Selective impacts on the vigour and mortality of *Aristida junciformis* (subsp. junciformis)

by

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Preface

The research contained in this dissertation was completed by the candidate while based in the Discipline of Grassland Science School of Life Sciences of the College of Agriculture, Engineering and Science, University of KwaZulu-Natal, Pietermaritzburg Campus, South Africa.

The contents of this work have not been submitted in any form to another university and, except where the work of others is acknowledged in the text, the results reported are due to investigations by the candidate.

Signed: Kevin Kirkman

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Signed: Craig Morris

Date: 2020/03/18

Declaration

I, Anke Scharlach, declare that:

(i) the research reported in this thesis, except where otherwise indicated or acknowledged, is my original work;

(ii) this thesis has not been submitted in full or in part for any degree or examination to any other university;

(iii) this thesis does not contain other persons' data, pictures, graphs or other information, unless specifically acknowledged as being sourced from other persons;

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Abstract

The aim of grazing management is to maximise livestock production by maintaining high sward quality. Many southern African grasslands have become degraded allowing grass species unfavourable for livestock production, such as *Aristida junciformis* subsp. junciformis, to become dominant thereby reducing the available sward quality. *Aristida junciformis* persists once established and is remarkably understudied. Three studies were conducted to investigate the dynamics of this grass and to find focused management techniques to control and manage *A. junciformis*. The studies compared the impact of a high density graze (HDG), targeted herbicide application and a control on the survivorship and productivity of *A. junciformis* tufts, on the species and cover composition and on the post-treatment seedbank. Tufts exposed to herbicide had a lower probability of survival ($p = 0.887$) than those subjected to a HDG ($p = 1.000$) or control ($p = 1.000$). After treatment implementation, grazed tufts were significantly ($p = 0.0018$) shorter than control tufts. The tufts displayed a linear growth rate under the control ($F_{1,8} = 456.84$; $P < 0.001$), increasing steadily over time, and a quadratic growth rate under the HDG ($F_{2,7} = 125.35$; $P < 0.001$), initially growing rapidly then declining towards the end of the growing season. There was no significant difference in the height ($p = 0.9481$) and the aboveground net primary productivity (ANPP) ($p = 0.7053$) between the tufts in the control and HDG paddocks. The plant species composition ($p = 0.4169$) and cover composition ($p = 0.4169$) did not differ among treatments, however there were significant shifts in species composition ($p = 0.0002$) and cover composition ($p = 0.0005$) over time ($p = 0.0002$). The directional shift in species and cover composition were similar in all paddocks. Most of the grazing resistant perennial grasses, or '*mtshiki*' species (*Eragrostis curvula*, *E. plana*, *Sporobolus pyramidalis* and *S. africanus*) and *A. junciformis* increased and *Themeda triandra* decreased over time. Total vegetation cover increased across all paddocks for all grass and forb species such that the bare soil cover was reduced from 53% to 34%. No *A. junciformis* seedlings emerged from the seedbank study. Most of the seedlings emerging from the seedbank (92%) and field studies (40%) were forbs. In the field study *A. junciformis* (30%) was second most dominant, followed by *T. triandra* (13%). The plant species composition of emerged seedlings did not differ among treatments ($p = 0.8134$). *Aristida junciformis* is and remains a persistent, indigenous weed that is difficult to eradicate. More research is required to prevent its establishment in areas not yet dominated but prone to its invasion and to eradicate it in veld where it is already dominant.

Keywords: *A. junciformis* subsp. junciformis, selective & non-selective disturbances, defoliation, seedling emergence, weed wiping, HDG

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1 Chapter One: Introduction

The objective of grazing management is to maintain pastures (Scott, 1955) to not only maximise livestock production (Fuhlendorf et al., 2001) but also to provide soil cover and to maximise and maintain the presence of palatable grass species (Scott, 1955). Different veld types experience different climates and thus receive different amounts of rainfall (Scott, 1955). As a result thereof, different veld types require different management techniques, such as burning, different grazing systems and resting, to either improve or maintain the veld condition. Poor management practices such as the exclusion of fire, prolonged selective grazing or overgrazing may lead to unpalatable grass species becoming dominant. One such grass species is *Aristida junciformis* Trin.et Rupr. subspecies junciformis (Venter, 1968; Van Zyl, 1998).

Aristida junciformis, commonly known as '*Ngongoni'* or wire grass, is a highly unpalatable (Botha, 2006; Van Oudtshoorn, 2012), long-lived perennial grass species, indigenous to southern Africa. It is most commonly found in the mesic grasslands or in the sourveld of KwaZulu-Natal, South Africa (Fish et al., 2015). Characterised by unpalatable, tough leaves and dense tufts (Fish et al., 2015), this grass is commonly associated with trampling (Scott, 1955), over-utilisation and over-all mismanagement (Venter, 1968; Chippendall, 1955). This is mainly attributed to cattle avoiding it once it reaches a height of about 30 cm (Van Zyl, 1998) and therefore initially over-utilise other grass species while grazing (selective grazing) such that the competition is reduced for *A. junciformis* and it becomes dominant (Van Oudtshoorn, 2012).

Once established, it is difficult to eradicate and is thus often called an indigenous weed (Edwards et al., 1979). From a biodiversity perspective, if *A. junciformis* becomes dominant, it reduces the plant species diversity and the diversity of other organisms such as birds and insects reliant on grassland diversity. From an agricultural perspective, if A. *junciformis* becomes dominant the species composition may be altered at the expense of the palatable grass species (Johnson, 1989) thereby reducing the forage quality and quantity resulting in a reduction in the grazing capacity (Johnson, 1989; Venter, 1968) and stocking rate thus minimising livestock production and ultimately reducing the economic potential associated with livestock production (Venter, 1968; Van Zyl, 1998). The same is true for the communal grazing lands of South Africa, which are common in the sourveld. Pastures infested with *A. junciformis* may threaten the existence of these communities since grazing is generally only valuable for 4 – 5 months of the year, during the rainy seasons of spring and summer (Scott, 1955).

A plethora of investigations are the result of the unfavourable characteristics *A. junciformis* presents, its obstinate persistence after establishment in the grassland and the difficulty associated with reducing its dominance. Understanding the physiology of this grass will enable us to better understand its ecology and therefore its response to different management techniques (Weinmann, 1955). It is the purpose of this study to identify a selective, focused, pasture management technique that is successful in controlling and managing *A. junciformis* (subsp. junciformis) by answering the question: Can selective disturbance by herbicide or grazing reduce the vigour and abundance of *A. junciformis* subsp. *junciformis* to the benefit of more palatable and productive forage grasses in the mesic grasslands of South Africa?

In the past time and energy have been invested to gain control *A. junciformis* using radical veld improvement techniques rather than sound veld management to receive faster results than the conventional management techniques have so far (Botha, 2006), since it is believed that the conventional management techniques are best for preventing the establishment of *A. junciformis* rather than lowering its dominance. The techniques that have been used in the past to control invasive plants (e.g. Simmons et al. (2007)) or undesirable grasses can be broadly classified into two groups, namely selective and non-selective grassland management techniques. In this introduction, I will describe each technique and provide the advantages and disadvantages of each.

Non-selective pasture management techniques (NPMT) are techniques which avoid selection such that all grasses receive the same treatment. In other words, target species such as *A. junciformis*, which would be targeted for removal, receive the same treatment as all other grasses or vegetation in the same area. Some examples of NPMT include fire or mowing. Another example of NPMT is mob grazing which is synonymous with non-selective grazing (NSG), high utilization grazing (HUG), short duration high intensity grazing (SDHI) or high density grazing (HDG) (referred to as HDG from this point forward). Trollope et al. (1990) defined HDG as grazing “until all the grass species have been heavily grazed.” HDG grazing is often implemented as livestock, such as cattle, have preferences for certain grass species (Ganskopp et al., 1997), forcing livestock to graze on all grasses. NPMT pose some advantages and disadvantages. An advantage of HDG is that livestock are forced to graze the available grasses such that even the unpalatable grasses are grazed. This technique is fairly easy to apply but may affect livestock production as the forage quality may be lower, resulting in lower intake by livestock, than in pastures that are in a good condition.

A study by Staples (1926) found that fires are a key to managing grasslands by providing early grazing, reducing the risk of destructive fires as well as reducing pests such as ticks. Opponents of the use of fire in pasture management contend that fires destroy pastures by reducing the vegetation cover, thus causing soil erosion and water run-off as well as encouraging weed growth (Staples, 1926) and emitting high amounts of carbon dioxide (Hall et al., 1991). Other problems that NPMT pose is that vacant niches can be created, which are then exploited by undesirable plants or grasses (Clark, 2014).

Since NPMT apply equal treatment to all species, they may benefit the palatable grass species which would be grazed in selective grazing where the unpalatable grass species would be avoided. However, target species such as *A. junciformis* generally do not experience selective pressures (Clark, 2014), which may be to its own advantage and to the advantage of other undesirable and persistent grass species. The application of equal treatment and success thereof therefore depends on the overall species composition present and particularly on the level of infestation by undesirable grass species or weeds.

From the analysis provided of the advantages and disadvantages of NPMT, it is clear that NPMT may be useful in maintaining veld that is still in a good condition which is, therefore, a problem if grasses that are undesirable for agriculture, such as the grazing resistant, perennial '*mtshiki*' grasses (*Eragrostis curvula, E. plana, Sporobolus africanus* and *S. pyramidalis*) (Mentis et al., 1982) or *A. junciformis*, are already dominant.

Selective pasture management techniques (SPMT) are techniques in which target species such as *A. junciformis* which would be targeted for removal, are targeted while simultaneously avoiding collateral damage on surrounding plant or grass species (Simmons et al., 2007). Examples of SPMT include prescribed fire, applied at a certain time to impact target species, hand-pulling of target species (Clark, 2014) or selective grazing in which animals are allowed to graze on the grass of their preference without being forced to graze unpalatable grass species. One other quite rare example of SPMT is the implementation of height-selective herbicide application as described and used by Botha (2006).

Advantages of the SPMT are that undesirable and unwanted grasses are removed without damaging or harming the desirable palatable grass species. A major disadvantage of SPMT is that, in the case of grazing, grazers may choose the palatable grass species over the unpalatable grass species such that the competitive ability of the palatable grass species is reduced, thus selective grazing is to the advantage of unpalatable grass species. While implementing a selective graze or prescribed burn are fairly easy and inexpensive, hand-pulling and weed wiping using a weed wiping broom are labour intensive and thus more expensive. The use of selective techniques together e.g. selective grazing and herbicide application, may be useful in managing and controlling the spread of *A. junciformis*.

The main factor that may influence the use of NPMT or SPMT is the level of *A. junciformis* infestation which then determines the cost and level of difficulty of eradication. If a pasture is infested, reverting it to its original state is more costly and difficult than maintaining pastures that are still in a good condition (Morris et al., 1992). Mowing, burning and grazing are fairly inexpensive while herbicide application may be more expensive and more labour intensive in terms of applying the herbicide. A major factor that needs to be taken into consideration is the timing of implementing and ending the graze and the timing of the herbicide application. The timing is important to reduce the level of collateral damage (personal observation) on surrounding vegetation. Since the NPMT pose more disadvantages than advantages it is believed that implementing more than one technique may be more successful since grasslands are complex and interconnected systems.

The main aim of this study is to identify a technique that will help manage and control *A. junciformis* in pastures dominated by *A. junciformis* and thus to identify a way to eradicate it. The impact of two mentioned selective techniques (fire and selective grazing, to induce height differences between palatable species and *A. junciformis*, followed by herbicide application) together will be analysed by observing the effects these techniques have on pastures dominated by *A. junciformis* and the effects this will have on the basal cover and relative abundance of the dominant *A. junciformis* tufts. Further, the effects of the combined selective techniques will be compared to a non-selective technique, namely a short duration HDG. Both treatments will be compared to a control, all of which will be burnt prior to the application of the techniques.

Another aim of this study is to determine whether implementing a HDG early in the growing season will reduce the competitive potential of *A. junciformis* in relation to surrounding species. It is hypothesised that the short duration, HDG will have no effect on the dominance and abundance of *A. junciformis*-dominated pastures and therefore that the use of selective techniques will reduce the relative abundance of *A. junciformis* and allow the relative abundance of other grass species to increase. It is predicted that herbicide application, following a selective graze to induce height differences, will be most successful in reducing the relative abundance of *A. junciformis*.

1.1 Rationale for the research (nature and scope)

Because *A. junciformis* is such a persistent, indigenous weed (Edwards et al., 1979) that threatens livestock production in communal grazing areas and in the agricultural production of South Africa, it is vital that a focused management technique is identified that will help manage and control pastures and veld that are prone to infestation by *A. junciformis* or are already dominated by it. Most research attempting to manage or control *A. junciformis* has thus far met with limited success. The current research aims to fill some gaps that still exist in the available literature and to identify a focused management technique that will help control and manage *A. junciformis* in veld and pastures on which livestock production is dependent. It is anticipated that the results of this research will open the door for further research and to ultimately improve livestock production.

1.2 Justification

This project may provide baseline information for *A. junciformis* infested veld and pastures and may give insight on how to improve the veld condition using targeted disturbance techniques, where primarily non-selective disturbance techniques have been used in agricultural veld management. Further, the project provides experimental evidence on the effect of selective disturbance treatments on the growth vigour and mortality of *A. junciformis*. Selective and non-selective disturbance treatments will be investigated to determine their respective impacts on the environment, their ease of application and usefulness for management and control of *A. junciformis*.

This project will provide evidence of the soil seed bank, which is indicative of the potential aboveground vegetation we may expect, if the *A. junciformis* tufts were better managed and possibly eradicated, to yield the germination of more palatable species, such as *T. triandra*, thus maximising agricultural production. Further, the project provides experimental evidence on the effect of selective disturbance treatments on the growth, vigour and mortality of *A. junciformis* tufts, where primarily non-selective techniques, such as fire, have been used in the past. Finally, the project provides experimental evidence of the effect of defoliation on re-growth rates of *A. junciformis*, enabling us to better understand management and control of *A. junciformis*, to allow desired palatable species to become dominant instead.

1.3 Aims

The main aim of this research study was to identify a practical management technique that is successful in controlling and managing *A. junciformis*. Other aims of the study include:

- identifying the impact of herbicide on the basal cover and relative abundance of *A. junciformis*;
- determining whether implementing a HDG early in the growing season will reduce the competitive potential of *A. junciformis* in relation to surrounding species;
- comparing the response of *A. junciformis* to severe defoliation in relation to undefoliated *A. junciformis* tufts;
- determining whether the belowground seed population is similar to the aboveground sward and
- determining whether or not *A. junciformis* suppresses colonisation of other species.

1.4 Objectives

The objectives of the study were:

1. To compare the effects of a selective technique (lenient graze followed by targeted herbicide application), a non-selective technique (HDG) and a control (only burned) on the mortality of *A. junciformis* and on the relative species composition in the sward to better understand how to reduce the abundance of *A. junciformis*.
2. To compare the effects of HDG to an ungrazed control on the regrowth and productivity of *A. junciformis* and on the relative cover abundance in the sward to better understand how to reduce the abundance of *A. junciformis*.
3. To compare seedbanks before and after treatment application in high, medium and low *A. junciformis* infestation levels.

1.5 Outline of dissertation structure

This dissertation is divided into eight main chapters. The overall outline and structure of the dissertation are presented as follows:

Chapter One: Introduction

This chapter introduces the project by providing an overview of the selective and non-selective techniques that have been used to control and manage *A. junciformis* in the past and outlines key themes that will be addressed further in the dissertation. The rationale as well as the justification, the aim and objectives of the research are presented in this chapter.

Chapter Two: Literature Review

The second chapter provides a review of the available literature for which both published and unpublished sources have been used. The available literature provides an understanding of the physiology and thus the ecology of *A. junciformis* to improve the general understanding of its behaviour under different management systems. Furthermore, the literature review provides an insight into the gaps that still exist within the available information.

Chapter Three: Methods and Materials

The third chapter provides information on the study site; the bioclimatic conditions that exist in the area, past research that has been conducted on the site and the agricultural changes that have been observed over time. The research design is described in this chapter as well as the tools used.

Chapter Four: Results of the survivorship of *A. junciformis* after HDG and herbicide application

This chapter presents the results of the effects of treatments (HDG, herbicide application and control) on the survivorship of *A. junciformis*. The results in this chapter are presented in the following order: 3.4.1 Survivorship of *A. junciformis* tufts under a HDG, herbicide and under a control and 3.4.2 Changes in the species composition in the field before and after treatment (HDG, herbicide application and control) implementation.

Chapter Five: Results of the productivity of *A. junciformis* after HDG and herbicide application

This chapter presents the results of the effects of treatments (HDG, herbicide application and control) on the productivity of *A. junciformis*. The results in this chapter are presented in the following order: 4.4.1 Distribution of grazing intensity for all paddocks; 4.4.2 Distribution of grazing intensity within each paddock; 4.4.3 Tuft height regrowth pattern of *A. junciformis* under control and HDG; 4.4.4 Treatment effect on regrowth height and biomass and 4.4.5 Treatment effects on species cover composition.

Chapter Six: Results of the effects of treatments on the seedling emergence

This chapter presents the results of seedling emergence in a seedbank study in a greenhouse and in the field. The seedbank study analyses the effect of aboveground *A. junciformis* density on the seedbank. The field study analyses the effects of treatments (HDG and control) on the seeedling emergence after treatment application. The results in this chapter are presented in the following order: 5.4.1 Seedbank studies – the total number and species composition of seedlings germinating from the seedbank; 5.4.2 Seedling emergency study – the total number and species composition of seedlings emerged in the field experiment, the pattern of emergence over time in total seedlings, *A. junciformis* and other grasses, the effect of treatments on total seedlings, *A. junciformis*, and other grasses that emerged and the effect of treatments on the overall species composition of emerged species.

Chapter Seven: Discussion

The discussion chapter discusses the results showing which areas of the study were successful and which were unsuccessful, based on the methodology applied and the characteristics of *A. junciformis* and other grass species on the study site. Some recommendations are made on how the effectiveness of the tools and methodology used could be improved for future research. Management suggestions are discussed for veld infested with *A. junciformis* and veld prone to infestation by *A. junciformis*. Finally, future research avenues are outlined.

Chapter Eight: Conclusion

The dissertation concludes with the findings of the research that link back to the hypotheses, aims and objectives provided in the first chapter.

2 Chapter Two: *Aristida junciformis* - an indigenous weed

2.1 Introduction

Aristida junciformis is a grass species indigenous to South Africa. Despite its value in stabilising soil, thereby preventing soil erosion, and capturing water in catchment and overgrazed areas (Van Oudtshoorn, 2012), this Increaser III species (indicative of selective grazing (Van Oudtshoorn, 2012)) is most commonly associated with poor or incorrect grazing or fire management (Edwards, 1981). It is reputed to be an aggressive indigenous invader (Johnson, 1989) and an unusable weed (Edwards et al., 1979). Its reputation is the consequence of the observed changes it brings with its establishment. These are its high level of unpalatability (Van Oudtshoorn, 2012), its ability to reduce the grazing capacity of the veld (Johnson, 1989; Venter, 1968) and the difficulty associated with managing and controlling it once it has established and its associated persistence (Johnson, 1989). One other feature is its ability to alter the species composition of surrounding vegetation at the expense of other grass species (Johnson, 1989) such as *Themeda triandra* Forssk., a grass vital for livestock and associated veld management as well as for conservation of biodiversity (Snyman et al., 2013). The impact and persistence of *A. junciformis* has serious implications for agricultural productivity and the natural environment (Ghebrehiwot et al., 2014), thus affecting the overall economy of Southern Africa.

Since it is so difficult to reduce the relative abundance of *A. junciformis* to minimise its negative impacts on livestock production, many efforts have been made to study and research it. Despite the efforts to create a better understanding of this grass to enable its eradication in infested areas, the available information is often fragmented, incomplete or unpublished and often not accessible and some of the research conducted is more than 100 years old. Furthermore, there is little indication that more investigations will be conducted to fill the gaps in knowledge and literature. The aim of this literature review is thus to fuse together the available information with the most recent literature to create a collective. The review will conclude with future research suggestions and how my research contributes to filling the knowledge gap.

2.2 Origin, classification, distribution and spread of *Aristida junciformis*

2.2.1 Origin and classification

The globally-distributed grass subfamily *Aristidoideae* is subdivided into three genera namely *Aristida, Stipagrostis* and *Sartidia* (Cerros-Tlatilpa et al., 2011). The *Aristida* genus is not only the largest but also the most widespread (Cerros-Tlatilpa et al., 2011) comprising of about 270 different *Aristida* species (Hilliard, 1987). The genus name *Aristida* originates from the term arista, meaning awn in Latin (Schmitz-Ruch, 1968). The *Aristida* genus mainly occurs in the tropics and subtropics of both hemispheres (Hitchcock, 1924; De Winter, 1965) (Figure 2.1), its four main locations being in North America, Central and South America, Australia and Africa (De Winter, 1965; Cerros-Tlatilpa et al., 2011).

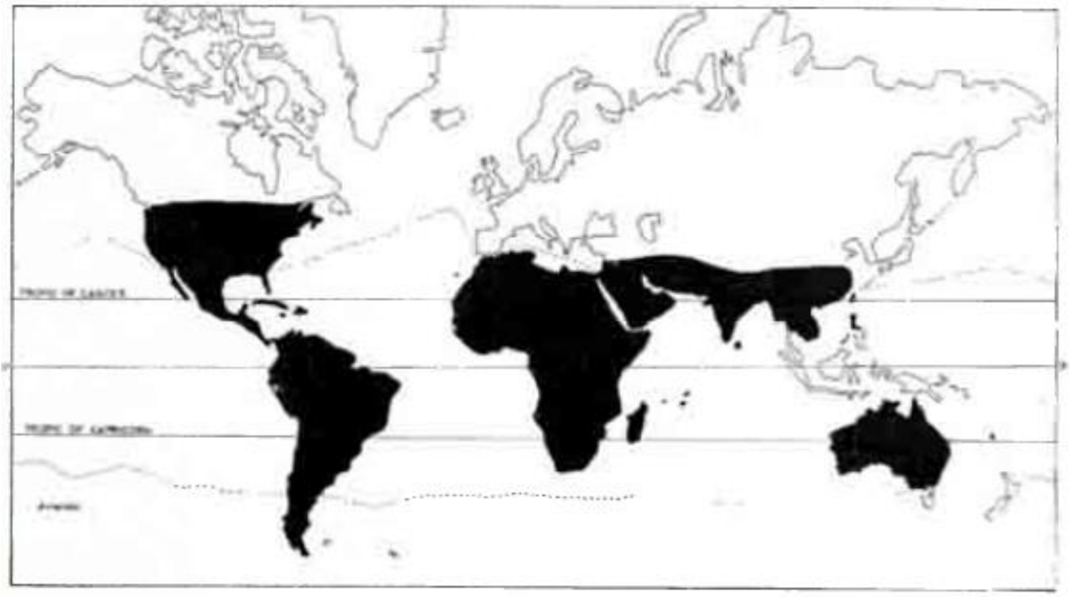


Figure 2.1 World Distribution of the *Aristida* genus (from De Winter (1965)).

A study of the North American species led to the classification of three *Aristida* sections: *Arthratherum, Chaetaria* and *Uniseta* (Hitchcock, 1924). The *Chaetaria* section has the widest distribution and the simplest floral structure and is thus considered to be the most primitive of the *Aristida* genus (De Winter, 1965). About 28 *Aristida* species - belonging to the *Chaetaria* section - are found in Southern Africa (Hilliard, 1987), one of which is *Aristida junciformis*. The species name *junciformis* means bulrush (junci) form (formis) in Latin (Latdict, Undated), though where this name originates from is unknown. *Aristida junciformis* has two subspecies: *Aristida junciformis* subspecies galpinii Stapf and *A. junciformis* Trin.et Rupr. subspecies junciformis, commonly known as wire or '*Ngongoni*' grass, which is the focus of this literature review.

2.2.2 Distribution

The distribution of *A. junciformis* prior to 1920 is uncertain (Van Zyl, 1998). A need to understand the distribution and spread of *A. junciformis*, its dominance and persistence and how to manage it and be able to revert *A. junciformis*-dominated veld back to its original veld condition has long been identified (Johnson, 1989). It is therefore important to understand why *A. junciformis* grows where it grows to be able to manage its spread.

It occurs in the tropical and subtropical areas as these are warm and wet rather than cold and dry (Van Zyl, 1998). *Aristida junciformis* usually grows on North-facing slopes (Johnson, 1989). It can generally be found in areas that receive between 250 – 750 mm rainfall annually and have relatively warm winter months (De Winter, 1965). It is of no surprise that *A. junciformis* is endemic to Africa, which hosts the ideal climate. It occurs from southern to East Africa (Van Oudtshoorn, 2012; Fish et al., 2015) (Figure 2.2) and can be found in Nigeria, the Republic of the Congo, the Democratic Republic of the Congo, Tanzania, Kenya, Zambia, Malawi, Angola, Namibia, Zimbabwe, Botswana, Lesotho, Swaziland, South Africa and Madagascar. In areas, such as Namibia or Angola, which receive less than 750 mm of rainfall a year, *A. junciformis* will generally only grow in areas where rain water can collect in the rainy season and prevail for an extended period (De Winter, 1965). Consequently it does not extend its distribution into dry areas which experience low rainfall (De Winter, 1965).

