Influence of fire on root distribution, seasonal root production and root/shoot ratios in grass species in a semi-arid grassland of South Africa

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The impact of fire (head and back fires) on the seasonal change in above- and belowground production in grass species, was quantified over two growing seasons (2000/01 and 2001/02) for semi-arid grassland. The behaviour of the head and back fires was also identified. Roots were extracted to a depth of 900mm with 50mm intervals, using a core and then separated from the soil by wet sieving and flotation. Sampling of both above- and below-ground phytomass, took place at approximately bi-monthly intervals to account for major seasonal changes. The intensity of the back fire was higher than the head fire at ground level. Most of the grass roots were found in the first 150mm soil layer. While fire increased grass root distribution over the first 100mm depth, it was decreased deeper in the soil. Root mass in semi-arid grassland is strongly seasonal, with the most active growth during the months of March and April when aboveground parts are dormant. Both above- and belowground phytomass production decreased significantly over the first year following burning. The above- and belowground phytomass (900mm depth) was respectively 806kg ha\(^{-1}\) and 2 002kg ha\(^{-1}\) less due to burning, over the first year after burning. The seasonal root/shoot ratios for the unburnt and burnt grassland ranged between 1.62 to 2.80 and 1.20 to 3.12 respectively. It seems that root mass exceeds aboveground biomass for this semi-arid grassland. Over the short-term, fire decreased productivity and could subsequently influence the sustainable fodder production of a semi-arid grassland ecosystem.

Introduction

In arid and semi-arid environments, productivity is controlled by a range of climatic factors, which initiate the biochemical and physiological processes that drive plant growth. The three most important limits to these processes are soil-water (Noy-Meir 1973, Le Houèrour et al. 1988, Bennie et al. 1997, Oesterheld et al. 2001), temperature (Christie 1981, Hunter 1989) and nutrient availability (Chapin 1991, Materrechera et al. 1998, Mazzarino and Bertiller 1999, Emmerich and Heitschmidt 2002, Schenck and Jackson 2002). Although water may be the most limiting environmental factor for production during dry periods in these areas (Snyman 2000, O’Connor et al. 2001, Ingram 2003, Wiegand et al. 2004), nitrogen can be more limiting during years of above-average rainfall (Wiltshire 1990, Van de Vijver 1999). In these drier areas, many grass species do not have a deep root system to access groundwater and are therefore reliant on subsurface soil-water after rainfall events (Drew 1979, Tainton 1981, McNaughton et al. 1998, Ingram 2003), often leading to a short growing season of only several weeks (Danckwerts and Nel 1989, Snyman 1998, Ekaya et al. 2001, Oesterheld et al. 2001).

Unfortunately, little work has been carried out to investigate the seasonal patterns of grass root growth and turnover (Manley et al. 1995, O’Connor and Bredenkamp 1997, Allsopp 1999, Wolfson and Tainton 1999, Ingram 2003, Ekaya et al. 2001) because past plant-ecological studies mainly concentrated on the aboveground plant parts of the grassland ecosystem. This is especially true in the fragile ecosystems of semi-arid climates where small climatic changes may have long-lasting consequences (Neary et al. 1999, Snyman 2003a, Wiegand et al. 2004). The fact that roots have no direct visual importance to grazing management systems, the difficulty in sampling because of the inability to distinguish live roots from dead and the high variability of the resultant data, are some of the most important reasons for the above problem (Smith 1985, Shackleton et al. 1988, Snyman 1994, McNaughton et al. 1998, Snyman 1999a, Ingram 2003). This lack further intensifies into the complete lack of data also on the impact of fire on both of the above- (Booysen and Tainton 1984, Everson 1999, Snyman 2003b, 2004a Neary et al. 1999), and belowground fractions (Trollope 1999, Downing and Marshall 1983, Tainton 1999) in specifically arid and semi-arid grasslands. Although yield measurements have seldom been taken in grassland burning experiments and most assessments of the effects of burning have been on visual
ratings, it has generally been assumed that fire should be excluded from these drier southern African grasslands (Tainton and Mentis 1984, Everson 1999, Snyman 2002, 2003c). Therefore, for effective management of these grassland ecosystems, it is essential to develop a better understanding of patterns of growth and production and how they relate to the driving influences of not only water, but also unforeseen veld fires, so as to maximise animal production and minimise potentially detrimental impacts. The overall effects of fire on ecosystems are complex, ranging from the reduction or elimination of aboveground biomass (Everson 1999, Snyman 2003b) to impacts on belowground physical, chemical and microbial-mediated processes (Neary et al. 1999, Snyman 2002, 2003c).

