THE UNIVERSITY OF CAPE TOWN

Effects of repeated fire on the Savanna/Forest Boundary

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Abstract

Savanna and forest/thicket can exit as alternate stable states, among others, determined by fire ecology feedbacks. Bush encroachment has become an ever increasing trend converting grassland and savanna biomes to forest/thicket. A severe firestorm occurred in the Hluhluwe-iMfolozi Game Reserve in north-eastern South Africa in September 2008. The fire penetrated closed thicket areas and opened up the landscape. The main aim of this study was to investigate whether repeated fire, following such an extreme fire event, could trigger a biome or regime shift; in this case from forest/thicket to savanna. Fire spread is determined by grassy fuel loads, primarily grass biomass in these ecosystems, and the fire weather at the time of the fire. Grass biomass was found to have significantly accumulated ($p=0.0002$) in the thicket areas in just three growing seasons since 2008, which allowed fires to burn the area again in 2012. In the 2012 fires, fire intensity, measured by char height on woody stems increased in relation to the increase in grass biomass up to a point after which increasing grass biomass had no effect. The 2012 fires were able to penetrate areas opened up by the 2008 firestorm despite high canopy cover created by tree resprouting. Tree mortality was cumulative with repeated burning (21% mortality post 2008 increasing to 47% mortality in 2012). This was linked to the vigour of post 2008 resprouting with much higher mortality of trees in 2012 that had few (<4) resprouting stems. Thus this study indicates that, a fire regime of sufficient frequency and intensities could potentially cause a vegetation state shift from forest/thicket to savanna. Therefore, this may provide management options for wildlife parks and protected areas.

Introduction

Savannas cover about 20% of the earth's vegetated land surface and support a large proportion of the world's human population and a majority of its rangeland and livestock (Bond and Midgley, 2000, Sankaran et al, 2004). Mesic savannas can exist where climate, soils, and topography suggest forest should dominate (Bond, 2008). However, the increased density of woody plants in grassy ecosytems (commonly referred to as bush encroachment in South Africa) has become an ever increasing phenomenon within grassland and savanna biomes over the last few decades. There are many hypotheses as to the possible causes of this bush encroachment phenomenon, including; increasing atmospheric CO_2 concentration (Bond and Midgley, 2000), reduced fire frequencies and/or intensities (Higgins *et al.,* 2000; Briggs *et al.*, 2005), increased rainfall (Sankaran *et al.*, 2005) and a lowering of the water table (King, 1987). Vegetation in the Hluhluwe Game Reserve (HGR) in South Africa is characterised by a mosaic of savannas and forests (and thickets, a drier form of closed canopy woody plant vegetation). HGR is among many areas that have experienced extensive woody thickening over the last century, resulting in a vegetation state conversion from savannas to closed forests/thickets. Bush encroachment has diminished the areas of open grassy ecosystems and fragmented the remnants. This increase in woody plant density has consequences for climate, land-use and conservation at an array of different spatial scales (Wigley *et al.*, 2010).

Savannas and forests/thickets exist as alternative stable ecosystem states, where both states can exist under the same set of environmental conditions (Bond and Parr, 2010). Rapid shifts ('regime shifts') can occur between states (Scheffer and Carpenter, 2003) through disturbance events such as fire. The idea is that positive feedbacks promote the necessary environmental conditions to maintain one ecosystem state but that these conditions are hostile to the alternative ecosystem state. In this context, alternative stable vegetation states characterised by sharp boundaries can co-exist to create landscape scale mosaics (Bond and Parr, 2010).

The savanna-forest boundary can be abrupt, with savanna changing to forest over distances of a few meters (Hoffman *et al.*, 2003). Climate, fire, hydrology, herbivory, as well as soil nutrients, texture and depth are all important in determining the location of the savanna/forest boundary (Furley, 1992; Hopkins, 1992; Tinley, 1982). Of these factors, fire is perhaps the most well-known determinant of savanna–forest boundaries worldwide and is the most likely factor that would cause an observable change within the time-frame of human observation (Hoffman *et al.* 2009, 2003). Fire helps maintain a dynamic balance between savanna and forest (Hopkins, 1992).

Savanna vegetation is very flammable, and may burn at intervals of 1 to 3 years, whereas forest is typically less flammable due to a dense canopy that excludes grasses and to changes in microclimate (Hennenberg *et al.*, 2006; Hoffmann *et al*, 2012). Therefore, most savanna fires do not penetrate far into forest/thicket as fire spread is linked to grassy fuel loads (Hennenberg *et al.*, 2006), thereby sharpening the savanna-forest boundary (Hoffman, 2003). In September 2008, a "fire storm" penetrated the closed forest/thicket of Hluhluwe-iMfolozi Game Reserve in north-eastern South Africa and was followed by further fires in 2012. These disturbance events may have triggered a process where the thicket vegetation state could revert back to a savanna vegetation state – and thereby provides a rare opportunity to investigate whether repeated fire can be used as a tool to promote conversion of forest-invaded areas to savanna or alternatively how fire management can be best used to facilitate forest recovery and reduce conversion to grassland.

The objective of the study was to explore fire regime management approaches to controlling bush encroachment. If rare disturbance events such as the 2008 firestorm in conjunction with follow up fires do provide opportunities for re-claiming savannas that have switched to thicket, then this could be beneficial in developing management options for wildlife parks and protected areas. Generally, savannas are a more desired ecosystem state, as they enhance the aesthetic wildlife viewing experience for tourists. The desired effect would be to achieve a landscape scale forest/thicket/savanna mosaic where savannas predominate, rather than obliterating one or the other vegetation state completely. The livestock farming sector may also reap the benefits, if methods are developed for switching currently un-economical and un-useable thicket to productive grasslands. Conversely, the study may also provide information on how best to restore burnt forest where forest conservation is the key management objective. There is concern that the Amazon forests, which have burnt during severe El Nino years, may be replaced by savannas (Barlow *et al.*, 2003). Forests are important regulators of atmospheric CO_2 (Barlow *et al.*, 2003), so this study could also have implications for climate change more generally.

The study investigated whether grasses were able to invade the forest/thicket areas that were opened up by the severe 2008 firestorm, thus providing a fuel load for future fires and lead to a sustainable reversion to savanna. Critical factors are the rate of grass colonisation of burnt forest/thicket areas and the rate at which flammable fuel loads accumulate. It is hypothesised that there would be a decline in grass biomass with an increase in shade (canopy cover of trees resprouting after the 2008 burn) and further that, sites that had higher grassy fuel loads would have greater fire spread and burn more intensely.

Panicum maximum, and related grass species which dominate recovering thicket, remain green until late in the dry season. In contrast, grasses such as *Themeda triandra* which dominate open savannas dry out early in the dry season and burn much more readily. Therefore, the flammability properties of these two grasses were explored; as it was hypothesised that *P. maximum* would not burn as readily in an early season fire. Therefore, the effects of an early season fire (that occurred on 11 June 2012) versus a late season fire (that occurred on 11 August 2012) was investigated. It was expected that a late season burn would have higher fire intensity than an early season burn, rendering a more complete burn. Bush encroachment may be controlled more effectively by late season burns where fully cured grass fuels allow fire to spread more readily into burnt thicket areas, thus facilitating restoration of savannas and their characteristic, flammable grasses. The assumption, here, is that dry, late season burns spread more readily and more intensely than early season burns and that higher intensity burns would cause greater mortality of resprouting forest species. This would slow recovery rates of forest/thicket species and promote conversion to a savanna. Thus it was hypothesised that a more intense fire would yield higher tree mortality than a low intensity fire.