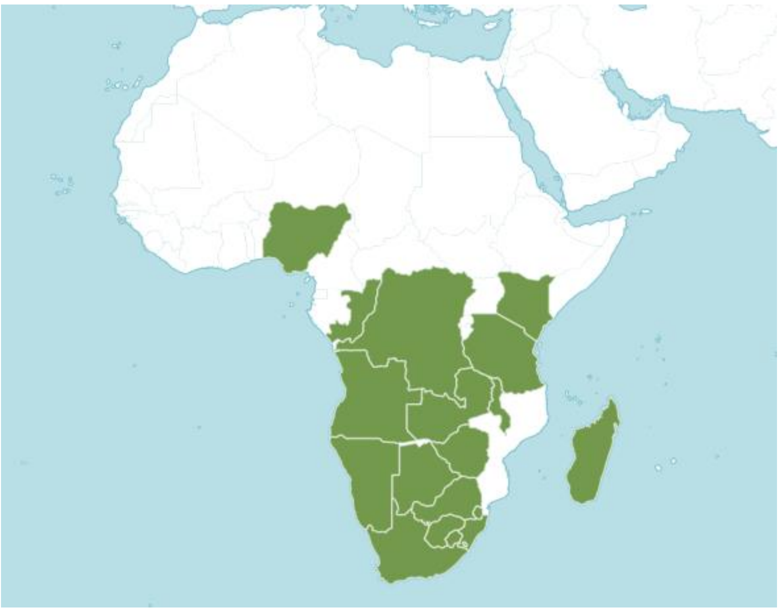


Figure 2.2 The distribution of *Aristida junciformis* in Africa (from Plants of the World online; accessed 30.07.2018).

According to Edwards et al. (1979) *A. junciformis* is found in all nine provinces of South Africa, covering about 17% or 200 000 km^2 of the country (Figure 2.3). In South Africa, *A. junciformis* subsp. galpinii is found in montane sourveld where annual precipitation is high (De Winter, 1965), while the distribution of *A. junciformis* subsp. junciformis is more extensive and can be found in Highland Sourveld, Southern Tall Grassveld (similar to the Tallgrass Prairie of America), *'Ngongoni'* Veld and Natal Mistbelt Ngongoni Veld (Acocks, 1988).

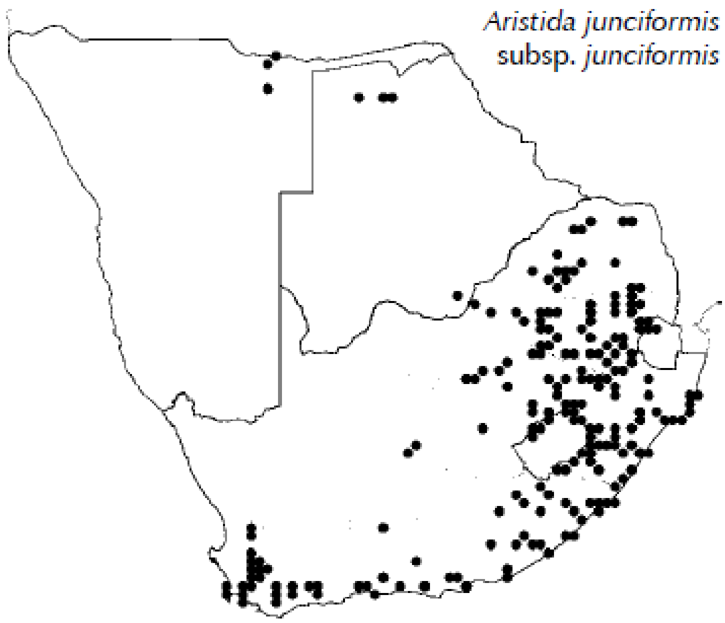


Figure 2.3 The distribution of *Aristida junciformis* in South Africa (from Fish et al. (2015)).

Aristida junciformis has an extensive distribution in KwaZulu-Natal. KwaZulu-Natal is a suitable location for the invasion of *A. junciformis* as it experiences warm, wet summers, where dry summers may limit its expansion (Johnson, 1989). Moreover the winters are not very cold. De Winter (1965) did not find any *Aristida* species in areas that experience very cold winters, indicating that temperature plays an important role in the distribution of *A. junciformis*. In KwaZulu-Natal, *A. junciformis* grows up to an altitude of about 1250m (Johnson, 1989).

2.2.3 The spread of *A. junciformis* in KwaZulu-Natal

It has been suggested that the grasslands, as we know them today, only existed as a successional stage, before being dominated by *A. junciformis* at the introduction and use of western agricultural practices (Bayer, 1955). Due to its prolific seed production, strong and deep root system and its high degree of unpalatability, *A. junciformis* was able to invade grasslands previously dominated by *Themeda triandra* (Van Zyl, 1998).

A review of the timeline of the encroachment of KwaZulu-Natal by *A. junciformis* revealed that it was absent from the Howick district and the experimental plots at the Cedara Agricultural Research Station about a century ago (Sawer, 1911). By 1930, it had begun to encroach plots that had not been burned following a heavy graze (Staples, 1930). Forty years later the experimental plots at the Cedara Agricultural Research Station were dominated by *A. junciformis* (Edwards et al., 1979). A similar pattern is observed in the long-term grassland trials conducted at the Ukulinga Research Station of the University of KwaZulu-Natal. When the long-term trials (Veld Burning and Mowing Trial and the Veld Fertilizer Trial) were established in 1950 by J.D. Scott, the veld was dominated by *Themeda triandra-Tristachya leucothrix* swards (Morris et al., 2001). Fifty years later, *A. junciformis* had established in the trials, though not dominant (Morris et al., 2001).

Overall, encroachment of KwaZulu-Natal by *A. junciformis* has taken place over the last eighty years (Edwards, 1981). It is interesting to note that the encroachment of *A.junciformis* is largely associated with poor veld management. The Southern Tall Grassveld is wedged between two *'Ngongoni'* veld types (Acocks, 1988), making it extremely prone to *A. junciformis* encroachment (Tainton, 1972a). Unfortunately, the encroachment and domination of *A. junciformis* is at the expense of other plant species (Van Zyl, 1998).

2.3 Characteristics

The characteristics of a plant determine its ability to reproduce, disperse, grow, compete with other plants and to tolerate environmental fluctuations as the characteristics are adapted to survivorship requirements (Fynn et al., 2011). In this section the characteristics of *A. junciformis* are described which give further insight into why this grass is able to become dominant in an area previously dominated by palatable species such as *T. triandra*. In each sub-section, a characteristic will be described according to the available literature and, where necessary, gaps in the available literature will be described in conjunction with recommended studies that could potentially be conducted.

2.3.1 Description of mature *Aristida junciformis* tufts

Aristida junciformis is a perennial (De Winter, 1965) climax grass that is densely tufted (Quattrocchi, 2006; Van Oudtshoorn, 2012; Fish et al., 2015) with many simple, wiry (De Winter, 1965) branched culms, though not at every node, that can grow up to 90 cm in length (Van Oudtshoorn, 2012; Fish et al., 2015). The culms are generally erect (Van Oudtshoorn, 2012; Fish et al., 2015), though they may often bend as they grow longer, with 3 or 4 dark nodes per culm (De Winter, 1965). The culms and nodes are hairless (De Winter, 1965). The ligules have a ring of hairs (Van Oudtshoorn, 2012; Fish et al., 2015).

2.3.2 Leaf morphology

Aristida junciformis leaves are rolled and narrow (0.1 – 0.3 cm wide) (Van Oudtshoorn, 2012), erect, almost needle-like (Fynn et al., 2005b) and can reach a length of up to 30 cm (De Winter, 1965; Van Oudtshoorn, 2012), though longer specimens have been identified (personal observation). The leaves are easily grazed in early summer when seedlings (De Winter, 1965; Quattrocchi, 2006) or regrowth emerge after a graze (Van Zyl, 1998). Once the leaves exceed a height of 30 cm, they are difficult to graze (Van Zyl, 1998). Furthermore, the leaves of *A. junciformis* are unpalatable, due to the distribution of lignin (Theron et al., 1966) resulting in high tensile strength of the leaves (Van Zyl, 1998). Tensile strength or mechanical strength is, according to Westfall et al. (1992), an important determinant for animal preference, as it improves the tolerance of a grass to trampling or grazing (Zhang et al., 2018).

According to a study by Theron et al. (1968b), which investigated the tensile strength of the leaves of 10 indigenous grass species, the force required to break the leaves of *A. junciformis* is 3000×10^{-3} dynes (the equivalent of 3×10^{-5} N) which is almost double that of the second strongest grass, *Tristachya hispida*, now known as *Tristachya leucothrix*. Furthermore, this study revealed that the tensile strength of most grass leaves increase steadily over the lifetime of the leaf (Theron et al., 1968b). In contrast, the tensile strength of *A. junciformis* remained constant throughout the duration of this study (Theron et al., 1968b). Its high tensile strength and its unpalatable leaves result in grazing avoidance thereby enabling it to increase its grazing tolerance.

Aristida junciformis has a high dry matter content of very low nutritional value and as a result thereof, has a grazing value (used to calculate veld condition scores) of zero (Morris, 2016). It has been estimated that the nitrogen content of the leaves is less than one percent while digestibility is less than 25% in mid-summer (Van Zyl, 1998). Furthermore, the leaves of *A. junciformis* do not become moribund unless they are constantly shaded (Van Zyl, 1998), thereby reducing tillering and leaf growth. *Aristida junciformis* is more tolerant to shade than *T. triandra* (Fynn et al., 2011). These characteristics make it unusable to livestock farmers (Quattrocchi, 2006).

Due to its fibrous and tough leaves, the grass has been called broom grass from the Afrikaans name 'besemgras' as it is often used to make brooms (Quattrocchi, 2006; Van Oudtshoorn, 2012). It is also used for weaving baskets (Traynor et al., 2010) or as a thatch grass (Kepe, 2005) It may also be used as an indicator of facultative wetlands (Traynor et al., 2010), in rehabilitation of denuded areas (De Winter, 1965) or areas previously used for agricultural purposes, though it has been established that it is a weak coloniser of transformed grassland if introduced vegetatively (du Toit, 2009).

2.3.3 Seed morphology and dynamics

The inflorescence (5 cm – 20 cm long, 1 cm – 8 cm wide) is comprised of a narrowly compacted panicle (De Winter, 1965; Van Oudtshoorn, 2012) consisting of spikelets that may be compacted or open and can be between 2 cm – 3 cm long (Van Zyl, 1998; Fish et al., 2015) if the awn length is included (De Winter, 1965). The lower glume of each spikelet (sheath of the seed) is about $^{2}/_{3}$ the length of the upper glume (Van Zyl, 1998). The lemma and column (9 cm) is linear-lanceolate in shape and has no articulation (De Winter, 1965). Each spikelet consists of a tri-partite awn (Quattrocchi, 2006) (Figure 2.4). The central awn (1.2 cm – 3.5 cm) is longer than the lateral awns (0.9 cm – 2.8 cm) (Van Zyl, 1998). The callus (seed tip) has beard-like barbs that point in the opposite direction of the swollen and naked callus tip (Van Zyl, 1998) (Figure 2.5).

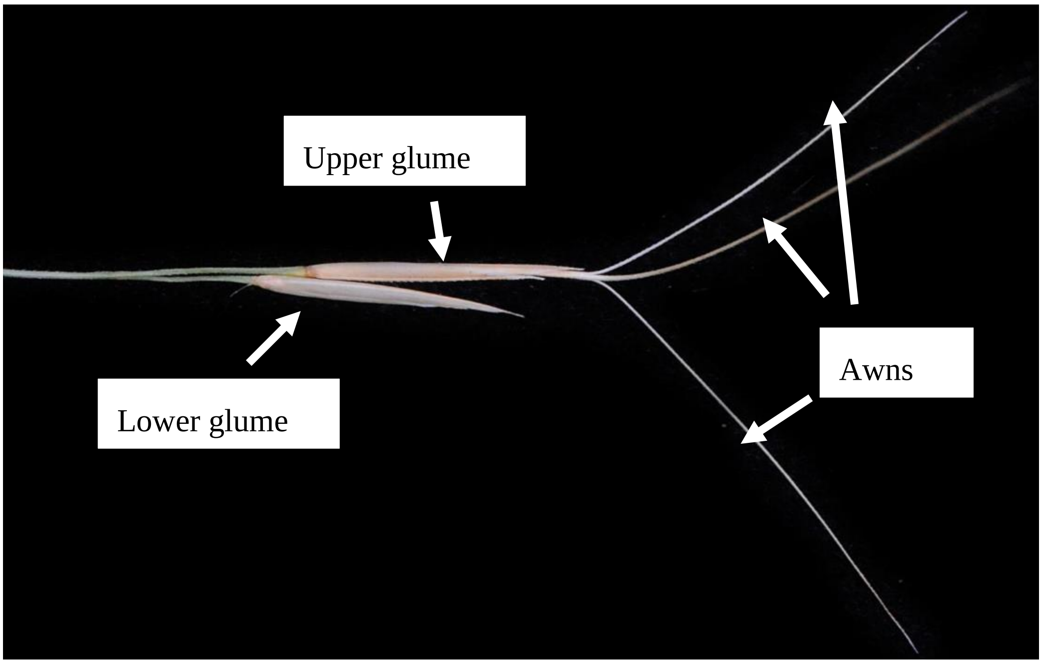


Figure 2.4 A single tri-partite *Aristida junciformis* subsp. *junciformis* awn (from Plants of the World online; accessed 30.07.2018).

Figure 2.5 Illustration of the caryopsis of *A. junciformis,* subsp. *junciformis* (Magnification × 6) (from Van Zyl (1998)).

The awns are used for orientating the caryopsis in its dispersal from the parent plant to a suitable microsite where it may be able to germinate (Van Zyl, 1998). The awns of *A. junciformis* are considered to be a pest in sheep-farming as they get entangled in the wool of sheep (De Winter, 1965). The sharp calli of the awns can penetrate through socks (personal observation) and through animal skin causing irritation (De Winter, 1965). If this irritation leads to the deterioration of the animal condition, it can have serious economic impacts.

According to Edwards et al. (1979), *A. junciformis* sheds its seeds from March to April. A single *A. junciformis* tuft can produce between 18 000 (Venter, 1968) and 19 000 seeds though only about 60% of these seeds are viable (Van Zyl, 1998). Venter (1968) discovered that seed viability was affected by seasonality. Viability of seeds collected in May (42%) was greater than for seeds collected in June (28%) (Venter, 1968). The viability of seeds collected in June decreased after a year (16%), whereby that of the seeds collected in May did not change after a year (Venter, 1968).

It is crucial that the orientation of the caryopses is correct, for germination to occur. Van Zyl (1998) discovered that germination was greatest if the caryopses landed in a vertical or upright position (67%) with the callus in the soil rather than falling horizontally (35%) or with the awns in the soil (1%). Ghebrehiwot et al. (2014) found that the *A. junciformis* plant possesses strong allelopathic potential, allowing the germination of *A. junciformis* seeds but almost completely inhibiting root or shoot growth of other grass species, consequently allowing *A. junciformis* to dominate natural grasslands. Germination is enhanced by removing the glume (Van Zyl, 1998) and by applying smoke-water treatment as described by Ghebrehiwot et al. (2009), suggesting that fire may encourage germination. Germination of *A. junciformis* seeds is inhibited by dead tillers producing a thick mulch on the soil surface (Van Zyl, 1998). However, the thick mulch may, if undisturbed, allow *A. junciformis* tufts to become completely dominant (Fynn et al., 2011) and may result in the increased abundance of dicotyledonous species such as *Rhus dentata*, Seringa (*Melia azedarach*) and wattle (*Acacia decurrens*), which are all woody species, if left undisturbed (Van Zyl, 1998).

Seed density is positively correlated with the density of flowering adults, and the number of seedlings is positively correlated with the number of seeds, declining in a leptokurtic manner within a 10 meter radius from the parent plant (Van Zyl, 1998). Seedling survival is fairly low – only about 13% of all seedlings survive into the following spring (Van Zyl, 1998), provided they are not grazed.

2.3.4 Root systems and soil interaction

There are very few root studies in the available literature specific to *A. junciformis*. Some studies have investigated the response of *A. junciformis* roots to metal pollution (Johnson et al., 1991) and the response of *A. junciformis* root growth to varying canopy treatments (Venter, 1968; Van Zyl, 1998; Ghebrehiwot et al., 2006). Consequently, very little is known about the roots of *A. junciformis* and it seems as if little effort has been made to conduct further studies to enable further and more detailed understanding.

The little that is known about the effect of soil type on the distribution of *A. junciformis* is that it grows in well-drained, dystrophic (oxygen poor and often acidic) (Ghebrehiwot et al., 2006) and infertile (Fynn et al., 2005b) or nutrient poor soils (e.g. sandy, clayey, stony or shallow soils (Fish et al., 2015)) with a low phosphorus content (Johnson, 1989). It has a high tolerance for aluminium (Fey, 1981).

Understanding of root growth was improved when Venter (1968) discovered that the *A. junciformis* plant has two apparent root systems. One system is well divided and is able to penetrate through the soil profile while the other system consists of thick, branched roots with a more narrow distribution (Venter, 1968). The latter system may consist of numerous rhizomes growing into the soil from the grass crown, producing more roots (Venter, 1968). Unfortunately, there are no pictures available in the literature to illustrate these differences. Why these two systems exist and the purpose of the existence of either root system is unknown.

The little that is known is that the roots are strong (pers. obs), thick and sponge-like (De Winter, 1965) and can grow up to 2m deep (Johnson, 1989). Its long root system may be beneficial in rehabilitation projects as it can stabilise the soil to prevent soil erosion, though it has been established that *A. junciformis* seedlings are poor colonisers of denuded areas (du Toit, 2009). The root characteristics combined with the dense basal area that *A. junciformis* is known to exhibit, have led to the conclusion that the roots may be a buffer to the plant when burning (Van Zyl, 1998) and enhances our understanding of why this grass is difficult to eradicate once it has become established. Ghebrehiwot et al. (2009) discovered that the shoot and root length of *A. junciformis* seeds that had been exposed to smoke-water treatment at 35°C was greater than under lower temperature or under the control in which seeds were only exposed to distilled water. It has also been discovered that intense and frequent defoliation restricts root growth (Venter, 1968) as the nutrients are channelled into producing new tillers (Van Zyl, 1998).

Weeds are known to alter the microbial community of the soil (Kourtev et al., 2002). *Aristida junciformis* is able to modify the soil pH and the number of cation exchange sites available by excreting exudates from the roots (Johnson, 1989). Furthermore, *A. junciformis* is able to tolerate and withstand high concentrations of soluble aluminium in the soil (Johnson et al., 1991). These characteristics enable it to alter the microbial community of the soil to inhibit the growth of other species growing in close proximity thus allowing it to become dominant (Van Zyl, 1998). As the pH of the soil increases so does the clay content - which *A. junciformis* favours - thus allowing it to increase its cover and abundance (Johnson, 1989). As Van Zyl (1998) describes it, the influence of the *A. junciformis* roots on the soil creates competition that prevents other species accessing the necessary resources. Those species that are able to survive the competition are often grazed. If grazed, these species use their root reserves to produce new tillers which results in the root volume shrinking, thus giving *A. junciformis* a competitive advantage that ultimately leads to its dominance.

2.3.5 Cytology and Embryology

According to De Wet (1958), determining the position of the *Aristida* genus is problematic. One such reason could be the fact that the nucleolus of the *Aristideae* persists into early metaphase – a feature it shares with the *Eragrosteae, Pappophoreae* and the *Sporoboleae* tribes (De Winter, 1965). However, the *Aristida* genus exhibits some characteristics which differ to those from the other tribes, that have enabled its classification into the *Aristideae* tribe and thus the *Aristida* genus. Polyploidy is one such feature. According to De Winter (1965), polyploidy among grasses is uncommon and seems to be limited to the *Aristida* genus – one of the most primitive sections of the *Aristideae* tribe. Recent research has shown that polyploidy is, however, common and widespread among grass families and genera (Levy et al., 2002), indicating that more research is probably required to update our knowledge with regards to the *Aristida* genus.

According to De Winter (1965), most *Aristida* species are diploids. *Aristida junciformis* is a tetraploid plant (2n = 44) (De Winter, 1965). *A. junciformis* has a chromosomal number of 11 which seems to be typical of the *Aristida* genus (De Winter, 1965). However, *A. junciformis* has also been noted to be one of six *Aristida* species in which chromosomes do not always exist in multiples of 11 (De Winter, 1965). In fact, it was found that *A. junciformis* chromosomes can exist in multiples of 12 (De Wet, 1954) or even in multiples of 13 (De Wet, 1958).

Based on cytology and leaf anatomy, the *Aristideae* tribe should be separated from the *Stipeae* tribe and should be removed from the subfamily *Eragrostoideae* (De Wet, 1958). This decision is supported by De Winter (1965), who highlights the differences between the *Eragrostoideae* and *Aristideae* tribes as shown in Table 2.3.5.1.

Table 2.1 A comparison between the *Eragrostoideae* and *Aristideae* tribes

Aristideae	*Eragrostoideae*
Lemmas: tightly clasp the grain	Lemmas: membranous and loosely clasp grain
Lodicules: elongate, fleshy base, membranous and obtuse apex	Lodicules: short, fleshy, truncate – usually with a small lateral horn
Epiblast: absent	Epiblast: present
Hilum: linear; more than half the grain length	Hilum: punctiform and basal
Epidermis cells: dumb bell-shaped or subcircular	Epidermis cells: kidney-shaped
Basic chromosome number: 11	Basic chromosome number: 7, 8, 9, 10, 12

The only problem with the conclusion that the *Aristideae* tribe should be separated from the *Stipeae* tribe and should be removed from the subfamily *Eragrostoideae*, is that it does not lead to the conclusion of its relation to the subfamily *Eragrostoideae* or the *Stipeae* tribe and thus to its classification (De Winter, 1965). Due to advances in understanding and technology, Cerros-Tlatilpa et al. (2011) were able to reconstruct the phylogenetic relationship among the *Aristida* species and between the *Aristida* species its relatives, using a non-coding chloroplast and nuclear DNA sequences. In addition to creating a phylogenetic reconstruction, Cerros-Tlatilpa et al. (2011) were able to date the origins, radiations and splits of lineages. This information is beyond the scope of this review.

The study of plant fertilization from two separate reproductive cells into a single cell and the development of an embryo is known as embryology. In contrast to most grass tribes there is barely any literature available on the embryology of the *Aristideae* tribe (Bhanwra, 1988). While only some progress has been made to describe the embryology of the *Aristideae* tribe (Bhanwra, 1988), the embryology of some *Aristida* species such as *A. contorta* (Mott, 1972) and *A. adscensionis* (Bhanwra, 1988) have been described.

De Winter (1965) provides a general embryonic description of the *Aristida* genus. They have no epiblast (outer layer of the embryo), but have a deep cleft between the coleorhiza (protective sheath around the radicle) and the bottom of the scutellum (modified seed leaf) (De Winter, 1965). The vascular strand diverges below the bottom of the coleoptile (sheath protecting emerging grass shoot tip) with a thickened internode leading up to the base of the coleoptile (De Winter, 1965).

The embryology of *A. junciformis* is poorly described in literature. Some embryonic features of *A. junciformis* that it has in common with the *Aristida* genus are that the embryo is about $^{1}/_{3}$ - $^{1}/_{2}$ the length of the caryopsis grain and is found on the ventral side of the caryopsis (De Winter, 1965). The hilum (scar indicating initial attachment point to the parent plant) is linear (De Winter, 1965). The pericarp (seed wall) is tightly attached to the caryopsis (De Winter, 1965). Unfortunately De Winter (1965) has not provided illustrations depicting his descriptions.

2.4 Morphology and flowering

The morphology and flowering process of *T. triandra* has been described quite extensively (Snyman et al., 2013). In contrast, the morphology and flowering process of *A. junciformis* has been described vaguely such that many research opportunities still exist. *Aristida junciformis* flowers from November to May (Van Oudtshoorn, 2012; Fish et al., 2015), the inflorescences generally appear in November. What triggers floral initiation is still unclear. Opperman et al. (1978) designed an experiment to determine whether soil water triggers floral initiation in *T. triandra* and found this to be true. A similar study could be conducted to determine whether it is the photoperiod, soil water or temperature that triggers floral initiation. What is known is that the flowering time of *A. junciformis* is dependent on day-length (Van Zyl, 1998).

Before emerging as a tiller in January, the terminal bud of an *A. junciformis* tiller remains at a height of less than 5 cm above the soil surface (these may be grazed at the young seedling stage (Van Zyl, 1998)) and grows slowly thereafter due to their low specific leaf area (Fynn et al., 2011). In places where early spring rains are experienced, *A. junciformis* begins to grow before species such as *T. triandra*, (Van Zyl, 1998), which may be one reason why *A. junciformis* seedlings are grazed initially. It is estimated that the *A. junciformis* bud grows at a rate of 0.6 m (Venter, 1968) a day, which is much slower than a *T. triandra* bud which grows about 2 cm a day (Van Zyl, 1998).

From March to April, the seeds mature (Van Zyl, 1998) and are shed (Edwards et al., 1979). It is unknown what triggers seed shed. With the exception of the rainfall range in which *A. junciformis* grows (500 – 1500 mm), little else is known about the rainfall requirements to promote germination. Van Zyl (1998) did find, however, that germination is highest where the seeds are imbibed in the dark at a constant temperature of 25°C.

Prior to the study by Venter (1968) little was known about the roots and tiller production in *A. junciformis.* It is still unclear, what triggers tillering. Van Zyl (1998) discovered that seedlings produced the most tillers if there was no competition with other species and that competition reduced tiller production, especially if there was a high density of adult *T. triandra* plants (Van Zyl, 1998). Unfortunately, a high density of adult *T. triandra* plants also affected the degree of tiller production in the *T. triandra* seedlings (Van Zyl, 1998). The ultimate finding of the study was, however, that a 46% reduction in tiller production of *A. junciformis* and *T. triandra* was observed when subject to root competition only (Van Zyl, 1998). This may be related to the response of adult plants to the frequency of defoliation, since defoliation results in the redirection of resources from the roots into the canopy to enable the production of new tillers (Van Zyl, 1998).

