number of high FDI days per month for the period 1950-2008 was graphed in order to determine the seasonality of when high FDIs occur and establish whether fire risk is greater earlier or later in the fire season.

Long Term frequency of "30, 30, 30" days

In order to assess the frequency and seasonality of extreme fire weather conditions, "30, 30, 30" conditions were graphed using the Egodeni weather records for the period 1960-1999. This basis of determining high fire danger risk days was used to determine the seasonality of weather "switches" rather than a compound index. The weather rule of thumb developed for use on the ground by fire fighting crews, is that fires occur when temperatures exceed 30°C, wind speeds exceed 30 km/hr and relative humidity is less than 30% (W. Trollope and C. Auston, pers. comm. c/o W. Bond). I further analysed the frequency of occurrence of such weather conditions for the Seme weather record over the period 2001 to 2008.

Causes of this extreme event: Preceding rainfall and grass fuel loads

Temporal variation in fuel load, especially of grass, is largely driven by the antecedent rainfall patterns of the area. Rainfall data was considered such that one summer's data was treated as an entity i.e. the rainfall for the summer of 1933/1934 (July 1933 to June 1934) is labeled 1934 and was used as such during analyses. The annual rainfall (mm) for the period 1933 to 2008 was analysed to determine whether the rainy seasons preceding the September 2008 fire were higher than usual. If they were, then there may have been higher productivity in those years and hence greater accumulation of fuel.

To determine whether preceding rainfall was indeed high and so may have contributed towards high grass productivity loads preceding the fire, I also correlated the rainfall records for Mbazwana Airfield (27°28'37.2''S 32°35'52.8''E 82m) and Egodeni for the period 1997 to 2006 (Appendix 7). I then used this correlation equation to patch the missing data in the Egodeni record (January to March 2007 and November and December 2008). The monthly rainfall for Egodeni for the years preceding (2006 and 2007) and the year of the fire (2008) were graphed.

Causes of this extreme event: Chromolaena odorata and fuel modification

Chromolaena, commonly known as Paraffinbush, uhalahala or uboyana, is a perennial evergreen South American shrub. It can be a scrambler and grows amongst trees. Leaves smell of paraffin when crushed. This plant was introduced accidentally and is now an invasive pest that dominates many areas throughout coastal Kwazulu Natal and in Zululand. *Chromolaena* will burn under high fire danger conditions and adds considerably to flammable fuel loads in thicket and forest margins. Fire damage in forests has often been attributed to change in fuel properties following *Chromolaena* invasion. However there are few published studies on this.

Data on *Chromolaena* clearing and invasion extent was obtained from the Invasive Alien Species Programme in the Hluhluwe-iMfolozi Park (H. Pretorius, pers. comm.). This was used to determine if fire patterns, where the fire stopped, and fire activity, were linked to *Chromolaena* abundance, as a fuel source in Hluhluwe. Since no direct data on the contribution of *Chromolaena* to pre-fire fuel load was obtainable, indirect and post-hoc methods were used to determine whether *Chromolaena* influenced fire impacts. Mapped *Chromolaena* densities for 2008 were recorded as low throughout the areas burnt (Appendix 5). This means spatial variation in *Chromolaena* density at the time of the fire and before does not account for the variation in fire severity during this fire. However, past clearing activities may have influenced the way the fire burnt, for example if cleared patches were left with piles of accumulated cut and dead fuel.

To test for residual impacts of *Chromolaena* clearing on fire severity, I determined whether there was a correlation between historical *Chromolaena* density and fire intensity, as measured on ground transects using minimum twig diameter. Historical density was determined based on the size of units mapped as joblots for clearing teams. Thus low density sites had large plots whereas high density plots were smaller. Using this as a surrogate for historical *Chromolaena* density, I could express impacts on fire severity measured in ground transects (see below).

Post-burn vegetation and understorey responses

Post-burn vegetation sampling was conducted in order to evaluate the impact of the fire on the vegetation and the potential recovery rates. Non-destructive line transect sampling was conducted in areas of different fire severities. Twenty sites were sampled for fire damage after the September burn and four unburnt patches sampled as control sites. The majority of transects were in burnt thicket patches and the rest in burnt forest. Samples were randomly located within a burnt patch, using random numbers along a fixed line of travel. At a sample site, trees were sampled along a transect using a wandering quarter method (Catana 1963) to select sample trees and the next closest tree >4 m tall, within 90° was sampled. A total of 25 individual trees were sampled per transect. Trees were identified using Pooley (1993). For each individual tree, the following responses were noted: dead, post-fire basal resprouting or post-fire epicomic resprouting.

The pre-burn stem diameter at 1 m above the ground was measured (cm) using a 50 m measuring tape. If the individual had multiple stems, all diameters were measured and the average of these measurements was calculated and included in analyses. A measure of fire intensity was obtained from measurements of minimum post-burn twig diameters within 2 m of the individual tree being sampled. These twig diameters were measured (mm) using vernier calipers. GPS readings were recorded at the beginning and end of each transect. Transects were paced out and 20 Disc Pasture Meter measures (DPMs) were recorded. These were evenly spaced along each transect to determine grassy cover and an estimate of fuel biomass. The presence or absence of *Chromolaena*, felled or standing, was noted. Other interesting observations and notes were made and photographs were taken at each transect. Two Bitterlich Wedge measurements of basal area were taken at each site, near the beginning and toward the end of each transect, as an estimate of pre-burn woody biomass (Moritz-Zimmermann *et al.* 2002). To investigate the impact of the fire on structural change of the vegetation, pre-and post-burn frequencies of tree size classes were determined (the diameter at breast height (DBH) size classes are defined as follows: 0: 0-4.9 cm; 1: 5-9.9 cm; 2: 10-14.9 cm; 3: 15-19.9 cm; 4: 20-24.9 cm; 5: 25-29.9 cm; 6: 30-34.9 cm; 7: 35-39.9 cm; 8: 40+ cm).

I determined size and species level influence on mortality. In addition, I explored the relationship between tree size and sprouting mode: basal or epicomic. The relationship between percentage tree mortality and fire intensity, as measured as minimum twig diameter, as a post-burn indicator of fire severity, were used and to determine how tree recovery varies with the type and intensity of the burn (Moreno and Oechel 1989).

RESULTS

Reconstructing the September 2008 fire event

Reconstructing the fire event has proven challenging, as people's memory of the fire event is variable. From interviewing members of the Hluhluwe staff, I have reconstructed how the fire progressed over the 48 hour period that it burnt on 14th/15th September 2008. The fire started midday, Sunday, 14 September 2008, in the direction of Pindasweni Gate, north of Qololenja (see ignition point in Figure 1). The weather conditions were conducive to runaway fires and the fire spread rapidly southwards towards the tarred access road and burnt into the forest patches near Pindasweni (also near ignition point indicated in Figure 1). A control burn on the north side of the road, from Kwahlaza in the direction of Hilltop, jumped the road due to high wind speeds and continued to burn southwards. Fire fighting was concentrated north of the tarred road where the highest risk was, and westward were the fire spread into the forest, threatening Hilltop. The fire was extremely severe, burning tree tops and destroying organic matter on the soil surface (D. Swart, pers. comm.).

By 06H00 Monday, after 36 hours continuous work, the fire fighting teams were exhausted. Weather conditions had changed and the fire was less of a threat. A back burn from west of upper Magangeni helped protect the Zululand Tree Project (ZLTP) fire plots. Other back burns had limited success (see Figure 1). But by 07H30, temperatures and wind speed rose again, accelerating the fire spread and limiting the effect of fire fighting techniques. At times wind speed was estimated at 60 km/hr during head fires and flames leapt ~50 m (D. Druce, pers. comm.). The fire began to die down by Monday afternoon and was extinguished by approximately 19H30.

The fire weather conditions of the 48 hours over which the fire burnt are graphed (see Figures 2a, b and c). Temperatures were fairly high, exceeding 30°C during the day on the Sunday and Monday. The wind failed to drop during the night of the 14th and the relative humidity remained low during that night. In Figures 2b and c, the distinct drop in wind speed and relative humidity are evident when the fire ceased on the evening of the 15th around 19H30. Fire fighting crews refer to extreme fire weather as "30, 30, 30" conditions, meaning that temperatures exceed 30°C, relative humidity is less than 30%, and winds exceed speeds of 30 km/hr (W. Trollope and C. Auston, pers. comm. c/o W. Bond). Such extreme weather conditions were met on the Sunday afternoon (12h00 and 18h00), and then again on the Monday (07h30 to ~16h30). The dry and very windy conditions, coupled with availability of much cut and dry *Chromolaena* fuel, are believed to have contributed to the severity of the fire, and the limitations of the fire fighting techniques and the resultant large scale damage.

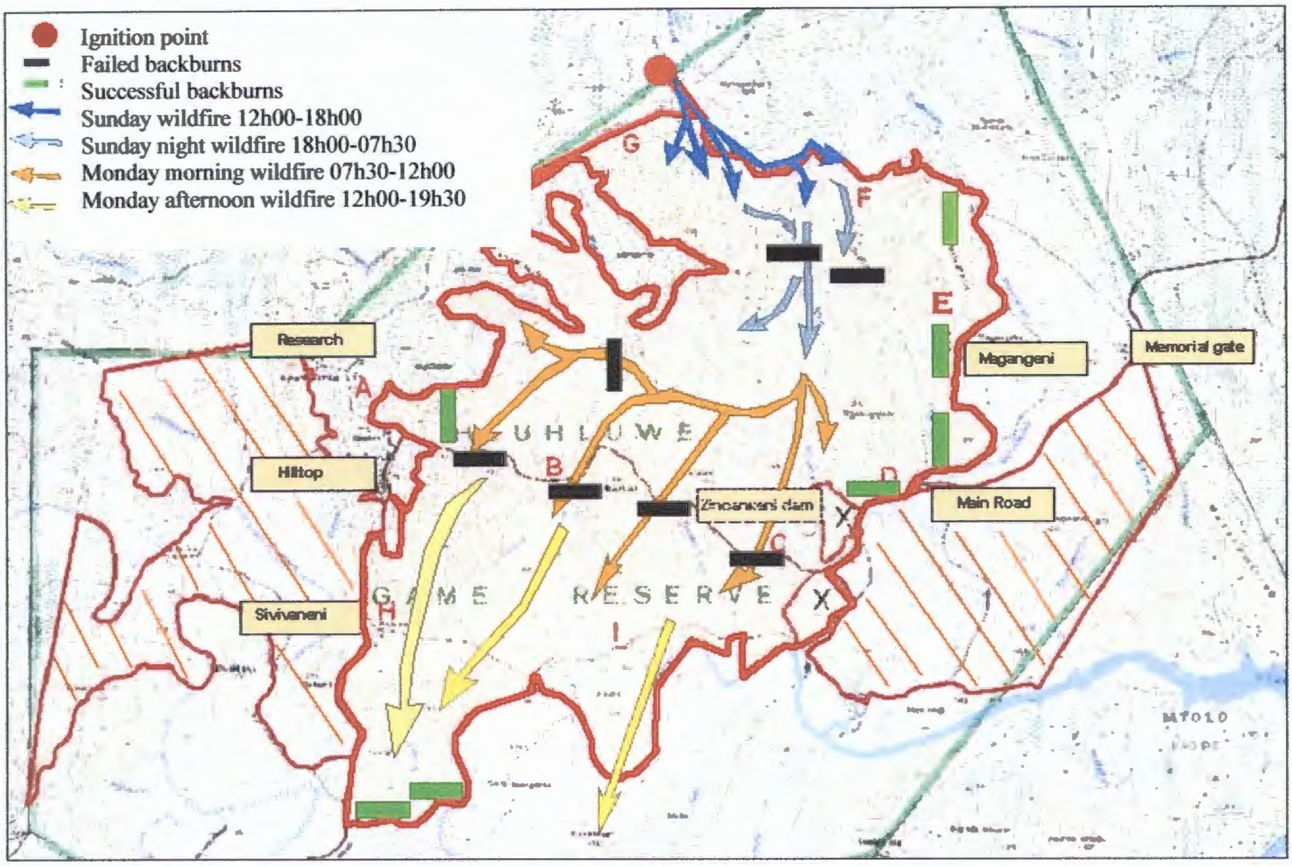

Figure 1: Fire event as recorded by the section manager, Dirk Swart. The bold red border illustrates the area burnt in September 2008 as defined by the GIS unit in Hluhluwe, and the hashed areas indicate control burns which were independent of the event under investigation. Arrows indicate the movement of the fire and blocks represent back-burns put in place by fire fighting crews.