Study area

The study was conducted in Hluhluwe iMfolozi Game Reserve (900 km^2; 288000 to 288260 S; 318430 to 328090 E), located in the Province of KwaZulu Natal, South Africa. The reserve is divided into Hluhluwe in the north, iMfolozi in the south connected by a corridor of state owned land in the middle. The reserve is characterised by hilly topography up to 540m elevation in the Hluhluwe Game Reserve area falling into broader river valleys at 40 m elevation in the iMfolozi Game Reserve area (Staver *et al.*, 2009). Rainfall is closely linked to elevation within the park (Balfour and Howison, 2001), producing a rainfall gradient from ~1000mm per annum in the higher elevations in Hluhluwe to ~600mm per annum in the lower elevations in iMfolozi (Staver *et al.*, 2009), with the rainy season peaking between October and March. The region experiences hot, wet summers and cool, dry winters; mean minimum temperature is 13°C and the mean maximum temperature is 35°C (Balfour and Howison, 2001).

Most of the reserve is covered by *Acacia* savannas, *Euclea* thickets, and patches of *Celtis-Harpephyllum* forests (Whateley and Porter 1983). Much 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). The dominant vegetation is *Acacia* savanna forming mosaics with forest and *Euclea* thicket in the northern end of the Hluhluwe Game Reserve. Fire is a major characteristic of the savanna landscape in Hluhluwe-iMfolozi, but the fire regime varies substantially within the park (Balfour and Howison, 2001; Staver *et al.*, 2009) and these savannas will carry fire if sufficient fuel is left in the dry season.

The study sites were restricted to the northern region of Hluhluwe (figure 1). Twenty four sites were selected. These sites were the same sites used by Catherine Browne (Browne, 2009) in her investigation of the September 2008 firestorm that had dramatic effects on the vegetation in the reserve.

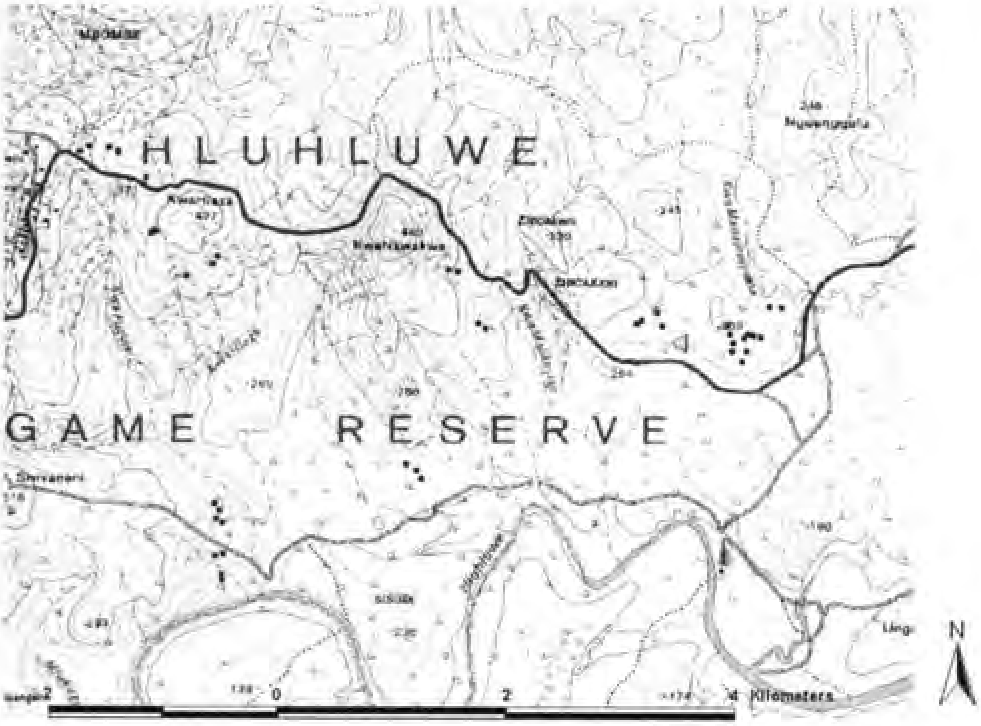

Figure 1: Topographical map illustrating the locations of the sites (red dots) sampled (Browne, 2009)

Methods

GPS coordinates were used to re-locate the 24 sites recorded after the 2008 firestorm (Browne, 2009) and field data was collected both prior to and after the 2012 fire season in HGR.

Pre-2012 fire measurements:

Straight line transects were setup at each site using a 100m tape measure. In order to determine whether there had been colonization and an increase in grass biomass (fuel load) in the thicket areas previously burnt in the 2008 firestorm, 20 evenly spaced Disc Pasture Meter (DPM) readings (Bransby & Tainton, 1977) were taken every 4 paces, thus each transect was approximately 80 meters long. At each DPM reading location, the dominant grass species were identified in order to gauge the grass species composition at each site. Tree canopy cover was then estimated for the site. Canopy cover estimates were included if a tree canopy directly covered a 20cm belt centred on the tape measure (10cm on each side of the tape) and if the tree was above 1.5m in height. Trees greater than this height were assumed to be above the grass layer, thus shading out the grass below. Canopy cover was then summed up and recorded as a total percentage tree cover for that site. The tree species were also identified at each site, using Pooley (1993).

Post-2012 fire measurements:

There were two fires that occurred in 2012, at different times of the fire "season". The first fire, which occurred on 11 June 2012, will be referred to as the "Early" fire and the second fire, which occurred 2 months later on 11 August 2012, will be referred to as the "Late" fire. Each fire burnt through half of the sites; therefore, there were 12 sites that were burnt by the Early fire and 12 sites that were burnt by the Late fire. These fires were most obviously separated by the main road that extends through the park from the main gate to Hilltop. Post-fire measurements were made one week after the Late fire. The spread of these two fires were mapped out onto a topographical map of the areas an aerial photograph and verified through visual ground-truth mapping (figure 2).