2.5 Ecophysiology and production

Ecophysiology has been described as the response of a plant to changes in its environment. More and more studies are focused on the ecophysiology of plants with expected climate change. The *Aristidoideae* species are C_4 grasses. C_4 grasses have developed ecophysiological traits that influence plant performance (Taylor et al., 2014). Fundamentally, all C_4 grasses share the same biochemical CO_2 pump (Taylor et al., 2014). It eliminates O_2 competition by increasing the concentration of CO_2 on the active site of Rubisco in the photosynthetic chloroplasts, thus eliminating competition of photorespiration and allowing photosynthesis to occur at higher temperatures (Taylor et al., 2014). Three subtypes of the C_4 biochemical pathways exist, namely NAD-ME (nicotinamide adenine dinucleotide-malic phosphate enzyme), NADP-ME (nicotinamide adenine dinucleotide-malic enzyme) and PCK (phospoenolpyruvate carboxykinase). Most *Aristidoideae* species that use the NADP-ME pathway are most commonly found in areas in which they may experience minimal water stress (Ellis et al., 1980). Consequently, this system is most effective in areas experiencing a warm and moist climate. Most C_4 grasses are adapted to high temperatures and low rainfall (Johnston, 1996), and thus inhabit the more arid environments (Venter, 2015). *Aristida junciformis* is thus able to live in either a warm and moist or arid environment. Irrespective of the distribution and functionality of the grasses, they are all at risk with expected changes in the rainfall patterns in southern Africa (Taylor et al., 2014; Venter, 2015).

Venter (2015) conducted a study to determine the effect of drought on the ecophysiology of selected C_4 photosynthetic *Panicoideae* and *Aristidoideae* grasses. More than one *Aristidoideae* grass was used to identify the differential responses to drought among subtypes and lineages (Venter, 2015). *Aristida congesta, A. diffusa* and *A. junciformis* were used to represent the *Aristidoideae* grasses. The gas exchange, chlorophyll fluorescence and leaf water relations were measured periodically during and after the simulation of a drought for almost two months. The results led to the conclusion that the *Aristidoideae* grasses are more drought tolerant than the *Panicoideae* grasses (Venter, 2015). The *Aristidoideae* grasses recovered the quickest, maintained a higher leaf water status during the drought and had lower metabolic limitations, associated with osmotic adjustment, than the *Panicoideae* grasses (Venter, 2015). Differences were noted in the metabolic limitation mechanisms between the species. It was found, for example, that the photosynthetic rate of all *Aristidoideae* grasses increased progressively with an increase in intercellular CO_2 concentration (Venter, 2015). Between species, *A. junciformis* had greater mitochondrial respiration rates than *A. congesta* and *A. diffusa* but lower Rubisco activity (Venter, 2015). Relative stomatal limitations were higher for *A. junciformis* than *A. diffusa* (Venter, 2015). The average osmotic adjustment was highest in *A. diffusa*, second highest in *A. junciformis* and lowest in *A. congesta*, though *A. junciformis* and *A. congesta* had fairly similar values (Venter, 2015).

Apart from the study by Venter (2015), no other studies have yet been conducted to better understand the ecophysiology of *A. junciformis* specifically, especially in face of climate change. *Aristida junciformis* may be successful in dry and arid areas if climate change should lead to more arid and dry conditions. However, from previously mentioned literature (e.g. De Winter (1965)), it is known that *A. junciformis* prefers to grow in wet areas such as water catchments or areas with high rainfall. It is expected that climate change and global warming will affect rainfall patterns such that grasslands may be more prone to bush encroachment (Ward, 2005; O'Connor et al., 2014). It would therefore be interesting to see how *A. junciformis* responds to flooding or shading.

Van Zyl (1998) found that *A. junciformis* sward distribution is affected by a number of environmental factors and limitations. Firstly, monotypic *A. junciformis* swards expand until they reach a maximum, determined by environmental factors, at which point they may self-shade or experience tiller or intraspecific competition (Van Zyl, 1998). Permanent shading may result in the death of *A. junciformis* tufts (Van Zyl, 1998) as a consequence of a reduced photosynthetic rate or the loss of water through transpiration.

Van Zyl (1998) conducted four experiments to examine the germination response of *A. junciformis* seed to light and temperature. Altering the amount and type of light can change the microenvironment (Van Zyl, 1998), affecting the ecophysiological functioning of the grass. This can be done by grazing or burning grass canopies.

The first experiment examined the germination response to different exposure times to red light after imbibition in the dark to simulate the removal of the grass canopy by defoliation or burning and to test whether the exposure length to red light was important for germination (Van Zyl, 1998). The results of the first experiment showed that germination was high for all treatments with no significant differences ($p>0.05$) between them (Van Zyl, 1998).

The aim of the second experiment was to determine whether *A. junciformis* seed is sensitive to changes in red and far-red light ratios (Van Zyl, 1998). To simulate this, seeds were imbibed in darkness for 24 hours after which some seeds remained in the dark, some were exposed to red, far-red light or both and then returned to the dark (Van Zyl, 1998). Germination was compared after 2 weeks (Van Zyl, 1998). It was found that there was no meaningful difference between the treatments exposed to light after imbibition, though the seeds that remained in the dark experienced higher germination, though not much different from the other treatments (Van Zyl, 1998).

The third experiment aimed to simulate seeds lying dormant on or in the soil before and after canopy removal (Van Zyl, 1998). *Aristida junciformis* seeds were imbibed either in darkness or far-red light for different time periods after which some seeds were exposed to red light and others not (Van Zyl, 1998). The lowest germination was observed in seeds exposed to far-red light for 72 hours with no exposure to red light again, while the highest germination was observed in seeds that remained in the dark for 72 hours or seeds that were exposed to far-red light for 72 hours followed by exposure to red light (Van Zyl, 1998).

The final experiment examined the germination response of *A. junciformis* seeds imbibed in darkness or light at different or constant temperatures, simulating temperature fluctuations experiences if exposed on the soil surface in relation to seeds under the grass canopy (Van Zyl, 1998). The highest germination, though not substantially different from the other treatments, occurred in treatments where seeds were imbibed in the dark at a constant temperature of 25°C (Van Zyl, 1998).

The findings provide insightful information into the germination response of *A. junciformis* seeds yet there are other factors that also play an important role in seed germination. Availability of water seems to exert the greatest control over plant physiology (Noy-Meir, 1973), though temperature, nutrient stress and shading are important components controlling physiology of plants. Adaptations to drought for *A. junciformis* have not been investigated nor reported. The leaf morphology of *A. junciformis* could still be investigated by counting the number of stomata it has, for example, or how it is affected by a loss of soil water.

As far as production goes, the rapid increase or spread of *A. junciformis* can increase the amount of herbage produced, yet it is of little use since it is unpalatable (Tainton, 1972a). Farr (1992, as cited in Van Zyl (1998)) doubted whether it could produce 20 kg/ha of live mass gain in a year, calling it "one of the most useless veld grasses in our country". Added to this, the affected *'Ngongoni'* veld is often in very poor condition (Van Zyl, 1998). Unfortunately, there is not more information available on its production.

2.6 Ecological response to various environmental factors

The ecological aspects (leaf morphology, seed demography, root system, cytology and embryology, morphology and flowering and ecophysiology and production) and adaptive features of *A. junciformis* are summarised in Figure 2.6.1.

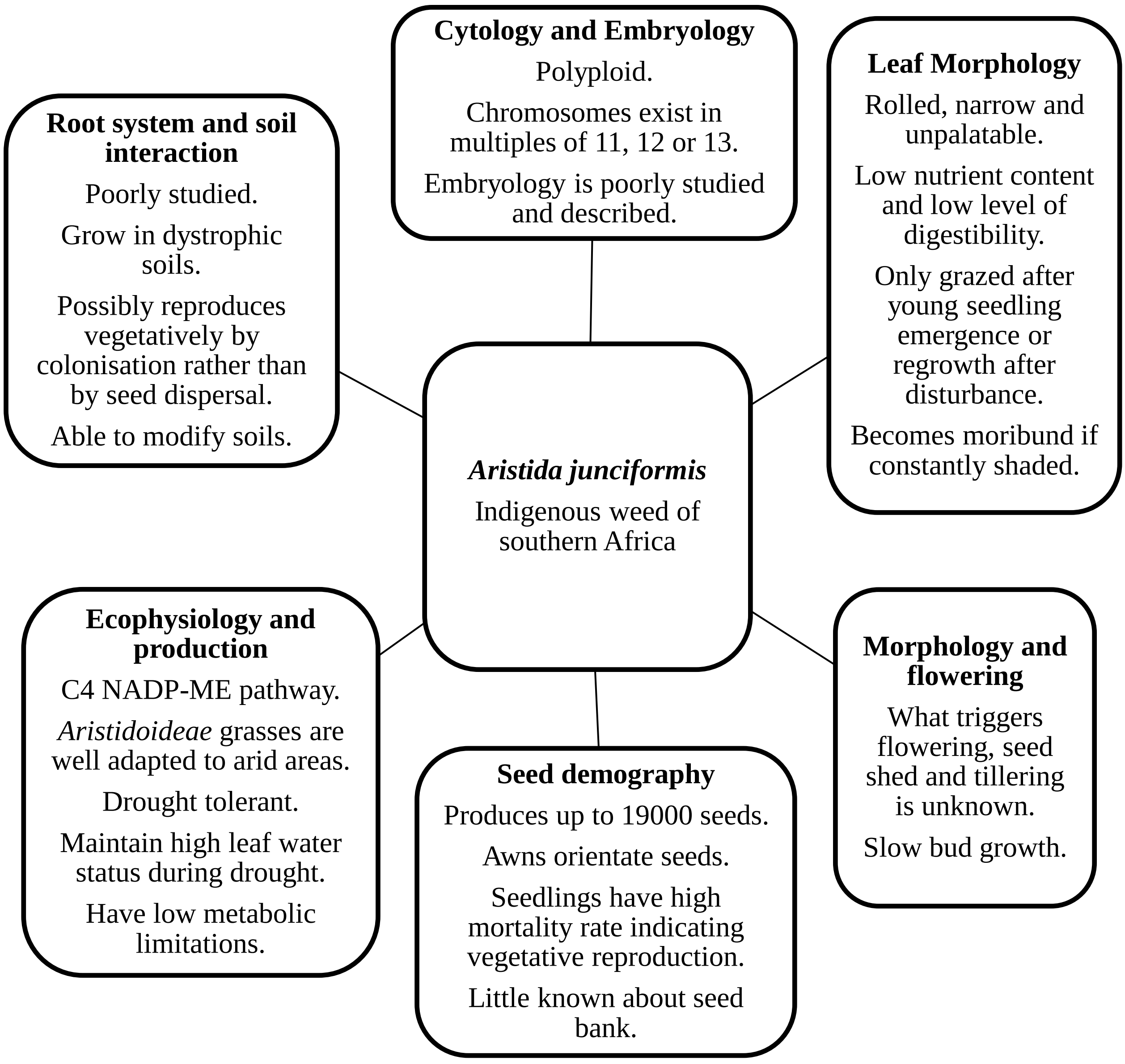


Figure 2.6 The ecological aspects and adaptive features of *A. junciformis*.

2.7 Forage quality, palatability and acceptability

There are a number of factors that affect the acceptability of pasture grasses. Young (1948) suggested an interrelated system consisting of three components, namely the conditioning of the organism, the response of the animal to nerve stimuli and the physical environment of the animal which determines the grass species that may be growing in its vicinity. Heady (1964) adds the type of animal as an additional factor, since different livestock animals have different feeding preferences. Physical characteristics of the available grass types determine whether the animal will forage on it or not. These factors include the overall nutritive value of the grass, the protein and sugar content, the absence or presence of lignin and crude fibres, the growth stage of the grass, the climate, the soil and the topography (Heady, 1964).

In reference to *A. junciformis*, the high cellulose or lignin content resulting in a low degree of digestibility (<25%) makes it a highly unpalatable grass for cattle and sheep, that is impossible to tear or break off (Stuart-Hill et al., 1982). It could, however, be grazed by members of the Equidae family such as horses, donkeys and zebras which bite the grass rather than tearing it out with their tongue and are hindgut fermenters which allow them to utilize forage of lower quality. However, evidence of grazing of *A. junciformis* by the Equidae family has not yet been described in literature.

Watson et al. (2011) and Weel et al. (2015) conducted studies using Mountain Zebra (*Equus zebra*) in the Bontebok National Park (BNP) and Baviaanskloof Nature Reserve (BNR) respectively. Watson et al. (2011) found that the zebra favoured areas which had been burned in the last 0 – 3 years before grazing, avoiding areas which had not been burned for more than 5 years. Further, Watson et al. (2011) calculated the suitability of the habitat based on the acceptability of the grass in relation to the distribution of zebra dung. In relation to *T. triandra* which was assigned an acceptability index value of 0.9, *A. junciformis* had an acceptability index value of 0.1 (Watson et al., 2011). It was discovered that the Habitat Suitability Index (HIS) and grass cover positively correlated with the distribution of zebra dung.

Weel et al. (2015) went further to reveal some interesting insights about the acceptability of *A. junciformis*. Mountain Zebras barely forage on *A. junciformis* (Weel et al., 2015). In winter it is not utilised at all (Weel et al., 2015), yielding it useless as a winter forage. Furthermore, the peak utilisation period of *A. junciformis* was found to be in early summer at which point its acceptability is the highest, declining to about a third of the acceptability level and thus reducing utilisation by late summer (Weel et al., 2015). Why the acceptability index value and utilisation of *A. junciformis* peaks in early summer is not described. Possible explanations could include regrowth or emergence of new seedlings in summer and the amount of water in the soil, though both sites experience winter rather than summer rainfall.

Of further concern is that valuable pasture grasses, such as *T. triandra*, are unable to provide the required energy and nutrition throughout the year (Snyman et al., 2013), as more and more veld is becoming dominated by *A. junciformis*. *Aristida junciformis* has almost no nutritive value and is not an important contributor to animal production like *T. triandra.* If production is reduced, so is the production of livestock which can have economic consequences. Particularly concerning is that *A. junciformis* does not become moribund, unless shaded, and probably reproduces vegetatively to outcompete other plant species and thus not only increases but also retains its dominance once it has been attained.

2.8 Influence of grazing, mowing and burning on *A. junciformis* and suggested management techniques

Species dynamics of the Southern Tall Grassveld are directly influenced by the available mulch, the soil nutrients and available moisture and are thus indirectly influenced by combinations of grazing burning and mowing (Morris et al., 1992). Understanding how these disturbances influence species dynamics and the vegetation composition (Morris et al., 1992) of a grassland is the key to appropriate grassland management. Maintaining or shifting a grassland back to its desired state may be costly and difficult (Morris et al., 1992). Insightful results of these interactions are provided by long-term studies (Morris et al., 1992; Fynn et al., 2005a), which influence management strategies. This section describes the responses of *A. junciformis* to grazing, mowing and burning**,** concluding with suggested management techniques for grasslands that are not yet dominated by *A. junciformis* as well as for *A. junciformis* dominated grasslands.

2.8.1 Grazing, Mowing and Clipping

A number of studies have been conducted to determine the effect of grazing on *A. junciformis* and the potential use of grazing in management of veld. Because of its extensive, strong and vigorous root system, Venter (1968) initially suggested that *A. junciformis* would be less sensitive and thus more resistant to defoliation than *T. triandra*. Instead Venter (1968) found that frequent defoliation and spring burning hinders the growth of *A. junciformis* in relation to other grass species. This is the first mention, as far as we know, of implementing a treatment early in the growing season, though there is no mention of early grazing. The second mention of implementing a treatment early in the growing season we were able to find was made by Westoby et al. (1989) who stated that it is possible that certain unpalatable grass species are more vulnerable to treatments such as grazing or burning early in the growing season than the surrounding palatable grass species and that making use of this knowledge, i.e. implementing a treatment at the right time, may force the grazing pressure off the palatable unto the unpalatable species. Westoby et al. (1989) did, however, mention that it is not well understood what exact amounts and/or sequences of applying a graze (or fire) could reduce the competitive advantage of unpalatable species, such as *A. junciformis*, without decimating the regeneration potential of surrounding palatable species. We know now that *A. junciformis* is grazed as a young shoot (Van Zyl, 1998) and that it grows slowly (Venter, 1968). We also know that a high density graze after the first spring rains is disadvantageous to *A. junciformis* (Morris et al., 1992), because it initiates growth in early spring, before *T. triandra* does, is more sensitive to defoliation than *T. triandra* (palatable grass species) and that defoliation can reduces its productivity, by up to 76% in the case of a heavy graze (Morris et al., 1993). This could be the result of reduced tillering, a reduced tiller growth rate and a reduction in average tiller size (Morris et al., 1993). Further studies could be conducted to determine what the impact is of implementing a heavy grazing at the beginning of the growing season and to determine the impact of severe defoliation on the roots of *A. junciformis* from which the tillers grow.

Morris et al. (1992) conducted a study to determine the response of *A. junciformis* to high density grazing, using sheep to implement a continuous graze at a high stocking rate. After removing the grazing pressure, they found that there was a switch in species dominance to *A. junciformis* (Morris et al., 1992). They concluded that through the disruption of continuous grazing at a high stocking rate by resting or burning, the invasion of *A. junciformis* was promoted leading to the ultimate conclusion that *A. junciformis* remains dominant under a stable burning and resting regime (Morris et al., 1992).

Unfortunately, no more studies have yet been conducted to determine the response of *A. junciformis* to continuous grazing at a high stocking rate. However, some studies have been conducted to determine the response of *A. junciformis* to mowing and clipping which can be considered grazing simulations. These have been conducted in consideration of the fact that *A. junciformis* is only grazed as a seedling (Van Zyl, 1998) and as a young shoot or only grazed by zebras and horses.

The response of a plant to defoliation depends on a number of factors, namely plant morphology, competition, duration and frequency of defoliation, season of defoliation and number of seasons defoliated. Defoliating neighbouring plants to reduce competition provides a competitive advantage for *A. junciformis*, especially since defoliation of surrounding plants reduces the impact of defoliation on *A. junciformis*, allowing it to continue growing while the other plants are defoliated (Venter, 1968). Defoliating neighbouring plants also increases the shoot yield of plants which are usually not defoliated (Morris, 2016). For *A. junciformis*, defoliating neighbouring plants led to an increase in shoot yield of over 700% (Morris, 2016). Interesting is that defoliation of *A. junciformis* by cutting results in a lower root mass (Morris, 2016). Further studies could be conducted to determine if resource partitioning is occurring.

As for frequency and season of cutting, not many studies are available. While reducing the basal cover and increasing the relative abundance of *T. triandra* over a long-term (Morris et al., 2001), regular cutting of perennial grass species changes the species composition (Fynn et al., 2005a). Summer mowing is known to increase the abundance of smaller grass species, such as *T. triandra*, and to decrease the abundance of taller grass species, such as *A. junciformis* (Traynor et al., 2010; Fynn et al., 2005a; Morris et al., 2001). Taller grass species such as *A. junciformis* favour annual mowing in winter or spring (Traynor et al., 2010; Fynn et al., 2005a).

2.8.2 Burning

Fire is a source of non-selective defoliation (Morris, 2016). According to Ghebrehiwot et al. (2009) there is a lack of understanding of the responses of germination and regeneration to fire. Two plant suites exist in southern African grasslands (Uys et al., 2004). One suite is tolerant of fire while the other is not (Uys et al., 2004). The mesic grasslands of South Africa are fire-dependent (Forrestel et al., 2014) for the development of vegetation (Zacharias et al., 1988) by controlling bush encroachment and removing moribund or unpalatable vegetation (Fynn et al., 2003) thereby maintaining diversity (Forrestel et al., 2014; Uys et al., 2004) and improving the nutritive value of the grasses (Morris et al., 2001). Fire also stimulates grass growth for some species (Fynn et al., 2003).

In fire-prone environments, seeds require a structure that will enable them to bury themselves, also known as a burial structure, to survive a burn (Zacharias et al., 1988). Grasses such as *A. junciformis* which do not have a burial structure may not germinate if exposed to fire unless the seeds have been buried prior to a burn (Zacharias et al., 1988). If *A. junciformis* seeds are buried prior to a burn they can escape the fire (Zacharias et al., 1988). Furthermore, *A. junciformis* seeds respond positively to smoke at temperatures of 35°C (Ghebrehiwot et al., 2009). Unfortunately, this does not explain why *A. junciformis* remains dominant in unburnt veld (Fynn et al., 2003).

The timing and frequency of burning affects transformation (Morris et al., 2001). There seems to be some disagreement among the literature about when to burn and how often, which is most likely linked to the ultimate goal of the management implemented. For example, if the goal is to promote species diversity, then it is appropriate to implement a burn at least every 2 to 3 years, according to the results provided from the long-term study conducted by Morris et al. (2001). If the goal is to maximise biomass production then it is appropriate to burn annually as this yielded almost double the biomass of the infrequently burned veld of the Tall Grassland Prairie (Benson et al., 2006). A requirement for managing *A. junciformis*-dominated veld requires a more specific understanding of the response of the grass to burning in relation to species that may surround it.

Fynn et al. (2003) discovered that burning in winter (i.e. outside the growing season) every year may increase the dominance of *T. triandra* (39%) more than for *A. junciformis* (1%). This seems to contradict the findings of Morris et al. (2001), who found that mowing in the summer before a burn will have little effect on species composition as will burning outside the growing season.

The findings of Forrestel et al. (2014) are that frequent fires may decrease the abundance of *A. junciformis* while Morris (2016), Ghebrehiwot et al. (2009), Van Zyl (1998) and Venter (1968) found that no burning or infrequent burning may result in tall and unpalatable grass species such as *A. junciformis* replacing short and palatable grass species such as *T. triandra* (Morris, 2016; Ghebrehiwot et al., 2009; Van Zyl, 1998; Venter, 1968).

Since only very few studies have been conducted, investigating the response of *A. junciformis* to burning in different seasons and at different times and frequencies, it is suggested that further studies be conducted. Studies that not only clarify why the findings of Morris et al. (2001) contradict those of Forrestel et al. (2014), but which also investigate what the effects would be if several management techniques were implemented in different seasons.

2.8.3 The Management Dilemma

Aristida junciformis is most commonly associated with mismanaged veld (Venter, 1968). Unfortunately, many areas are prone to be invaded by *A. junciformis*, which can have serious consequences for the economy since it degrades the veld condition and thus reduces the grazing capacity (Venter, 1968). Management of mesic grasslands is thus critical to prevent further spread and to control existing degraded grasslands. According to Venter (1968), small scale improvements are possible, though even under good management the veld may still become encroached by *A. junciformis*.

Keeping this in mind, management of veld invaded and dominated by *A. junciformis* becomes more difficult, especially considering that grassland interactions are complex and interconnected. Management of mesic grasslands can only be successful if management techniques are implemented appropriately. As far as I know, there are no studies analysing the consequences of interactive grassland management, i.e. studies are generally conducted only on grazing, mowing or burning. Further studies could be conducted to determine whether a combination of grazing, mowing and burning may be more successful.

Morris et al. (2001) make the following grazing management suggestions for the mesic grasslands to maintain the grasslands in good condition and to prevent further encroachment of *A. junciformis*:

1. To maintain grassland composition, rotational grazing is better than continuous grazing;
2. Disrupting a continuous graze should be avoided to prevent *A. junciformis* and other unpalatable grasses invading and
3. There is no difference between multi-camp grazing or grazing on a few camps only if a rotational grazing system is implemented.

These suggestions are useful but make no mention of implementing fire nor when to graze and support their suggestion that more studies should be conducted to understand effects of mowing and burning and the consequence of these interactions on species diversity (Morris et al., 2001). Another way of gaining a better understanding of how to manage areas invaded and dominated by *A. junciformis* would be to better understand the response of palatable species, such as *T. triandra* to management techniques such as grazing, mowing, burning or even fertiliser application to increase their abundance.

2.9 Conclusions and future research

There is more research available than expected. Most of this research has arisen in the last two decades. A literature review by Shackleton (1991), showed that only four studies were conducted focusing on *A. junciformis* – one for seed production, germination and establishment, one for nutrient analysis, palatability and preference ratios and two general studies, which are not categorized. Even though there seems to be more information available, often the information provided is unpublished, incomplete or inaccessible, especially if the research is fairly dated - which illustrates the need for further research. In this section, the gaps in research that could still be filled are tabulated in a short summary (Table 2.2), according to each section described in the review.

Table 2.2 The Gaps to be Filled

Section	**The Gap**
2.2.2 Distribution 2.2.3 Spread	Need to understand the current distribution of *A. junciformis* to understand its spread.
2.3.2 Leaf Morphology	Need to understand the effect shading has on the leaf morphology of *A. junciformis*
2.3.3 Seed Demography	Need to understand seedling viability in different seasons and with different treatments such as fire, smoke, drought and grazing.

2.3.4 Root systems and soil interaction	Very little is known about the roots. Need to understand why two root systems exist and the importance of each. Studies could be conducted to determine the importance of the roots and the effect of treating the roots on the canopy growth. Other studies that could be conducted are the use of *A. junciformis* for phytoremediation.
2.3.5 Cytology and Embryology	Almost no available literature on the embryology of *A. junciformis* and as far as I know, no illustrations are available for visualisation.
2.4 Flowering and Morphology	Only vaguely described. The bud growth rate of *A. junciformis* has only been estimated (Venter, 1968). Unanswered questions include: • What triggers floral initiation: photoperiod, soil water or temperature? • What triggers tillering? • What triggers seed shed? • What are the rainfall requirements to promote germination of *A. junciformis* seeds?
2.5 Ecophysiology and production 2.6 Ecological response to various environmental factors	There is a lack of understanding of the ecophysiology and there is almost no information available on the production of *A. junciformis*. Unanswered questions include: • What is the expected response of *A. junciformis* with expected climate change? • What is the response of *A. junciformis* to drought or loss of soil water?
2.7 Forage quality, palatability and acceptability	It has been suggested that members of the Equidae family could graze *A. junciformis*, however, no mention of this has been made in published literature and investigations could be conducted to determine if this is true and how dependent they are on *A. junciformis* as a food source. Further unanswered questions include: • Why does the acceptability index value of *A. junciformis* peak in summer? • How does the presence of *A. junciformis* affect production in natural parks in relation to agriculture?