Although historic fires can be recorded as a normal phenomenon, fire can currently be seen as one of the largest anthropogenic influences on terrestrial ecosystems, after urban and agricultural activities (Van de Vijver 1999). Large parts of the semi-arid grasslands of southern Africa are characterised by large-scale accidental, man-caused runaway fires driven by August winds (Edwards 1984). Records of lightning strike densities in southern Africa show them to range from less than one strike km$^{-2}$ yr$^{-1}$ (Tainton et al. 1993). In semi-arid grasslands the density of lightning flashes could be approximately four strikes km$^{-2}$ yr$^{-1}$ (Everson 1999). Even if the frequency of ignition is low (say one fire from 500 ground flashes), a large number of fires would have been ignited each year in semi-arid areas. Either lightning or man caused these unplanned events, and they not only have a short-term influence on productivity of the grassland ecosystem but may also have a major residual effect on the next growing season, depending on successive climatic conditions and post-fire management (Booysen and Tainton 1984, Snyman 2003b, 2004a, Trollope 1989). This information can serve as a guideline in claims arising from unforeseen fires, in which thousands of rands can be involved, and which are often based on unscientific evidence. The objective was therefore to quantify short-term (two years) influence of a one-year grassland burning on above- and belowground productivity.

**Material and Methods**

**Site description**

The research was conducted in Bloemfontein (28°50’S, 26°15’E, altitude 1 350m), which is situated in the semi-arid (summer annual average 560mm) region of South Africa. Rain falls almost exclusively during summer (October to April), with an average of 78 rainy days per year. Mean maximum monthly temperatures range from 17°C in July to 33°C in January, with an average of 119 frost days per annum (Schulze 1979).

The study area is situated in the Dry Sandy Highveld Grassland (Grassland Biome) (Bredenkamp and Van Rooyen 1996) with a slope of 3.5%. Botanical (grass species) composition of the study site was determined over the 1995/96 to the 1998/99 seasons by Snyman (1999b, 2000), where the average grassland condition score was expressed as a percentage of that in a benchmark site. At the start of this study the veld was in good condition (veld condition score was 92% of that of the benchmark site) and dominated by the climax species *Themeda triandra* with *Eragrostis chloromelas* and *Eliorus muticus* also occurring relatively abundantly. Soils in the study area are mostly fine sandy loams of the Bloemdal Form (Roodepoort family — 3 200) (Soil Classification Working Group 1991). Clay content increases with soil depth from 10% in the A-horizon (0mm to 300mm) to 24% in the B1-horizon (300mm to 600mm) and 42% in the B2-horizon (600mm to 1 200mm). Bulk densities were 1 484kg m$^{-3}$ for horizon A, 1 563kg m$^{-3}$ for horizon B1 and 1 758kg m$^{-3}$ for horizon B2, while their upper limits of the soil-water holding capacity were 69mm, 73mm, 82mm and 82mm respectively (Snyman 2000).

**Treatments and data collection**

The research was conducted on 18 plots of 10m x 10m each, with an edge effect of 5m around every plot. The three treatments included fire burning against the wind (back fire), with the wind (head fire) (Trollope 1978), and a control with no burning. The treatments were randomly allocated to the plots. Half of the burn plots were burnt on 30 August 2000 and the other half on 23 August 2001. Therefore every plot was burnt only once during the trial period. The control was harvested at the same time as the burning treatments, to a height of 30mm. The head and back fire treatments were applied on the same day to ensure that the two types of fires were comparable over a similar range of environmental variables. The fire treatments were applied during the time when the soil and grass fuel were initially very dry and then spring rainfall thoroughly wetted the soil, causing the grass sward to become relatively green. Burning took place in the morning with a light wind blowing. To limit the fire to every burnt plot, the plants surrounding each plot were cut short and soaked before burning. The plots were excluded from any grazing over the two-year trial period. At the end of each growing season, every treatment was defoliated to a height of 30mm.

The fuel load was estimated by cutting 10 quadrats (m$^2$ each) in the control plots adjacent to the burnt plots (Snyman 2000), which only comprised the growing season’s production. The fuel water content was estimated by harvesting 10 grass samples at random from tufts of the dormant grass species in the plots. The fuel water was expressed as a percentage on a dry matter basis.