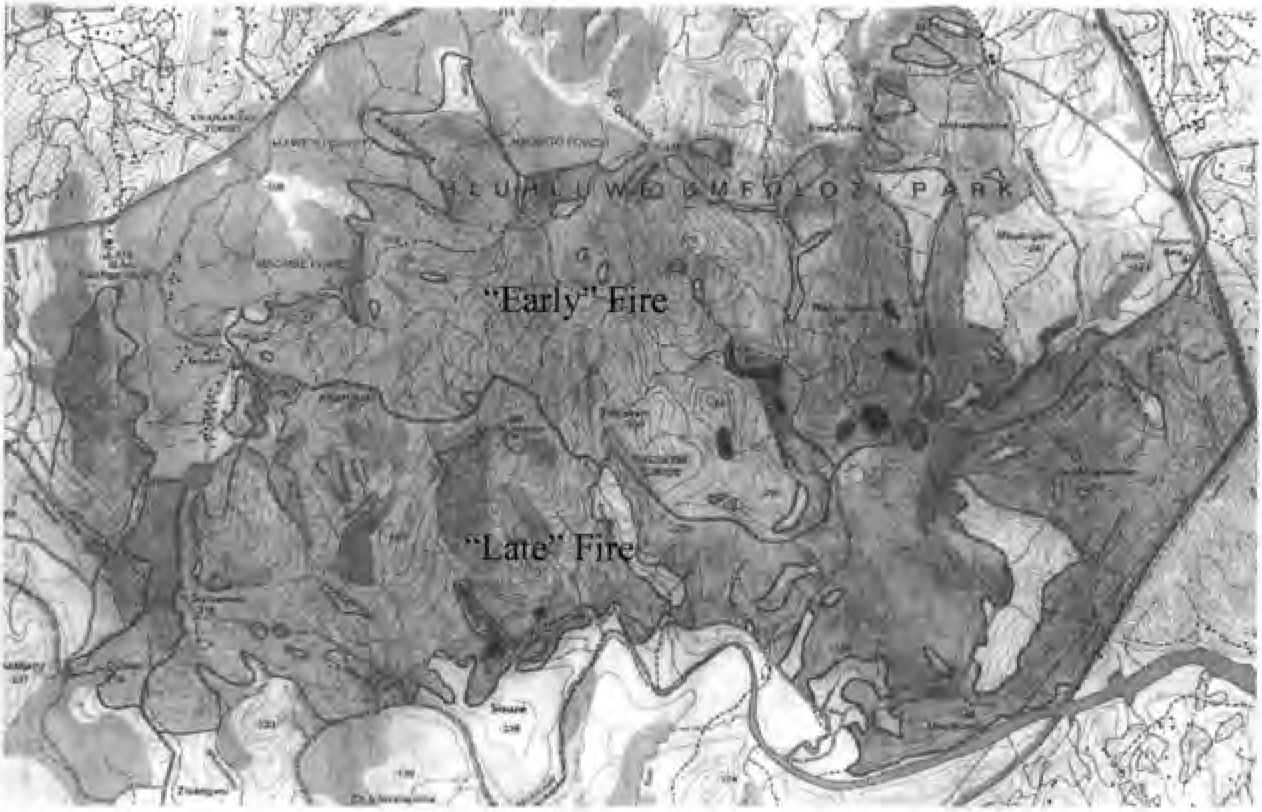

Figure 2: Topographical map illustrating the extent of both the Early and Late fires in 2012 (shaded in grey). The thick lines (dark green) indicate the areas where fire did not penetrate in 2012.

Early fire sites:

At each Early fire site, char height was measured (the height above ground of blackened bark or leaves) as a post-hoc estimate for fire intensity (Williams *et al.*, 2003) of 12 trees. Char height was used as opposed to scorch height (the height above ground of dead, scorched leaves), because trees were generally shorter than 5m, thus char height would render a better ex-post proxy indicator of fire intensity (Williams *et al.*, 2003). Char height was recorded for two trees at the start of the transect line and for trees within two meters of the transect line approximately 10 meters intervals thereafter until char height on 12 trees were measured at the site. The area of un-burnt patches (if any) was estimated within 10m of the transect line on each side. Since the Early fire occurred in July, there was enough time for the trees to have responded to the fire through resprouting sufficiently to be measurable at these sites during the post fire data collection phase, Resprouting response was sampled for trees that were >4m tall at each site along the transect using the wandering quarter method (Catana, 1963), where the next >4m tall tree was selected within 90° of that tree. A total of 25 trees were sampled at each site and were identified using Coates- Palgrave (2002). The resprouting responses for each tree was recorded as: Basal resprouting (B), Canopy resprouting (C), both (B&C) or none (trees assumed to have died). The Diameter at Breast Height (DBH) was also measured for each tree and the numbers of stems were counted.

Late fire sites:

Char height was measured at Late fire sites site and the unburnt areas (if any) were estimated, using the same methods that were used at sites in the Early fire. However, post fire measurements at these sites took place only one week after the late fire occurred, therefore, not enough time had passed for trees to exhibit a resprouting response to the fire, and therefore, resprouting responses to fire could not be measured.

Fuel characteristics:

Themeda triandra and *Panicum maximum* are the two main fuels that were considered. Generally, *T. triandra* is the dominant grass in these HGR savannas and *P. maximum* was the dominant grass present in the 24 thicket sites. The flammability of the two grasses differs, where *T. triandra* is more flammable than *P. maximum*. The different fuel properties of the dominant grasses could influence fire management where under the same weather conditions fires that burn readily in savannas, may be extinguished in recovering thicket largely because of the high moisture content of the *Panicum* *maximum*-dominated grass fuels, among other reasons (e.g. under canopy humidity, wind speed, fuel continuity and temperature variances). Therefore the fuel characteristics for *T. triandra* and *P. maximum* were compared. Ten samples of each species were collected from the fire exclusion plots at Gontshi look-out in Hluhluwe. This was done by taking a DPM reading for a sample, then all the grass that was underneath the DPM was taken as a sample. This was done for 10 samples of *T. triandra* and 10 samples of *P. maximum*. The wet weights of each sample were recorded and then each sample was placed into an oven at 80°C for 24 hours. The samples were then re-weighed and the dry weights were then recorded. This was then used to calculate the moisture content of each sample:

$$moisture\ content\ \% = \frac{the\ difference\ between\ wet\ weight\ and\ dry\ weight}{wet\ weight}\ x\ 100$$

Bulk density of the two grass species was then calculated. This was done by first acquiring the volume of the fuel as measured in the field and then dividing the volume by the wet weight:

$$Volume\ of\ fuel\ cm^3 = \pi r^2\ X\ DPM\ height$$

$$Bulk\ Density\ g.cm^{-3} = \frac{wet\ weight}{volume\ of\ fuel}$$

The specific gravities of the two grass species were obtained in order to be used to calculate the packing ratios of the *T. triandra* and *P. maximum*. A graduated cylinder was filled with water until the water level reached 1L and weighed. Once the weight was recorded, the cylinder was emptied. A sample of *T. triandra* was packed tightly into the graduated cylinder and then weighed on a scale. Once the weight was recorded, the scale was zeroed; water was then poured into the cylinder with grass until the grass was completely submerged and the weight was recorded. The grass was tightly packed into the cylinder in order to keep the grass firmly in the cylinder, so that the water could completely submerge the grass without it floating. This was done for all 10 samples of *T. triandra* and *P. maximum*. The weight of the water with grass in it was subtracted from the weight of just the water in order to acquire the specific volume of the grass. The specific gravity of the grass samples was then calculated:

$$Specific\ gravity\ g.mL = \frac{grass\ weight}{specific\ volume\ of\ the\ grass}$$

Formulas for specific gravity, packing ratios and bulk density were acquired from Van Wilgen *et al* (1990).

Fire Model:

The BehavePlus5 model (Hoffman *et al.*, 2012) was used to simulate fire behaviour for a typical savanna in Hluhluwe-iMfolozi Game Reserve, in order to gauge how fire behaviour changes under different fire weather conditions, using moisture scenarios as a proxy for fire season. This model is based on Rothermel's (1972) fire spread equations, and predicts fire behaviour for a user-defined set of fuel and environmental conditions (Hoffman *et al.*, 2012). The model was parameterized to simulate four moisture scenarios as a proxy for different periods within the fire season under the same weather conditions. These include: fully cured fuel to represent late in the dry season and fully green fuel as a representative of early in the dry season when the fuels are not yet dried out and contain high moisture contents. The 2/3 cured fuel and 1/3 cured fuel represent the periods between the fully cured and fully green fuels. The model simulations required information on fuel loads of living and dead grass, which were obtained from measured values by van Wilgen & Wills (1988) in Hluhluwe-iMfolozi Game Reserve. The model parameters used for each simulation are presented in supplemental information (Appendix 1).