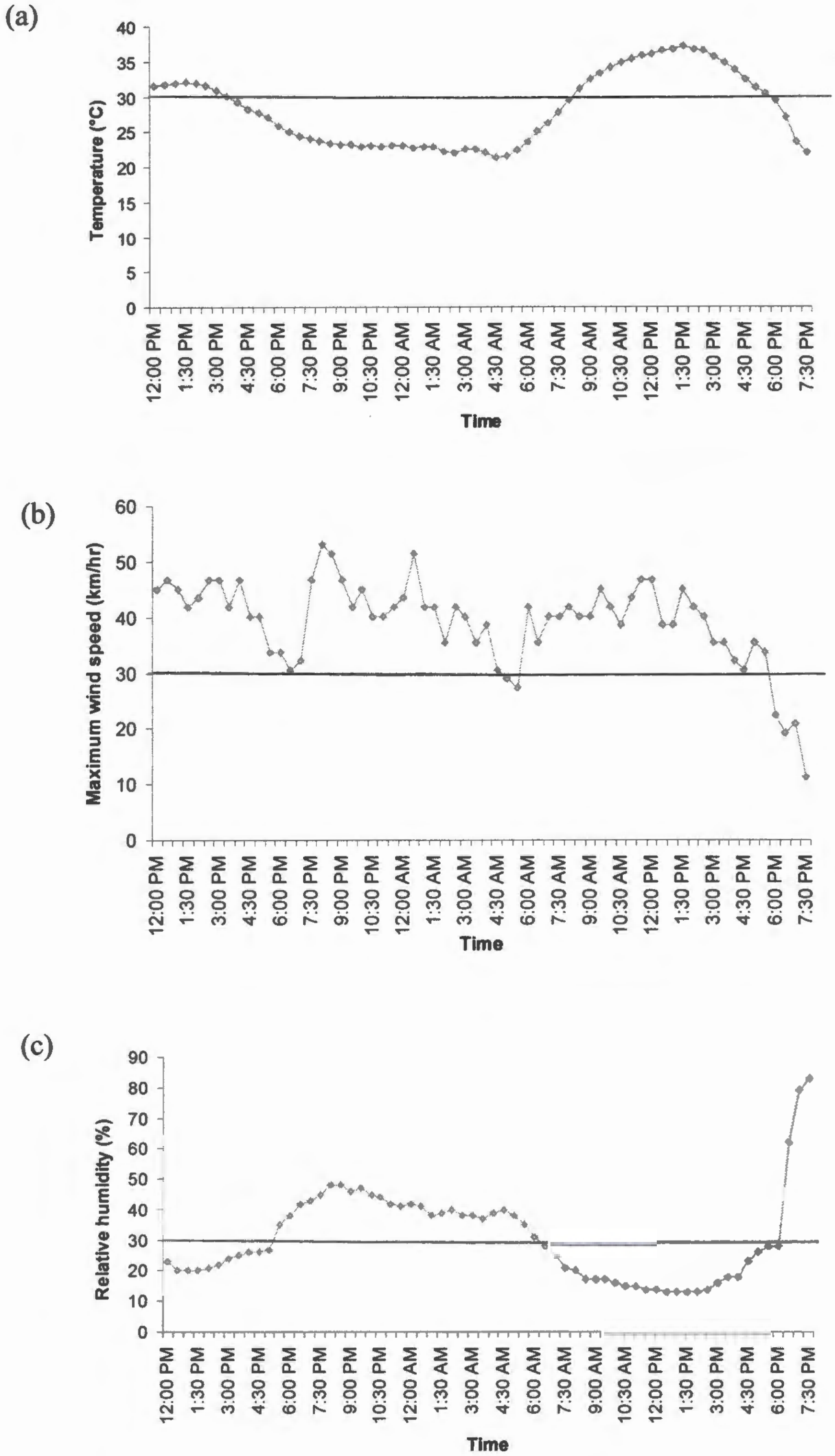

Figure 2: Weather conditions over the 48 hour period fire 14-15 September 2008.
(a): Temperature (°C). (b): Maximum wind speed (km/hr). (c): Relative humidity (%). The horizontal lines indicate the relative thresholds for extreme fire danger.

Satellite data

The temporal pattern of fire radiative power from the SEVERI product (Figure 3) shows a pattern that corresponds to the section ranger's report on the movement of the fire (Figure 1). Fire pixels were detected after this fire in the study area (18-19 September 2008), but may not be from the same location as those of the 14-15 September (Figure 3).

The fire burnt over two days without going out at night, and was far more severe on the Monday and apparently most severe during midday on the 15th (Figure 3). This map and graph of the fire (Figures 1 and 3) allow correlation of fire damage to thicket/forest with changing rates of spread/radiative power during the fire. From Figures 1 and 3, it appears that the destructive force of this event was released in a few hours on the second day.

The Landsat image taken on the second day of the fire, 15 September 2008, was taken in the morning and so, although the fire is visible on the image, it does not portray the full burn extent (Appendix 1). Later satellite images were examined but proved not to be useful for determining the burnt area. The November image (Appendix 2) was obscured by cloud cover, and the 4 December image (Appendix 3) is too late after the fire event, as vegetation had grown back after the advent of the rainy season and the burn scar was obscured. Unfortunately, the MODIS burnt area product is of too coarse a scale to map the fire extent (Appendix 4). Thus the ranger's map is the best available estimate of the burn area which was ~4810 ha.

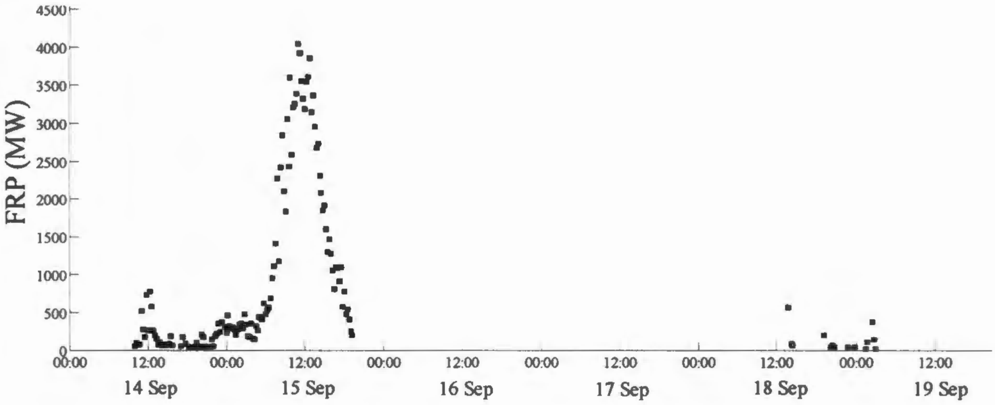

Figure 3: Temporal profile of fire radiative power (FRP) measured by the SEVERI satellite within the study area over the period of 14-19 September 2008 (courtesy of P. Freeborn and W. Marais 2009)

Landscape patterns of fire severity

Figure 4 provides a landscape perspective of the impact of the September 2008 fire. The extent of thicket cover and of thicket burnt in the fire was mapped in June 2009. This shows that the fire was extreme, in that it burnt into thicket and forest, which is not common in the study area.

Thicket and forest patches did not burn until peak severity conditions on the Monday. The Sunday fire appears to have been a normal savanna fire burning to the edges, but not beyond, of thicket and forest patches. I was unable to observe Pindasweni forest patches that burnt near the ignition point (Figure 1) due to road inaccessibility.

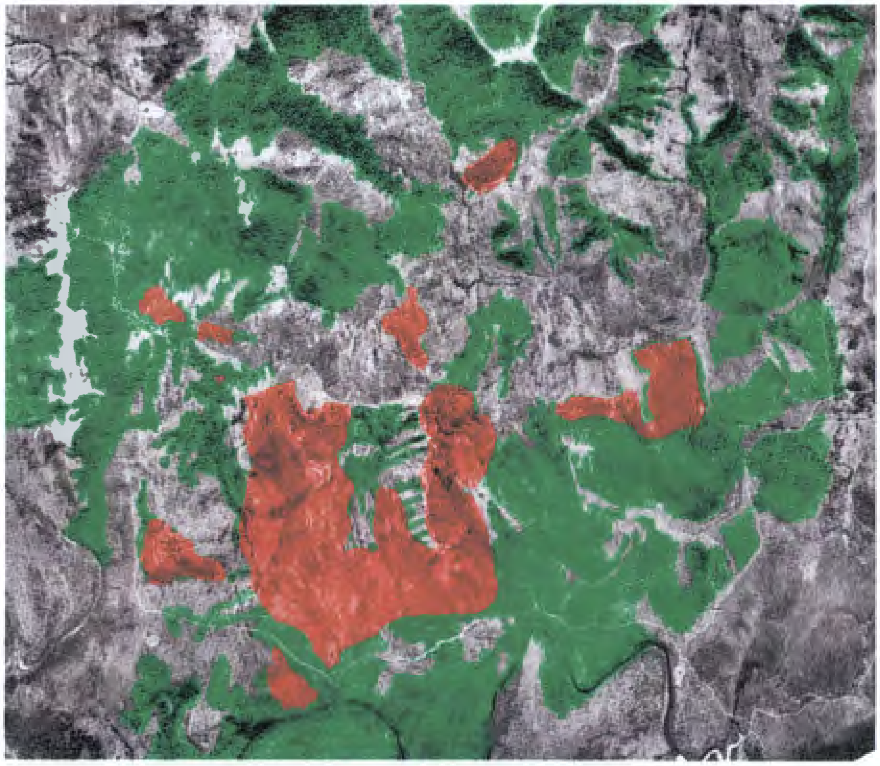

Figure 4: Map indicating the extent of the northern region of the park that is covered by thicket (green) and the areas that burnt in the September 2008 fire (red) based on ground mapping using an aerial photograph taken in 2004

Causes of this extreme fire event and its severity: Weather conditions

To establish whether this weather was extreme during the fire event, I used weather records available from 2001 to 2005. The worst fire danger days having FDIs 50 to 60+, (yellow or worse days, Trollope, unpublished) mainly occurred in the months August, September and October (Figure 5). Despite days of weather conditions conducive to fires, high severity savanna fires do not occur in the rainy season from November to April (Balfour and Howison 2001). This is because the grasses green-up and the high moisture content reduce rates of fire spread.

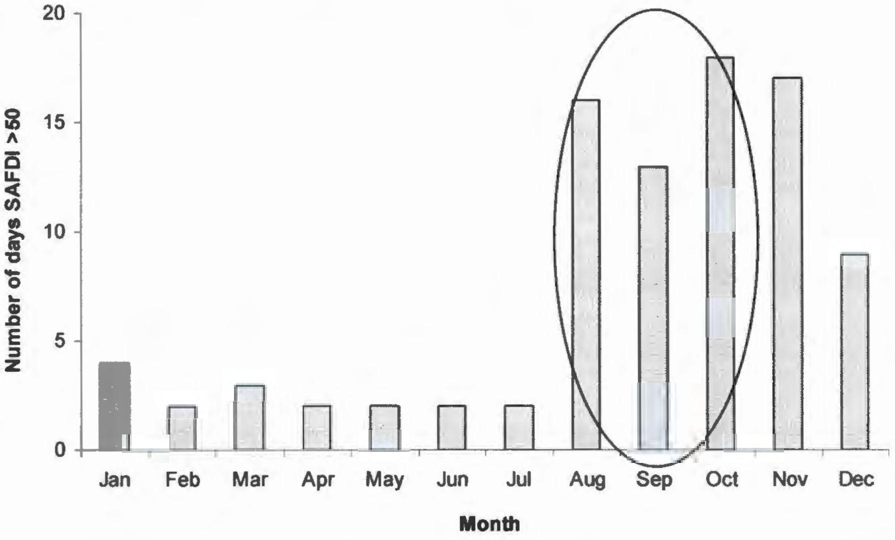

Figure 5: Graph illustrating when worst fire danger index (FDI) days (FDI>50) occur for the Seme weather record from the period 2001-2005. The circle indicates the months in which FDIs>50 were most common. (Lowveld formula)

Within the month of September 2008, the 14th and 15th both had FDIs >50, with Monday 15th reaching a SAFDI value of 64. However 12 days had FDIs >50 in September 2008 and so the FDIs on the fire days were not particularly extreme.

Ignition, fire weather, fuel amount, and its flammability, are fundamental conditional processes leading to fire occurrence (Archibald *et al.* 2009, Bradstock 2009). Bradstock (2009) refers to these as the four "switches" simultaneously required for fire to occur. He proposes that fire will cease to burn, should any one switch be "off".

FDIs are calculated from temperature, relative humidity and wind speed. Decomposing these data for September 2008, as recorded in the Seme weather database, it is noted that the fire days (14 and 15 September) were among the highest recorded values for the hottest, windiest and lowest relative humidity days in that month (Figures 6a, b and c), indicating their combined potential as fire "switches".

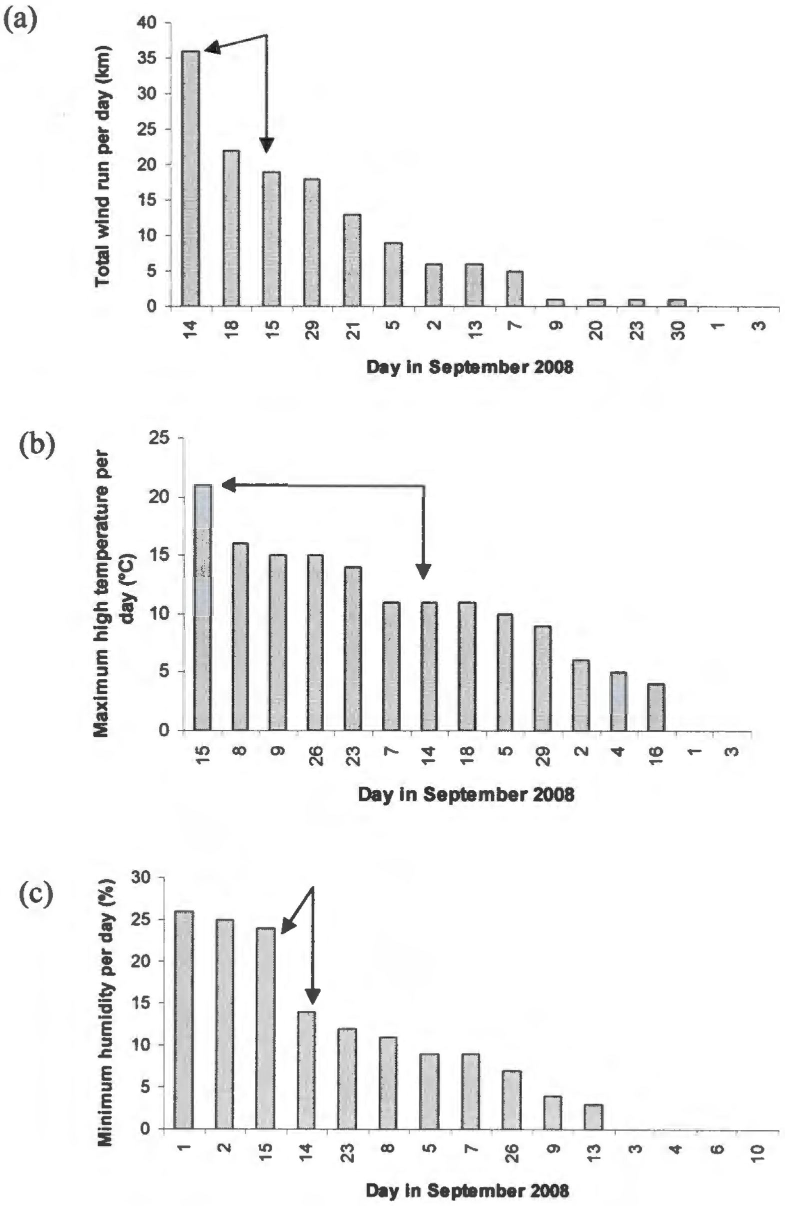

Figure 6: Days in September 2008 ranked from highest to lowest (a) daily wind run (km), (b) daily temperature (°C), (c): minimum relative humidity (%).The arrows indicate the days when the fire occurred (14th and 15th September 2008).