**Fire behaviour**

The mean length of the flames was estimated visually once the fire was burning uniformly. The rates at which the head and back fires moved over the plots were measured using a stopwatch. The wind velocity was recorded at the start, during and at the end of the fire with a hand anemometer held at a height of approximately 1.7m. Wind velocities recorded during the fire were assessed to be the most representative for that time of year. Air temperature and relative humidity were measured immediately prior to burning with a whirling psychrometer.
The following fire behaviour model (Trollope 1999) was used to predict the fire intensities to which the treatment blocks were subjected for each season’s burning:

\[ FI = 2.729 + (0.8684x_1) - (530.1/x_2) - (0.1907x_3^2) - (596.1/x_4) \]

where:
- \( FI \) = fire intensity (kJ s\(^{-1}\) m\(^{-1}\))
- \( x_1 \) = fuel load (kg ha\(^{-1}\))
- \( x_2 \) = fuel-water content (\%)
- \( x_3 \) = relative humidity (\%)
- \( x_4 \) = wind speed (m s\(^{-1}\))

Fire intensities were estimated and classified into one of the categories proposed by Trollope and Potgieter (1986).

Chrome-alumel thermocouples connected to a portable electronic temperature recorder were used to record the temperatures 10mm under the soil, at ground level, grass canopy height and 1m above ground level. The mean grass canopy height was 230 ± 25mm for the August 2000 and 2001 fires. A single probe was placed in a vertical plane at each level and because only single measurements could be taken in each plot, great care was taken in choosing measuring sites representative of the whole plot. Considering the above, by chance all the measurements in all the plots were taken precisely in the middle of each plot. Temperature recordings covered the duration of the burn and were discontinued once the temperatures had returned to ambient levels. Variation in soil heating has been studied using various temperature measuring devices such as thermo-color pyrometers (Hobbs and Atkins 1988), thermocouples and analogue devices (Trollope 1978). Such devices can only be deployed over a limited area and must be installed prior to a fire occurring (Auld and Tozer 1999).

**Effect of fire behaviour on grass vegetation**

Botanical (grass species) composition was determined with a bridge-point apparatus (Walker 1970, Snyman and Fouché 1991), where 500 points (nearest plant and strikes) were recorded per plot before the fire as well as 1, 4, 8 and 20 months after the fire. Grassland condition was determined according to the method of Fourie and Du Toit (1983). When the species were classified, the desirability in terms of grazing value (dry-matter production, palatability, nutritive value, whether perennial or annual, and grazing resistance) as well as the ecological status (Decreaser and Increaser species), as defined by Foran et al. (1978), were taken into consideration. The classification of dry Themeda-Cymbopogon grassland into different ecological groups as described by Fourie and Visagie (1985) was used. At the end of each season, as well as two months after burning, plant density was determined by counting all plants within eight quadrats of 0.5m x 0.5m each per plot.

The aboveground and belowground phytomass productions for all treatments were determined every second month at the end of October, December, February and April of the 2001/02 growing season. The August 2000 burn treatments were therefore defoliated (30mm height) and root mass was determined the first time in 2001, after resting for a full growing season. As the burn treatments of the two separate years were defoliated the first time and root mass determined the same year, variation of climate on phytomass productions was largely excluded. The root mass was also determined during the end of the months of March, June and 15 August (when grass started sprouting) to more clearly identify the possible peak periods of development (Weinmann and Reinhold 1946, Weinmann 1940, 1948, Alberda 1957, Moore 1989). Just before the burning (end August) root mass was also determined in the burnt plots.

Root mass was estimated at 50mm intervals to a depth of 900mm together with the aboveground production estimated from a sample of 10 soil cores systematically distributed over each plot. The soil cores were collected with an auger (70mm diameter) during the abovementioned months. Sieving was through two sieves, a 2mm mesh followed by a 0.5mm mesh. After most of the roots had been extracted via successive washings of the core through the 2mm mesh, the remainder of the soil was spread in a shallow tray and water was run continuously through to separate the fine roots by flotation. The outflow from the tray passed through the 0.5mm mesh sieve. No attempt was made to distinguish between live and dead roots. Harvested materials were oven-dried at 90°C for 72h before being weighed.

**Statistical analysis**

The layout was a fully randomised design with three replications for each treatment. Two-way analysis of variance at 95% confidence level (burning x soil layer) was computed for root mass. All other data on fire behaviour, aboveground phytomass and root/shoot ratio were analysed using a one-way analysis of variance technique (Winer 1974). Data from harvests in different years were analysed separately. Plant density sub-sampling was employed where data averaged across quadrats within plots and then analysed. Significance between treatments was conducted by Tukey’s test, with the Number Cruncher Statistical System (2000) software package being largely used (Hintze 1997).