Data Analyses:

The data were analysed using Microsoft Excel 2010 and Statistica 10.

A Wilcoxon's paired sample test was used to test whether differences between grass biomass in 2009 and 2012 were statistically significant. A least-squares regression was used to explore the relationships between grass fuel loads in 2012 and 2009, the average char heights of the Early and Late fires and mean char heights and the area unburnt. A Student's t-test was used to assess statistical differences in the fuel characteristics of *P. maximum* and *T. triandra*, i.e. packing ratios, bulk densities and percentage moisture content, to test if the difference between the average char heights of the Early and Late fires that occurred in 2012 were statistically significant and to test if the differences between the areas unburned in the Early fire and the Late fire were statistically significant. A Chi-squared test of independence was used to test is the difference between the classes DPM counts between 2009 and 2012 were significant and also to whether the mortality trees with different stems abundances were significantly different from the overall average mortality of the trees.

Results

Vegetation characteristics before fires:

After one growing season in 2009, grasses were present in the thicket areas that were burnt in the 2008 firestorm, although there were more areas that did not have grasses present in 2009 (figure 3). By 2012, grasses had spread into all the sites more extensively and were able to colonize areas that had no grass (figure 3). Additionally figure 4 indicates that there was a significant increase in fuel load in the thicket areas after two growing seasons (from 2009 to 2012). There was variation in the amount of fuel present at each site; grasses that experienced more shade were not able to accumulate as much biomass as grasses that grew in areas that were less shaded. Canopy cover had an effect on the amount of grass that was able to grow at each site. Figure 5 demonstrates this effect, as canopy cover increased; there was a decline in the amount of fuel present at each site.

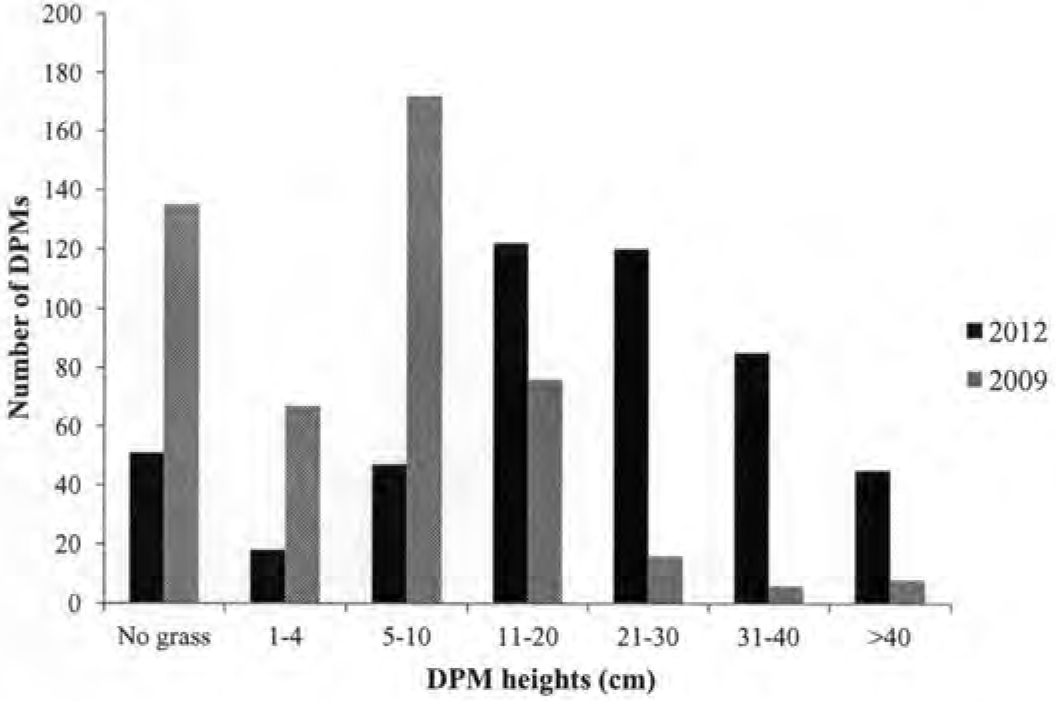

Figure 3: Number of DPM counts at different heights in all sites before 2012 fires (X^2=2094.1, DF=6, p<0.001)

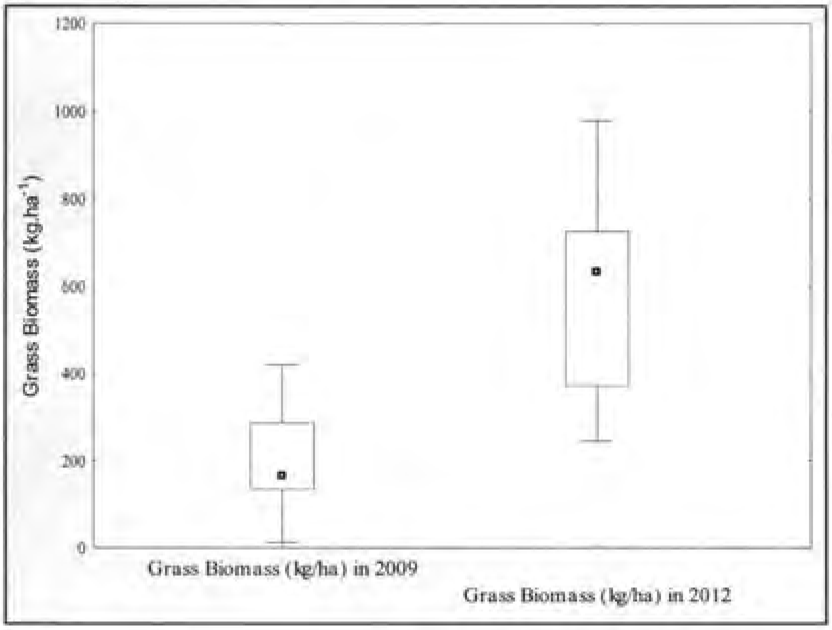

Figure 4: Comparison of grass biomass (kg.ha^{-1}) in sites in 2009 and in 2012 prior to subsequent fires. The box represents the median, 1st quartile and 3rd quartile. The whiskers represent the minimum and maximum values. (N=24, Z=4.23, p=0.00002)