<table>
<tr><td>2.8.1 Grazing, mowing and clipping</td><td>Not many studies are available describing the response of A. junciformis to the frequency or seasonality of cutting.
Unanswered questions include:
What is the response of A. junciformis to sever grazing early in the growing season?
What is the response of A. junciformis to continuous grazing at a high stocking rate?
What is the impact of severe defoliation on the roots of A. junciformis?
What is the impact of severe defoliation on tillering of A. junciformis tufts?
What is the impact of severe defoliation on the regrowth of A. junciformis in relation to no defoliation?
What is the impact of severe defoliation by different animals (e.g. sheep, cattle, goats) on A. junciformis tufts?
Does grazing of A. junciformis result in resource partitioning?</td></tr>
<tr><td>2.8.2 Burning</td><td>There is a lack of understanding of the response of A. junciformis regeneration and seedling germination to fire (Ghebrehiwot et al., 2009).
Unanswered questions include:
Do A. junciformis seedlings germinate if exposed to a fire?
Other studies that could be conducted:
Investigate what effect frequency and timing (or seasonality) of burning has on the ecophysiology and production of A. junciformis.
Investigate the effects of separate management techniques in relation to several management techniques implemented simultaneously in different seasons or at different frequencies.</td></tr>
<tr><td>2.8.3 The Management Dilemma</td><td>As far as I know, there are no studies analysing the consequences of interactive grassland management, i.e. studies are generally conducted only on grazing, mowing or burning. Further studies could be conducted to determine whether a combination of grazing, mowing and burning may be more successful.
Unanswered questions include:
What small scale changes can be implemented to better control and therefore manage A. junciformis?</td></tr>
</table>

	Other studies that could be conducted: • Investigate the response of species diversity from the implementation of different management techniques. • Investigating the effect of herbicide on *A. junciformis*.

In conclusion, there are still gaps in the literature. Though many may seem less significant, efforts should be made to fill these as they may in fact be the key to understanding how *A. junciformis* remains dominant. Since there is a lack of understanding of ecophysiology, it is suggested that available studies are replicated and monitored over long time periods or conducted in different grassland types to determine the response of *A. junciformis* to defoliation under different environmental and climatic conditions where competition may exist between different plants.

This dissertation consists of three main studies which aim to answer some of these questions. The aim of the first study was to compare the effects of non-selective and selective treatments on the mortality of *A. junciformis* tufts (compared to untreated plants), to determine which treatment type is more successful. Three treatments were implemented after a spring burn which compared: (i) a high density graze, (ii) a lenient graze to induce height differences in grasses to which herbicide were applied and (iii) a control (burn only). The aim of the second study was to determine the regrowth rate and production of *A. junciformis* after severe defoliation by cattle in relation to undefoliated *A. junciformis*. The aim of the third study was to determine whether the density level of aboveground *A. junciformis* has an effect on the abundance of *A. junciformis* seeds in the seedbank of the soil. Soil samples of different *A. junciformis* densities were planted in a controlled environment and the seedling emergence monitored. To support the findings of this investigation, a second experiment was conducted in the field comparing the germination of seedlings in severely defoliated pastures with seedling germination in undefoliated pastures.

3 Chapter Three: Methods and Materials

3.1 Introduction to the experimental studies conducted

Three studies were conducted to determine the effect focused disturbance treatments have on *A. junciformis*. These are a study of the survivorship (3.1.1) of *A. junciformis* and its productivity (3.1.2) following the application of three treatments - an early, intense cattle graze at a high stocking rate, herbicide application following a cattle graze at lenient intensity and a control – and a comparison of seedling emergence (3.1.3) from a seedbank study in a greenhouse (3.1.3.1) and in the field (3.1.3.2) to determine the effect high, medium and low *A. junciformis* densities have on seedling emergence of all species (3.1.3.1) and to determine the effect an early, intense cattle graze at a high stocking rate and a control have on seedling emergence in the field (3.1.3.2).

3.1.1 Survivorship of *A. junciformis* following an early, intense cattle graze at a high stocking rate, herbicide application and a control

The survivorship study aimed to determine whether targeted disturbance by herbicide application or HDG reduces the abundance of *A. junciformis* to the benefit of more palatable and productive grasses in mesic grasslands. The objective was to conduct paddock-scale trials comparing the effects of selective herbicide application, following a moderate intensity cattle graze to induce height differences between palatable and unpalatable species such that *A. junciformis* is avoided and is thus tall enough to apply the herbicide more easily, and the effects of an early, intense, cattle graze at a high stocking rate for a short period (HDG) against an untreated control. It was hypothesized that *A. junciformis* mortality would be lower under the control than under the HDG and herbicide application. It was predicted that the cattle would choose to feed on more palatable grasses than *A. junciformis*, if given a choice. It was predicted that the herbicide application would reduce the vigour and abundance of *A. junciformis* more to the benefit of palatable and productive grasses than HDG.

3.1.2 Productivity of *A. junciformis* following an early, intense cattle graze at a high stocking rate and a control

The productivity study aimed to determine whether the productivity of *A. junciformis* would be compromised by a HDG event in relation to an ungrazed control. Productivity was measured in terms of its regrowth rate and its final biomass. The objective was to conduct paddock-scale trials comparing the effects of a HDG against an untreated control. It was hypothesized that the productivity of *A. junciformis* would be lower under the HDG than under the control. It was predicted that the

HDG would compromise the productivity of *A. junciformis* such that *A. junciformis* tufts in HDG paddocks would have a lower biomass than those in control paddocks and that the regrowth of *A. junciformis* tufts in HDG paddocks would be reduced relative to the *A. junciformis* tufts in control paddocks.

3.1.3 Seedling emergence study

This study consisted of two experiments; a greenhouse and a field experiment. The first aim of both experiments was to identify how the density of *A. junciformis* affects the emergence of *A. junciformis* seedlings. In both experiments seedling emergence was observed. The experiments differed in that one consisted of soil samples collected in the field, before treatments were applied, which were then placed in a greenhouse to facilitate germination (referred to as the seedbank study from this point forward), while the other consisted of monitoring the emergence of seedlings in fields which had been burnt in spring and which were either grazed (HDG) five weeks after the burn or remained undefoliated (referred to as the field study from this point forward). Each experiment is explained and described in more detail.

3.1.3.1 Seedbank study

The aim of the seedbank study was to determine whether the density of *A. junciformis* affects the emergence of *A. junciformis* seedlings The objective was to collect soil samples from sites with low, medium and high density of *A. junciformis* and compare the soil seedbank composition with the aboveground vegetation composition. It was hypothesized that the density of *A. junciformis* affects the emergence of *A. junciformis* seedlings. It was predicted that the density of *A. junciformis* is directly proportional to the emergence of *A. junciformis* seedlings.

3.1.3.2 Field study

The aim of the field study was to determine whether defoliation of foliage, more specifically of *A. junciformis*, enhances seedling germination of *A. junciformis* seedlings and of other species. It is expected that defoliation will result in stunted root growth, as the roots channel the nutrients up to the canopy to enhance tillering, thus reducing the competitive ability of *A. junciformis* relative to other plant species. The aim of the field study was thus also to determine whether the presence of *A. junciformis* supresses germination of other species, but in the field. The objective was to clear above-ground foliage by introducing a cattle graze at a high stocking rate into the HDG paddocks and to monitor seedling emergence in the field. It was hypothesized that seedling germination of all species, including *A. junciformis*, is enhanced by defoliation of above-ground foliage. It was predicted that (a) removing foliage would enhance seed germination of all species and, ultimately, that (b) the presence of *A. junciformis* suppresses the growth of other species.

3.2 Study Site

With the exception of the seedbank study, all studies were conducted at the Ukulinga Research Farm, University of KwaZulu-Natal, Pietermaritzburg (29°24'E, 30°24'S; 840 m.a.s.l) (Tsvuura et al., 2017) and, more specifically on the previously established Days-In-Days-Out trial paddocks (Morris et al., 1996) and the paddocks to the west of these (Figure 3.1). These sites were selected for their high abundance of *A. junciformis* and due to their close proximity to each other to minimise spatial influences and to account for environmental variability. Their dimensions are provided in Table 3.1.

The site has been used for agricultural research for many years. Agricultural livestock as well as small wildlife such as birds, rodents, reptiles, amphibians and insects are all found on the property (personal observation). The farm is located on the southern outskirts of Pietermaritzburg and is neighbour to the Bisley Valley Nature Reserve. The farm is broadly classified as Tall Grassveld by Acocks (1975, as cited in Van Zyl (1998)). More precisely, the farm is classified as sub-escarpment Savanna (Mucina et al., 2006) and more specifically as KwaZulu-Natal Hinterland Thornveld type vegetation (Mucina et al., 2006), also known as Coast Hinterland Thornveld according to the classification by Camp (1997). KwaZulu-Natal Hinterland Thornveld receives most of its annual rainfall (650 – 1000 mm) in the summer (Mucina et al., 2006). The monthly temperatures range from -1.8 °C to 37.2 °C between June and January respectively (Mucina et al., 2006) occasionally experiencing frost in the winter (Camp, 1997). According to the benchmark species composition provided by Camp (1997), the Coast Hinterland Thornveld (KwaZulu-Natal Hinterland Thornveld) is generally dominated by *Themeda triandra* Forssk., *Tristachya leucothrix* Trin. ex Nees and *Heteropogon contortus* (L.) Roem. & Schult. Heavily grazed areas may also contain *Eragrostis capensis* (Thunb.) Trin., *E. chloromelas* Steud., *E. curvula* (Schrad.) Nees, *E. superba* Peyr., *E. racemosa* (Thunb.) Steud., *Sporobolus pyramidalis* P. Beauv. and *S. fimbriatus* (Trin.) Nees (Camp, 1997).

The KwaZulu-Natal Hinterland Thornveld is becoming increasingly dominated by the unpalatable grass *A. junciformis* (Tainton, 1972a). As a consequence of incorrect burning and grazing management, the condition of this grassland type is quickly deteriorating (Camp, 1997; Venter, 1968). Further, the grassland is threatened by bush encroachment, which is why fire plays an integral role in the management of this vegetation type (Camp, 1997). The extensive invasion of *A. junciformis* into the KwaZulu-Natal Hinterland Thornveld and the Mixed Thornveld vegetation types is concerning, especially since it is unpalatable, has low nutritive value and does not easily become moribund with lack of defoliation. It thus provides a greater fuel load in the burning season (Camp, 1997).

Table 3.1 The dimensions of each paddock used in this study and the calculated area of each

Paddock Number	Width (m)	Breadth (m)	Area (m^2)
1	39.60	27.40	1085.04
2	32.30	27.40	885.02
3	50.20	27.40	1375.48
4	26.10	27.40	715.14
5	33.20	27.30	906.36
6	52.00	27.30	1419.60
7	42.10	27.30	1149.33
8	36.10	27.30	985.53
9	38.10	27.30	1040.13
10	26.00	25.40	660.40
11	26.00	24.70	642.20
12	24.24	25.40	615.67
13	24.24	24.70	598.73
14	27.84	25.40	707.14
15	27.84	24.70	687.65

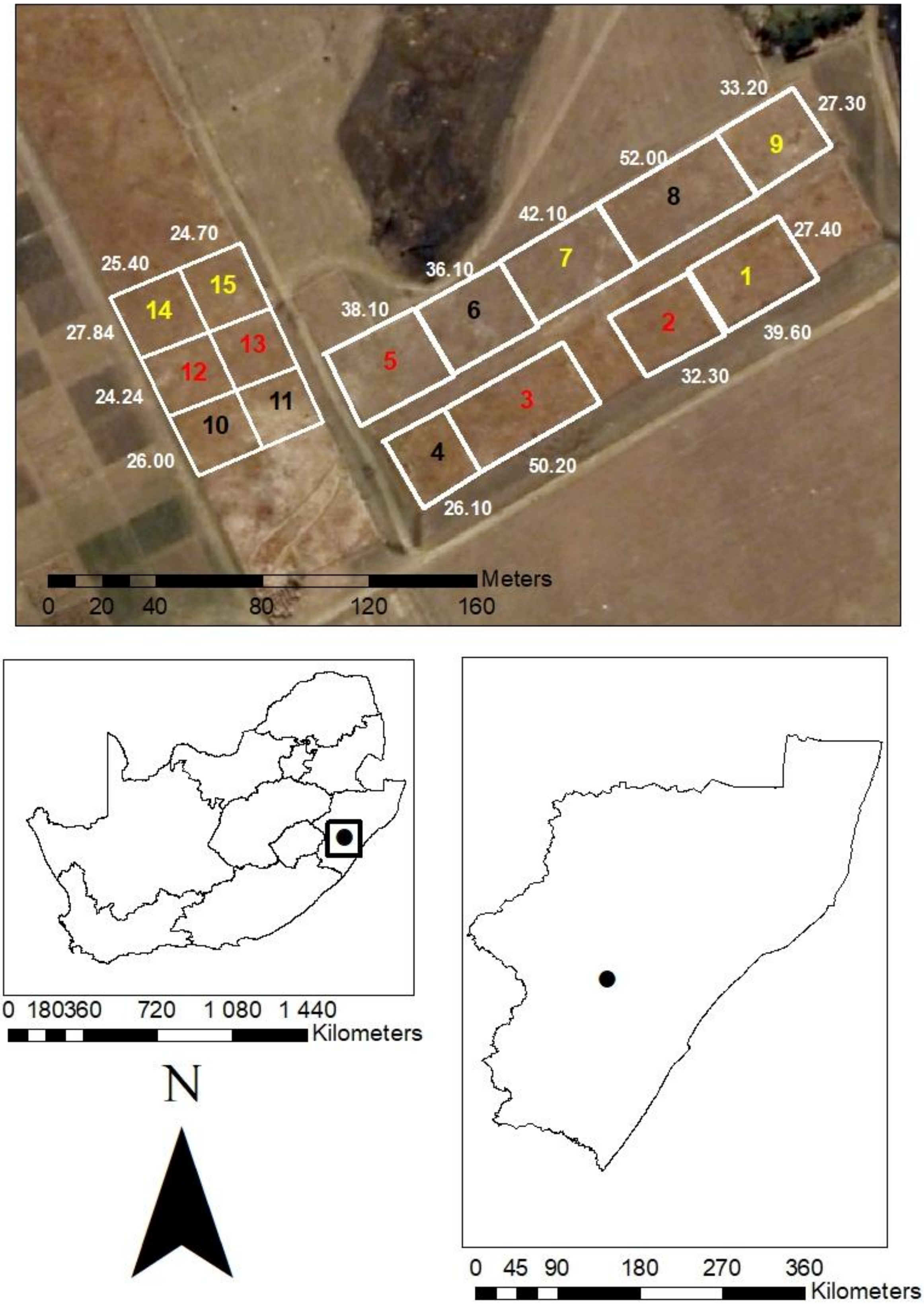


Figure 3.1 The Days-In-Days-Out trial paddocks and the paddocks to the west of these at Ukulinga Research Farm, Pietermaritzburg, KwaZulu-Natal, South Africa, used for this study. The coloured numbers represent the different treatments: yellow – control; red – herbicide application; black – HDG grazing.

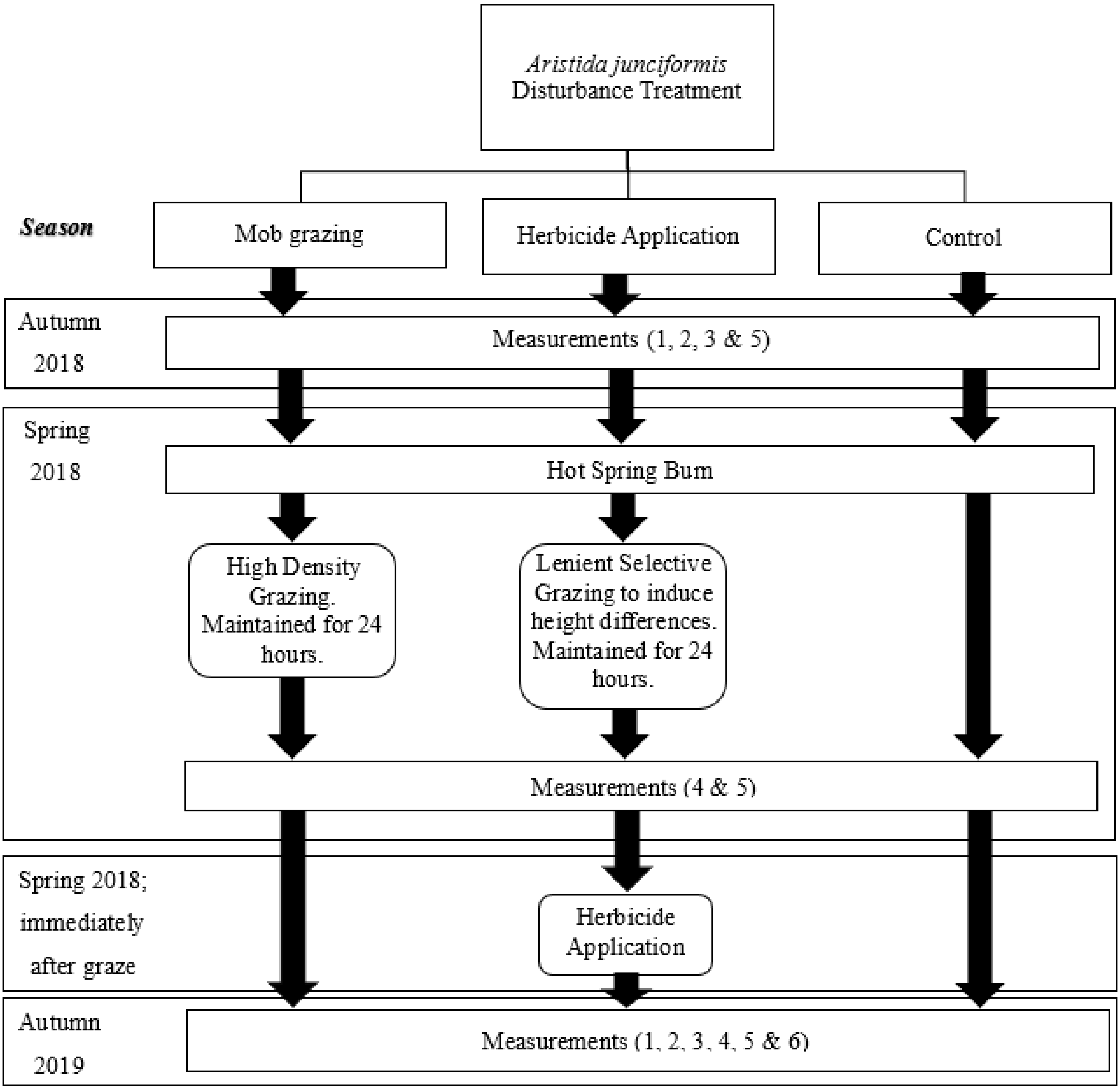
3.3 Procedure

This study comprises the application of three treatments, namely a control that was ungrazed and to which no herbicide was applied, a short duration, high intensity cattle graze (HDG) and selective application of herbicide. For the herbicide application, a lenient graze was applied to induce height differences between the *A. junciformis* tufts, which were avoided by the cattle as they were unpalatable in late spring. Five replicates of each of the three treatments were established, thus fifteen paddocks were used in total. The trial was arranged in a randomised block design. Each paddock was randomly allocated a treatment (Figure 3.1). The treatments and respective measurements were approved by the Ethical Clearance Committee of UKZN, PMB (AREC/008/018M). A timeline for treatment application and data collection is provided in Figure 3.2.

In this project, six measurements were taken. These are divided into field and tuft scale studies that consist of measuring the total (%) basal cover of the paddocks, the relative abundance of grasses and forbs, the population tuft size and distribution of adult and seedling *A. junciformis* tufts, the survivorship of *A. junciformis* tufts and tuft leaf table height measurements. The measurements were used for the three studies as described in the previous section. Measurements for all studies were taken at three different times throughout the trial period. The seedbank study, conducted in a greenhouse, was conducted in mid-summer 2018. The first set of measurements, to develop a baseline for the survivorship and productivity studies, were taken in early autumn 2018, the second set of measurements were taken in late spring 2018 and the final set of measurements were taken again in early autumn 2019. The seedling emergence study in the field was also conducted from late spring 2018 to early autumn 2019, when seedlings stopped emerging.

For the survivorship and productivity studies, baseline data were collected in early autumn of 2018, in all paddocks, for (1) the total basal cover of the vegetation, (2) the relative abundance of grass and forb species (%) and (3) the population tuft size distribution of *A. junciformis*, including *A. junciformis* seedlings (% by circumference class). Fifty *A. junciformis* tufts were marked for comparison of (4) survivorship between treatments. The (5) leaf table height of the marked tufts was measured as well. Seedling emergence (6) was only monitored after the treatments had been applied (Figure 3.2). A spring burn was applied to all paddocks in September 2018 under conditions conducive for an intense fire and treatment application commenced five weeks after the burn. Immediately after the treatment application, (4) the survivorship of the marked *A. junciformis* tufts was noted. Grey *A. junciformis* tufts were considered dead while green *A. junciformis* tufts were considered to be alive. Their (5) leaf table height measurements were taken for the productivity study.

All paddocks were then left to rest until summer 2019 at which time the field and tuft scale data were collected again. Detailed methods for each study are described in the sections to follow.



* Footnote: Measurements include field scale studies that consist of measuring (1) the total basal cover, (2) the relative abundance of grass species and forbs (%) and (3) the population tuft size distribution of *A. junciformis*, including *A. junciformis* seedlings (% by circumference class) and of tuft scale studies that consist of measuring (4) the survivorship of *A. junciformis* after treatment application and (5) leaf table height measurements. Seedling emergence (6) was monitored in HDG & control paddocks only.

Figure 3.2 Flow Diagram of the planned application of treatments and the respective measurements taken.

3.3.1 Field Scale Studies

The field scale studies consisted of measuring the total (%) basal cover of the paddocks and the relative abundance of grasses and forbs. The nearest plant or point-to-tuft technique (Hardy et al., 1993), was used to simultaneously determine the total vegetative basal cover (%) and the relative abundance of grasses and forbs (Foran et al., 1978) within each paddock that was used in sampling.

Each paddock was divided into 4 squares and a pointer was randomly placed in each square 50 times such that 200 points were sampled per paddock (n = 200). From each point the distance (cm) to the nearest plant was measured and recorded and each plant identified. Grass species were identified to species level to understand the relative grass species composition of each paddock. Forbs were recorded as "forbs" and were not identified to species level.

The monitoring transect which uses the "logging of the line" method adapted from the Landscape Function Analysis (LFA) technique (Tongway et al., 2004) was used to create a profile of the population tuft size and distribution of adult and seedling *A. junciformis* tufts before and after treatment application. A tape measure was placed as close to the ground as possible and pulled tight. At each point where a different plant species was identified, a note was made of the measurement at which it was identified and the bare soil patches in between were recorded too. Each profile was one meter long and 5 profiles were created for each paddock (Figure 3.3). The exact points of where the samples were taken was marked, recorded and mapped to ensure repeatability from spring 2018 to autumn 2019.

Figure 3.3 An example of the "logging of the line" technique. Image not drawn to scale.

3.3.1.1 Seedling emergence in the field

The field study was conducted in control and HDG paddocks (Figure 3.1). All paddocks were exposed to a spring burn in late August 2018. The HDG paddocks were exposed to a high intensity, short duration cattle graze in late October 2018 (Table 3.1). In each of the control and HDG paddocks used in this study, three quadrats (1 m × 1 m in size) were unsystematically placed (n = 30) and demarcated using white conduit markers (Figure 3.4).

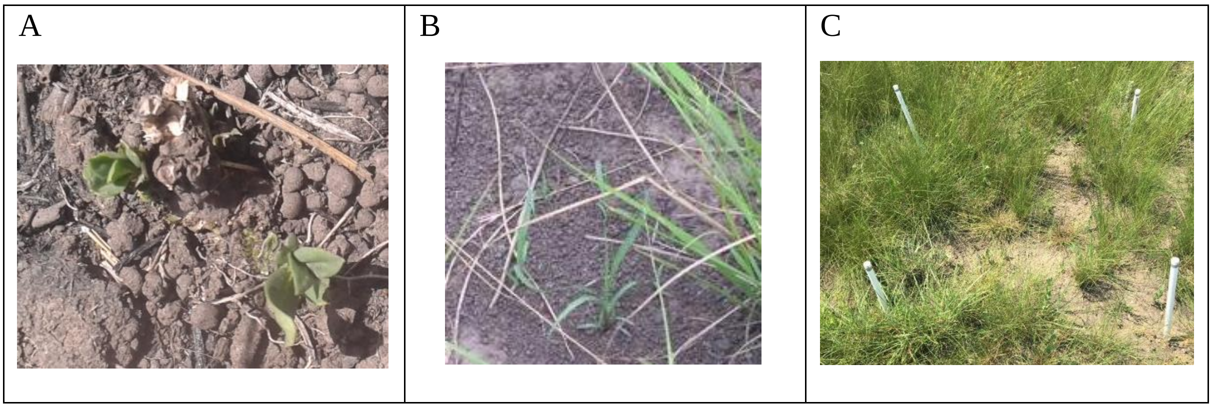


Figure 3.4 Seedling emergence in the field: A – forb emergence, B – grass emergence, C – an example of a seedling emergence quadrat

Figure 3.5 An example of an *A junciformis* seedling next to an exisiting *A. junciformis* tuft.