**Results and Discussion**

**Environmental variables influencing fire intensity**

Average aboveground phytomass production of the two growing seasons preceding the August 2000 and August 2001 burn treatments were 1 453kg ha\(^{-1}\) and 1 200kg ha\(^{-1}\) respectively. The long-term production over a 25-year period used for this study area is 1 377kg ha\(^{-1}\) (Snyman and Fouché 1991, O’Connor et al. 2001), which differs little from the average fuel load (1 327kg ha\(^{-1}\)) during the August fires. It can generally be concluded that both the two fires, regardless of other environmental influences, were of average intensity for this veld type. The plant material just before the fires was very dry with an average of 18% and 21% water content respectively for the August 2000 and 2001 fires. Trollope and Potgieter (1986) used 21% as the threshold fuel-water content. Wind came from a westerly direction at an average of 2.44m s\(^{-1}\) and 2.33m s\(^{-1}\) respectively for the August 2000 and 2001 fires. The relative humidity for the two fires was 43% and 41%.
Building the above-mentioned parameters as obtained in this study into the fire behaviour model of Trollope (1999), the predicted fire intensity for the August 2000 and 2001 fires should have been 1 145 kJ s⁻¹ m⁻¹ and 766 kJ s⁻¹ m⁻¹ respectively. Therefore the fire intensities for the two seasons ranged between a moderately hot and cool fire (Trollope and Potgieter 1986).

**Fire behaviour**

*Rate of spread and flame height*
The head fire for the August 2000 and August 2001 fires was on average 7.79 and 5.62 times respectively faster ($P < 0.01$) than the back fire on the same day (Table 1). The higher spread rate of the head fire during August 2000 can be ascribed to the higher wind speed reigning vs that of the August 2001 fire. The spread of head fires would therefore seem to be influenced to a greater degree by environmental conditions than back fires (Snyman 2004b).

The data in Table 1 clearly illustrate the two times greater ($P < 0.01$) flame lengths occurring in head fires in comparison to back fires. The greater flame height occurring with the 2000 fire can possibly be ascribed to the higher (21%) fuel load of the 2001 fire.

**Fire intensity of head and back fires**
The intensity of the fire 10mm under the soil in the case of both the head and back fires did not vary much, with a respective increase in temperature of only 6°C (9°C to 15°C) and 12°C (9°C to 21°C). The average duration of the different temperatures for the August 2000 and 2001 fires, at ground level, grass canopy level and 1m above the ground in the head and back fires is presented in Table 2. Considering the duration of the temperatures at ground level, the data in Table 2 clearly show that the various temperatures were maintained for a longer period in the back fires than was the case with the head fires. At 1m above the ground, the back fires hardly increased the air temperature and if so, then only for a brief period. The reason for the high fire intensity difference up to a height of 1m above the soil level in the case of the head and back fires is found in the greater flame length of the head fires.

In conclusion, the data in Table 2 suggest that back fires are generally more intense than head fires at ground level, whereas head fires are hotter than back fires at canopy level and above. It is also clear that head fires have a greater potential for developing higher temperatures than back fires at all levels given the appropriate environmental conditions. This observed pattern accorded with previous research (Snyman 2004b, 2005).

**Botanical composition**
The botanical composition in the case of both the head and back fires was not influenced much over the two growing seasons. *Themeda triandra*, *Cymbopogon plurinodis* and *Elionurus muticus*, the species that decreased most with the fire, decreased by 30%, 81% and 72% respectively. These three species constituted only 16% of the total species frequency. The frequency of the other species remained relatively constant, before and after the fire. Only *Eragrostis chloromelas* and *Tragus koelerioides* drastically increased due to the fire. The fact that these species split into smaller tufts because of the fire could have resulted in an over-estimation of the frequency of these species. These two species constituted only 6% on average of the total species frequency. Over the first growing season after the fire, the veld condition score (expressed as a percentage of that of a benchmark site) decreased by only 3.3% (86.6% vs 83.3%) due to fire (head and back fire). Also, according to many researchers (Scott 1984, Tainton and Mentis 1984, Auld and Bradstock 1996, Engle et al. 1998, Snyman 2003b, 2004a), various burning regimes do not appear to fundamentally change the composition of grassland, although both the frequency of defoliation by fire and the season of burning can cause shifts in the relative abundance of constituent species (O’Connor and Bredenkamp 1997, Morris and Fynn 2001). Other studies have been concerned with changes in vegetation composition due to fire on grasslands (Pase 1971, Pase and Knipe 1977, Whisenant et al. 1984, Cox 1998, West and Yorks 2002).