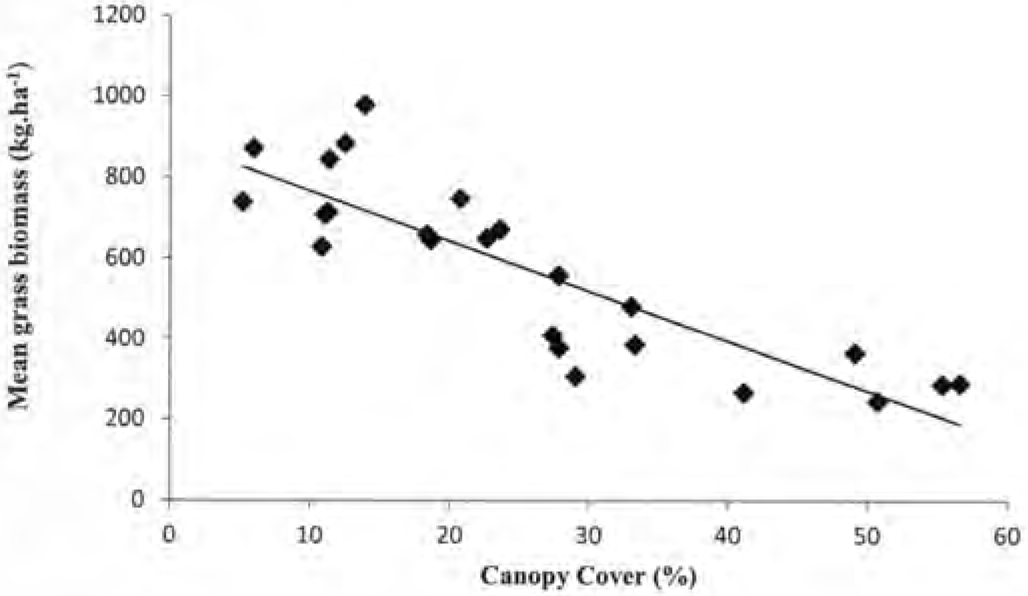

Figure 5: Relationship between canopy cover (%) of trees that resprouted after the 2008 fire and the average grass biomass (kg/ha) at each site in 2012, prior to subsequent fires (r^2=0.74, p<0.001). The solid line is described by the equation: $y = 12.393x + 889.81$

Fuel characteristics:

T. triandra is generally more flammable than *P. maximum,* because it is able to dry out earlier than *P. maximum*. There was a significant difference found between the moisture content, where *T. triandra* was found to be dryer than *P. maximum* (table 1), when sampled in August near the end of the dry season. The lower the bulk density and packing ratio of the fuel, the more flammable it would be, because there would be more oxygen available to a fire if the fuel was less densely packed. *T. triandra* had lower bulk density and packing ratio than *P.* maximum; however there was no significant difference between the bulk densities and the packing ratios of the two species (table 1).

Table 1: Fuel characteristics of *T. triandra* and *P. maximum* as measured in August 2012 (Moisture contents: N (*T.triandra*)= 10, N (*P. maximum*) =10, df=18, p=0.009)

Species	**Average bulk density (g/m3)**	**Std dev. (bulk density)**	**Average packing ratio**	**Std dev. (packing ratio)**	**Average moisture content (%)**	**Std dev. (moisture content)**
T. triandra	0.002	0.0005	0.004	0.001	24	2.21
P. maximum	0.003	0.001	0.006	0.002	30	5.95

Effects of fire season:

The mean char heights of the Early fire were significantly lower than the mean char heights of the Late fire (figure 6). The Late fire had higher intensity than the early fire. There was, however, a larger variability in the char heights recorded at the Late fire sites than those that were recorded at the Early fire sites (figure 6). Table 2 displays the fire simulation model results on the effects of fire season, as represented by grass curing, on fire behaviour. Fully green fuel would likely be a scenario where fire occurred early in the dry season and therefore exhibiting a low intensity fire. The fully cured fuel moisture scenario represents a fire that occurs late in the dry season as all the fuel would have dried out, thereby promoting a higher intensity fire. Table 2 indicates that fire intensity and ROS (rate of fire spread) and flame length are higher later in the dry season under the same weather conditions and fuel characteristics than earlier in the dry season. Simulated rate of spread, for example, more than doubles from partially cured to fully cured grass fuels.

Table 2: Model outputs for the effects of different moisture scenarios on fire behaviour. (ROS= maximum rate of fire spread)

Moisture scenario	ROS(max) (m/min)	Fireline Intensity (MW/m)	Flame Length (m)	Bulk density (g/m^3)	Packing ratio
Fully cured fuel	49.6	10.487	5.5	0.002	0.004
2/3 cured fuel	39.3	8.842	5.1	0.002	0.004
1/3 cured fuel	23.4	4.793	3.8	0.002	0.004
Fully green fuel	5	0.331	1.1	0.002	0.004

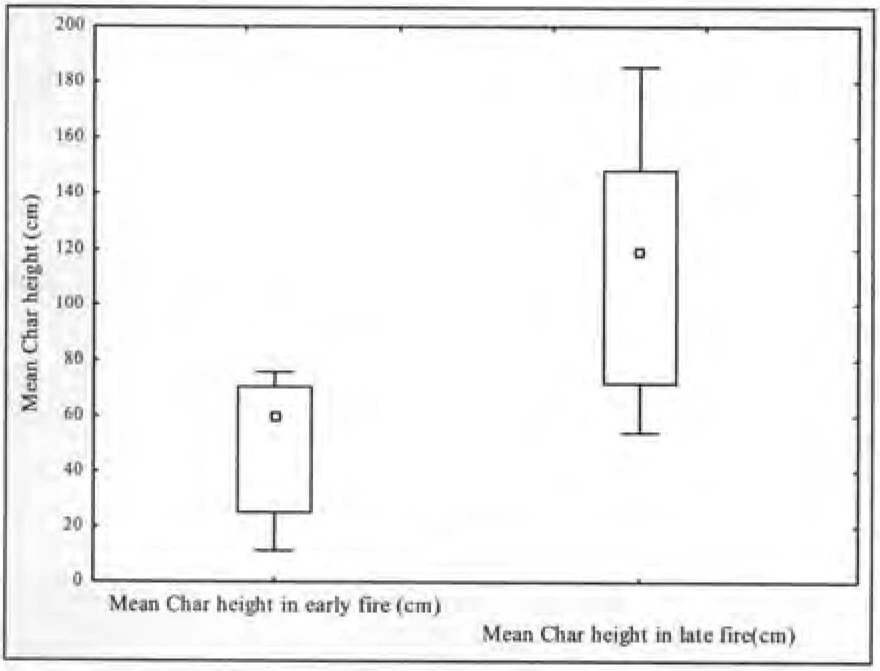

Figure 6: Comparison of mean char heights (cm) at sites in the Early fire versus Late fire. The box represents the median, 1st quartile and 3rd quartile. The whiskers represent the minimum and maximum values. (N (Early)=12, N (Late)=12, DF=22, p=0.0001)

The effect that grass biomass had on the intensity of the fire as measured by char height in displayed in figure 7. In the Early fire, there was higher char height (or fire intensity ($MW.m^{-1}$)) when more grass biomass was present at the site. However, this was not seen in the Late fire; where grass biomass had a less direct relationship with the char height. In the less intense Early fire, canopy cover had an effect on whether the fire burnt through the site (figure 8). Fire intensity was lower in sites that had higher percentages of canopy cover. However, there was no apparent direct effect of canopy cover on fire intensity in the more intense Late fire. In the Late fire, the most intense fire was found in a site that had a high percentage of canopy cover but in some cases; there was a relatively low intensity in sites that had high canopy cover (figure 8).