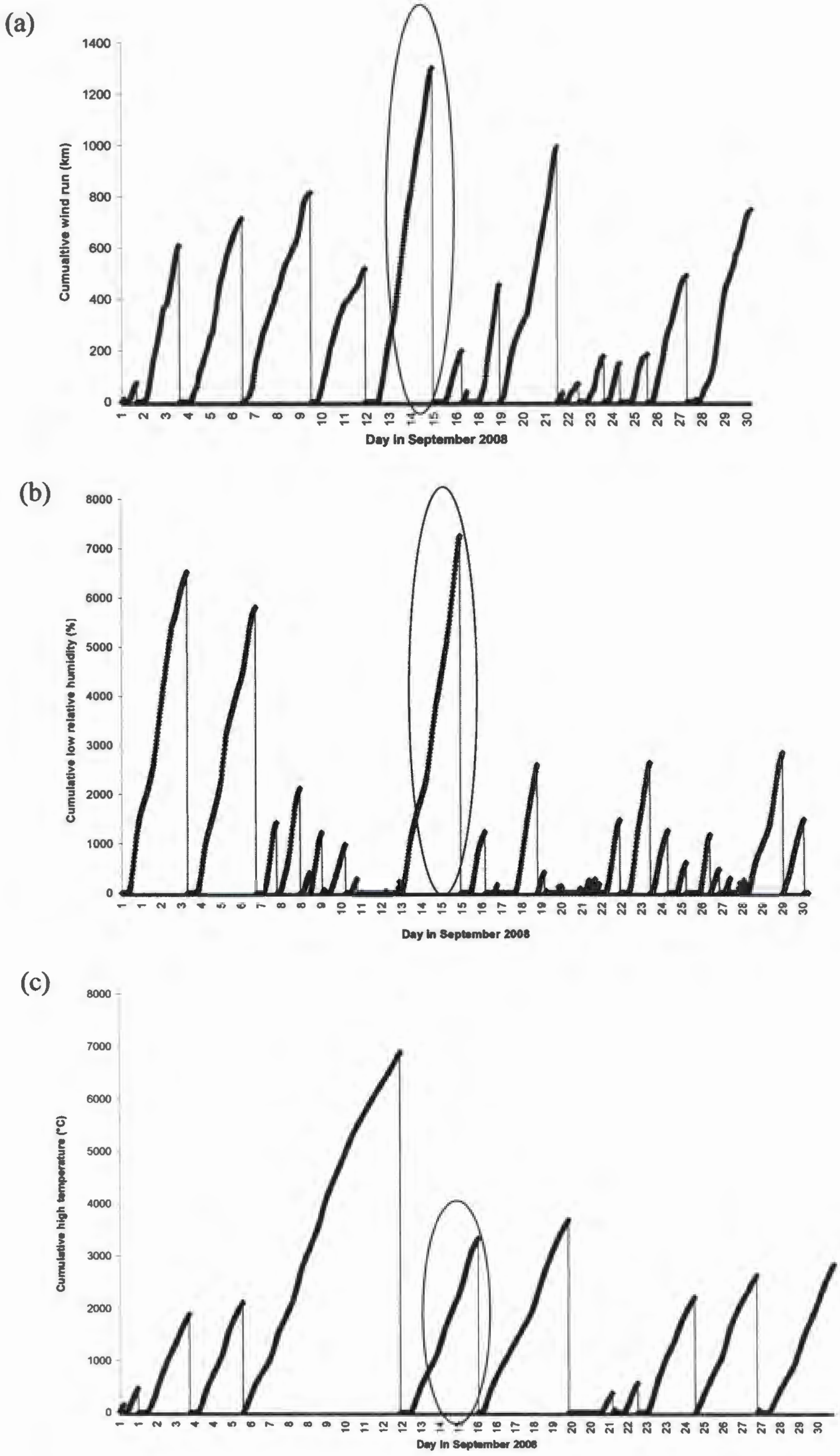

Figure 7: September 2008 cumulative weather records (a) wind run (km), (b) low relative humidity (%), (c) high temperature (°C). The fire days are circled.

The drying effects of high wind, high temperature and low relative humidity are cumulative so that a daily weather value may be less revealing than the sequence of values. Figures 7a, b and c show cumulative wind run, low relative humidity and temperature (see methods for equations). The peak values of these cumulative weather values indicate the duration of high fire risk conditions before conditions return to being low risk and the fuels re-hydrate. The most extreme conditions for cumulative wind run (km), as well as low relative humidity (<80%) occurred over the 14th/15th of September 2008. The height of the lines above the x-axis indicate how extreme the conditions are and therefore these graphs give an idea of the duration and severity of cumulative conditions conducive to fire. From Figures 7a and b, it can be seen that the fire days (14th/15th September 2008) had the longest cumulative wind run and lowest cumulative relative humidity respectively. Although the temperatures were not cumulatively the highest on the fire days in the month of September 2008 (Figure 7c), they were preceded by a long hot spell from the 6th to 12th September 2008.

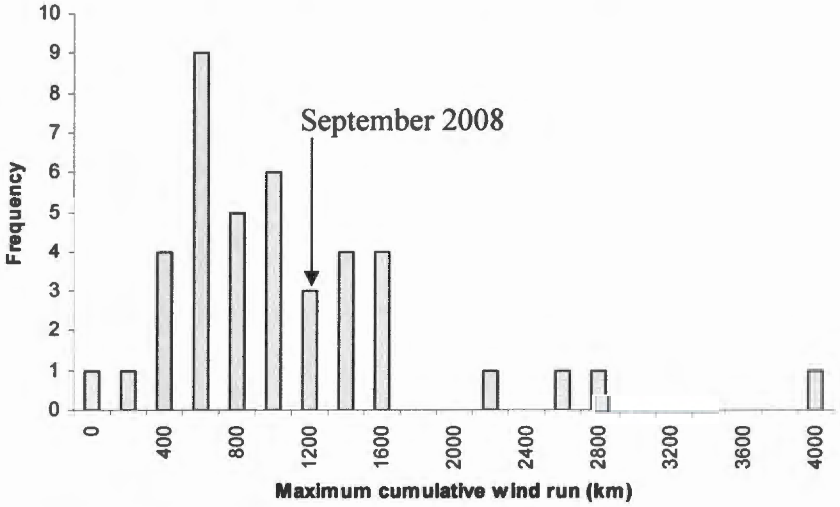

Figure 8(a): Maximum cumulative wind run (km) record for the fire seasons (May-October) for Seme over the period 2001-2008.

Figure 8a shows the frequency distribution of the windiest periods over the period 2001 to 2008, from Seme monthly weather records, as measured from the cumulative wind run (km). The September 2008 fire had a cumulative wind run of 1300^+ km (Figure 8a) which is just under the 75th percentile. This indicates that September 2008 was a windy period but 30% of the values from the data record for the period 2001-2008 exceeded this wind run. There were months when wind run was much worse.

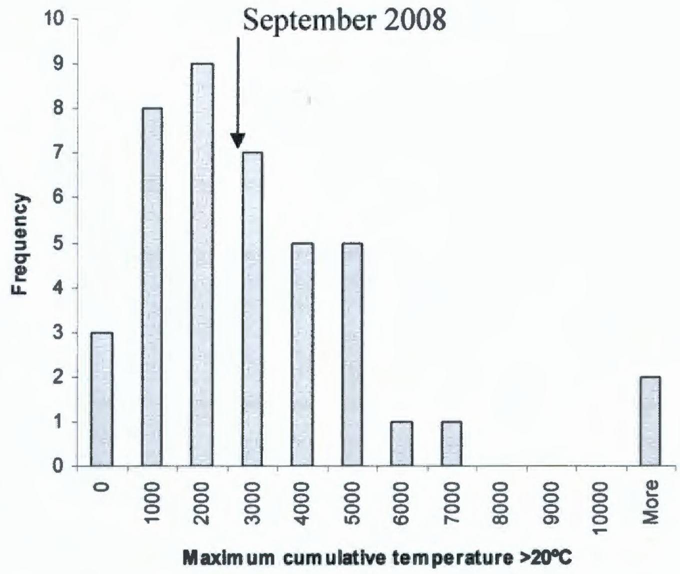

Figure 8b: Maximum cumulative temperature (>20°C) record for the fire seasons (May-October) for Seme over the period 2001-2008

Figure 8b shows the frequency distribution of the hottest periods, as measured from the cumulative temperatures >20°C. The data are for the period 2001-2008 from the Seme monthly data. The September 2008 fire had a cumulative temperature 3400^+ (Figure 8b) just under the 75th percentile, indicating that September 2008 was a hot period. However, 35% of the values from the data record for the period 2001-2008 exceeded this maximum temperature. There were months when the run of high temperatures was much longer and more severe.

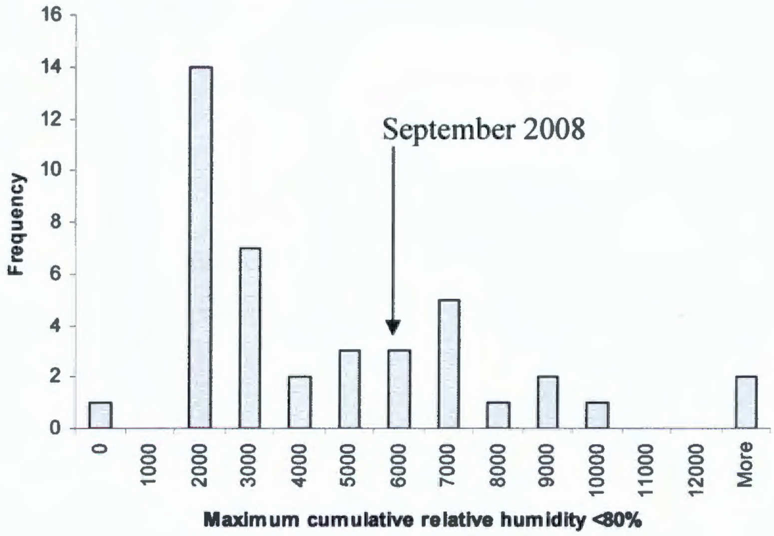

Figure 8c: Maximum cumulative relative humidity (<80%) record for the fire seasons (May-October) for Seme over the period 2001-2008

Figure 8c shows the frequency distribution of the lowest relative humidity periods, as measured from the cumulative relative humidity <80%. The data are for the period 2001-2008 from the Seme monthly data. The September 2008 fire had a cumulative relative humidity 6300^+ (Figure 8c), in the 75th percentile, indicating that September 2008 was a period with low relative humidity. However, one quarter of the values from the data record for the period 2001-2008 exceeded this low relative humidity. There were months when there were much longer periods of low relative humidity.

Long term frequency of high fire danger days

Long term weather records of Hluhluwe have been assembled from measured or modeled sources and were obtained from S. Archibald (CSIR). These provide some indication of fire weather over multiple decadal periods. The maximum cumulative McArthur FDI for 2008 was 664. Most (90%) of the values of maximum cumulative McArthur FDIs for the Egodeni data record over the period 1950-2008 were greater than this, implying that there were years when fire danger was much worse. There is a <5% chance of reaching the high cumulative FDI values obtained for 1992 and 1970 (Figure 9). The 2008 Hluhluwe maximum cumulative McArthur FDI and fire weather was high but not exceptionally high.

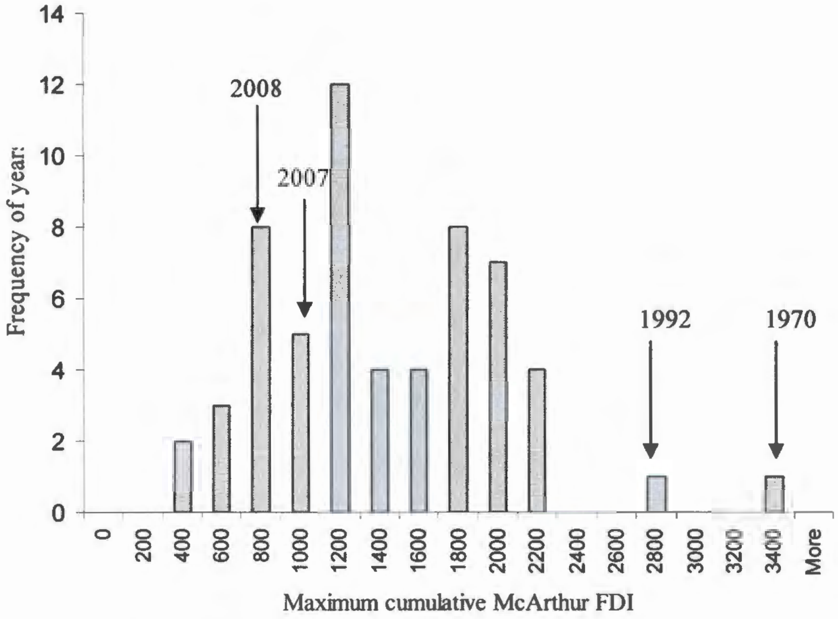

Figure 9: Frequency of maximum cumulative McArthur FDI for the period 1950-2008

High FDI days in Hluhluwe for the period 1950 to 2008 are most common in January, February and September (Figure 10). The fire under investigation falls in September, a month that typically has high FDIs late in the fire season.