### Table 1: Behaviour of head and back fires for the August 2000 and August 2001 fires. Least significance differences (LSD) are calculated at the 1% level

|                      | Head fire | Back fire |
|----------------------|-----------|-----------|
| Rate of spread (m min⁻¹) |           |           |
| Mean                 | 4.75      | 3.88      |
| Minimum              | 4.50      | 3.75      |
| Maximum              | 5.00      | 4.00      |
| LSD: 2000 = 2.16     |           |           |
| LSD: 2001 = 2.04     |           |           |
| Flame height (m)     |           |           |
| Mean                 | 1.05      | 0.98      |
| Minimum              | 0.90      | 0.90      |
| Maximum              | 1.25      | 1.05      |
| LSD: 2000 = 0.36     |           |           |
| LSD: 2001 = 0.31     |           |           |

### Table 2: Duration of temperatures at ground level, grass canopy height and 1m above the ground in head and back fires in seconds (H = head and B = back fire)

| Temperatures (°C) | Ground level | Grass canopy | 1m above ground |
|-------------------|--------------|--------------|-----------------|
| ≥20               | 131          | 112          | 76              |
| ≥30               | 122          | 109          | 69              |
| ≥40               | 118          | 99           | 65              |
| ≥60               | 108          | 60           | 51              |
| ≥80               | 73           | 52           | 45              |
| ≥100              | 54           | 45           | 41              |
| ≥120              | 0            | 43           | 36              |
| ≥140              | 0            | 39           | 32              |
| ≥160              | 0            | 37           | 28              |
| ≥180              | 0            | 36           | 23              |
| ≥200              | 0            | 33           | 19              |
| ≥300              | 0            | 24           | 13              |
| ≥400              | 0            | 18           | 6               |
| ≥500              | 0            | 10           | 0               |
Plant density

Fire had a drastic influence on the plant density (Table 3). As the plant density did not vary much from season to season for unburnt grassland, only the mean value is given in Table 3. The influence of the back and head fires on plant density did not differ much and is therefore presented as an average in Table 3. Again, it is clear from Table 3 that the densities of Themeda triandra, Cymbopogon plurinodis and Elionurus muticus were influenced most by the fire. The species which only appeared after the fire were Aristida congesta and Tragus koelerioides. Most species' densities were not influenced by the fire. Various researchers have also found a decrease in density on semi-arid grassland due to fire (Emmerich and Cox 1992, Everson 1999, West and Yorks 2002, Snyman 2004b), but Tainton and Mentis (1984) could detect no decrease in the higher rainfall areas.

Root distribution with depth

As expected, regardless of the fire treatment, most of the root distribution was concentrated within the top soil layers with a decrease in roots with depth (Table 4). The same root distribution pattern was also noted by various other researchers (Dahlman and Kucera 1965, Cresswell et al. 1982, Smith 1985, Shackleton et al. 1988, Moore 1989). Root distribution did not differ much between head and back fires over all depths for both seasons (Table 4). Presumably, in response to increased concentrations of nutrients in the surface layers of the soil, the root mass for most grass species is located in the top 50–100mm (Table 4) (Ross 1977, Downing and Marshall 1983). A significant interaction (P ≤ 0.01) was obtained between root distribution and soil depth deeper than 50mm for both burnt and unburnt grassland. Fire significantly increased root distribution over the first 0–100mm depth (19%) and decreased it deeper than 100mm (Table 4). The above increase in root distribution due to fire only occurred six months after the fire, while the decrease in depth was already noticeable two months after the fire. A further increase in root distribution by fire occurred during the second season over the 50-100mm layer (Table 4) with the greatest increase in the second half of the season. The increase in root distribution over the top soil layers due to fire can possibly be ascribed to the increase in the concentration of various soil properties (Materechera et al. 1998, Emmerich 1999). Allen (1964) found that P was fixed after burning, while fire could also act as a potent mineralising agent, causing the rapid transformation of organic nitrogen into inorganic forms (Dunn et al. 1979, Hobbs and Schimel 1984).

The decrease in plant cover due to fire may largely be responsible for the decrease in root distribution as well as poorer soil-water content with water deeper down the soil profile (Snyman 2003c). According to Wolfson and Tainton (1999), it seems logical to assume that there is a close relation between the survival or length of life of a tiller and...
the roots that develop from it. In contrast, Shackleton et al. (1988) reported no root mass reduction by burning of the aboveground material (as measured 18 days after a fire) in higher rainfall areas.

As the unburnt plots never wilted during the study period, the root distribution pattern is a good illustration of what can be expected under optimal conditions. In contrast, the depth distribution of the roots could have been hampered by the wetting of largely the whole soil profile. According to Oosthuisen and Snyman (2001), the root distribution of grasses is limited to only the top soil layers under optimal soil-water conditions, while the roots of the same grasses penetrate the soil profile much deeper when water becomes limiting. Climax grasses dominated the experimental plots, with their rooting patterns enabling the plants to access both surface and deeper sub-surface water. Roots close to the soil surface produce fine rootlets that are maintained under most soil conditions, but could die as the soil dries out for long periods (Drew 1979).