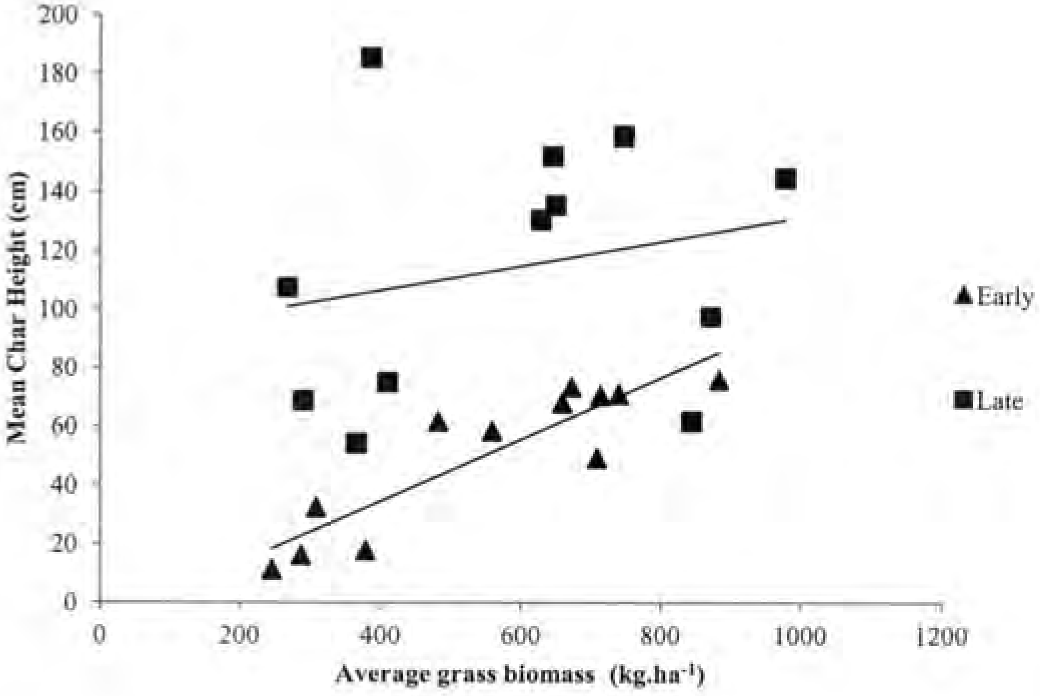

Figure 7: Effects of pre-burn grass biomass on fire intensity (using maximum char height (cm) as a proxy) at each site for the Early fire and the Late fire. (Early fire: $r^2$0.80, $p<0.001$), (Late fire: $r^2=0.05$, $p>0.05$)

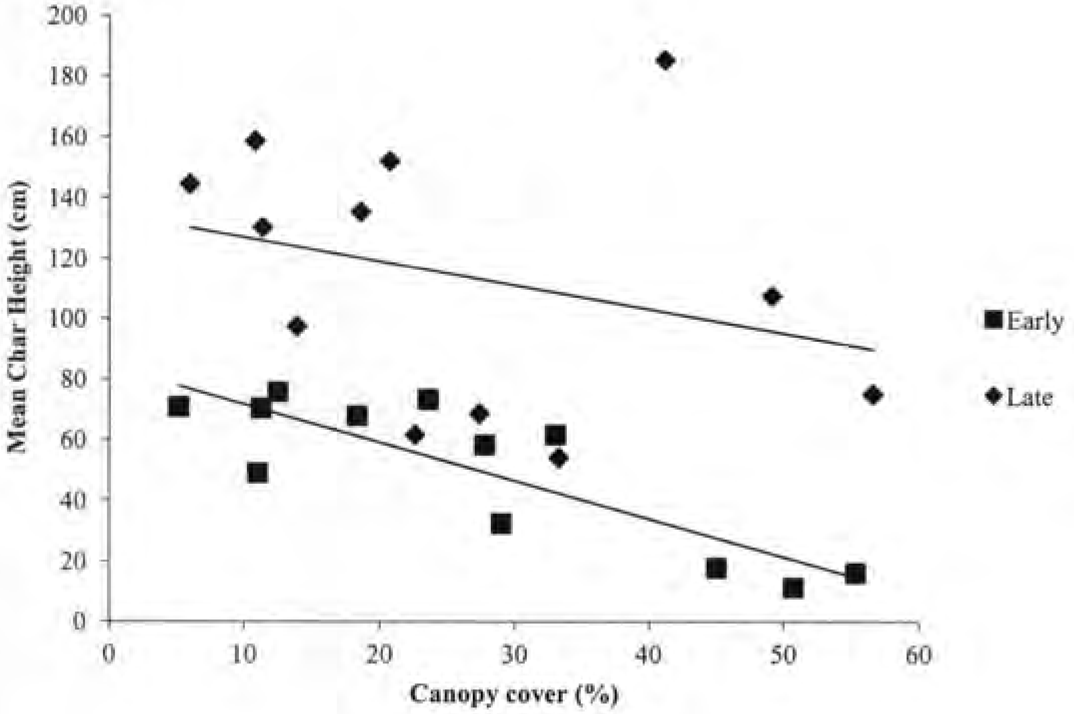

Figure 8: Effects of canopy cover on the intensity of the fire at each site (using maximum char height (cm) as a proxy) for sites in the Early fire and the Late fire. (Early fire: $r^2=0.72$, $p<0.05$), (Late fire: $r^2=0.08$, $p>0.05$)

A higher intensity fire allows for a more complete burn, which allows the fire to consume almost all vegetation in the area. Figure 9 demonstrates that the Late fire exhibited a more complete burn than the Early fire did as there was significantly less area that was unburned at each site in the Late fire than there was at the sites in the Early fire.

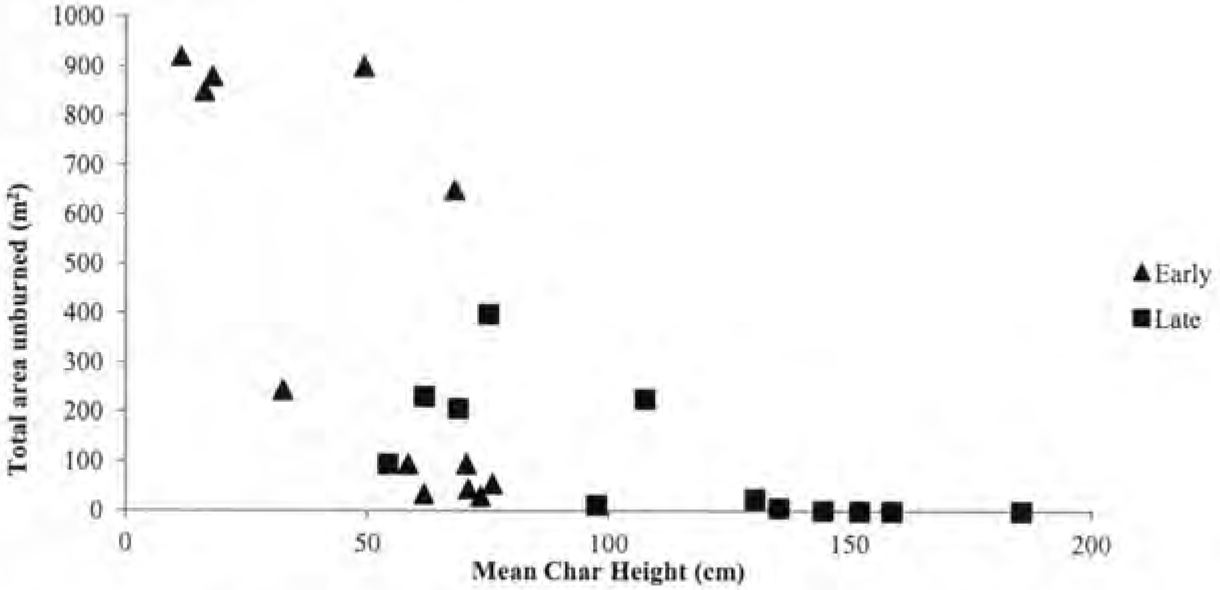

Figure 9: Effects of fire intensity (using maximum char height (cm) as a proxy) on the completeness of burn (as measured by the area unburned (m^2)) at each site in the Early and Late fires, (N (Early) =12, N (Late) =12, DF=22, p=0.02)