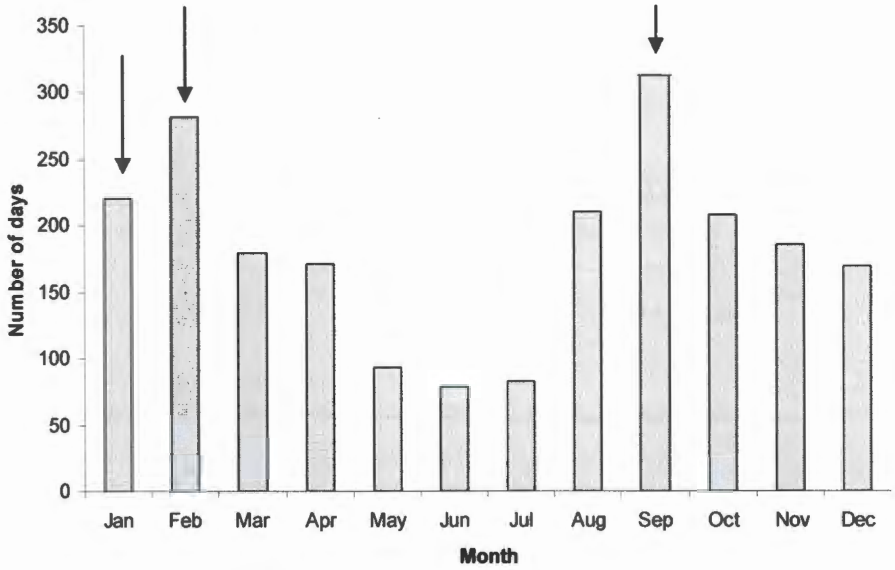

Figure 10: Seasonality of high FDI days in Hluhluwe for the period 1950-2008. Arrows indicate the months in which high FDIs were most common. (McArthur formula)

Long term frequency of "30, 30, 30" days

Over the Egodeni weather record for the period 1960 to 1999, days when simultaneous conditions of temperature >30°C, wind speed >30 km/hr and relative humidity <30%, predominantly occurred in the fire season, August to October. September was the peak month for such conditions (Figure 11). A total of 194 days of the 14610 days in this data series experienced "30, 30, 30" conditions, and when we restricted analysis to include only fire season months, a mere 138 days fit these conditions. This shows that such conditions are rare, with ~3 days of the year experiencing them.

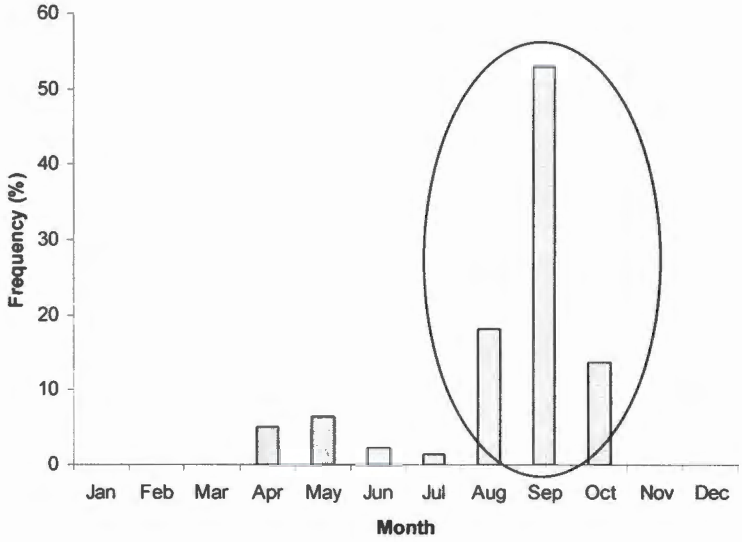

Figure 11: Seasonality of "30, 30, 30" days in Hluhluwe for the period 1960 to 1999

Analysis of each component, temperature, relative humidity and wind, highlighted the rarity of occurrence of all three 30 conditions occurring simultaneously. From the Seme weather record for 2001 to 2008, "30, 30, 30" conditions occurred for a total of 70 hours in a weather record of 4139 hours or 1724 days or 4.72 years (Table 2). This is a frequency of approximately 1 day in 591 days, or 1.6 years or ~ 2 days every 3 years.

Table 2: The frequency of weather components and of "30, 30, 30" conditions for the Seme weather record for the period 2001 to 2008. N is the number of half-hourly weather output records.

	N	Temperature >30°C	Relative humidity <30%	Wind >30 km/hr	30, 30, 30 conditions
Total 2001-2008	82778	7757	2739	3814	140
Hours	41389	3878.5	1369.5	1907	70
Days	1725	162	57	79	2.9
Years	4.72	0.44	0.16	0.22	0.01

Causes of this extreme event: Preceding rainfall and grass fuel loads

The rainy seasons preceding the fire may have contributed to high fuel loads and hence high fire severity. However the two years preceding the fire did not have unusually high amounts of annual rainfall (mm) according to the Egodeni rainfall record for 1933 to 2008 (Figure 12). The rainy season for 2007 (855 mm) and 2008 (747 mm) were drier than the mean rainy season for the period 1933 to 2008 (990 mm). However, rainfall data for the months January, February and March 2007 are missing from this record, thus making 2007 an underestimate that should be approximately doubled. It would seem that 2007 was in fact a high rainfall year. Hence there may have been accumulation of fuel preceding the September 2008 fire. The time since this area was last burnt is varied but most areas where thickets burnt have did not burn the year before the fire and therefore fuels may have accumulated (Appendix 6).

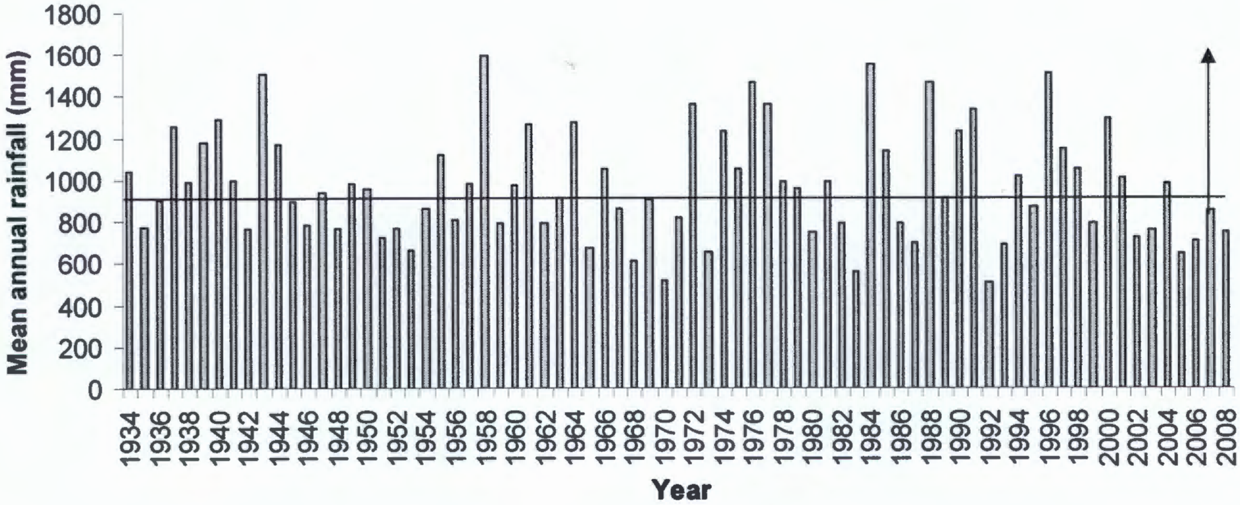

Figure 12: Mean annual rainfall (mm) as recorded at Egodeni (Hilltop) for the period 1933 to 2008. Data is missing for 1999 and therefore this year was omitted from the record. The horizontal line represents the mean annual rainfall over the entire period. The arrow represents an estimate of the actual amount of rainfall (mm) in 2007.

Since data was missing in the Egodeni long term rainfall record, Mbazwana Airfield rainfall records were correlated with the Egodeni record (Appendix 7) and the data was patched. Using this patched data the monthly rainfall (mm) in the two years (2006 and 2007) preceding the fire in September 2008 were found to have been high (Figure 13). The rainy season in Hluhluwe is November to April.

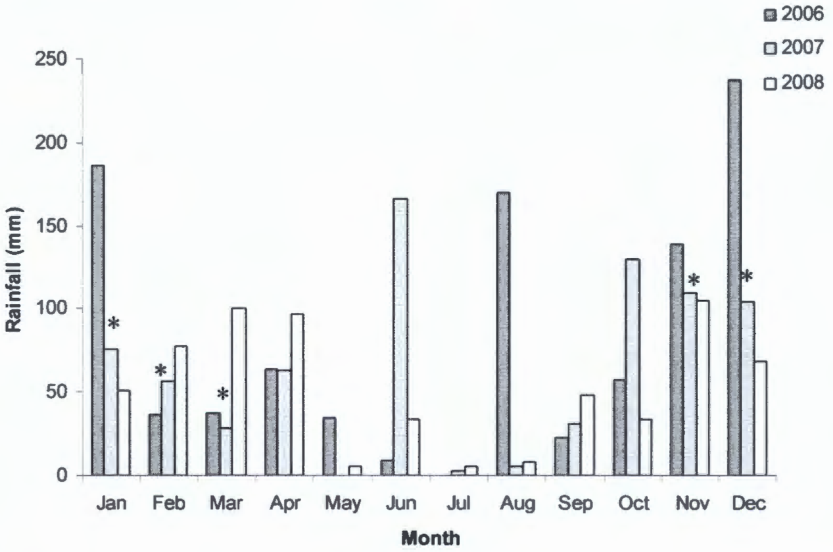

Figure 13: Monthly rainfall for Egodeni for the period 2006 to 2008. Patched data are indicated with *

Causes of this extreme event: Chromolaena and fuel modification

The relationship displayed in Figure 14 shows an essentially flat line, with no significant relationship between minimum post-burn twig diameter (mm), as a measure of fire intensity, and relative treatment plot size, ($r = 0.22$, $N = 20$, $p > 0.05$). Fire intensity was not significantly greater or less in smaller clearance plots, representative of higher densities of *Chromolaena.*

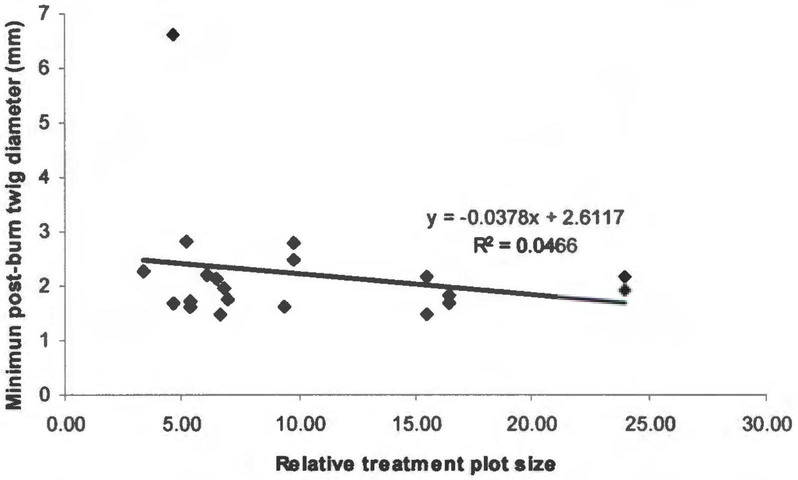

Figure 14: Relationship between fire intensity, as measured by minimum post-fire twig diameter and *Chromolaena* relative clearance treatment plot size, representative of clearance effort required and hence historical *Chromolaena* density. Small plot sizes equate to high *Chromolaena* density.

The impacts of *Chromolaena* invasion on grass biomass measured in the current survey was tested using joblot sizes within which intensities were sampled (Figure 15). Though grass biomass (kg/ha) is highly variable, the relationship was significantly positive ($r = 0.49$, $N = 20$, $p < 0.05$; Figure 15). This grass biomass tended to increase when historical density of *Chromolaena* was low.

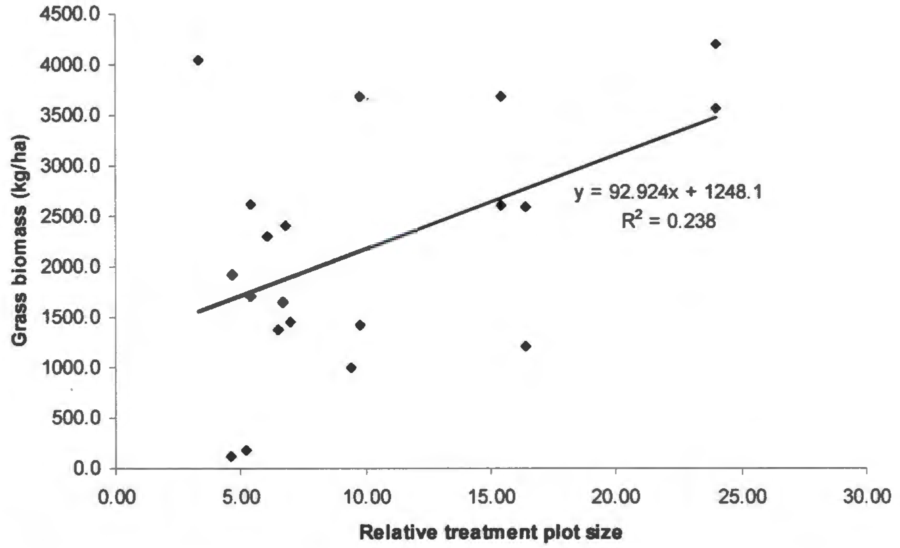

Figure 15: The relationship between *Chromolaena* relative treatment plot size and present grass biomass (kg/ha).