Climax grasses in semi-arid areas have been known to draw water from deeper than 2m during drought periods (Snyman 1994), and in the Chihuahuan Desert up to 1.4m (Gibbens and Lenz 2001).

Both the burnt and unburnt grassland show a strong concentration of roots in the top 150mm soil layer where the averages for roots occurring, for the unburnt grassland and one year after the fire for the head and back fires, were 71.83%, 75.76% and 76.50% respectively (Table 4). Typically, more than 85% of roots in unburnt grasses are to be found in the top 300mm of soil (Tainton 1981, Moore 1989, Snyman 1998). There is evidence, however, that the deeply penetrating roots are considerably more efficient per unit weight of root than are the surface roots, so the value of these roots should not be underestimated (Wolfson and Tainton 1999). In arid and semi-arid environments, many grasses do not have a deep enough root system to access ground-water and are reliant on surface water after rainfall events (Drew 1979), leading to a short growing season (Sala et al. 1991), which can further be hindered by fire (Table 4).

Two years after the fire the difference in root distribution between burnt and unburnt grassland is still significant with the roots in the burnt part still better distributed over the top 100mm (Table 4). Though no root cores were drawn deeper than 900mm, it should not have made a big difference to total root mass, as most of the roots occur above that.

**Below-ground phytomass production and seasonal trends**

Over the first year following the fire, root mass was lowered ($P \leq 0.01$) by fire (Figure 1). The second season after the fire, the root mass of the burnt parts did not differ much from that of unburnt grassland over almost all depths (Figure 2). Though the back fire had a greater decrease ($P > 0.05$) in root mass than the head fire over the first season after the fire, the difference grew smaller as the second season progressed, following the fire.

The peak root mass (up to 900mm depth) of the unburnt grassland was 80% and only 11% higher than that of the burnt grassland, one season and two seasons respectively, after the fire (on average for the head and back fires). The peak root mass of 4.549kg ha$^{-1}$ for unburnt grassland compared well with other peak values for South African semi-arid grazahough according to Wolfson and Tanton (1999) and Ingram (2003) root biomasses in semi-arid grasslands are strongly seasonal, the general trend was very similar over the two seasons with this study.

The belowground phytomass production fluctuated considerably over the study period (Figure 1), which is a common problem with root studies (McNaughton 1985, Smith 1985, Shackleton et al. 1988). Regardless of burn treatment, the grasses grew most actively during the months of March to April. Peak autumn values for unburnt grassland were approximately 77% and 84% higher for respectively the head and back fires, one season after burning and 4% and 19% respectively for the second season after burning.

Notable of the considerable decrease in root mass occurring mid-winter is that root mass was most influenced especially in the top soil layers (0–100mm) and also showed the most marked increase in autumn (Figure 1). Also significant in Figures 1 and 2 is that the root mass in unburnt grassland, one and two years after the burning treatments, declined to almost the same mass during mid-winter over most depths. The increase in root mass occurring with the onset of the growing season can largely be linked to the increase in tuft sizes (litter production) as the season progresses (Snyman 1998). Almost all grasses in the unburnt and second-season-after-burning plots were fully in seed twice over the season, which was during the end of October and February. It seems therefore that probably the slight levelling out of the root mass for 30 October 2001 (Figures 1, 2a and 2b) and 28 February 2002 (Figures 1a, 2a and 2b) may be partly affected by this reproductive development. This is supported by Ueno and Yoshihara (1967) and Distel and Fernandez (1988), where diminished root growth was associated with flowering of grasses. The aboveground production of this rangeland follows normally two growth cycles over the growing season, namely September to end December and starting again at the beginning of January to the end of March (Snyman 1999c, 2000). The slower aboveground growth during the end of the abovementioned periods, in which most grasses become dormant, may contribute to the slightly higher root mass building up to 30 December 2001 (Figures 1a, 2a and 2b) and the high peak at 30 April 2002 (Figures 1a, 2a and 2b) in the unburnt and second-season- after-burning plots.