Tree responses to fire:

A more intense fire should be able to cause more "damage" to a tree than a less intense fire, thus it is hypothesised a more intense fire should yield higher tree mortality. However, figure 10 indicates that an increase in fire intensity (as measured by maximum char height (cm)) had no effect on the tree resprouting success (r^2=0.01). However, there is not a large variability in fire intensity per site in the Early fire. The ability of a tree to resprout may be linked to the pre-burn status of trees. Trees that had more stems were able to survive a fire more readily than trees with less stems (figure 11), thus trees that had less stems or a lower resprout vigour suffered a higher percentage mortality after the fire in June 2012 (figure 11). After the September 2008 firestorm, there was a total tree mortality of 21% (Browne, 2009). Of the trees that survived the 2008 firestorm, 47% of the trees that were sampled were killed after the July 2012 fire. Therefore, after 2 fires in a 4 year period, there was 58% tree mortality in the sample sites.

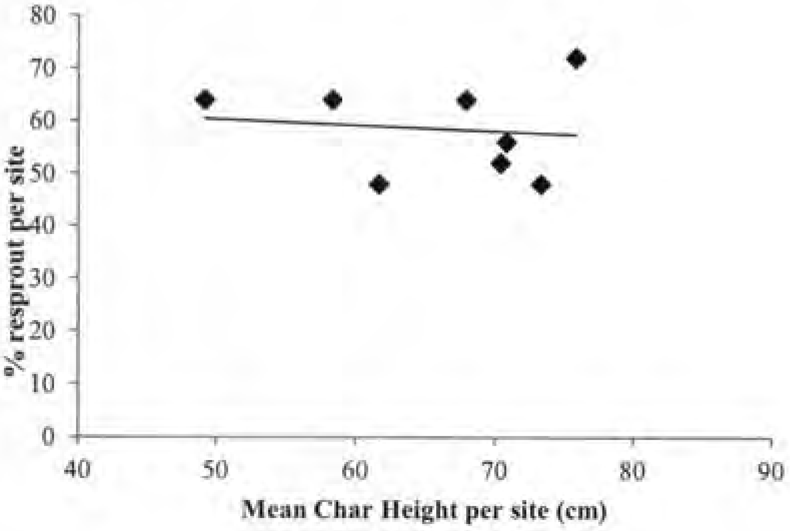

Figure 10: Effects of fire intensity (using maximum char height (cm) as a proxy) on the percentage of resprouting trees present in the sites in the Early fire, (r^2=0.01, $p>0.05$)

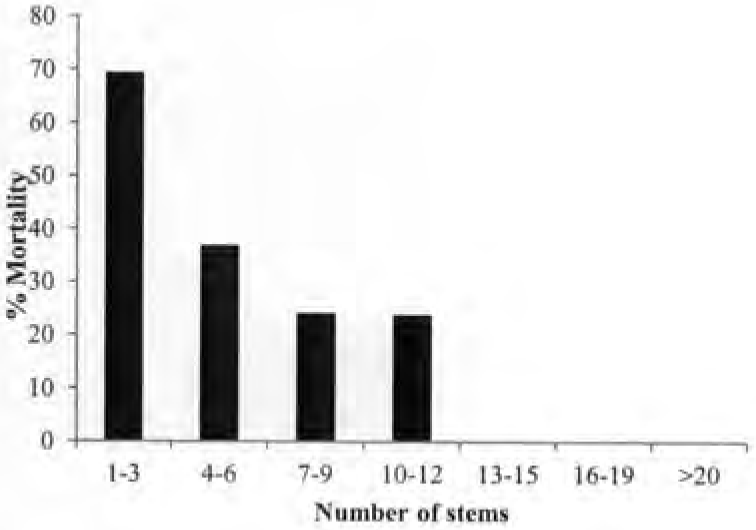

Figure 11: Percentage mortality of trees with differing number of stems after the Early fire. (X^2=112.5, DF=3, $p<0.001$)

Discussion

The September 2008 firestorm was able to penetrate deep into the thicket areas in the Northern region of Hluhluwe-iMfolozi Game Reserve (Browne, 2009), which created an opening for grasses to re-colonise the area, provide sufficient fuel loads for future fires (figure 4 & 5) and potentially cause a regime shift; in this case, from thicket back to savanna. Whether fire can subsequently and repeatedly burn through the area again is hypothesised to be an important aspect affecting the likelihood of a shift from one stable state to another.

This would largely depend on rates of re-colonisation of burnt forest areas by grasses and the accumulation of adequate fuel loads to support subsequent fire at sufficient intensity to result in substantial and cumulative woody plant mortality and a grass species composition shift to a *T. triandra* dominated grass layer, characteristic of a stable savanna state. In the Hluhluwe burnt thickets, colonising grasses, dominated by *P. maximum* with higher moisture content, remain green longer in the dry season than the dominant savanna grasses (Table 1; see Trollope, 1984a). Thus development of a suitable fuel load to burn will also depend on moisture contents of the fuel at the time of burning, as well as the prevalence of woody plant cover which suppresses grass colonisation (Hennenberg *et al.*, 2006, Mordelet & Menaut, 1995) and fuel load accumulation (figure 5). Scholes & Archer (1997) pointed out that in general an increase in woody plant cover or density results in a decline of grass production.

Despite the dominance of *P. maximum* within the sites, it is evident from figure 2 that there were sufficient fuel loads to carry a fire. Only three growing seasons passed since the 2008 firestorm before subsequent fires were able to burn through the thickets in 2012. Fuel load may be essential for carrying fires, especially the lower intensity Early fire (figure 7). However, once fire intensity reaches a certain level (char height >1m), fires become less affected by vegetation dynamics (fuel load and canopy cover) when spreading into the forest/thicket patches (figure 7 & 8). The relationship between fire intensity ($MW.m^{-1}$) and char height (cm) for Australian eucalypt savannas is shown in figure 12. Therefore char height differences indicate that the Late fire burnt the area with more intensity (figure 6), which may have enabled it to spread more readily into the thicket areas than the Early fire, rendering a more complete burn (figure 9). However, leaf litter may have been overlooked as a sufficient fuel for carrying fires within the forest/thicket patches. Leaf litter is more compact than grasses and may need a higher ignition temperature than grasses (Hennenberg *et al.*, 2006). Therefore, later fires may carry enough intensity for spread into and through forest/thicket patches and could be a suitable management option for controlling bush encroachment.