The seedling emergence began a week after the HDG paddocks had been grazed. The number of seedlings in each quadrat for both the control and HDG paddocks were counted and recorded. Seedlings were defined by the emergence of vegetation (seedling or tiller) from bare soil (Figure 3.5). Where classification was not immediately possible, seedling species were marked with coloured paper clips until identification was possible. The defoliation trials were examined on a biweekly basis. Observation began in early September 2018, however seedlings only began to emerge in early November 2018. Seedling emergence was observed and recorded until no new seedlings emerged. Seedlings stopped emerging after 130 days, in mid-March 2019.

3.3.2 Tuft Scale Studies

The tuft scale studies consisted of measuring the survivorship and productivity of *A. junciformis* tufts. To determine survivorship, 100 live *A. junciformis* tufts within each paddock were marked in early autumn 2018. A tuft was considered to be live if any green leaf material was present. Tufts were characterised as being live if they were green. Though it has not been proven, it is possible that *A. junciformis* reproduces vegetatively by tillering, often leading to extremely large tufts or overlapping of tufts (pers. obs.) and therefore only *A. junciformis* tufts which could be differentiated from the surrounding *A. junciformis* tufts were marked. These tufts were generally about 40 cm high and had a diameter of about 60 cm. Tufts were marked by measuring the distance from the tuft to two perpendicular fences demarcating the paddocks. Where two perpendicular markers existed, two ropes were spanned to facilitate relocation of the same tufts. The point of intersection of the two perpendicular ropes then indicated where the measured tuft was (Figure 3.6).

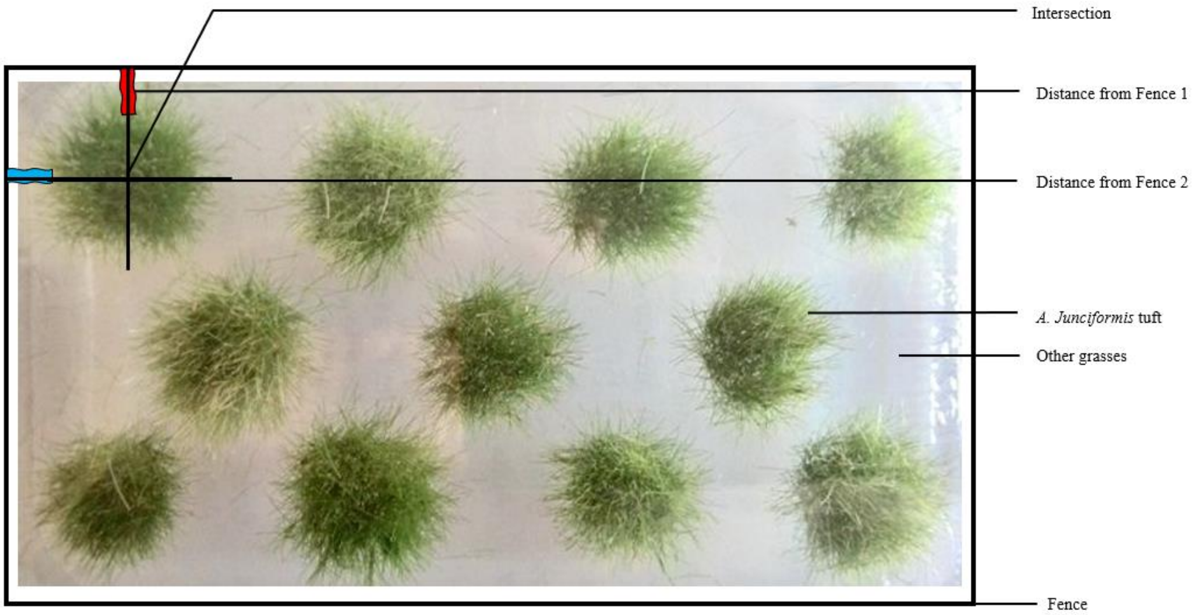


Figure 3.6 Aerial view of how *A. junciformis* tufts were marked to determine survivorship after treatment application.

The heights of each of the 100 tufts per paddock were measured with a rising plate disc pasture meter to avoid excessive sward compression. as would be experienced with a normal falling plate disc pasture meter. In late August 2018, following the first spring rains, the markers were removed and a hot spring burn was applied to all paddocks. The paddocks were allowed to rest until the last week of October 2018, when a high stocking rate of cattle were introduced to graze at a high intensity for 24 hours (Table 3.1). After the HDG, the markers were returned to their original positions. Every marked *A. junciformis* tuft was checked to determine whether it survived the treatments. *Aristida junciformis* tufts were considered to be alive if any green leaf material was present while completely grey *A. junciformis* tufts were considered to be dead. Tufts that were partially green and grey were considered alive as they had the potential to recover.

Immediately after the HDG the heights of 30 *A. junciformis* and 30 other grass tufts (consisting of a variety of species such as *C. caesius*, *C. dactylon*, *C. gayana*, *D. amplecetens*, *E. curvula*, *E plana*, *H. hirta*, *P. maximum*, *P. natalense*, *S. africanus*, *S pyramidalis*, *S. sphacelata*, *T. leucothrix* and *T. triandra*) in the HDG paddocks were measured to determine which were grazed more. Ten *A. junciformis* tufts in each of the HDG and control paddocks were marked (n=100). Their leaf table heights were measured immediately after the graze and every second week thereafter. Initially the leaf table height was measured from the ground to the point where the grass was grazed using a ruler. After the tufts had grown to more than 20 cm, the leaf table height was measured from the ground to the point containing about 80% of the leaf height of the *A. junciformis* tuft, using a tape measure. Leaf table height measurements ended in March 2019, after the marked *A. junciformis* tufts no longer grew at which point they were harvested using clipping shears. The harvested biomass samples were bagged, dried for 48 hours at 70°C and weighed.

3.3.2.1 Seedbank study

a. Vegetation assessment

The trial paddocks comprised of varying levels of *Aristida junciformis* density. To establish the grass species composition and abundance of each species, aerial cover estimations were applied within a square quadrat using the Braun-Blanquet cover abundance method (Mueller-Dombois et al., 1974), but using absolute cover values (Tedder et al., 2012). To do so, 5 sites of each level of *A. junciformis* density (high, medium or low density) were identified from the chosen pastures, such that a total of 15 sites were used for aerial cover estimations. At each site 10 square quadrats (each measuring 0.3 m × 0.3 m) were unsystematically placed (n = 150). At each quadrat, the cover of each grass and forb species in the quadrat was allocated a cover abundance value as per the Braun-Blanquet cover abundance method (Mueller-Dombois et al., 1974), but using absolute cover values (Tedder et al., 2012). Grass species nomenclature followed Van Oudtshoorn (2012) and forbs were simply categorised as “forbs”.

b. Soil sampling

After conducting aboveground species composition sampling, topsoil samples were collected from the same sites from which the aerial cover estimations were taken. Twenty-five soil samples were collected for each category of *A. junciformis* density, such that 75 soil samples were collected in total. Samples were collected using a bucket auger to a depth of 10 cm. Surface litter was removed prior to soil collection.

After collection the samples were spread out on separate trays and allowed to dry for a day. Due to inconsistent weather during soil drying, only some samples were completely sun dried and the remaining samples were dried using a fan at low speed. Drying was necessary to prevent germination before commencing the seedbank trial.

After drying, the samples were placed in plastic trays (20.5 cm × 16 cm × 6 cm) to facilitate germination of seeds within the samples. The trays were lined with paper towels followed by a layer of Umngeni grit sand (1 cm deep) to prevent waterlogging of the samples. The soil samples were then measured to a consistent volume of 600 ml and spread on top of the Umngeni sand to a depth of 2 cm. Five control trays were set up in plastic trays containing only a paper towel lining and a layer of Umngeni grit sand (1 cm deep) and were used to show that the Umngeni sand would have no effect on the seedlings emerging from the soil samples taken from Ukulinga. All trays were arranged in a completely randomised design under 40% green shadecloth, in Wartburg approximately 50 km from Ukulinga Research Farm (Figure 3.7). The samples were irrigated twice a day on warm, sunny days, once a day on cool days and were not irrigated on rainy days.

The trays were checked for germination every day. After germinating, the seedlings were photographed, described and given codes for identification. All seedlings were counted and removed after counting. Representative specimens were transplanted for identification at maturity. This process continued until germination no longer occurred after twelve weeks.

Figure 3.7 Seedling germination in a greenhouse at a cover of 40% shade.

3.4 Treatment application

3.4.1 Herbicide disturbance application following a lenient graze

After the spring burn in 2018, cattle were introduced into each Herbicide-specified paddock and allowed to graze for a 24-hour period (See Table 3.8). The aim was to allow cattle to graze at a moderate intensity to allow for some selective grazing to induce height differences between the palatable species and the *A. junciformis* tufts. While grazing, it was ensured that the cattle had sufficient water. After grazing, the *A. junciformis* tufts were treated with the herbicide Round-Up© (4%), which has low mammalian toxicity, is not residual and is easily washed away by rain (Terry et al., 1996). Ropes were spanned in the herbicide-specified paddocks such that lanes, about 1m wide, were created. This allowed for systematic application of the herbicide and maximised chances of applying the poison to all grass tufts. The herbicide was applied using a weed-wiper broom (Figure 3.8). The cattle were not introduced into the paddocks again.

Figure 3.8 An adapted weed-wiper.

3.4.2 Non-selective grazing disturbance application

Following the spring burn in 2018, seven cattle were introduced into each HDG paddock and allowed to graze for a 24-hour period (See Table 3.2). It was ensured that the cattle had sufficient water while grazing. After the cattle were removed, they were not introduced into the paddocks again.

3.4.3 Control

The control paddocks remained ungrazed and untreated for the duration of the study, following the spring burn in 2018 (See Table 3.2).

Table 3.2 The stocking rate of each paddock and the treatment applied to each

Paddock no.	Treatment applied	No. of cattle in each paddock	No. of cattle per ha (rounded off to lowest whole number)	Other Comments
1	Control	0	0	
2	HDG	7	79	
3	HDG	7	50	
4	Herbicide	3	41	
5	HDG	7	77	5 cattle escaped over night
6	Herbicide	3	21	
7	Control	0	0	
8	Herbicide	7	30	
9	Control	0	0	
10	Herbicide	7	45	
11	Herbicide	7	46	
12	HDG	7	113	One cow escaped into paddock 14
13	HDG	7	116	
14	Control	2	28	Escaped cow (see paddock 12)
15	Control	0	0	

3.5 Data Analyses

3.5.1 Survivorship

To determine the effect the treatments (control, herbicide application and HDG) had on the mortality and survivorship of the *A. junciformis* tufts, a Generalised Linear Mixed Model (GLMM) was conducted in R (Team, 2018). The data were logit transformed and a one-way Analysis of Variance (ANOVA) was conducted as well as a post hoc Tukey's test.

To determine the effect of treatment (control, herbicide application and HDG), changes over time (May 2018 vs May 2019) and treatment × time interactions on plant species composition, a permutation multivariate analysis of variance (PERMANOVA) with 9999 permutations was performed on Bray-Curtis distances. Percentage abundances of species was log(x+1) transformed to reduce skewness. Treatment and time were fixed effects with paddock (n = 15) included as a random effect, nested within treatment, to account for initial variation in composition among paddocks. A similarity percentages (SIMPER) analysis revealed which species contributed most to the differences in species composition. SIMPER and PERMANOVA analyses were done using Primer 6 (Clarke et al., 2006). Differences among treatments and time were visually represented with non-metric multidimensional scaling (NMDS) using Canoco 5 (ter Braak et al., 2012) with the 2-D configuration rotated by principal component analysis (PCA) to represent the maximum variation along the horizontal axis.

3.5.2 Productivity

The heights of both *A. junciformis* and other grass tufts had been measured to describe the distribution of the grazing intensity in each paddock, to describe the extent to which severe grazing of *A. junciformis* and other grasses had been achieved through a HDG. These height measurements were divided into 5 cm height classes and presented graphically. An independent (unpaired) t-test assuming unequal variance was conducted to determine if the distributions of the heights was similar for the *A. junciformis* and other grass tufts, to determine whether the HDG had a significant effect on both the *A. junciformis* and other grass tufts.

Linear and Polynomial regression analyses were used to describe the pattern of mean height change over time of marked tufts in the control and HDG grazed treatments. The regrowth height of the grazed *A. junciformis* tufts was analysed using a Linear Mixed Model (LMM). The data were log transformed and a one-way ANOVA and post hoc test were conducted in R©. A LMM was also used for the analysis of the harvested biomass. The data were log transformed and a one-way ANOVA and post hoc test were conducted in R©. A Kolmogorov-Smirnov test was also conducted to test for equal distributions of the tuft heights of *A. junciformis* against the other grasses after the HDG treatment.

To determine the effect of treatment (control and HDG), changes over time (March 2018 vs March 2019) and treatment × time interactions on species cover composition, a permutation multivariate analysis of variance (PERMANOVA) with 9999 permutations was performed on Bray-Curtis distances. Percentage abundances of species was log(x+1) transformed to reduce skewness. Treatment and time were fixed effects with paddock (n = 10) included as a random effect, nested within treatment, to account for initial variation in cover composition among paddocks. A similarity percentages (SIMPER) analysis revealed which species contributed most to the differences in species cover composition. SIMPER and PERMANOVA analyses were done using Primer 6 (Clarke et al., 2006). Differences among treatments and time were visually represented with non-metric multidimensional scaling (NMDS) using Canoco 5 (ter Braak et al., 2012) with the 2-D configuration rotated by principal component analysis (PCA) to represent the maximum variation along the horizontal axis.

3.5.3 Seedbank study

The proportion of each species identified under low, medium and high *A. junciformis* densities were tabulated to show what species may have potentially emerged as seedlings in the greenhouse. Descriptive statistics of the emerged seedlings were tabulated to show what proportion of seedling species emerged under the various *A. junciformis* densities. Descriptive statistics of the emerged seedlings were also used to show the differences in number of seedlings under the various *A. junciformis* densities.

3.5.4 Field study

To determine the effect the treatments (control, herbicide application and HDG) had on the species composition of the emerged seedlings, four Generalised Linear Mixed Models (GLMM) were conducted in R ©, using log transformed data. One GLMM analysed the effects of the treatments on overall seedling emergence in the field. The other three GLMMs analysed the effects of the treatments on the emergence of (1) forbs seedlings, (2) *A. junciformis* seedlings and on (3) other grass seedlings.

To determine the effect of treatment (control and HDG) on the emerged seedling species, a permutation multivariate analysis of variance (PERMANOVA) with 9999 permutation was performed on Bray-Curtis distances. Percentage abundances of species was log(x+1) transformed to reduce skewness. Treatment was used as a fixed effect with paddock (n = 10) included as a random effect, nested within treatment, to account for initial variation in composition among paddocks. A similarity percentages (SIMPER) analysis revealed which species contributed most to the differences in species composition. SIMPER and PERMANOVA analyses were done using Primer 6 (Clarke et al., 2006). Differences among treatments and time were visually represented with non-metric multidimensional scaling (NMDS) using Canoco 5 (ter Braak et al., 2012) with the 2-D configuration rotated by principal component analysis (PCA) to represent the maximum variation along the horizontal axis.

4 Chapter Four: Survivorship Results

The results in this chapter are presented in the following order: 4.1 Survivorship of *A. junciformis* tufts under a HDG, herbicide application and under a control and 4.2 Changes in the species composition in the field before and after treatment (HDG, herbicide application and control) implementation.

4.1 Survivorship of *A. junciformis* tufts under a HDG, herbicide application and under a control

The rate of mortality varied among the treatments ($p < 0.00001$; Table 4.1 & 4.2). The probability of *A. junciformis* tufts surviving before treatment implementation was almost 1 since live *A. junciformis* tufts were selected before treatment application (Figure 4.1). Over the four months after treatment implementation, the estimated probability of survival of the marked tufts in the control and HDG paddocks was close to 1 ($p < 0.0001$), because none of the tufts died. In contrast, a total of 74 of the 250 *A. junciformis* tufts in the herbicide application treatment paddocks had died by March 2019. The estimated probability of an *A. junciformis* tuft surviving the herbicide application was lower ($p = 0.705 \pm 0.05584$) than surviving a HDG ($p = 1.000 \pm 0.00914$) or the control ($p = 1.000 \pm 0.00914$; Figure 4.1).

Table 4.1 Analysis of Deviance (Type II Wald chisquare tests) of the effects of treatments and time on the proportion of marked *A. junciformis* tufts (logit link function) that were alive immediately after treatment implementation in November 2018 and four months after treatment implementation, in March 2019

	Chisq	Df	Pr(>Chisq)
Treatment	29.564	2	$3.804e^{-7}$
Time	21.323	1	$3.880e^{-6}$
Treatment:Time	24.118	2	$5.793e^{-6}$

Table 4.2 Estimated coefficients from a GLMM (logit link) of the effects of treatment (control, herbicide application and HDG) on the proportion of marked *A. junciformis* tufts (logit link function) that were alive immediately after treatment implementation in November 2018 and four months after treatment implementation, in March 2019. The Intercept represents the control prior to treatment application. Treatment T1 and Treatment T2 represent the times prior to and after treatment application respectively while H represents the HDG and HA represents the herbicide application

	Estimate	Standard Error	z-value	Pr(>|z|)
Intercept	3.97200000	0.504	7.887	$3.10e^{-15}$
Treatment T1 H	-0.00002079	0.711	0.000	1.0000000
Treatment T1 HA	0.10180000	0.715	0.142	0.8870000
TimePost	-0.00001441	0.632	0.000	1.0000000
Treatment T2 H	0.00004896	0.894	0.000	1.0000000
Treatment T2 HA	-0.00003203	0.791	-4.052	0.0000508

Paddock number (SD = 0.5022) was included as a random intercept for this GLMM.

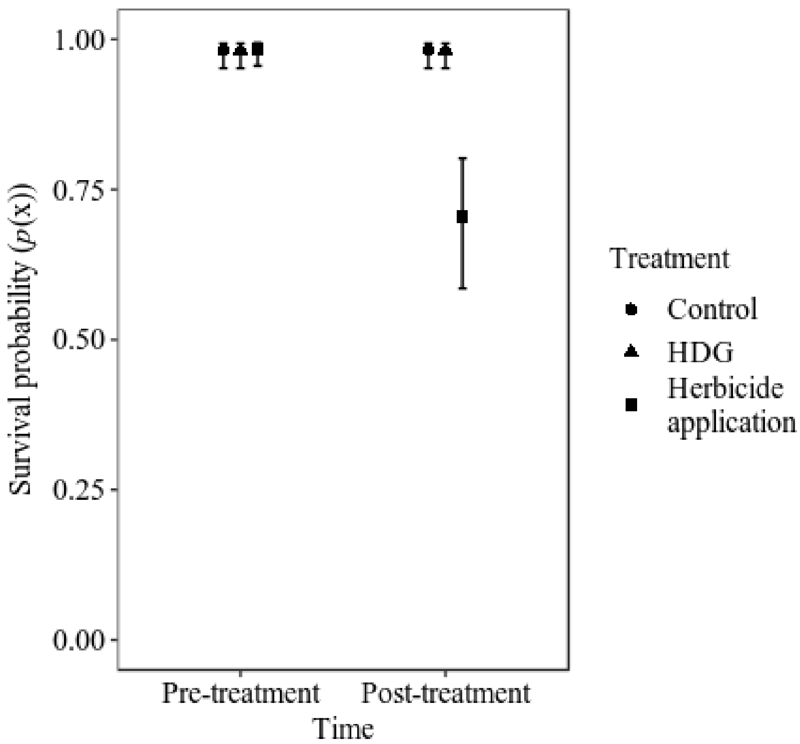


Figure 4.1 The probability of survival of *A. junciformis* tufts before treatment implementation (March 2018) and after implementation of treatment (March 2019).

4.2 Changes in the species composition in the field before and after treatment (HDG, herbicide application and control) implementation.

The plant species composition did not differ among treatments before treatment implementation ($p = 0.4169$). However there was a significant shift in species composition over time ($p = 0.0002$) from March 2018, before treatment implementation, to March 2019, after treatment implementation (Table 4.3). Furthermore, there was no treatment × time interaction ($p = 0.3827$), indicating that the directional shift in species composition over time was similar in all paddocks, as is shown in the NMDS (Figure 4.2).

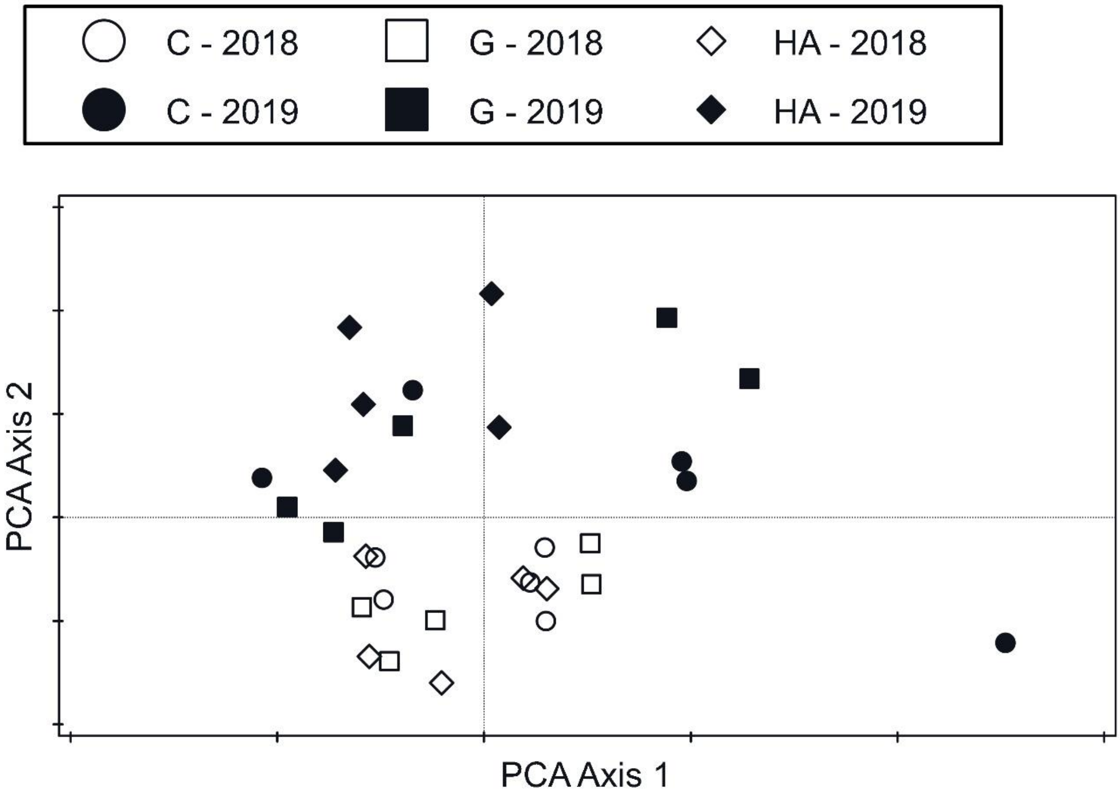


Figure 4.2 An NMDS of differences in species composition among treatments and time with the 2-D configuration rotated by principal component analysis (PCA) to represent maximum variation along the horizontal axis. Open symbols represent pre-treatment (March 2018) and filled symbols represent post-treatment (March 2019) nearest plant species composition assessments.

Table 4.3 A PERMANOVA of the effects of treatment (control, herbicide application, HDG) and time (pre- and post-treatment implementation in March 2018 and March 2019 respectively) on species composition. Statistically significant p-values (<0.005) are marked in bold

Source	df	SS	MS	Pseudo-F	P(perm)	Unique perms
Treatment	2	879.98	439.99	0.9622	0.4169	9594
Time	1	1852.30	1852.30	7.3907	**0.0002**	9951
Paddock (Treatment)	12	5487.30	457.28	1.8245	0.0095	9871
Treatment×Time	2	542.47	271.23	1.0822	0.3827	9929
Res	12	3007.60	250.63			
Total	29	11770.00				

A decline of *T, triandra* from March 2018 to March 2019 contributed the most (> 16%) to the observed dissimilarity, followed by *T. leucothrix* (>9%) (Table 4.4). The lowest contribution to the observed dissimilarity was made by *H. contortus* which was found on site but was not measured in the nearest plant species composition analyses. It is important to note that *A. junciformis* increased over the experimental period from 29.30% to 33.27% to become most dominant after treatment implementation where forbs were originally most dominant (41.57%) before treatment implementation (Table 4.4).

Table 4.4 SIMPER analysis presenting the mean percentage contribution, of all paddocks, by species to the dissimilarity (Bray-Curtis) in species composition between vegetation surveyed in March 2018 (pre-treatment) and March 2019 (post-treatment). Note: data are from untransformed data and contributions from log-transformed data.

Species	March 2018		March 2019		Contribution (%)
	Mean (%)	S.E.	Mean (%)	S.E.	
Vachellia trees	0.20	0.082	0.00	0.000	1.75
Aristida junciformis	29.30	2.382	33.27	4.214	4.89
Bidens pilosa	0.07	0.045	0.00	0.000	0.59
Cymbopogon caesius	0.57	0.137	2.67	0.809	8.48
Cynodon dactylon	0.00	0.000	0.47	0.322	2.26
Chloris gayana	0.87	0.198	0.00	0.000	5.93
Digitaria amplectens	0.00	0.000	2.20	1.114	5.58
Eragrostis curvula	9.00	1.501	6.13	0.780	6.39
Eragrostis plana	0.00	0.000	0.20	0.107	1.40
Ferns	0.07	0.045	1.93	1.933	2.87
Forbs	41.57	2.380	30.47	3.250	6.28
Hyparrhenia hirta	0.17	0.063	0.53	0.401	3.08
Panicum maximum	0.03	0.033	0.07	0.067	0.76
Panicum natalense	0.00	0.000	1.47	0.624	6.29
Sedges	0.27	0.083	0.40	0.214	3.52
Sporobolus africanus	0.03	0.033	0.07	0.067	0.85
Sporobolus pyramidalis	0.23	0.083	0.60	0.412	3.86
Setaria sphacelata	0.40	0.163	3.13	1.527	8.62
Tristachya leucothrix	5.57	1.165	11.80	2.187	9.92
Themeda triandra	11.50	2.648	4.60	1.737	16.72

5 Chapter Five: Productivity Results

The results in this chapter are presented in the following order: 5.1 Distribution of grazing intensity for all paddocks; 5.2 Distribution of grazing intensity within each paddock; 5.3 Tuft height regrowth pattern of *A. junciformis* under control and HDG; 5.4 Treatment effect on regrowth height and biomass and 5.5 Treatment effects on species cover composition.