Post-burn vegetation responses determined from transect data

To assess the impact of the fire, the structural and compositional changes in post-burn thicket patches were assessed. It was found that a highly significant shift in structure occurred following the fire ($\chi^2 = 20.04$; df = 4; $p < 0.01$; Figure 6). The post-burn landscape is more open (see Figure 17) and more trees have reverted to low, multi-level resprouting shrubby forms (Figure 16).

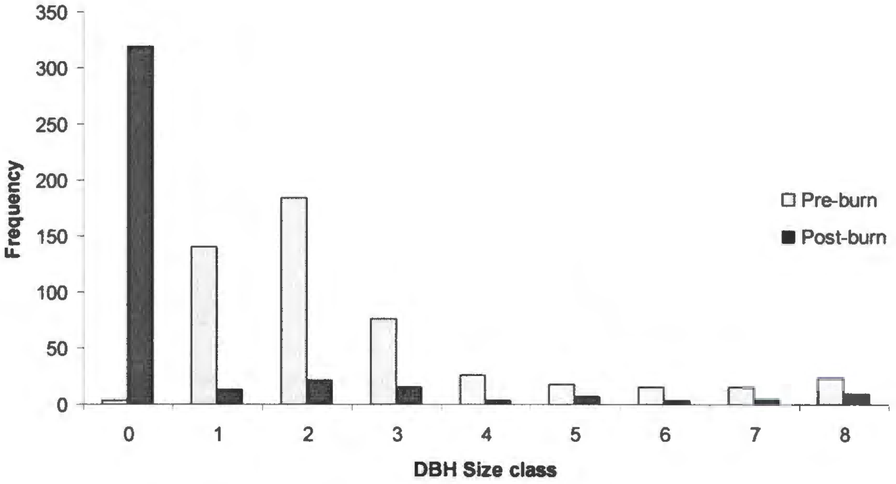

Figure 16: Structural change between pre-burn and post-burn. (The diameter at breast height (DBH) size classes are defined as follows: 0: 0-4.9 cm; 1: 5-9.9 cm; 2: 10-14.9 cm; 3: 15-19.9 cm; 4:20-24.9 cm; 5: 25-29.9 cm; 6: 30-34.9 cm; 7: 35-39.9 cm; 8: 40+ cm)

Figure 17: Photographs of the burnt areas sampled, illustrating that the post-burn patches are open (Photographs taken by C. Browne 2009)

Transect data indicates a large change in structure (Figure 16). However, not much change in density occurred. The total mortality resulting from this fire was 21% of the 503 trees sampled. Tree mortality, as a result of the fire, occurred in trees of varying sizes and there is no significant difference in the percentage of trees that died in the differing DBH size classes ($\chi^2 = 2.69$; df = 4; $p > 0.05$; Figure 18).

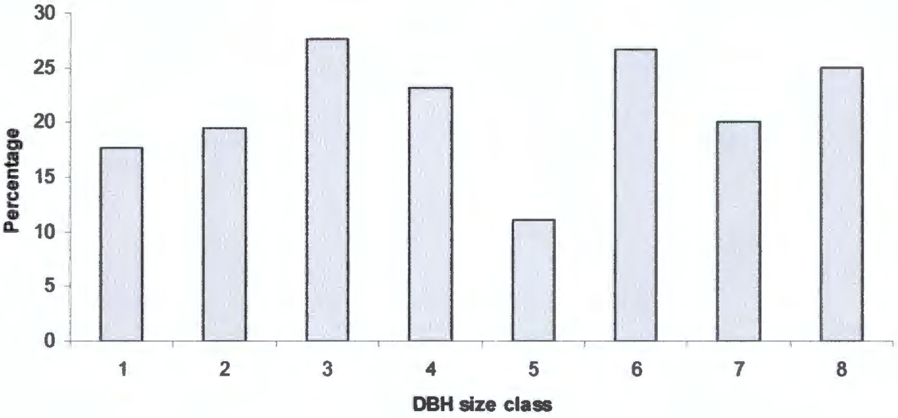

Figure 18: Overall mortality in trees in relation to size. (See figure 6 for DBH size classes)

The size of the individual tree influenced its post-fire response (Figure 19). Sprouting from the canopy (epicomic resprouting) appeared to increase with increasing tree size and basal sprouting was found to be highest in the smaller trees. Epicomic/canopy resprouting was significantly different in the differing DBH size classes ($\chi^2 = 20.04$; df = 4; $p < 0.01$; Figure 19). Conversely, basal resprouting was found to be not quite significantly different between differing DBH size classes ($\chi^2 = 9.395$; df = 4; $p = 0.052$; Figure 19).

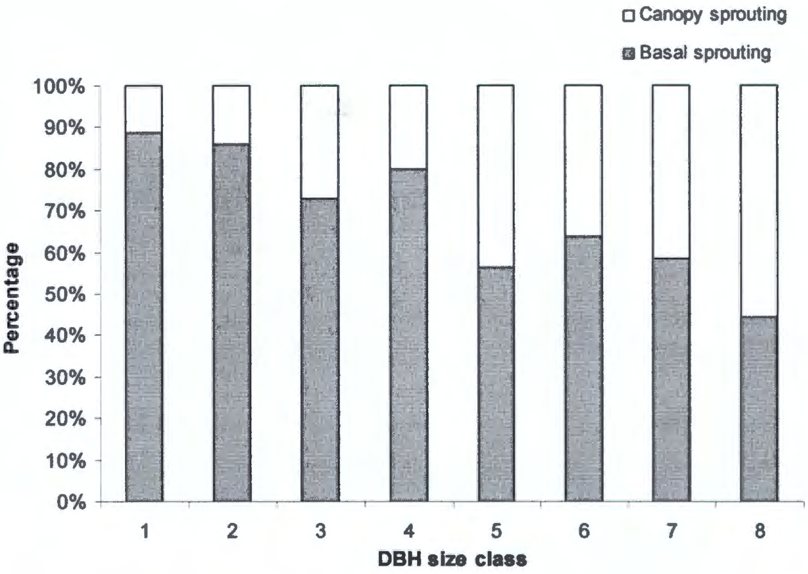

Figure 19: Tree post-fire responses in relation to tree size (See figure 6 for DBH size classes)

Mortality occurred fairy evenly over the varying species sampled (Table 1). Of the common species, *Euclea racemosa* showed lower sensitivity to fire than *Sideroxylon inerme* (11.1% and 72.7% mortality respectively; Table 1).

Table 1: Tree mortality analysis of all trees sampled post-burn (Total N = 503). The number of individual trees per species (N), pre- and post-burn is indicated. Bold indicates the species, where there were fewer observed than expected deaths. * indicates the species which had significant differences between observed and expected numbers of dead trees.

Species	Pre-burn N	Post-burn N	% mortality	% of all trees	% of dead trees	Chi^2
Euclea racemosa	180	160	11.1	35.8	19.0	8.2 *
Berchemia zeyheri	103	81	21.4	20.5	21.0	0.0
Euclea natalensis	42	33	21.4	8.3	8.6	0.0
Sideroxylon inerme	22	6	72.7	4.4	15.2	28.3 **
Bersama tysoniana	19	18	5.3	3.8	1.0	2.3
Celtis africana	18	15	16.7	3.6	2.9	0.2
Croton sylvaticus	18	11	38.9	3.6	6.7	2.7
Calpurnia aurea	16	9	43.8	3.2	6.7	4.2 *
Canthium inerme	8	7	12.5	1.6	1.0	0.3
Acacia robusta	7	2	71.4	1.4	4.8	8.2 *
Euclea divinorum	7	5	28.6	1.4	1.9	0.2
Sclerocarya birrea	6	5	16.7	1.2	1.0	0.1
Rhus chirindensis	5	4	20.0	1.0	1.0	0.0
Spirostachys africana	5	4	20.0	1.0	1.0	0.0
Cordia caffra	4	3	25.0	0.8	1.0	0.1
Dovyalis caffra	4	2	50.0	0.8	1.9	1.8
Ekebergia capensis	8	8	0.0	1.6	0.0	0.8

Tree mortality differed among transects ranging from <5% to 40%. There was no significant relationship between fire intensity, as measured using post-burn minimum twig diameter, and the percentage mortality of trees in sampled transects (r = 0.16, N =19, $p > 0.05$; Figure 20).

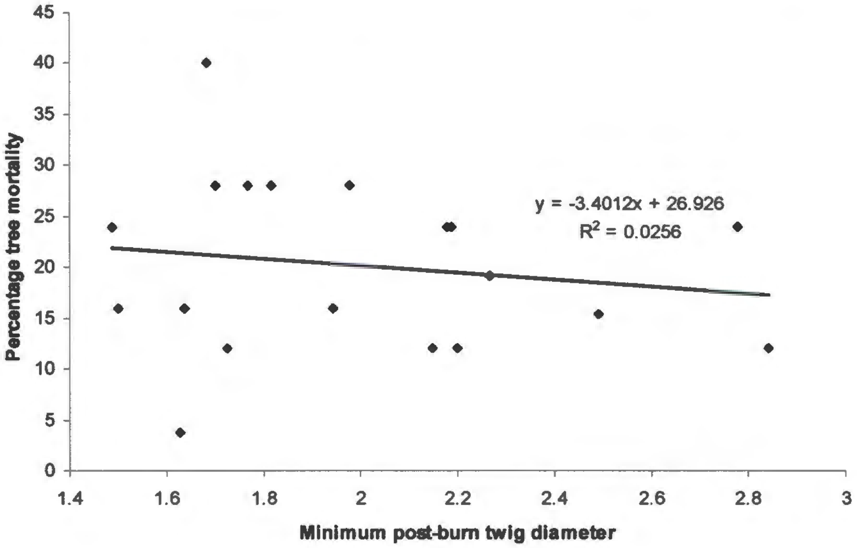

Figure 20: Overall tree mortality in relation to minimum post-burn twig diameter, as a measure of fire intensity

Post-burn responses of the understorey

Transects varied in their understorey composition with some being grassy and others dominated by forbs. Overall there was a significant negative relationship between grasses and forbs (r = 0.53, N =30, $p < 0.05$; Figure 21), with grass dominated transects being more abundant than forb dominated ones.

Grass biomass, an estimate from the settling height of the disc pasture meter calculated for Hluhluwe (equation to convert grass height to biomass: 12.62 + 26.11* DPM for metal disk (cm) = spatial biomass (kg/ha)) (Waldram *et al.* 2008), was highly variable. Median biomass was 1800 kg/ha with some transects supporting >3500 kg/ha. Such high productivity in the first year post-burn suggests that some of the burnt transects have sufficient fuel to burn again the year after the fire.

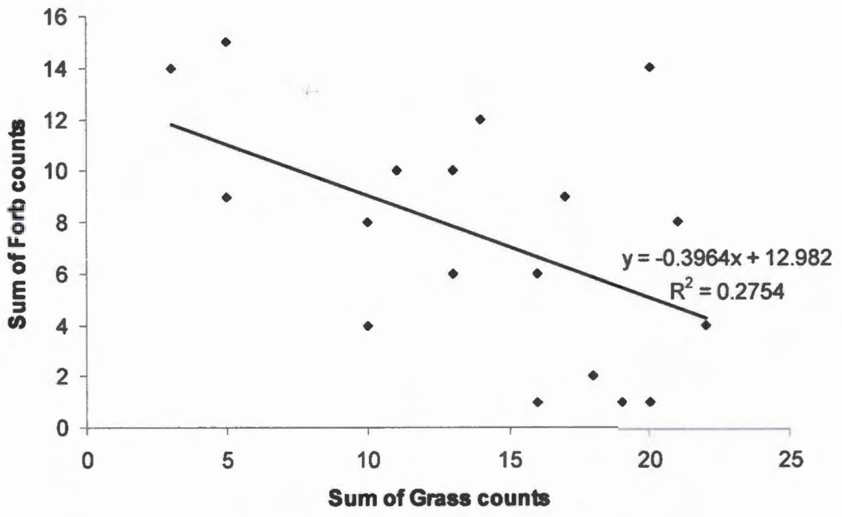

Figure 21: Grass and forb cover, illustrating the composition of the understorey of post-burn sites sampled

DISCUSSION AND CONCLUSIONS

The aim of this report was to determine the causes of the extreme fire event in Hluhluwe in September 2008; to examine the consequences of this event on forest and thicket patches; and to evaluate the future of forest-grassland mosaics and how they are influenced by the frequency of such severe fires. Fire burning into non-savanna vegetation is a novel situation that is not well researched. Through understanding of the causes of such an extreme event, managers in the future could either ignite fires under extreme conditions to help savannas recover from bush encroachment, or be under high alert when extreme conditions arise. To my knowledge this is the first South African study addressing the climatic conditions of severe grass-fueled fires burning into forests and attempting to characterise what leads to such extreme events.

The September 2008 fire was an extreme event because thicket and forest patches burnt and their entire composition and structure changed. The impact of this event is going to last for decades. Forests and thickets that developed over decades changed over 48 hours. Was this event desirable or undesirable? The fire was desirable from the point of view of reducing bush encroachment, but undesirable due to the loss of forest and the biodiversity it supported. This fire created the potential for a system switch, allowing the return of savanna or the invasion by savanna onto the now open landscape. This fire was extreme both at the landscape and transect scales. The causes and consequences of this extreme event discussed herein were investigated post-hoc.