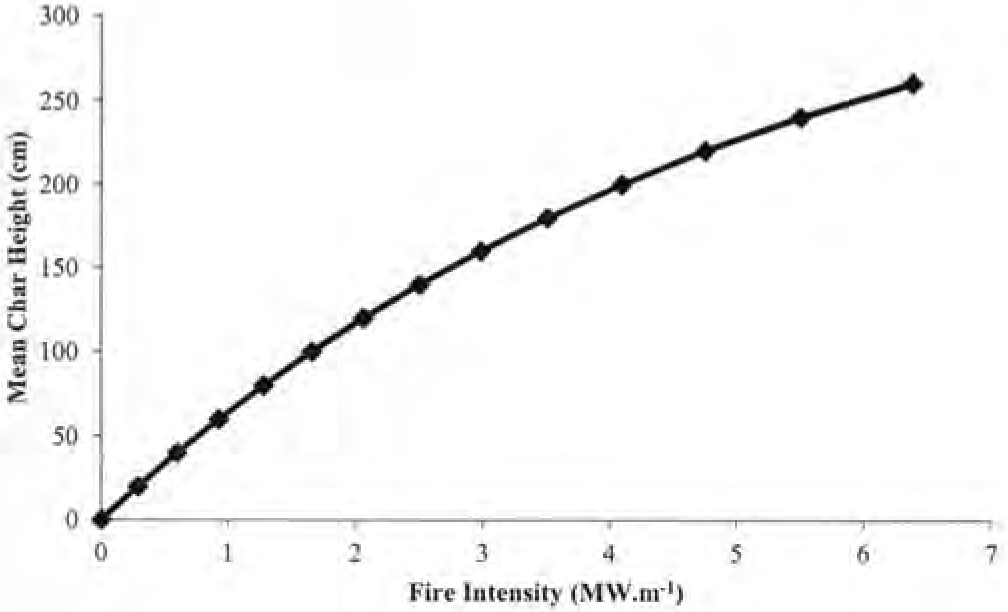

Figure 12: Relationship between mean char height (cm) and fire intensity ($MW.m^{-1}$) for Northern Australian savannas. The line is described by the equation: $y=3.7(1-e^{-0.19x})$, (Modified from Williams *et al.*, 2003), ($r^2=0.91$)

It is likely that the fuel moisture scenario differed substantially between the two fires, which may be an influential factor that affects fire intensity. Bulk densities and packing ratios are related to the moisture contents of the fuels, such that, lower bulk density and packing ratios can sustain burning at higher moisture contents (Hoffman *et al.*, 2012). However, these may have had less effect, as the moisture content was likely to be higher during the time of the Early fire (table 2). Although the fire model was simulated for a typical savanna fire, table 2 further supports that a later fire might be more desirable for fire managers intending to burn through forest/thicket patches and impede bush encroachment by creating greater penetration and possibly causing higher levels of tree mortality. Actual fire intensities will also be affected by fire weather conditions (temperature, humidity, wind speed and rainfall) leading up to the events, as well as, during the fires. However, these data were not available for this study as fire weather data was not specifically recorded by either the fire management teams or weather stations at HGR.

Post-fire resprouting is an essential strategy for trees to survive a savanna fire. Contrary to predictions, resprouting ability of forest and savanna trees does not differ consistently; forest trees are able to resprout after a fire as readily as savanna trees (Beckett, 2010; Hoffman *et al.*, 2003, 2009). Relatively high fire intensities will cause "damage" to trees and force them to resprout after a fire (Govender *et al.*, 2006), rather than kill them (figure 10). Trees may accomplish this by having underground storage capability to provide reserve root carbohydrates to enable a tree to resprout quickly after a fire until sufficient leaf area has developed to sustain plant growth (Hoffman *et al.*, 2009). There may be a "life stage effect", where the "vigorous resprouter" life stage (trees that sprouted many stems post-2008 firestorm), have large underground storage reserves and are able to survive fires more effectively through resprouting than the "non-vigorous resprouter" life stage (trees that did not sprout many stems post-2008 firestorm) (figure 11). The non-vigorous resprouters may be allocating resources to other "areas", such as tree height. Whereas the vigorous resprouters would likely restore their underground reserves post-fire. Although only two fires were available for this, it may be inferred that more frequent fires could deplete the underground reserves and cause higher tree mortality, as was noted for the 2012 fire.

Evidence from this study suggests that the 2008 firestorm has facilitated conditions that seem to have a real prospect of regime shift from forest/thicket to savanna. Based on the pattern found, fire management options may be suggested. However, further questions still remain to be unanswered and would need to be addressed in order to develop a more comprehensive suite of fire management options, especially the one of fire weather. Fire weather conditions are a critical factor when considering fire intensity and fire season, in order to achieve the ideal burn conditions to maximize the completeness of the burns and tree mortality. Fire season would need to be further considered so as to identify an ideal timeframe/"window" in which fires should be ignited and how leaf litter may have a role in carrying fires within forest/thicket areas. Finally, vegetation dynamics might need refining, such as facilitating a species composition shift from *P. maximum* to *T. triandra*, or whether this is plausible at all and the post-fire woody species recruitment and survival rates.

Recommendations

It seems that grasses are opportunistic; capable of re-colonising and accumulating in newly opened up forest/thicket areas. An appropriate fire management option for a wildlife park, such as, HGR that experienced a rare firestorm event that penetrated closed thicket might be to allow grasses to recover in these areas in order to provide sufficient fuel loads for subsequent fires. Fires later on in the dry season would be more desirable, as they would be able to achieve greater penetration and burn through the area more completely, possible causing enough damage to either achieve higher levels of mortality or trigger tree resprouting, thereby increasing the individual tree vulnerability to repeated fires. In order to further control bush encroachment, it may be beneficial to burn the areas more frequently in order to "knock back" the trees by depleting their underground reserves and cause tree mortality. This would help re-adjusting the mosaic of thicket/forest/savanna vegetation, pre-dominated by savannas in the landscape. This same system may be adapted by the livestock sector. However, farmers would need to wait until very late in the dry season to maximise fire intensity, mortality and increase vulnerability of trees to repeated fires, only protecting essential grazing areas and buildings from the fire. In both the protected and livestock farming management scenario's, the density of grazers also affects the ability of the system to build up enough fuel to repeat the cycle within two to three growing seasons.

Alternatively, where forest conservation is the key management objective, the opposite may apply. In order to reduce the fuel load, managers would need to burn early in the dry seasons, so that the intensity of the fires is not high enough to spread into and within the forest areas. Thus facilitating forest recovery, as fires would be extinguished at the forest margin due to insufficient fuel loads for fire spread.

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Appendix 1

Table 3: BehavePlus5 model parameters used for simulation of fire behaviour (data from van Wilgen & Wills, 1988)

BehavePlus 5.0.5 (Build 307)			
Mon, Oct 22, 2012 at 11:13:49			
Input Worksheet			
Inputs: SURFACE			
Input Variables		Units	Input Value(s)
Fuel/Vegetation, Surface/Understory			
	Fuel Model Type		D
	1-h Fuel Load	tonne/ha	3.12
	10-h Fuel Load	tonne/ha	0.2
	100-h Fuel Load	tonne/ha	0
	Live Herbaceous Fuel Load	tonne/ha	6.1
	Live Woody Fuel Load	tonne/ha	0.4
	1-h SA/V	m2/m3	6562
	Live Herbaceous SA/V	m2/m3	5906
	Live Woody SA/V	m2/m3	5900
	Fuel Bed Depth	m	0.44
	Dead Fuel Moisture of Extinction	%	20
	Dead Fuel Heat Content	kJ/kg	19500

	Live Fuel Heat Content	kJ/kg	19500
Fuel Moisture			
	Moisture Scenario		d311, d312, d313, d314
Weather			
	Midflame Wind Speed (upslope)	km/h	15
Terrain			
	Slope Steepness	%	0
Notes			
Run Option Notes			
Maximum reliable effective wind speed limit IS imposed [SURFACE].			
Calculations are only for the direction of maximum spread [SURFACE].			
Fireline intensity, flame length, and spread distance are always for the direction of the spread calculations [SURFACE].			
Wind is blowing upslope [SURFACE].			