5.1 Distribution of grazing intensity for all paddocks

After the HDG it was found that less than 30% of the *A. junciformis* tufts and more than 40% of all other grass tufts were grazed short, to a height of 50 cm or shorter (Table 5.1). More than 75% of the *A. junciformis* tufts and 67% of the other grass tufts were grazed shorter than 10 cm (Table 5.1). Of the 150 measured *A. junciformis* tufts, 6 tufts were not grazed by cattle and were 20 cm in height or taller, and of the 150 other grass tufts measured, 10 tufts were not grazed by cattle and were 23 cm or taller.

Table 5.1 Frequency and percentage of *A. junciformis* and other grasses contributing to each height category across all five grazed paddocks immediately after the HDG in November 2019

	A. junciformis		**Other grasses**	
Category (cm)	**Frequency**	**Cumulative %**	**Frequency**	**Cumulative %**
5	42	28.2%	64	43.0%
10	71	75.8%	36	67.1%
15	23	91.3%	21	81.2%
20	6	95.3%	10	87.9%
25	1	96.0%	6	92.0%
30	3	98.0%	5	95.3%
35	3	100.0%	3	97.3%
40	0	100.0%	0	97.3%
45	0	100.0%	3	99.3%
50	0	100.0%	0	99.3%
>50	0	100.0%	1	100.0%

The Kolmogorov-Smirnov test for equal distributions of the tuft heights of *A. junciformis* against the other grasses after the HDG treatment revealed that the mean tuft height did not differ, but the distribution of the heights did ($D = 0.16$, where D is the maximum distance between the cumulative height distributions; $p = 0.03818$).

After the HDG, the mean height of the *A. junciformis* tufts was 8.83 cm, ranging from 3 cm to 35 cm, while the average height of the non-*A. junciformis* tufts was 9.97 cm (SE ± 0.76 cm), ranging from 1 cm to 51 cm (Table 5.2). The height of the *A. junciformis* and of the other grass tufts was skewed to the right, though the kurtosis value indicates that the height of the *A. junciformis* tufts was more positively skewed (6.70) than of the other grasses due to a few tall ungrazed *A. junciformis* tufts (4.13; Figure 5.1). The independent t-test showed that the *A. junciformis* tufts were grazed more uniformly (sd = 5.845) than the other grass tufts (sd = 9.347). Moreover, the *A. junciformis* tufts were grazed shorter than the other grass tufts (-1.14 cm ± 0.34 cm) but not significantly so (t = 1.266, p = 0.206).

Table 5.2 Descriptive statistics for the tuft height (cm) of *A. junciformis* and other grass tufts after the HDG application

	A. junciformis	Other grasses
Minimum	3.00	1.00
First Quartile	5.00	4.00
Median	7.00	6.00
Third Quartile	10.00	12.00
Maximum	35.00	51.00
Mean	8.83	9.97
Standard Deviation	5.58	9.35
Standard Error	0.48	0.76
Variance	34.17	87.37
Mode	7.00	4.00
Kurtosis	6.70	4.13
Range	32.00	50.00

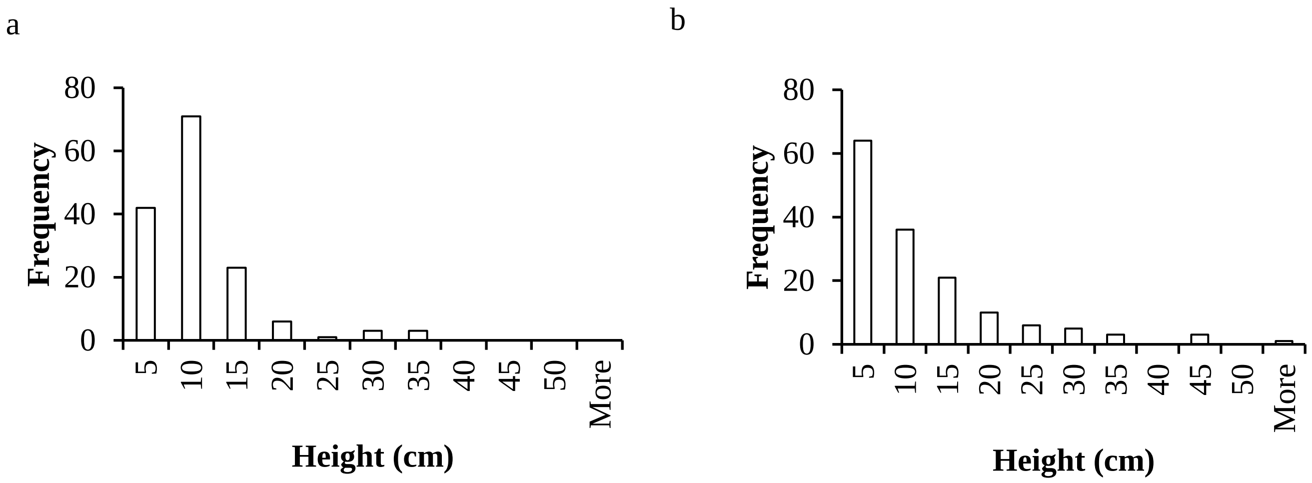


Figure 5.1 Height-frequency graphs of (a) 150 *A. junciformis* and (b) 150 other grass tufts measured in all paddocks after the HDG was implemented.

5.2 Distribution of grazing intensity within each paddock

The average tuft height of the *A. junciformis* was greatest in paddock 5 (14.37 cm), followed by paddock 3 (10.97 cm) and lowest in paddocks 2 (5.33 cm) and 13 (5.63 cm; Table 5.3). In contrast, the average tuft height of the other grass tufts was also greatest in paddock 5 (20.60 cm), followed by paddock 13 (11.00 cm; Table 5.4). The average tuft height of the other grass tufts was lowest in paddocks 2 (4.93 cm) and 12 (4.87 cm; Table 5.4). All measured grass tufts in paddock 2 were grazed to a height of 10 cm and lower, with all grass tufts remaining lower than 20 cm in paddock 12. The remaining paddocks (3, 5 and 13) had greater variability in tuft height. None of the measured *A. junciformis* tufts were taller than 35 cm (Figure 5.2), while approximately 23% of the other grass tufts in paddock 5 were taller than 35 cm (Figure 5.2). Cumulative percentages of tufts grazed in each height class for the measured *A. junciformis* and other grass tufts are attached in the Appendices.

Table 5.3 Descriptive statistics of *A. junciformis* tuft heights (cm) within each HDG paddock, immediately after implementation of the HDG

	Paddock no.				
	2	**3**	**5**	**12**	**13**
Mean	5.33	10.97	14.37	7.87	5.63
Standard Deviation	1.83	6.99	7.15	2.80	1.94
Standard Error	0.33	1.28	1.30	0.51	0.35
Median	5.00	8.50	12.50	7.00	5.00
Mode	4.00	7.00	8.00	7.00	5.00
Sample Variance	3.33	48.93	51.07	7.84	3.76
Kurtosis	0.50	4.65	2.00	1.09	2.71
Range	7.00	29.00	30.00	11.00	9.00
Minimum	3.00	3.00	5.00	4.00	3.00
Maximum	10.00	32.00	35.00	15.00	12.00

Table 5.4 Descriptive statistics of other grass tuft heights (cm) within each HDG paddock, immediately after implementation of the HDG

	Paddock no.				
	2	**3**	**5**	**12**	**13**
Mean	4.93	8.47	20.60	4.87	11.00
Standard Deviation	2.20	8.16	12.75	2.83	5.78
Standard Error	0.40	1.49	2.33	0.52	1.05
Median	5.00	4.50	16.50	4.00	10.50
Mode	4.00	2.00	12.00	3.00	12.00
Sample Variance	4.82	66.60	162.59	7.98	33.38
Kurtosis	-0.20	0.81	-0.44	16.64	0.37
Skewness	0.34	1.30	0.81	3.67	0.89
Range	9.00	27.00	44.00	15.00	21.00
Minimum	1.00	2.00	7.00	3.00	3.00
Maximum	10.00	29.00	51.00	18.00	24.00

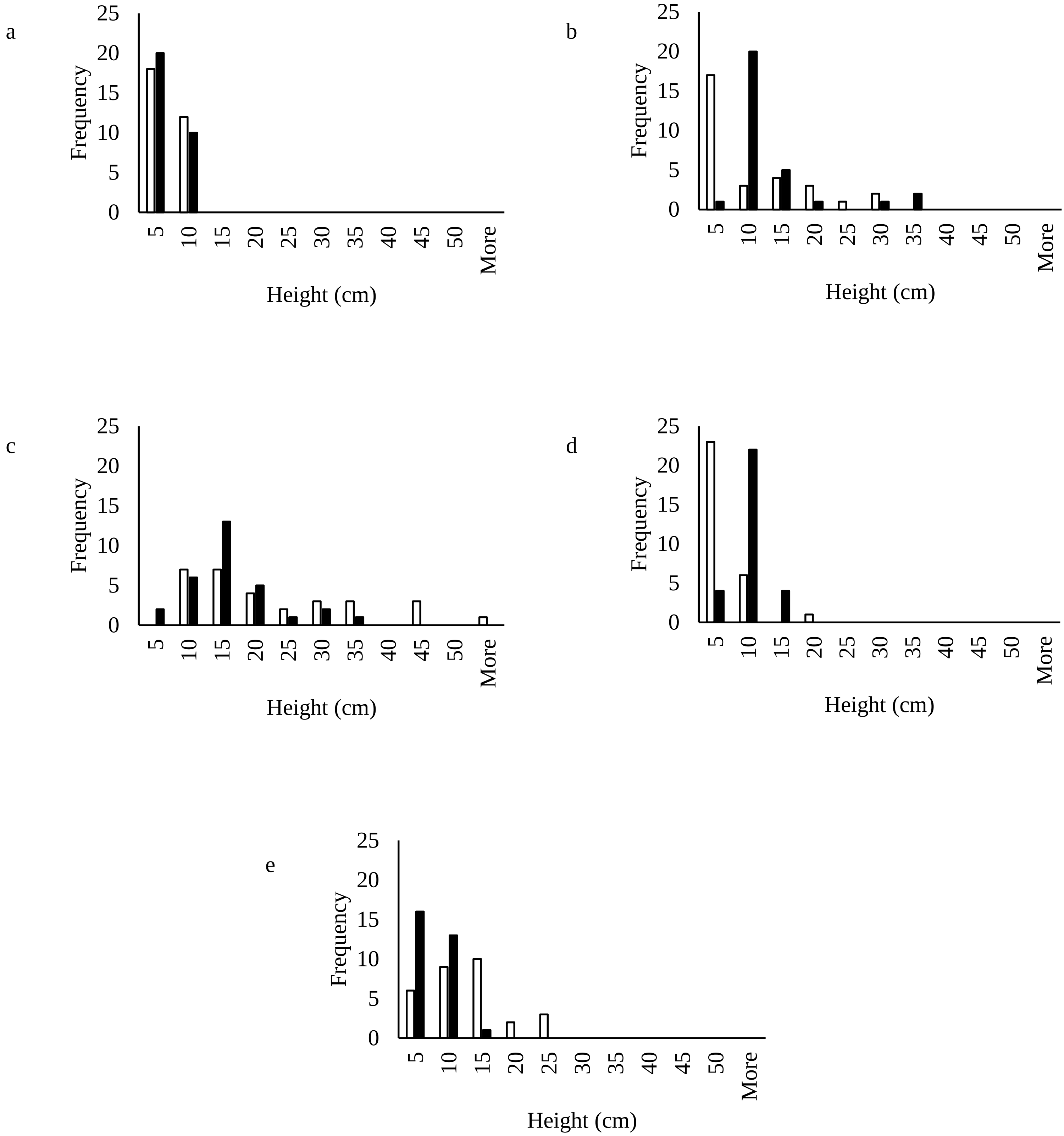


Figure 5.2 Height-frequency graphs of 30 *A. junciformis* tufts (black) and 30 other grass tufts (white) measured in each HDG paddock immediately after the HDG was implemented; (a) paddock 2, (b) paddock 3, (c) paddock 5, (d) paddock 12 and (e) paddock 13.

5.3 Tuft height regrowth pattern of *A. junciformis* under control and HDG

The regrowth height of the monitored *A. junciformis* tufts under the control and HDG are shown in Figure 5.3. The regression analyses revealed that the best fit of the height regrowth of the selected *A. junciformis* tufts in the control was linear and in the HDG was quadratic. A complex non-linear asymptotic model described a similar pattern of change (not shown), but with a slightly lower goodness of fit.

The treatments had an effect on the regrowth of the selected *A. junciformis* tufts (Table 5.5). Initially the grazed *A. junciformis* tufts were significantly ($p = 0.0018$) shorter (-0.785 ± 0.145) than those in the control paddocks (2.749 ± 0.103; Table 5.6). At about four weeks after the HDG the heights of the *A. junciformis* tufts in the control (1.593 ± 0.055) and the HDG (0.707 ± 0.0776; Table 5.6) paddocks were almost equal in height after which the *A. junciformis* tufts in the HDG paddocks were taller than those in the control paddocks, but not significantly so ($p = 0.9481$). In contrast to our expectations *A. junciformis* tufts in the control paddocks displayed a steady linear growth rate (about 6.75 cm per week) over the four-month measuring period ($F_{1,8} = 456.84$; $P < 0.001$) while the *A. junciformis* tufts in the HDG paddocks had a quadratic growth response ($F_{2,7} = 125.35$; $P < 0.001$), initially growing rapidly then declining towards the end of the growing season (Figure 5.3).

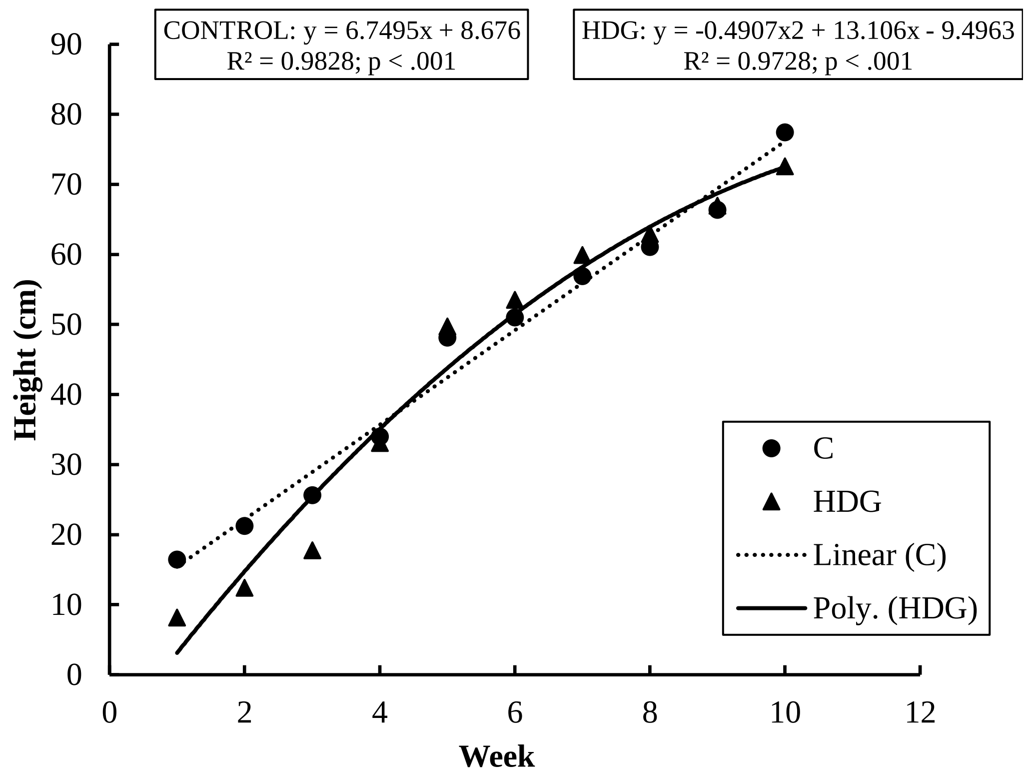


Figure 5.3 Pattern of change in mean (± se) height (cm) after grazing of marked *A. junciformis* tufts (n=50) in control (represented by C) and HDG (represented by G) treatment paddocks.

Table 5.5 Analysis of Deviance Table (Type II Wald chisquare tests) of the effects of treatments and time on the height of monitored *A. junciformis* tufts (log transformed) immediately after the graze and four months after the graze

	Chisq	df	Pr(>Chisq)
Time	2520.6462	1	$<2.2e^{-16}$
Treatment	9.5235	1	0.002029
Time:Treatment	83.2439	1	$<2.2e^{-16}$

Table 5.6 Estimated coefficients from a LMM (log transformed) of the effects of treatment (control & HDG) on the height of monitored *A. junciformis* tufts immediately after the graze (T1) and four months (T2) after treatment implementation. H represents the HDG and the Intercept represents the control.

	Estimate	Standard Error	df	t value	Pr(>|t|)
Intercept T1	2.74942	0.10259	9.27533	26.801	$4.19e^{-10}$
as.factor T2	1.59268	0.05483	188.00000	29.050	$< 2e^{-16}$
Treatment H T1	-0.78515	0.14508	9.27533	-5.412	0.000384
as.factor T2:treatmentH	0.70742	0.07754	188.00000	9.124	$< 2e^{-16}$

Paddock number (SD = 0.2124) was included as a random intercept for this LMM.

5.4 Treatment effect on regrowth height and biomass

The Analysis of Deviance (Type II Wald chisquare tests) for the harvested biomass yielded a p-value of 0.695 (Chi-sq = 0.1537; df = 1) showing that treatment had no effect. This was supported by the results shown in Table 5.7.

Table 5.7 Fixed Effects of the LMM (log transformed) for height of *A. junciformis* tufts monitored from November 2018 to March 2019. H represents the HDG and the Intercept represents the control

	Estimate	Standard Error	df	t value	Pr(>|t|)
Intercept	4.55618	0.12717	7.98964	35.827	$4.12e^{-10}$
Treatment H	0.07064	0.18019	8.04911	0.392	0.705

Paddock number (SD = 0.2282) was included as a random intercept for this LMM.

The mean height of the grazed *A. junciformis* tufts were initially significantly ($p = 0.0018$) shorter than the control tufts (estimated means of 1.96 cm (± 0.103) and 2.75 cm (± 0.103) respectively) but after four months there was no difference ($p = 0.9481$) in height (estimated means of 4.26 cm (± 0.103) and 4.34 cm (± 0.103) respectively; Figure 5.4a)

The total aboveground dry matter (AGDM) harvested at the end of the growing season did not differ between the *A. junciformis* tufts in the control (estimated mean of 4.56g (± 0.127)) and HDG (estimated mean of 4.63g (± 0.128)) paddocks ($p = 0.7053$; Figure 5.4b).

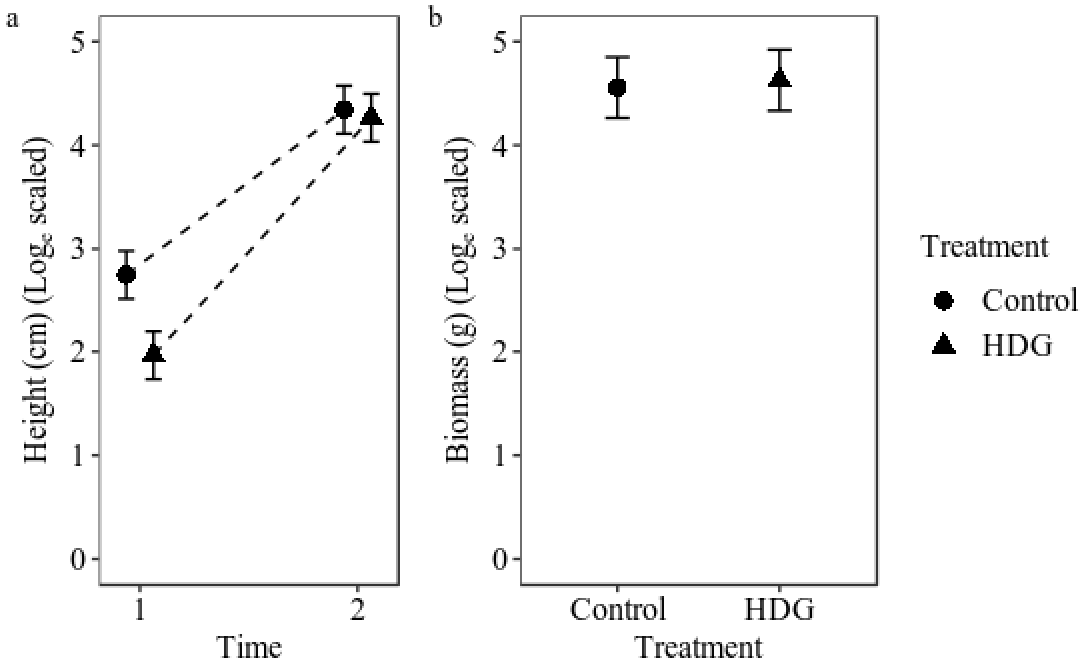


Figure 5.4 The effect of HDG and an undefoliated control on (a) the mean heights (log$_e$) of *A. junciformis* immediately after the HDG and after *A. junciformis* tufts stopped growing four months later and (b) the mean (±se) total above-ground dry matter of *A. junciformis* tufts harvested at the end of the growing season.

5.5 Treatment effects on species cover composition

The plant cover composition did not differ among treatments ($p = 0.5994$), however there was a significant shift in species composition over time ($p = 0.0005$) from March 2018, before treatment implementation, to March 2019, after treatment implementation (Table 5.8). Furthermore, there was no treatment × time interaction ($p = 0.1986$), indicating that the directional shift in species composition over time was similar in all paddocks, as is shown in the NMDS (Figure 5.5).

Table 5.8 A PERMANOVA of the effects of treatment (control, herbicide application, HDG) and time (pre- and post-treatment implementation in March 2018 and March 2019 respectively) on cover composition. Statistically significant p-values (<0.005) are marked in bold

Source	df	SS	MS	Pseudo-F	P(perm)	Unique perms
Treatment	2	87.706	43.853	0.690	0.5994	9575
Time	1	217.510	217.510	13.244	**0.0005**	9968
Paddock (Treatment)	12	762.620	63.552	3.870	0.0011	9930
Treatment×Time	2	53.139	26.569	1.618	0.1986	9956
Res	12	197.070	16.423			
Total	29	1318.000				

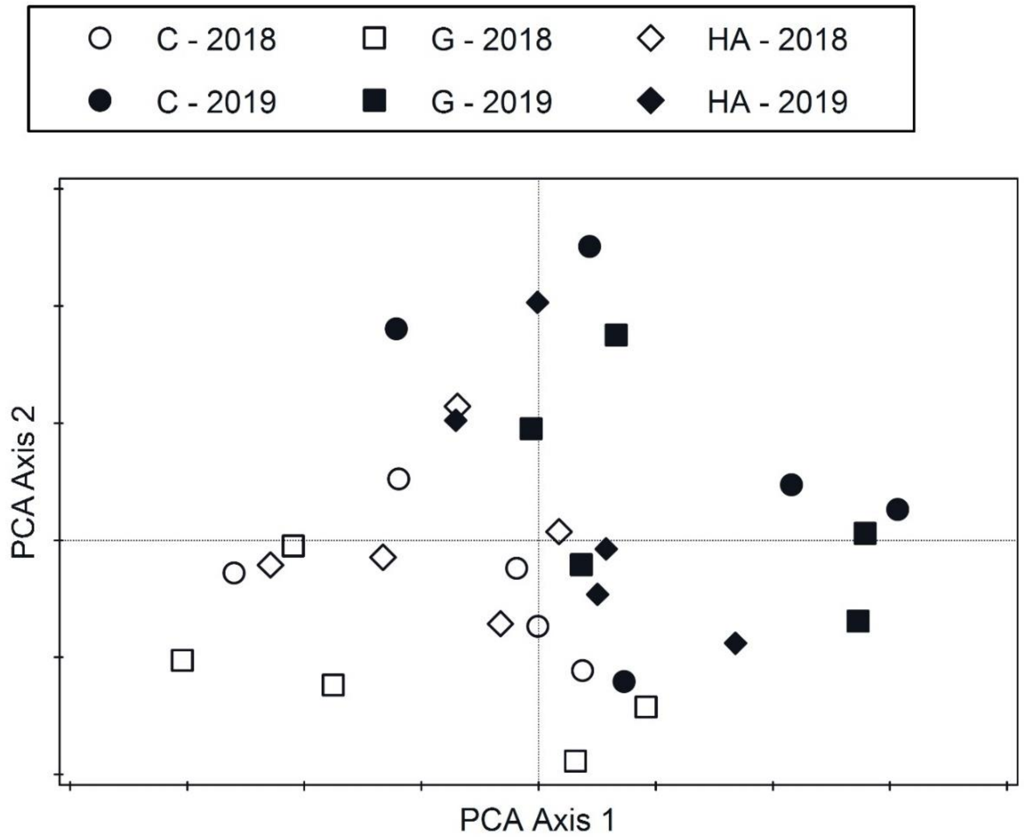


Figure 5.5 An NMDS of differences in cover composition among treatments and time, where C = control, G = HDG and HA = herbicide application. Empty symbols represent pre-treatment (March 2018) and filled symbols represent post-treatment (March 2019) line-intercept cover composition assessments.