We can start by eliminating some suggested causes of the fire. The argument of *Chromolaena* as a fuel source being the cause of the severity of the September 2008 fire can be dismissed since fire severity was found not to be related to proxies of past *Chromolaena* density (Figure 14). There was generally little *Chromolaena* at the time of the burn. In some densely invaded thickets, the fire did not burn and in areas where there was minimal *Chromolaena,* the thicket did burn. The amount and type of fuel present in a landscape influences the likelihood of a fire burning and contributes to the "switches" required for a fire to burn (Bradstock 2009). Grass can accumulate over successive years and carry-over from one fire season to the next. Thus if an area is not burnt for two or three years, there would be elevated levels of dead grass available to burn (Midgley *et al.* 2006, Archibald *et al.* 2009). Fire severity is linked to fire occurrence and grass biomass (Hennenberg *et al.* 2006). The area burnt in the September 2008 fire has been infrequently burnt over the period 2004 to 2008 (Appendix 6) and therefore fuel biomass has had the opportunity to accumulate. Due to the importance of combustible fuel load, fire probability and intensity may increase with annual precipitation in both savanna and forest (Hennenberg *et al.* 2006). For this reason rainfall records were analysed and it was found that in the two years preceding this event annual precipitation was high. Grass fuel is linearly related to rainfall (Higgins *et al.* 2000). Thus there were large grass fuel loads, including standing dead litter from previous growing seasons at the time of the fire.

This fire event was not related to the sequence of FDIs preceding the burn. Relative to the frequency of FDIs over a 50 year period, the 2008 FDI was not even close to the mean of FDIs and should thus have been a low risk fire year (Figure 9). This is very surprising considering the woody fuels that burnt. Not only was 2008 a low risk year relative to the long term record, but there was also no significant build-up of high risk days before the fire. The fire was not preceded by a long period of high risk FDIs and long periods of hot, dry conditions. This situation is very different from the kinds of extreme fires that occur in woody systems such as fynbos, since there is no long term build-up on annual or weekly time scales, and the fire was not linked to major droughts or climatic cycles such as El Ninõ. Therefore, such fires cannot be predicted for weeks/months in advance. FDIs from the long term record (1950-2008) proved to be rather uninformative and were not a good predictor of fire occurrence. The McArthur FDI, incorporating a measure of cumulative drought, failed to predict this fire event. This FDI emphasises a combination of extreme drought and weather prerequisite for crown fires in woody ecosystems. It is interesting, then, that the FDIs were therefore poor predictors of fire conditions that burnt forest and thicket in woody fueled systems in this savanna-forest mosaic. This suggests that current fire behaviour science may be inadequate for predicting movement of fire from grassy to woody fuels.

Why did the FDI not provide the warning needed? One problem is that FDI does not consider the amount and dryness of fuel. In the long term record for the park, high FDIs were recorded in drought years when there was no grass available to burn. Sufficient fuel is vital for the spread of fire in most types of vegetation (Bradstock 2009). There is a seasonal issue in that no curing models exist for South Africa so that high FDI may be predicted for a day in the middle of the rainy season when the grass is too green to burn. I used Balfour and Howison (2001) to determine the fire season in Hluhluwe in order to exclude days when fuel sources were too green to burn in the long term records.

A fundamental problem with FDIs is that they are a compound index. This means that the weather component(s) responsible for the fire are difficult to identify. The severity of a fire may depend more on certain threshold conditions being met. Rather than using a single value like an FDI to indicate fire risk, one can use the Bradstock (2009) concept of “switches” where a set of prerequisite conditions is necessary for a fire. The idea is that all “switches” need be activated simultaneously in order for a fire to occur. The switches that are hierarchical of conditional processes governing fire are: the amount of fuel, its flammability, fire weather and ignition (Archibald *et al.* 2009, Bradstock 2009). This is a useful concept to explain the multiple factors influencing fires and their severity. Indeed this is implicit of the "30, 30, 30" weather rule used by fire fighting crews. For a severe fire to occur, the "30, 30, 30" weather conditions need to be met (temperatures >30°C, wind speed >30 km/hr, and relative humidity <30%). In addition, there needs to be enough dry fuel and a source of ignition.

I attempted to utilise the "30, 30, 30" switch concept, since FDIs failed to explain how unusual this event was. The "30, 30, 30" concept was used to assess the frequency (or rarity) of extreme fire weather days and shows that this was a very rare event, as such conditions are only met two days every three years. Was this fire event one of those days when "30, 30, 30" conditions occurred? The wind factor seems to have a strong influence on fire as it is common to get temperatures exceeding 30°C. But, how unusual is it to get all three "30s" and any of the other switches on simultaneously? These "30, 30, 30" conditions occurred very quickly, developing overnight and only lasting a few hours, without any long term build-up. Why and how frequently did such conditions occur in the past and what is their predicted frequency in the future? Although "30, 30, 30" conditions are rare, what may be rarer is having an ignition source when the weather is "30, 30, 30", which we had for this fire.

The increase in bush encroachment in Hluhluwe over the past few decades suggests a lack of severe fires in the past (Watson and MacDonald 1983, Ward 2005, Wigley *et al.* 2009). Had fires such as those of September 2008 occurred more frequently, encroaching thickets would have been burnt and replaced by grasslands. Several severe fires that burnt into Hluhluwe thicket and/or forest patches have been observed in the last ten years. Has the climate changed so that extreme weather events favouring such fires are more frequent than in the past? Unfortunately Hluhluwe lacks full long term historical weather records, particularly wind data which is considered a critical factor. There is no record of wind, other than from the Seme weather station, for Hlulhuwe. The wind values used in the CSRI data set to calculate past FDIs were extracted from extrapolated values from an EU climate 'product' (S. Archibald, pers. comm.) and cannot be used with confidence for historical conditions.

It is also very difficult to predict the future frequencies of severe fire weather conditions; whether to better organize fire protection teams or to project global change impacts on future forest distribution. This is because the weather conditions associated with this burn are so ephemeral and develop so rapidly. Based upon my analyses of the causes of the fire and the damage caused, I would suggest that the best indicators of the potential for an extreme fire event are the "30, 30, 30" switches. While the composite indices, such as FDIs, do not appear to be effective predictors, they should be maintained to complement the "30, 30, 30" switch concept. The '30, 30, 30" weather rule/concept is simpler to apply, easy to remember, and has captured the extreme weather conditions of this fire. In order to use it better, a well-maintained weather station with a minimum of temperature, relative humidity, and wind is needed, to complement the existing long term rainfall record.

With the view of climate change bringing about longer dry seasons and widespread increases in forest flammability and subsequent large-scale fire events, it is likely that drastic compositional and structural alterations in vegetation will occur (e.g. Cochrane 2003). These changes may lead to ecosystem shifts (Barlow and Peres 2008). The onset of "30, 30, 30" conditions when a mild fire is already burning may be very important. The ability to predict fire regimes, and their consequences in the future could be improved by furthering our understanding of the dynamics of flammable connectivity and the relationships between fire switches. This extreme event transformed thicket and forest structure (Figure 16). Unexpectedly there was no significant relationship between fire intensity and the percentage mortality of trees of varying sizes. Indeed some trees had dead canopies without having been burnt at all. Wilting of leaves from the advancing fire front was apparently enough to kill canopies (of savanna trees) of the sensitive species with no direct flaming combustion. Previous studies found that post-fire tree mortality may be highest in both the smallest and largest size classes in tropical forests (Williams *et al.* 1999, Barlow *et al.* 2003 in Barlow and Peres 2008). Epicomic resprouting was found to be more common in larger trees and basal resprouting in smaller trees. Mortality was fairly evenly distributed over species, though some (*Euclea racemosa*) were more, and some (*Sideroxylon inerme*) less tolerant of fire damage. Barlow and Peres (2008) found that episodic wildfires can lead to dramatic alterations in both the composition and structure of forest, with cascading changes in composition after each additional fire event. The September 2008 fire resulted in just that, with phenomenal alteration in vegetation composition and structure, but not in density.

Many areas have sufficient grass to burn again and others do not. The high level of grass productivity in the first year since the fire indicates that there is sufficient fuel to burn annually in many thicket patches. Fires do not spread below a threshold of a certain biomass height of approximately 5 cm (Zululand Grass Project, unpublished data). However, some (30%) of transects sampled had very low grass cover but still burnt. This suggests that grass is not essential for fire to carry into thicket and forest patches in this case, contrary to findings of Hennenberg *et al.* (2006). Burning late in the dry season has the potential for returning thickets to grasslands. Since it appears that grass biomass was not a necessity of this severe fire, the conclusion of weather conditions coupled with the simultaneous necessary switches being activated, caused this event. Such events have the potential to be exploited but to try creating them would be lethal.

In summary, this event was not the result of *Chromolaena,* or of a long drought period. Such events are not predicted well by composite indices, such as FDIs, however they seem to be linked to threshold conditions/ switches. These conditions are rare and so such events are rare. The build up to such events are short and therefore there is little warning of their occurrence. These events are not linked to global climatic cycles, or multi decadal weather patterns, but appear rather to result from unusual weather combinations. In order to identify when such conditions occur, utilizing the "30, 30, 30" approach seems feasible. Though this is not the basis of the South African Fire Act, it seems logical and its ease of application carries merit. There may be a possibility of using synoptic charts in order to identify approaching fire weather conditions, but that is beyond the scope of this project. What was unusual about this fire was that it burnt from grasslands into non-flammable vegetation. The reason(s) for this may depend on the savanna-forest boundary and future study of these areas could be interesting.

Bush encroachment may not have occurred to the extent to which it has, if such events had occurred in the past. The frequency, causes and consequences of fires are changing. In the past few years South Africa has experienced fires destroying vast areas of nature, property, livestock and an increased number of human lives. This is a large issue for disaster managers, who have been following FDIs, perhaps not the ideal tool in Savanna systems. It would be very interesting to analyse other extreme events using the "30, 30, 30" approach, with the objective of testing its utility and its application in the field.

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REFERENCES

Archibald, S., Roy, D.P., van Wilgen, B.W., and Scholes, R.J. 2009. What limits fire? An examination of drivers of burnt area in Southern Africa. *Global Change Biology* **15**: 613-630, doi: 10.1111/j.1365-2486.2008.01751.x

Balfour, D.A. and Howison, O.E. 2001. Spatial and temporal variation in a mesic savanna fire regime: responses to variation in annual rainfall. *African Journal of Range and Forage Science* **19**: 43-51

Barlow, J., Peres, C.A., Lagan, B.O., and Haugaasen, T. 2003. Large tree mortality and the decline of forest biomass following Amazonian wildfires. *Ecology Letters* **6**: 6-8. doi: 10.1046/j.1461-0248.2003.00394.x

Barlow, J. and Peres, C.A. 2008. Fire-mediated dieback and compositional cascade in an Amazonian forest. *Philosophical Transactions of the Royal Society* **363**: 1787-1794

Bond, W.J. and Midgley, G.F. 2000. A proposed CO_2-controlled mechanisms of woody plant invasion in grasslands and savannas. *Global Change Biology* **6**: 865–869.

Bond, W.J., Midgley, G.F. and Woodward, F.I. 2003. The importance of low atmospheric CO_2 and fire in promoting the spread of grasslands and savannas. *Global Change Biology* **9**: 973-982

Bradstock, R.A. 2009. A Biogeographical model of fire regimes in Australia: contemporary and future implications. *Global Ecology and Biogeography* (In Press)

Britz, M.L. and Ward, D. 2007. Dynamics of woody vegetation in a semi-arid savanna, with a focus on bush encroachment. *Africa Journal of Range and Forage Science* **24**: 131-140

Catana, A.J. 1963. The Wandering Quarter Method of estimating population density. *Ecology* **44**(2):349-360

Cochrane, M.A. 2003. Fire science for rainforests. *Nature* **421**: 913-919

Greyling, T. and Huntley, B.J. 1984. Directory of southern African conservation areas. *South African National Scientific Programmes Report* **98**: 1-311.

Hennenberg, K.J., Fischer, F., Kouadio, K., Goetze, D., Orthmann, B., Linsenmair, K.E., Jeltsch, F., and Porembski, S. 2006. Phytomass and fire occurrence along forest-savanna transects in the Comoé National Park, Ivory Coast. *Journal of Tropical Ecology* **22**: 303-311

Higgins, S.I., Bond, W.J., and Trollope, W.S.W. 2000. Fire, resprouting and variability: a recipe for grass-tree coexistence in savanna. *Journal of Ecology* **88**: 213-229

Higgins, S.I., Shackleton, C.M., and Robinson, R. 1999. Changes in woody community structure and composition under contrasting landuse systems in a semi-arid savanna, South Africa. *Journal of Biogeography* **26**: 619-627

King, N.D. 1987. Vegetation dynamics in Hluhluwe game reserve, Natal with emphasis on the bush-encroachment problem. Msc. Thesis, University of Natal.

Kraaij, T. and Ward, D. 2006. Effects of rain, nitrogen, fire and grazing on tree recruitment and early survival in bush-encroached savanna, South Africa. *Plant Ecology* **186:** 235-246

Landsat 7 raw reflectance data from USGS. Available from: http://landsat.usgs.gov , searched August 2009

McArthur, A.G. 1966. Weather and grassland fire behaviour. Forestry and Timber Bureau, Australia, Leaflet No.100, 23pp.

Midgley, J.J., Balfour, D., and Govender, N. 2006. Is carry-over of grass biomass between years important in determining savanna fire regimes? *African Journal of Range and Forage Science* **23(1)**: 81-83

Modis Burnt Area and Active Fire data products. Available from: http://modis.gsfc.nasa.gov , searched August 2009

Moreno, J.M. and Oechel, W.C. 1989. A simple method for estimating fire intensity after a burn in California chaparral. *Acta Oecologica* **10**(1): 57-68

Moritz-Zimmermann *et al.* 2002. Available from: http://www.nt.gov.au/nreta/natres/natveg/seminar/pdf/veg_workshop_fieldbook_as.pdf, searched on 28 September 2009.