Clearly, seasonal patterns of root initiation and growth have emerged from studies which, to date, have been undertaken largely on the temperate species (Shackleton et al. 1988, Wolfson and Tainton 1999). Most researchers, to date, support the finding of this study that root growth in grasses at sites with reasonably distinct wet and dry seasons is most rapid during late summer and early spring, with another burst of growth during autumn (Weimann 1948, Alberda 1957, Dahlman and Kucera 1965, Shackleton et al. 1988, Moore 1989, Ekaya et al. 2001). Some researchers reported that the least grass root growth occurred during summer and mid-winter (Sims and Singh 1971, Singh and Yadava 1974, Tainton 1981, Shackleton et al. 1988). Other researchers have unfortunately failed to detect seasonal trends (Hadley and Kieckhefer 1963).
As the botanical (grass species) composition contained a large component of *Eragrostis* species before the fire, the large variation or decrease in root mass over the first 300mm soil layer (Figure 1) due to the fire could possibly be ascribed to certain root characteristics of this species. The roots of this grass species are covered by a cylindrical mass of sand granules or zone of mucigel, which are cemented to each other by plant slime. The plant slime is excreted by the root hairs (Coetzee and Page 1945, Theron 1955, Drew 1979, Wild 1988). It may be that this cylindrical mass of sand granules is responsible for the higher root mass before the fire. Marked production of mucigel by the root cap and epidermal cells is thought to allow root growth through dry media without desiccation injury, the mucigel ensuring close contact with the sand to facilitate water uptake (Drew 1979). This further characteristic of the roots of *Eragrostis* species could also have helped contribute towards the large quantity of roots penetrating deeper into the soil profile. The root system of *Elionurus muticus* with relatively large tufts is very superficial (Opperman et al. 1974, Snyman 2000) and formed a large component of the botanical composition. The large percentage die-back of this species due to fire could also to a large extent have contributed towards the decrease in root mass over the first 0–300mm soil depth due to fire.

**Above-ground phytomass production**

Fire decreased ($P \leq 0.01$) aboveground phytomass production or regrowth of the burnt grassland over the first season after the fire (Figure 3). For the second season following the fire, the production was still lower than that of unburnt grassland, but statistically significant ($P \leq 0.01$) only at the onset of the season. As the first frost already occurred in the beginning of April in both growing seasons and the plants already then became dormant aboveground and ceased growth, the March root mass is presented in Figures 3 and 4, to relate it to aboveground production. The production in the case of the head and back fires was not significantly ($P > 0.05$) different for any month, though the back fire had the lowest production throughout. This lower production could possibly be ascribed to the higher intensity of the back fire, which caused the lower plant density. Over the first season following the fire, the average production for head and back fires was not significantly ($P > 0.05$) different for any month, though the back fire had the lowest production throughout. This lower production could possibly be ascribed to the higher intensity of the back fire, which caused the lower plant density. Over the first season following the fire, the average production for head and back fires was not significantly ($P > 0.05$) different for any month, though the back fire had the lowest production throughout.

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*Figure 1:* Monthly root mass (kg ha$^-1$) for the unburnt (A) and burnt (B = head fire and C = back fire) grassland over the first growing season after burning. Horizons (mm): A (0–300), B1 (300–600) and B2 (600–900). LSD (0.01) for 0–900mm depth = 396
Figure 2: Monthly root mass (kg ha$^{-1}$) for the burnt (head fire = and back fire = grassland over the second season after burning. Horizon (mm): A (0–300), B$_1$ (300–600) and B$_2$ (600–900). LSD (0.01) for 0–900mm depth = 376

Figure 3: Cumulative above- (A) and belowground (first 900mm depth — B) phytomass production (kg ha$^{-1}$) for the unburnt and burnt (first season after burning) grassland, measured every second month. Least significance differences (LSD) are calculated at the 1% level.

Figure 4: Cumulative above (A) and belowground (first 900mm depth — B) phytomass production (kg ha$^{-1}$) for the unburnt and burnt (second season after burning) grassland, measured every second month. Least significance differences (LSD) are calculated at the 1% level.
influence on production when compared to a single burn in two years in the tall-grass prairies of south-central Oklahoma. The average seasonal production of 2.34 kg ha$^{-1}$ obtained on unburnt grassland (29% higher rainfall than the long-term average) compares well with the long-term average for this area, varying between 0.022 kg ha$^{-1}$ to 2.145 kg ha$^{-1}$ (Snyman 1999c, O’Connor et al. 2001, Snyman 2002). The aboveground biomass for the arid Rift Valley Province of Kenya ranged from 17.7 kg ha$^{-1}$ to 2.427 kg ha$^{-1}$ (Ekaya et al. 2001).