A decline of bare soil from March 2018 to March 2019 contributed the most (> 36%) to the observed dissimilarity, followed by an increase in grass cover (Table 5.9). Forbs and *A. junciformis* also increased in cover across all paddocks for the duration of this study.

Table 5.9 SIMPER analysis presenting the percentage contribution to the difference in cover composition (Bray-Curtis) by forbs, bare soil, *A. junciformis* and all remaining grass species between March 2018 (pre-treatment) and March 2019 (post-treatment). Note: means are from untransformed data and contributions from log-transformed data.

Species	March 2018		March 2019		Contribution (%)
	Mean (%)	SE	Mean (%)	SE	
A. junciformis	18.02	0.64	22.65	0.87	17.51
Bare Soil	53.05	2.25	34.51	1.08	36.68
Forbs	13.53	0.74	18.51	0.65	16.06
Grasses	15.40	0.33	24.33	0.45	29.74

6 Chapter Six: Seedling Emergence Results

The results in this chapter are presented in the following order: 6.1.1 Seedbank studies – the total number and species composition of seedlings germinating from the seedbank; 6.1.2 Seedling emergency study – the total number and species composition of seedlings emerged in the field experiment, the pattern of emergence over time in total seedlings, *A. junciformis* and other grasses, the effect of treatments on total seedlings, *A. junciformis*, and other grasses that emerged and the effect of treatments on the overall species composition of emerged species.

6.1 Seedbank study

6.1.1 Vegetation species composition of sites from which soil samples were taken

Aristida junciformis was most common in the medium and high aboveground *A. junciformis* densities and therefore most common on average (51.36%) followed by *E. curvula* (19.35%) which was most dominant under the low aboveground *A. junciformis* density from soil samples taken in January 2018 (Table 6.1). *E. plana* was not present in the measured species composition but was observed on site.

Table 6.1 Proportional, average species composition of grass and other plant species growing under low, medium and high aboveground *A. junciformis* densities from which soil samples were taken in January 2018

Species	Low (%)	Medium (%)	High (%)	Average (%)
Aristida junciformis	25.56	44.30	84.23	51.36
Chloris gayana	3.06	0.20	0.00	1.09
Eragrostis curvula	29.31	27.63	1.10	19.35
Forbs	13.66	17.01	12.61	14.42
Heteropogon contortus	0.00	0.71	0.00	0.24
Panicum natalense	0.31	0.00	0.16	0.16
Sedges	0.03	0.03	0.03	0.03
Setaria sphacelata var. sericea	3.18	0.00	0.00	1.06
Setaria sphacelata var. sphacelata	21.54	0.61	0.29	7.48
Sporobolus pyramidalis	0.38	0.00	0.00	0.13
Themeda triandra	0.50	6.04	0.72	2.42
Tristachya leucothrix	2.48	3.47	0.86	2.27

6.1.2 Seedling emergence from the seedbank study

A total of 4682 seedlings germinated from the planted soil samples of which 92% were forbs and 8% were grass species, none of which were *A. junciformis* seedlings. The most seedlings emerged from the soils sampled from sites with medium aboveground *A. junciformis* densities (1669 seedlings, sd = 33.92) while the fewest emerged from the soils sampled from sites with high aboveground *A. junciformis* densities (1596 seedlings, sd = 24.62; Table 6.2, Table 6.3). A total of 22 seedlings (sd = 6.39) emerged from the control. The species composition of the emerged seedlings is shown in Table 6.2 of which 25 grasses and 22 forbs were unidentified as these died after the transplant. Further descriptive statistics are provided in Table 6.3.

Table 6.2 Proportional, mean species composition of grass and other plant species germinating under low, medium and high abundance of *A. junciformis* plants and their mean composition. Numbers in brackets indicate the total number of seedlings that emerged. Results are given in percentage (%)

Species	Control (22)	Low (1596)	Medium (1669)	High (1395)	Mean
Blepharis integrifolia	0.00	1.00	1.68	0.72	0.85
Chamaecrista comosa	4.55	0.00	0.12	0.00	1.17
Cirsium vulgare	0.00	0.31	0.30	0.07	0.17
Crabbea hirsuta	0.00	1.44	1.26	1.08	0.94
Commelina africana	0.00	0.13	0.00	0.07	0.05
Conyza chilensis	0.00	18.17	20.19	20.86	14.81
Diclis reptans	0.00	34.52	35.65	37.42	26.90
Digitaria sanguinalis	0.00	0.25	0.12	0.00	0.09
Persicaria senegalensis	4.55	5.70	7.49	7.46	6.30
Persicaria	0.00	0.00	0.06	0.22	0.07
Rumex	0.00	0.38	0.00	0.07	0.11
Senecio variabilis	0.00	20.68	23.37	26.52	17.64
Solanum nodiflorum	0.00	0.94	0.60	0.00	0.38
Unidentified Grasses - 25	0.00	12.34	6.83	3.66	5.71
Unidentified Forbs - 22	90.91	4.14	2.34	1.86	24.81

Table 6.3 Descriptive statistics for the seedling emergence under low, medium and high levels of *A. junciformis* in comparison to a control (Umngeni grit sand)

	Low	Medium	High	Control
Mean	63.84	66.76	55.80	4.40
Standard Deviation	26.35	33.92	24.62	6.39
Standard Error	5.27	6.78	4.92	2.86
Median	59.00	58.00	51.00	0.00
Mode	40.00	49.00	51.00	0.00
Sample Variance	694.14	1150.69	605.92	40.80
Range	101.00	156.00	105.00	14.00
Minimum	34.00	21.00	17.00	0.00
Maximum	135.00	177.00	122.00	14.00

6.2 Field study

6.2.1 Vegetation assessment of field study

During the seedling emergence period, forbs (40.50%), *A. junciformis* (29.65%) and *T. triandra* (13.10%) were found to be the three most dominant species respectively (n = 30; Table 6.4). Some species were found on site that did not contribute much (e.g. *B. pilosa*, some ferns and small *Vachellia* trees) or did not contribute at all (e.g. *E. plana*, *P. maximum*, *P. natalense* and *S. africanus*; Table 6.4)

Table 6.4 Proportional species composition of grass and other plant species growing on the experimental sites used for the field study and the mean species composition of all sites used in the field study before the burn in August 2018

Species	Paddock Number										
	1	2	3	5	7	9	12	13	14	15	Mean
Vachellia trees	0.00	0.50	0.50	0.00	0.00	0.50	0.00	0.00	0.00	0.00	0.15
Aristida junciformis	24.00	40.50	31.50	24.00	41.50	45.00	14.00	22.50	24.50	29.00	29.65
Bidens pilosa	0.00	0.00	0.00	0.00	0.00	0.50	0.00	0.00	0.00	0.00	0.05
Chloris gayana	0.50	1.50	0.00	2.00	2.50	0.00	1.00	0.00	1.00	1.00	0.95
Cymbopogon caesius	0.50	0.50	0.50	0.50	0.50	0.00	1.00	0.50	2.00	0.50	0.65
Eragrostis curvula	8.00	2.00	3.00	19.00	8.00	5.50	15.50	6.50	4.00	5.00	7.65
Fern	0.00	0.00	0.00	0.00	0.50	0.00	0.00	0.00	0.00	0.00	0.05
Forb	31.50	50.50	56.00	49.50	39.50	40.00	34.50	24.50	44.50	34.00	40.45
Hyparrhenia hirta	0.00	0.00	0.00	0.00	0.50	0.00	0.00	0.50	0.50	0.50	0.20
Sedge	1.00	0.00	0.50	0.00	0.00	0.50	0.50	0.00	0.50	0.00	0.30
Setaria sphacelata	0.00	0.00	0.00	1.50	1.50	0.50	0.00	0.00	0.00	0.00	0.35
Sporobolus pyramidalis	1.00	0.00	0.00	0.00	0.50	0.50	0.00	0.00	0.50	0.00	0.25
Themeda triandra	29.00	1.50	6.50	2.50	2.50	2.50	20.00	28.50	14.50	23.50	13.10
Tristachya leucothrix	4.50	3.00	1.50	1.00	2.50	4.50	13.50	17.00	8.00	6.50	6.20

6.2.2 Seedling emergence in the field study

A total of 1049 seedlings (n = 30) emerged in the field study of which 468 emerged from the HDG-specified sites (n = 15) and 581 emerged from the control-specified sites (n = 15). The mean density of seedlings that emerged across all paddocks was 32.30 (± 17.46) seedlings per square meter. Mean totals ranged from approximately 12 – 50 per square meter (CV% = 54.04). Figure 6.1 shows the average number of seedlings that germinated or emerged over the observation period (n = 30). No more seedlings emerged after week 16 (Figure 6.1).

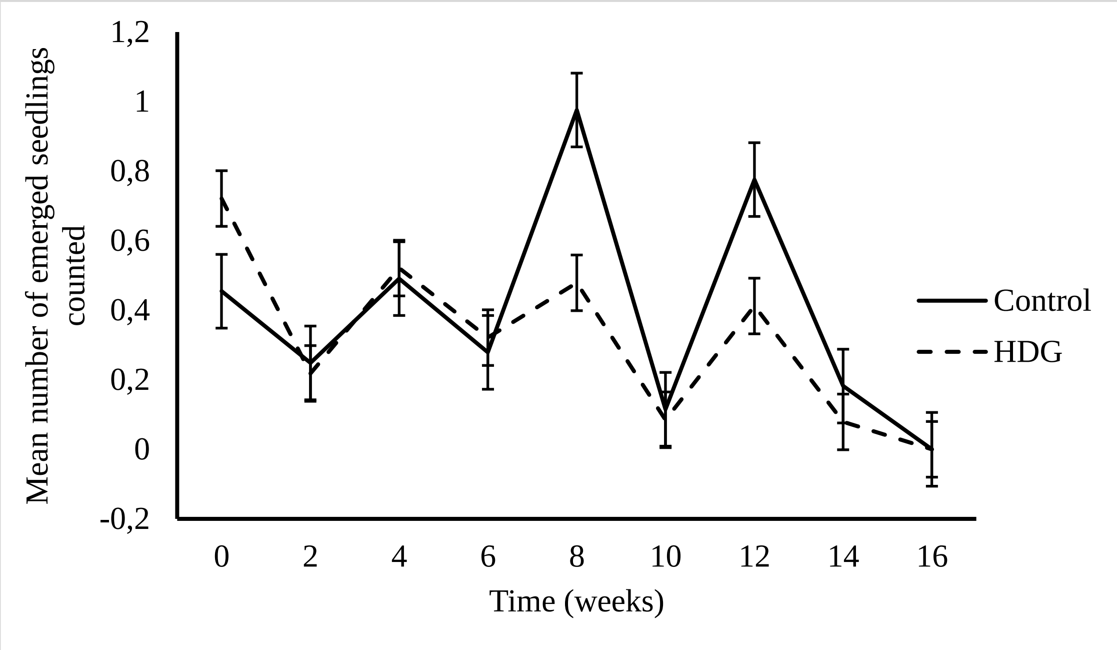


Figure 6.1 The mean number, for all ten paddocks, of seedlings that emerged in the control and HDG treatments.

Figure 6.2 shows a detailed emergence over time under both the control and the HDG. Initially more seedlings emerged under the HDG than under the control until about week 8 after which more seedlings emerged under the control than under the HDG. Seedling emergence stopped after week 16 under both treatments (Figure 6.2).

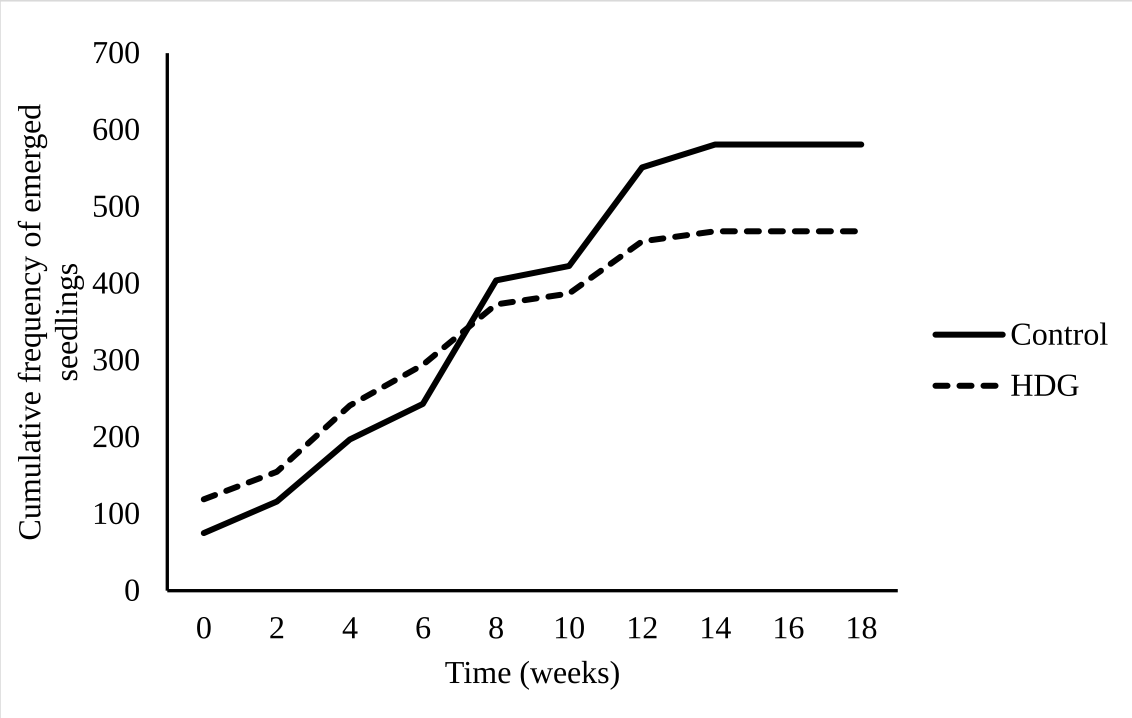


Figure 6.2 Cumulative frequency of seedlings that emerged under the control and HDG (n=10) over time.

6.2.3 Treatment effects on seedling emergence

After the treatment implementation seedling emergence decreased over time under both the control and the HDG. Initially it decreased more for the control until week four after which it decreased more for the HDG (Figure 6.3). Fewer *A. junciformis* seedlings and tillers than other plant species emerged under both the HDG and control (Figure 6.4). The number of other plants seedlings that emerged was lower under the control than under the HDG until about week eight after which more seedlings emerged under the control than under the HDG (Figure 6.5). One rapid growth spurt is observed under the control for the other plant species between weeks 10 and 12 after which seedling emergence slowed down until no more new seedlings emerged in week 16 (Figure 6.5). Fewer *A. junciformis* seedlings germinated under the control than under the HDG throughout the observation period. Under the HDG, 25 *A. junciformis* seedlings emerged while only 13 *A. junciformis* seedlings emerged under the control. No *A. junciformis* seedlings emerged after week 8 (Figure 6.6). More forbs emerged under both the HDG and the control than any other species (Figure 6.7). Forbs were the only “species” that still emerged after week 11 (Figure 6.7).

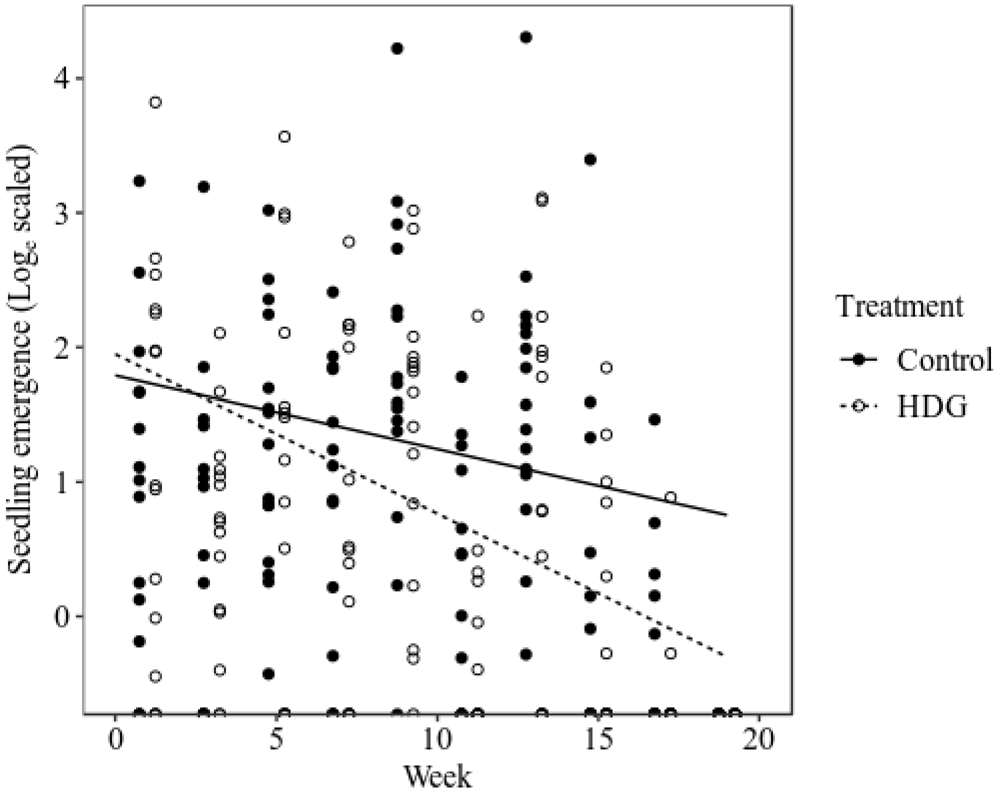


Figure 6.3 Total number of seedlings (across 10 paddocks; 5 control and 5 HDG paddocks) that emerged. The lines indicate fitted polynomials.

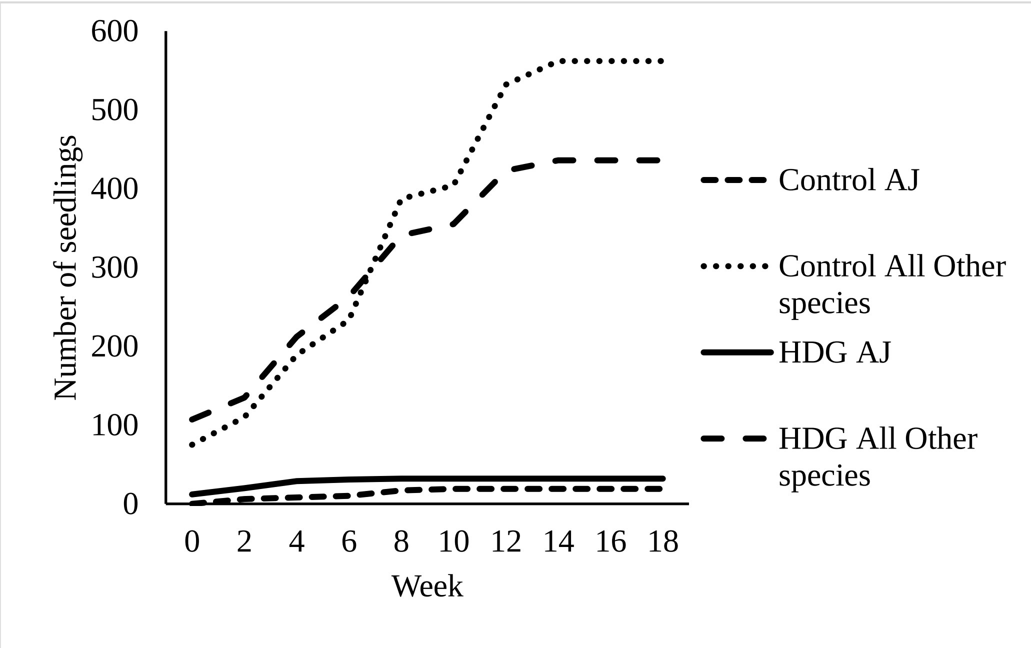


Figure 6.4 Total number of *A. junciformis* (AJ) and all other plant seedlings that emerged in the control and HDG paddocks (n=10).

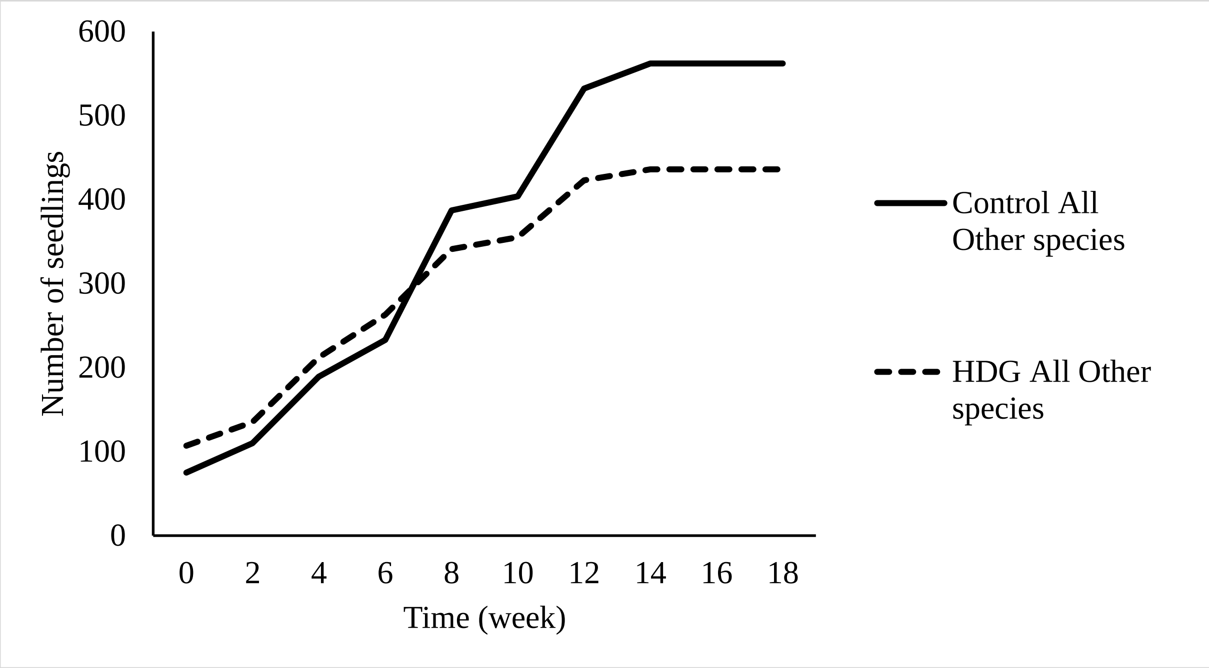


Figure 6.5 Seedling emergence over time for all plant species, except *A. junciformis*, from the HDG and control paddocks (n=10).

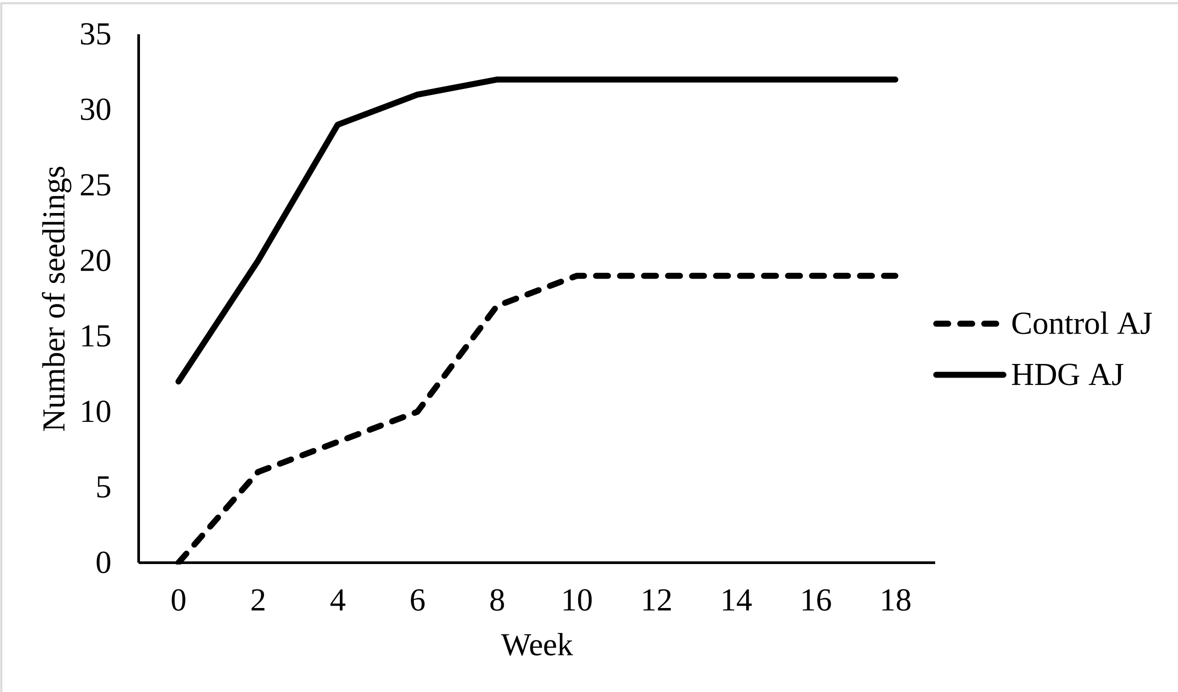


Figure 6.6 Seedling emergence over time for *A. junciformis* only, from the control and HDG paddocks (n=10).