Mucina, L.M. and Rutherford, M.C. 2006. The vegetation of South Africa, Lesotho and Swaziland. SANBI, Pretoria

Pooley, E. 1993. The Complete field guide to trees of Natal, Zululand and Transkei.

Roberts, G., Wooster, M.J., Perry, G.L.W., Drake, N., Rebelo, L.M., and Dipotso, F. 2005. Retrieval of biomass combustion rates and totals from fire radiative power observations: Applications to southern Africa using geostationary SEVERI imagery. *Journal of Geophysical Research* **110**, D21111, doi:10.1029/2005JD006018

Roy, D.P., Jin, Y., Lewis, P.E., and Justice, C.O. 2005. Prototyping a global algorithm for systematic fire-affected area mapping using MODIS time series data. *Remote Sensing of Environment* **97**: 137-162

Skowno, A.L, Midgley, J.J., Bond, W.J., and Balfour, D. 1999. Secondary succession in *Acacia nilotica* (L.) savanna in the Hluhluwe Game Reserve, South Africa. *Plant Ecology* **145**: 1-9

South African Weather Service (SAWS). Available from: http://dev2.weathersa.co.za , searched June 2009

Trollope, W.S.W. Fire Danger Rating System for Controlled Burning. Department Livestock and Pasture Science, University Fort Hare, Alice, South Africa (unpublished)

van Wilgen, B.W. and Everson, T.M. 1990. Report on a trial of two fire danger rating systems. CSIR Division of Forest Science and Technology, Pretoria.

van Wilgen B.W., Everson, C., Tolhurst, K., Willis, C., Fleming, G., Pero, L., and D'Abreton, P. 2000. National Fire Danger Rating System. Unpublished report, Environmentek, CSIR, Pretoria.

Waldram, M.S., Bond, W.J., and Stock, W.D. 2008. Ecological Engineering by a Mega-Grazer: White Rhino Impacts on a South African Savanna. *Ecosystems* **11:** 101-112

Ward, D. 2005. Do we understand the causes of bush encroachment in African savannas? *African Journal of Range and Forage Science* **22**(2): 101-105

Watson, H.K. and Macdonald, I.A.W. 1983. Vegetation changes in the Hluhluwe-Umfolozi Game Reserve Complex from 1937 to 1975. *Bothalia* **14**: 265-269

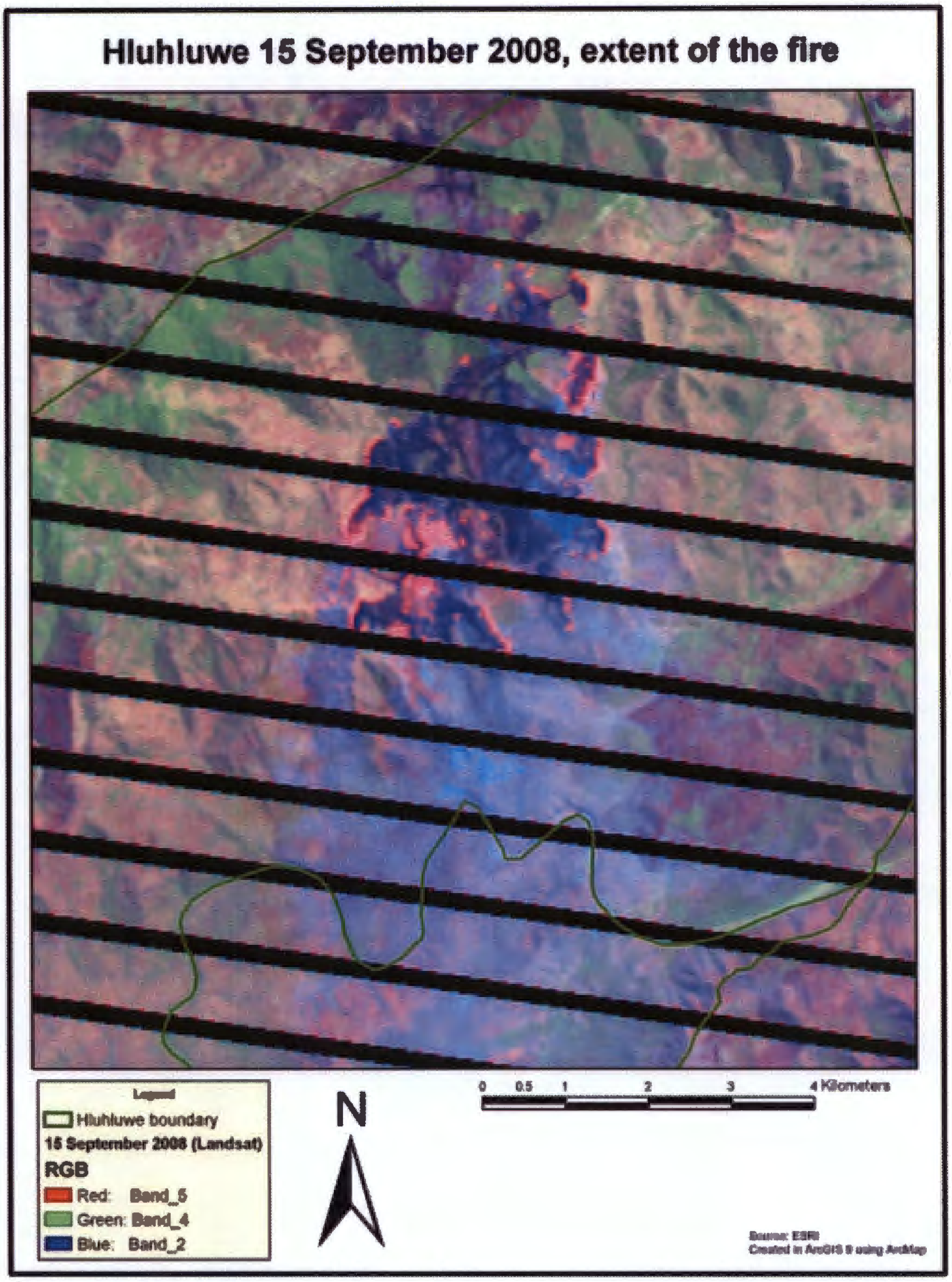
Whateley, A.J. and Porter, R.N. 1983. The woody vegetation communities of the Hluhluwe-Corridor-Umfolozi Game Reserve Complex. *Bothalia* **14**: 745-758.

Whately, A.J. and Porter, R.N. 1975. Vegetation Map of HUP. Unpublished NPB Report, Hluhluwe Research Centre

Wigley, B.J., Bond, W.J., and Hoffman, M.T. 2009. Thicket expansion in a South African savanna under divergent land use: local vs. global drivers? *Global Change Biology*, doi: 10.1111/j.1365-2486.2009.02030.x

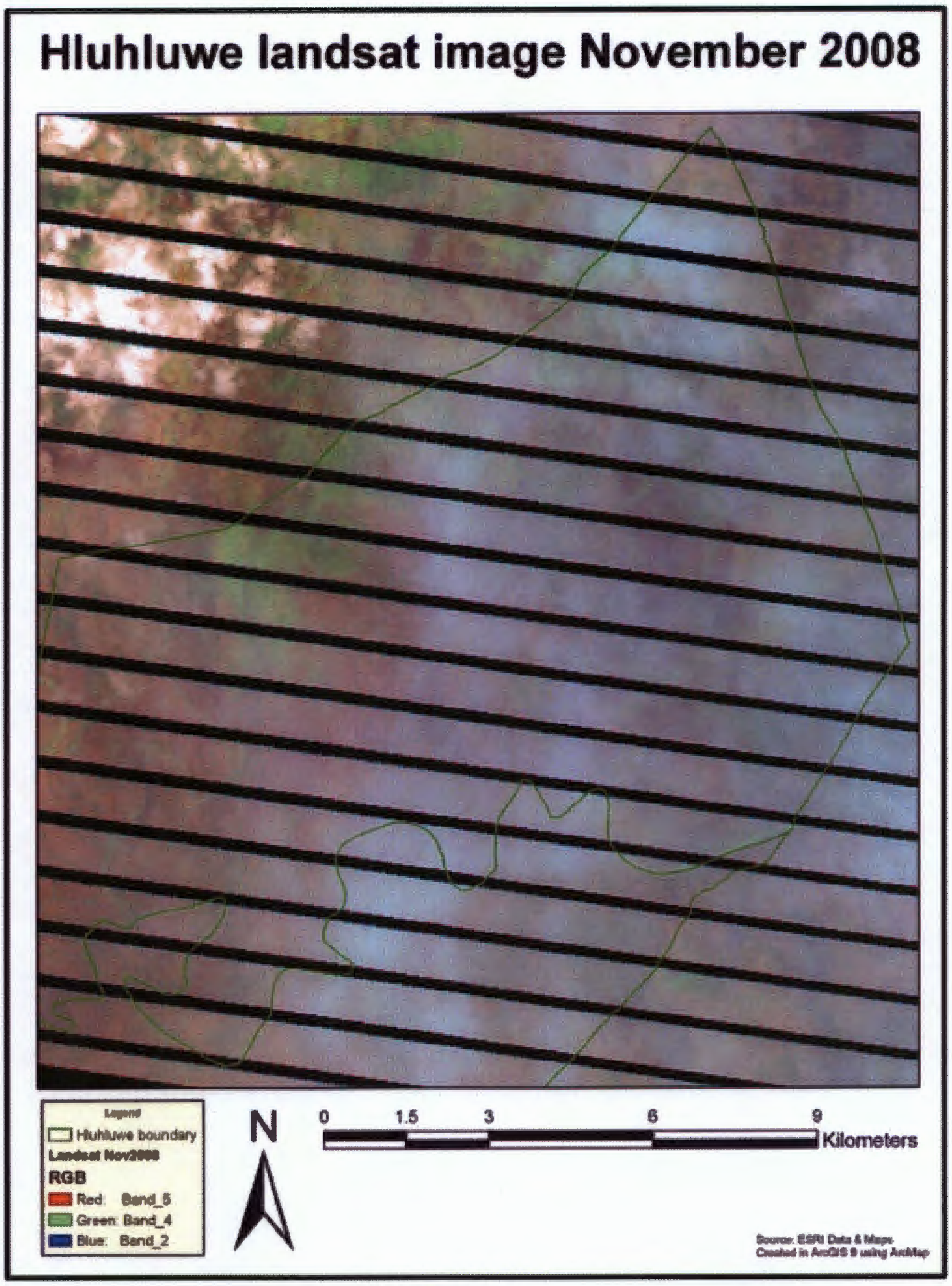
Williams, R.J., Cook, G.D., Gill, A.M., and Moore, P.H.R. 1999. Fire regime, fire intensity and tree survival in a tropical savanna in northern Australia. *Australian Journal of Ecology* **24:** 50-59

APPENDIX 1



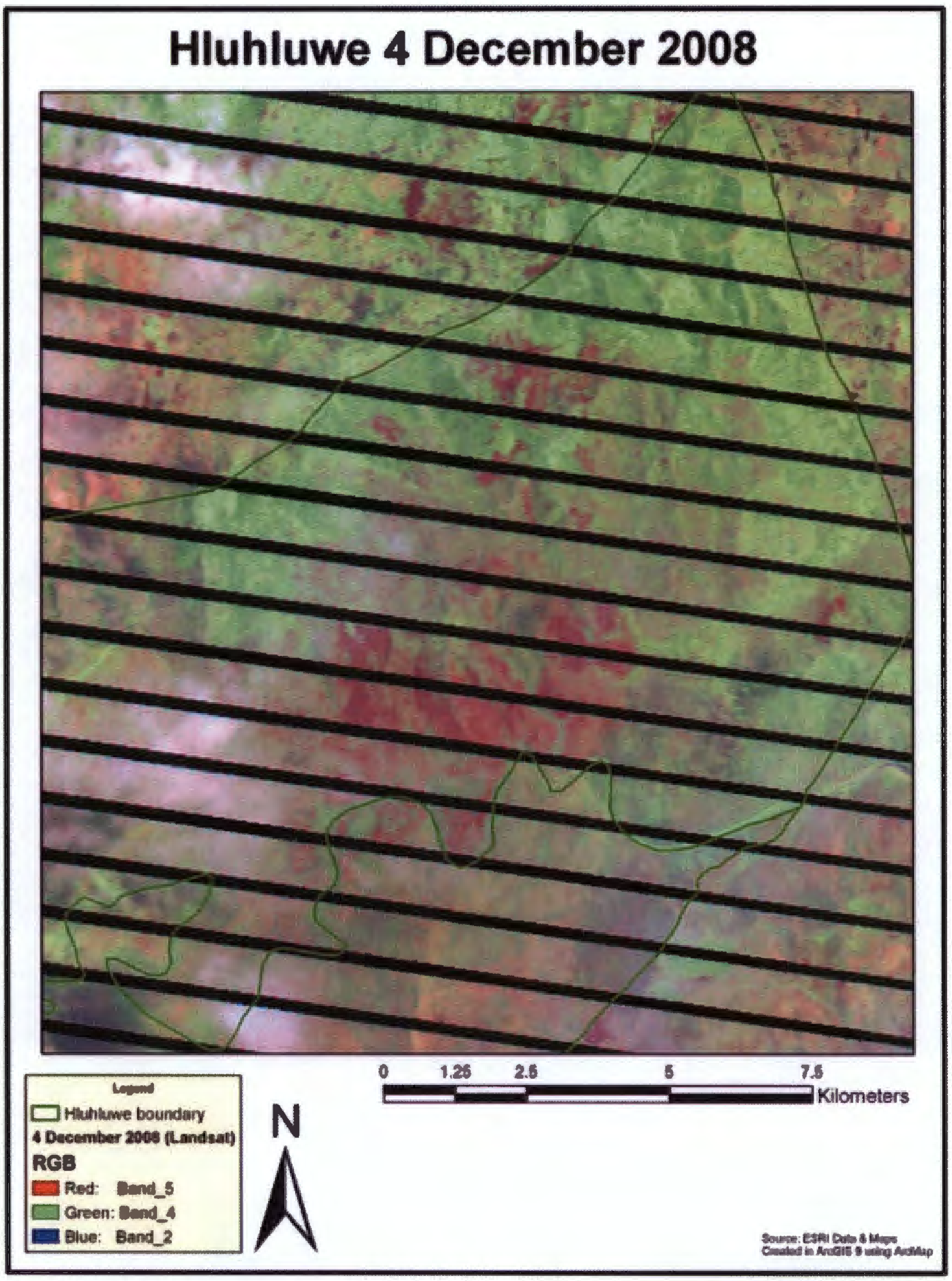
The actively burning fire on the morning of 15 September 2008 can be seen above (red). The green lines indicate the park boundaries and the black lines are a result of data errors on the satellite sensor. (Landsat 7 from USGS)