The better seasonal root development, together with better plant covers of the unburnt grassland than that of burnt grassland, largely contributed towards the higher aboveground production. Typically, nutrient uptake is maximised by increases in root length and density (Boot and Mensink 1990), increased absorptive capacity (Christie and Moorsby 1975) and root exudates (Drew 1979). The aboveground compartment serves as input into the belowground compartment through the process of photosynthesis and translocation (Trlica 1977, McNaughton 1979). Peaks in aboveground biomass therefore usually precede belowground biomass peaks (Ekaya et al. 2001), which is also the case in this study, regardless of burning. The root mass reached a peak value only at the end of April, vs aboveground production which peaked in the beginning of April with the first frost (Figures 1–4).

### Root/shoot ratio

The root/shoot ratios for both one season and two seasons following the fire, as well as for unburnt grassland, are presented in Table 5. With the exception of October, the ratios of unburnt grassland were higher ($P \leq 0.01$) than that of the burnt grassland. This phenomenon is valid for both one and two seasons following the fire (Table 5). For almost all months, the head fire had a slightly ($P > 0.05$) higher ratio than the back fire. This could possibly be due to the higher intensity of the back fire, which was more detrimental towards the root mass than aboveground production. As the first frost had already occurred at the beginning of April in both growing seasons and the plants already then became dormant, the March root masses are used in Table 5 to calculate the root/shoot ratio for April.

The ratios in Table 5 are comparable to most other published work in that the ratio decreases with age (Bray 1963, Aung 1974, Shackleton et al. 1988, Wolfson and Tainton 1999). Increases in temperature, decreases in light and an increase in the nitrogen supply may also lead to increases in this ratio (Wolfson and Tainton 1999).

For most months, the ratio within a burn treatment following a fire is higher during the first year than in the successive year (Table 5). The reason for this is that the aboveground production was influenced less than the roots by the fire over the first year following the fire. The root masses (over the first 900mm depth), responsible for the aboveground phytomass production for the different months for a growing season following the fire and two seasons thereafter, are graphically presented in Figures 3 and 4 respectively. From Figures 3 and 4 it is clear that in semi-arid areas it seems that root mass is generally greater than aboveground biomass (Shackleton et al. 1988, Schenk and Jackson 2002). The decrease in aboveground phytomass due to burning for the first (2000/01) and second (2001/02) growing seasons after burning were respectively 806 kg ha$^{-1}$ and 175 kg ha$^{-1}$ compared to the 2002 kg ha$^{-1}$ and 1027 kg ha$^{-1}$ decrease of root mass. The conclusion can therefore be made that belowground growth is more sensitive to burning than that of aboveground. The latter is one of the reasons for the decrease in root/shoot ratio with burning.

Despite differences in sampling and depth of excavation, in general the average root/shoot ratio recorded in this study from unburnt grassland over the two seasons (1.64) is comparable to that found in other semi-arid areas, for example, *Astrebla lappacea* grassland (2.1–3.5 Hall and Lee 1980, Christie 1981), *Themeda triandra* grassland (0.7 Downing and Marshall 1983) and *Eragrostis* spp. grasslands (0.2 to 3.0 Ross 1977, Montani et al. 1996). According to Shackleton et al. (1988), root/shoot ratios are also strongly seasonal in semi-arid grasslands, as in this study.

### Conclusions

The time for recovery of belowground systems will not only depend on the burning intensity and its effects on key ecosystems processes and components, but also on the previous land-use practices. Therefore, the impacts of fire on belowground systems can be highly variable and may not be predictable. However, from results obtained in this study, it was clear that poor root development accompanying fire will, over the short term, decrease the plant’s susceptibility to drought and will reduce its capacity to extract mineral nutrients from the soil. This effect has been strongly implicated in the increasing frequency of man-made drought in the arid and semi-arid regions in southern Africa, in particular. Vegetation cover, through limiting runoff and promoting infiltration, is an important control on the amount and efficiency of plant production, which is also negatively influenced by fire, especially in the more arid areas. The fact that underground production is more sensitive to fire than aboveground production further emphasises the importance of a well-distributed root system for sustainable utilisation of
the grassland ecosystem in arid areas. As the largest percentage of roots is limited to the top soil layer and is responsible for production, the importance of deeper roots contributing towards survival of the plant during water stress must not be underestimated. Peak root mass is attained during the dormant months when active growth has ceased, with the storage of photosynthate to promote rapid regrowth during the dormant months when active growth has ceased, with the storage of photosynthate to promote rapid regrowth at the onset of the growing season.

The overall effects of fire on belowground systems, and the resulting processes that feed back to aboveground systems, are complex. It is clear from this study that over the short term, fire could strongly influence the sustainability of the ecosystem in the drier areas. Therefore, frequent or seasonal fires as a management tool can have long-term negative effects on belowground systems. The management of grassland after a fire must be handled more circumspectly in arid and semi-arid areas.

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