APPENDIX 2



Above is the Landsat image taken of Hluhluwe Game Reserve in November 2008. This image is obscured by cloud cover. The green lines indicate the park boundaries and the black lines are a result of data errors on the satellite sensor. (Landsat 7 from USGS)

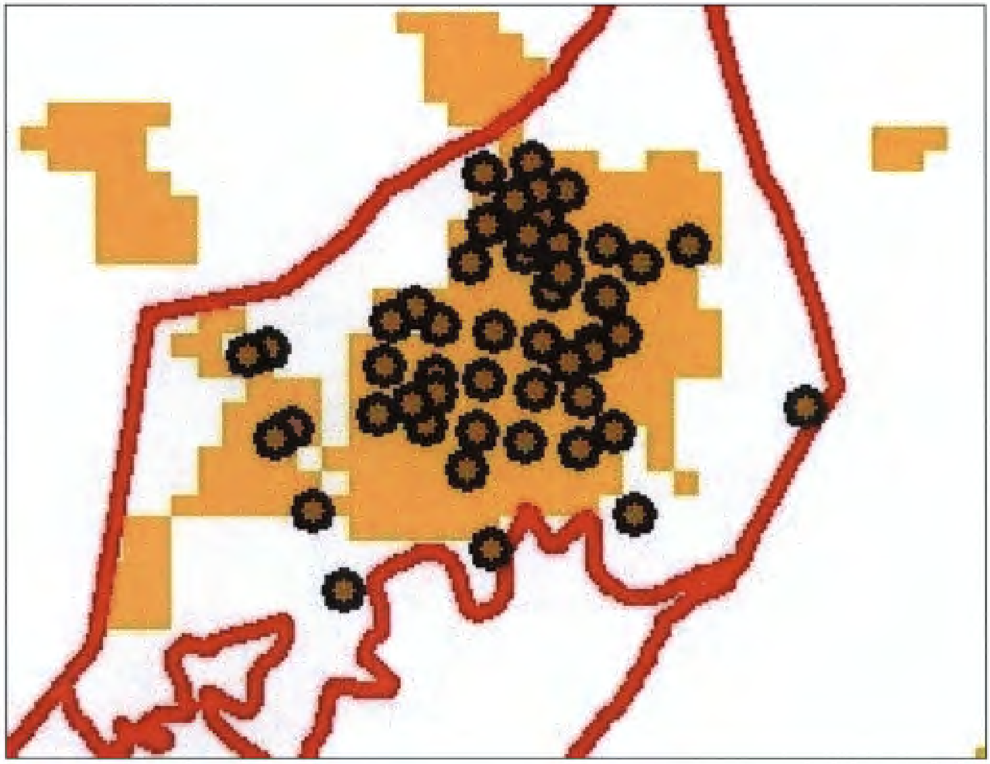
APPENDIX 3



Source: ESRI Data & Maps
Created in ArcGIS 9 using ArcMap

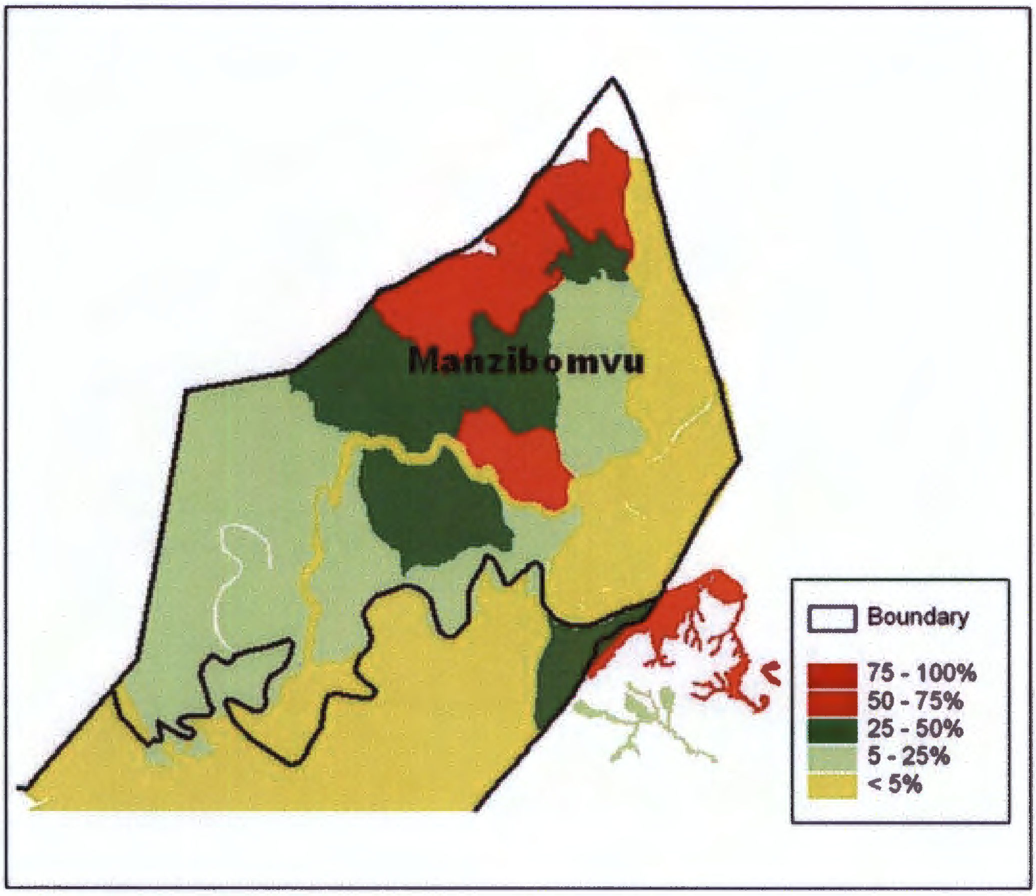
Above is the Landsat image taken of Hluhluwe Game Reserve 4 December 2008. The green lines indicate the park boundaries and the black lines are a result of data errors on the satellite sensor. (Landsat 7 from USGS)

APPENDIX 4



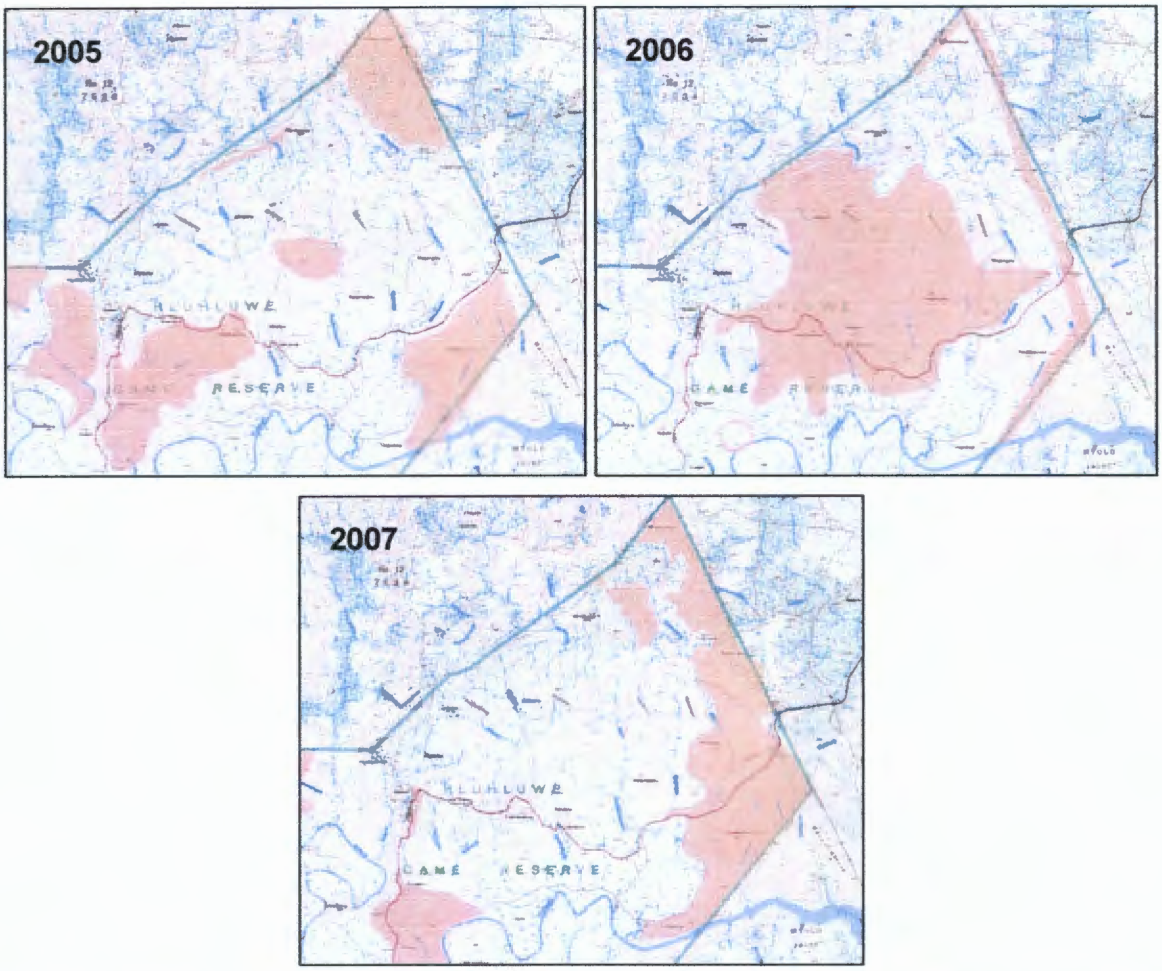
MODIS burnt area product of the September 2008 fire in Hluhluwe Game Reserve. The red lines indicate the Hluhluwe-iMfolozi Park boundaries. The dots represent pixels where fire was actively burning at the time the satellite went over and the shaded (orange) areas are all pixels which appear as burn scars in the satellite image.

APPENDIX 5



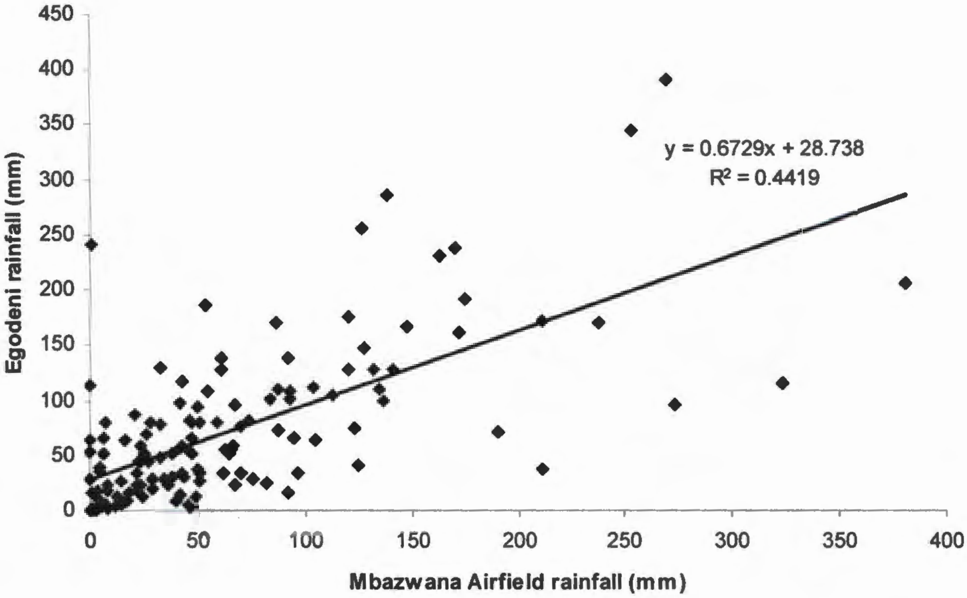
Map of the distribution of *Chromolaena ordata* in 2008 in Hluhluwe Game Reserve, provided by the Invasive Alien Species Programme. (Supplied by H. Pretorius 2009)

APPENDIX 6



Burn maps of Hluhluwe Game Reserve over the period 2005 to 2007. Green lines represent the park boundaries and the red shaded areas, the burnt areas as defined by the Hluhluwe GIS unit (Supplied by G. Clinning 2009)

APPENDIX 7



Correlation between the monthly rainfall records from weather stations located at Egodeni (28°4'15''S 32°2'25.7''E) and at Mbazwana Airfield (27°28'37.2''S 32°35'52.8''E) over the period 1997 to 2006