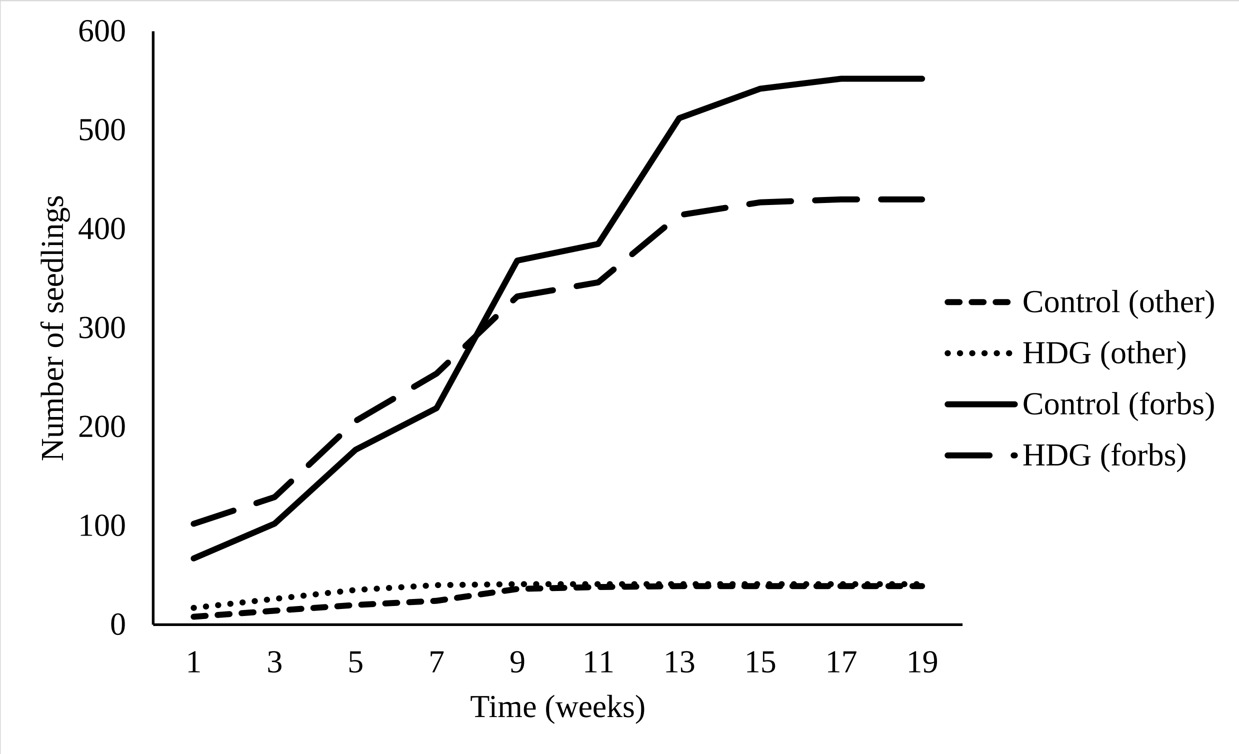


Figure 6.7 Total number of forbs and all other plant seedlings that emerged across 10 paddocks; 5 control and 5 HDG paddocks.

6.2.4 Treatment effects on seedling species composition

The Analysis of Deviance tests for all emerged seedlings, all grass seedlings, excluding *A. junciformis*¸ all forb seedlings and all *A. junciformis* seedlings are provided in Table 6.5. The results show that treatment had no effect on the emergence on the seedlings of any of the categories described. This is further supported by the results provided in Table 6.6.

Table 6.5 Analysis of Deviance (Type II Wald chisquare tests) of the effects of treatments and time on the seedling emergence in the field (log transformed) for all emerged seedlings, all grass seedlings, excluding *A. junciformis*¸ all forb seedlings and all *A. junciformis* seedlings

Analysis of	Chisq	df	Pr(>Chisq)
All seedlings	0.9292	1	0.335
Grass seedlings	0.9373	1	0.333
Forb seedlings	0.2747	1	0.600
A. junciformis seedlings	0.2463	1	0.620

Table 6.6 Estimated coefficients from all GLMMs - all emerged seedlings, all grass seedlings excluding *A. junciformis*, all forbs and all *A. junciformis* seedlings (log transformed) of the effects of treatment (control and HDG) on the seedling emergence after treatment implementation in November 2018. Seedlings stopped emerging in March 2019. The Intercept represents the control and H represents the HDG. The paddock numbers were included as random intercepts for the GLMMs

		Estimate	Std. Error	z-value	Pr(>|z|)	Std. Dev
All Seedlings	Intercept	3.5958	0.2247	16.000	$<2e^{-16}$	0.4928
	TreatmentH	-0.3078	0.3193	-0.964	0.335	
All grass - *A. junciformis*	Intercept	0.1765	0.4424	0.399	0.690	0.8116
	TreatmentH	-0.6482	0.6695	-0.968	0.333	
Forbs	Intercept	3.3202	0.2361	14.060	$<2e^{-16}$	0.4590
	TreatmentH	-0.1670	0.3185	-0.524	0.600	
A. junciformis	Intercept	-0.4742	0.5999	-0.790	0.429	1.0880
	TreatmentH	0.4100	0.8262	0.496	0.620	

Slightly more seedlings emerged under the control than under the HDG (Figure 6.8a). Similar results were observed for the emergence of forbs at the same scale, though it is clear that the most seedlings that emerged were composed of forb seedlings (Figure 6.8b). More grass seedlings excluding *A. junciformis* emerged under the control than under the HDG treatment, though the scale indicates that far fewer grasses emerged than forbs (Figure 6.8c). In contrast to the emergence of the other categories, fewer *A. junciformis* seedlings emerged under the control than under the HDG treatment and similar to the grass seedlings, not many *A. junciformis* seedlings emerged overall (Figure 6.8d).

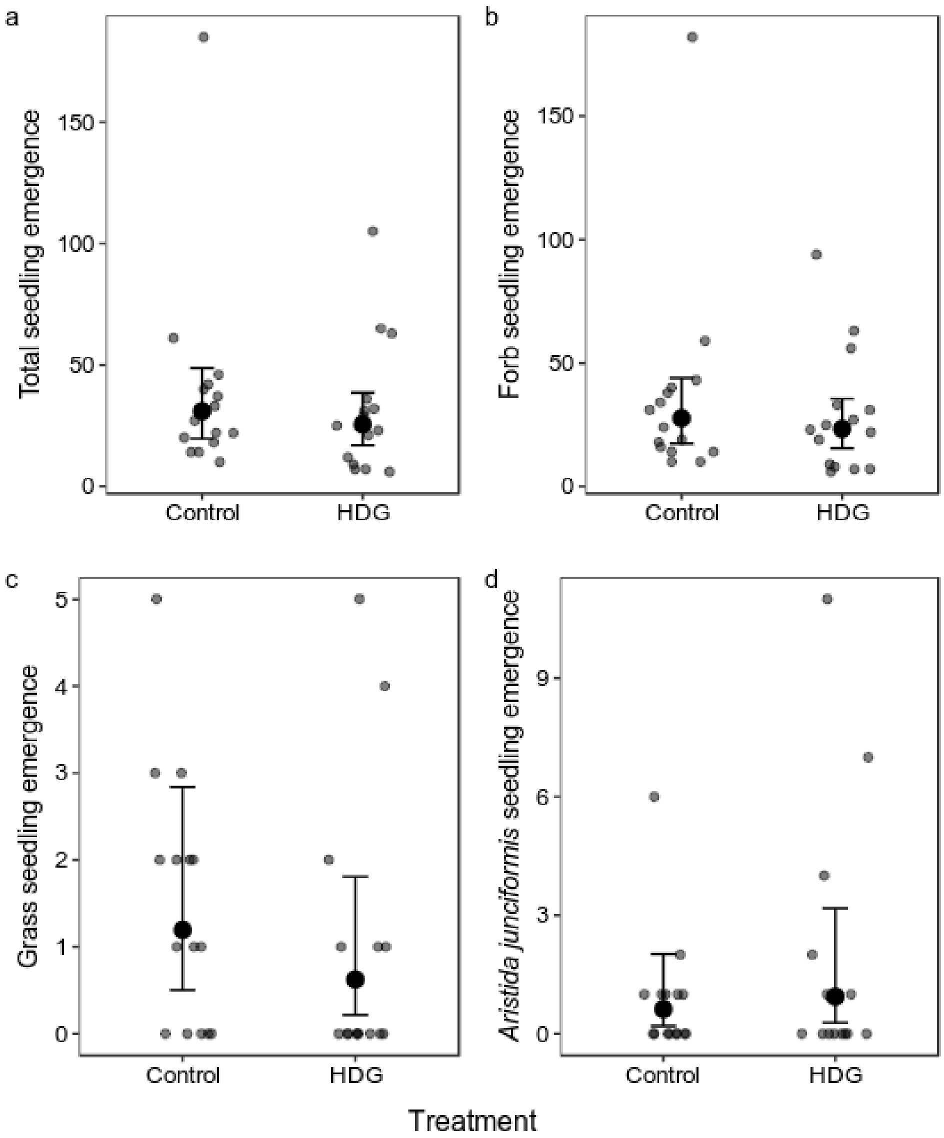


Figure 6.8 The (a) total seedling emergence for all HDG and control paddocks (n=10) and of each plant category - (b) forb seedling emergence, (c) grass seedling emergence and (d) *A. junciformis* seedling emergence under five control and five HDG paddocks. Dots represent mean seedling emergence, lines the standard erros of each mean. Note: graphs drawn to different scales.

The plant species composition of emerged seedlings did not differ among treatments ($p = 0.8134$; Table 6.7). This is supported by the NMDS (Figure 6.9).

Table 6.7 A PERMANOVA of the effects of treatment (control, herbicide application, HDG) and time (pre- and post-treatment implementation in March 2018 and March 2019 respectively) on cover composition. Statistically significant p-values (<0.005) are marked in bold

Source	df	SS	MS	Pseudo-F	P (perm)	Unique perms
Treatment	1	155.29	155.29	0.3639	0.8134	126
Res	8	3413.90	426.74			
Total	9	3569.20				

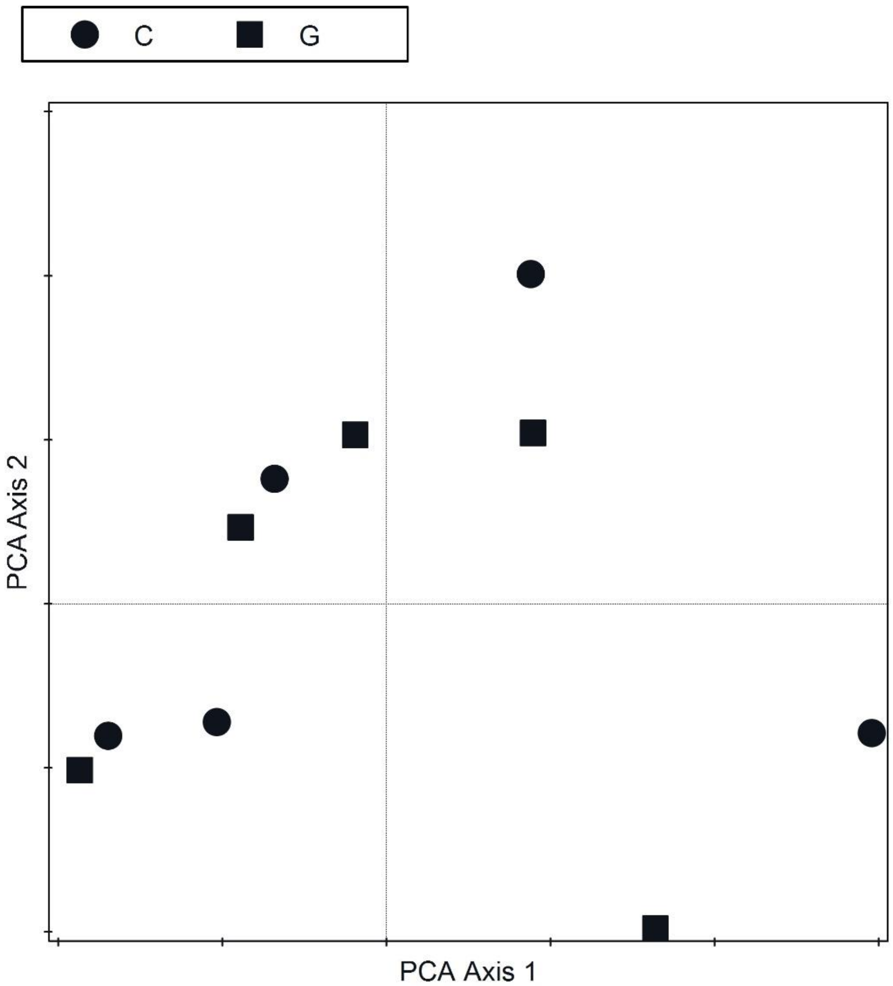


Figure 6.9 An NMDS of differences in seedling emergence among treatments with the 2-D configuration rotated by principal component analysis (PCA) to represent maximum variation along the horizontal axis. Square symbols (G) represent the HDG and circle symbols (C) represent the control.

Forbs contributed the most to the emerged seedlings in both the control (91.32%) and the HDG (91.79%) and contributed the most to the observed dissimilarity (>33%; Table 6.8). The lowest contribution to the observed dissimilarity was made by *E. capensis*, which, like *E. curvula* and the sedges, did not emerge in the HDG, but also had less seedlings emerge in the control. It is important to note that more *A. junciformis* seedlings emerged under the HDG than under the control and contributed to more than 20% of the observed dissimilarity (Table 6.8).

Table 6.8 SIMPER analysis presenting the percentage contribution by species to the dissimilarity (Bray-Curtis) in species composition between vegetation surveyed in November 2018 to March 2019 under the control and HDG. Note: data is from untransformed data. Values marked as undef. could not be calculated due to insufficient results

Species	Control		HDG		Contribution (%)
	Mean (%)	S.E.	Mean (%)	S.E.	
Andropogon amplectens	1.64	0.1866	1.65	0.1012	13.37
Aristida junciformis	2.95	0.2973	3.59	0.1834	20.27
Eragrostis capensis	0.16	undef.	0.00	undef.	0.92
Eragrostis curvula	0.19	undef.	0.00	undef.	1.08
Forbs	91.32	6.7831	91.79	13.3416	33.87
Sedges	0.82	0.1012	0.00	undef.	4.64
Tristachya leucothrix	2.08	0.1897	2.74	0.1834	20.78
Themeda triandra	0.84	0.1012	0.24	undef.	5.06

7 Chapter Seven: Discussion

Eradicating *A. junciformis* from infested grasslands is a priority of veld management since it threatens livestock production, the existence of many self-sustaining communities and the overall South African economy. The aim of this research study was to determine the effect two focused disturbance treatments (HDG and herbicide application) would have on the mortality and vigour of *A. junciformis*. It was expected that the herbicide application would be more successful in killing and reducing the vigour of *A. junciformis* than the HDG and that the herbicide application would be more beneficial to palatable and productive grasses than the HDG. It was also expected that the reduction of foliage by the HDG and herbicide application would enhance seedling germination of all species since *A. junciformis* suppresses the growth of other species.

This chapter discusses the success of the studies conducted in relation to the hypotheses and expectation described. I present the discussion in five main themes:

7.1 Resistance of *A. junciformis* to herbicide application

7.2 Resilience of *A. junciformis* to grazing

7.3 Replacement of *A. junciformis* by seedlings and observed species and cover composition changes

7.4 Recommendations for rehabilitating and managing *A. junciformis* dominated grasslands

7.5 Research suggestions for future research

7.1 Resistance of *A. junciformis* to herbicide application

Aristida junciformis is resistant to herbicide application. Though the herbicide application was most successful in reducing the probability of survival of *A. junciformis*, it did not successfully kill *A. junciformis*. After the herbicide application, most tufts remained green with only 30% of the *A. junciformis* tufts being completely grey. The herbicide application did also not work exactly as planned since some tufts were half grey and half green after the herbicide application. These tufts were classified as being alive as they had the potential to fully recover.

Most studies attempting to eradicate weeds by herbicide application have been focussed on woody species such as *Lantana camara* (Gooden et al., 2009; Urban et al., 2011; Vardien et al., 2012) or *Solanum mauritianum* (Olckers et al., 1991; Witkowski et al., 2008), as they supposedly present more concerning issues than other plant species (Milton, 2004). A few herbicide-based eradication studies have been conducted for grasses. Most of these are not based in South Africa (e.g. Ruffner et al. (2010); Bakker et al. (2003); Phillips (2000)), but remain useful as they often share characteristics with the mesic grasslands of South Africa. This is especially true for the Tall Grasslands of North America, which are similar to the mesic grasslands of South Africa in that both plant community structures are shaped by grazing and fire (Hartnett et al., 1996; Dalgleish et al., 2008) and are dependent on fire for its persistence and maintenance and for managing bush encroachment (Benson et al., 2006).

The most useful studies are studies based in southern Africa. A study by Wiseman et al. (2002) attempted to eradicate *A. junciformis* and replace it with other indigenous grasses. This study is similar to the one presented in this dissertation as attempts were made to eradicate *A. junciformis*. Unlike the study by Wiseman et al. (2002), no attempts were made to replace *A. junciformis* in this study since this study aimed to identify the influence *A. junciformis* has on the seedbank before and after treatment application. Unfortunately the study by Wiseman et al. (2002) provides no results on the success of treatments on the mortality of *A. junciformis* but remains useful for further herbicide studies as presented in section 7.5 of this discussion.

The only study that was found to be similar and thus useful to the study presented in this project was conducted by Botha (2006). Sites that had been treated with Round-up ©, had reduced *A. junciformis* abundance from 33.5% (untreated) to 14%, with no other grass species showing a significant response. Their success did, however, not come solely from the herbicide application but also from the post-treatment grazing which broke the algal cap that had developed during the long selective grazing periods which allowed seedlings of species such as *E. curvula* to establish (Botha, 2006).

With the exception of the studies presented by Botha (2006) and Wiseman et al. (2002), no other studies have analysed the effect of herbicide application on the mortality and vigour of *A. junciformis*, as far as I know.

The outcome of this study was unexpected since it was expected that more *A. junciformis* tufts would be killed after the herbicide application. Possible explanations for the low level of success associated with the application may be the use of the weed wiping broom where the wick was clogged by the ash that remained in the veld after the early spring burn reducing the effectiveness of the tool. It was also noted that the tufts which were half green and half grey were often green in the centre of the tuft while the outskirts were grey, which suggests that the wick was not as prone to clogging on the side as it was in the front. A second wipe may have improved effectiveness in eradicating *A. junciformis*.

Another factor that may have affected the results include the time of the lenient graze which was used to induce height differences between *A. junciformis* and all other grass species. If the cattle had grazed later in the season, the *A. junciformis* tufts would have been taller such that the cattle would have avoided it therefore grazing only the palatable species, such that weed wiping may have been more efficient. The herbicide application could also have been more successful if a vehicle drawn applicator had been used (e.g. Botha (2006)), if a different herbicide had been used (e.g. Phillips (2000)) or if a surfactant had been used. Terry et al. (1996) found that the surfactant concentration was a major determinant of the efficacy of the herbicides used in their study.

7.2 Resilience of *A. junciformis* to grazing

Aristida junciformis is resilient to a HDG. Immediately after the HDG, the veld seemed almost lawn-like (Tainton, 1972b) with all species seemingly totally utilised (Daines, 1980). After being undisturbed for approximately 11 weeks, the *A. junciformis* and other grass tufts were similar in height and biomass. This indicates that *A. junciformis* is resilient to a HDG.

The general consensus seems to be that *A. junciformis* is more sensitive to defoliation than most palatable species such as *T. triandra* (Morris et al., 1993; Fynn et al., 2005b). However, *A. junciformis* is also considered to be resistant to frequent and intense defoliation (Tainton, 1972b). This may be mainly attributed to the unfavourable characteristics of *A. junciformis* which cause livestock to avoid it, thus increasing its competitive ability in relation to other grass species allowing it to maintain its dominance or spread into places where previously palatable species existed (Venter, 1968; Tainton, 1972b). One of the main reasons it is avoided by cattle is its low degree of palatability which is influenced by its tough leaves that contain high levels of cellulose (Tainton et al., 1976) and the resulting breaking tension (Theron et al., 1968a). *Aristida junciformis* has a very high breaking tension that remains constant, irrespective of seasonality (Theron et al., 1968b). Since *A. junciformis* is grazed as a young shoot (Van Zyl, 1998), or where it co-exists with palatable species (Brown et al., 2018), and since it is sensitive to defoliation, a HDG early in the growing season should be detrimental for *A. junciformis* (Morris et al., 1992) and beneficial for palatable species which are not as sensitive to grazing (Westoby et al., 1989).

Considering that *A. junciformis* is more sensitive to grazing, it is interesting to note that *A. junciformis* is so resilient after a HDG. As far as I know, no studies have had similar findings to those presented in this study. Its resilience may be explained by its high level of unpalatability and the selective grazing that may occur as a result thereof. A study conducted by O'Reagain et al. (1995) showed that cattle graze grass species in a particular sequence. Preferred species were always grazed first, while species of intermediate preference were utilised a little. If approximately 60% of the tillers of the preferred species had been grazed, the utilisation of the species of intermediate preference increased. Only after more than 80% of the tillers of the preferred and intermediate species had been grazed were the least-preferred grass species grazed. Cattle were also found to graze previously defoliated but preferred species rather than undefoliated but least-preferred species (O'Reagain et al., 1995).

In the context of this study, however, where the HDG was successfully implemented, since no species or area selective grazing (Theron et al., 1966) took place and the HDG was thus non-selective, the only possible explanation is its regrowth rate which was much higher than expected. It was expected that the HDG would be more successful in reducing the vigour of *A. junciformis* particularly since an early graze is supposedly disadvantageous, especially since the *A. junciformis* tufts were grazed shorter than most of the palatable species and since a hot and dry period followed shortly after the HDG was implemented, though it was also expected that this could also harm the palatable species. It was also expected that the HDG would not be a suitable management technique for veld dominated by *A. junciformis* since the available literature had described unfavourable changes resulting from HDG, e.g. species composition (Tainton, 1972b), which is supported by the changes observed in this study, as described in section 7.3 of this discussion.

Considering that less than 30% of the *A. junciformis* and more than 40% of the other grass species were severely grazed, a second HDG could negatively impact palatable grasses more than it would impact *A. junciformis*. A second HDG could compound selective grazing of palatable grass species especially since *A. junciformis* leaves become tougher over the growing period (Theron et al., 1968b) which would result in the palatable species being grazed again, since the stocking density does not affect the sequence of grazing but just affects the rate at which the sequence is grazed (O'Reagain et al., 1995).

Another explanation that could explain why the *A. junciformis* was so resilient in this study may be that perennial C4 grasses, like *A. junciformis* can use repeated fires to their advantage (Milton, 2004). The perennial C4 grasses are generally unpalatable and fibrous in the dry season such that they are avoided by game and livestock. This allows them to generate large amounts of herbage that may become moribund over time thus providing a large fuel load that promotes burning (Milton, 2004). This gives perennial grasses the competitive advantage over indigenous species which are more palatable and thus more adapted to grazing, but are not adapted to fire (Milton, 2004). In this way, *A. junciformis* may have increased its competitive advantage after the burn and before the HDG was implemented, especially since most of the veld had not been burnt at least 12 years prior to the burn in 2018 (pers. comm.).

Other actors that may explain why *A. junciformis* was resilient in this study include its strong (yet understudied) root system (Venter, 1968) and its high abundance of tillers, more than other local species, enabling it to recover fast after a disturbance (Morris et al., 1993) and allowing it to easily invade and dominate once established.

7.3 Replacement of *A. junciformis* by seedlings and observed species and cover composition changes

Aristida junciformis could not be killed or weakened thus replacing it will be impossible. Since it was believed that the treatments would be more successful in killing *A. junciformis* and altering the overall cover and species composition more successfully, a seedbank study and seedling emergence study in the field had been conducted to determine what species would emerge before (seedbank study) and after a disturbance (field study). Even though the treatment application was not as successful as expected, the seedling emergence studies still produce insightful information.

Most of the seedlings that emerged from the seedbank study were forbs (92%). None of the grasses that emerged from the seedbank study could be identified as *A. junciformis* seedlings, since all the seedlings that emerged which could not be identified were transplanted for further identification at a later stage of which most died. Uys (2006) also observed high seedling mortality in his seedbank study, though the transplanted seedlings died from heat stress due to malfunction of cooling apparatus in the greenhouse.

It is surprising that no *A. junciformis* seedlings emerged since it is known for producing a high abundance of viable seeds (Van Zyl, 1998; Venter, 1968) that germinate readily (Johnson, 1989). A number of factors have been identified that could explain why no *A. junciformis* seedlings emerged from the seedbank study. Since the study was conducted in a drought period, it is possible that the *A. junciformis* seeds could not penetrate the hard soil (Pieterse et al., 1986) which could have resulted in seed desiccation (Wiseman et al., 2002) or seed predation (Mokotjomela et al., 2013; Van Zyl, 1998; Adams, 1996; Everson, 1994) prior to soil sample collection. According to Edwards (1970), up to 30% of all seeds are caught in vegetation thus obstructing seed fall and preventing seeds from being collected in the soil seed bank.

The most likely explanation for the low seedling emergence may, however, be that the seedbank did not have any grass seeds to germinate since most grasses, like *A. junciformis* are known to drop their seeds at the end of the growing season. The soil samples collected for this study were collected in January and not in March or April when *A. junciformis* usually sheds its seeds (Edwards et al., 1979). As a result thereof it is possible that few or even no *A. junciformis* seeds were present in the soil upon collection for potential emergence.

An alternative school of thought explaining why no *A. junciformis* seedlings emerged from the seedbank may be that *A. junciformis*, does not reproduce by seeds but reproduces vegetatively, like most perennial species seem to do (Major et al., 1966; Coffin et al., 1989; Everson, 1994). This is supported by the findings of the study by Uys (2006), who only observed 11 seedlings germinate from 360 soil samples, suggesting that grasses do not maintain a seed bank, and Benson et al. (2006)

who also found that successful recruitment of perennial grass seeds was rare in the Tall Grassland prairie of America. This is further supported by the findings of several studies (e.g. Champness et al. (1948); Major et al. (1966); Thompson et al. (1979); Coffin et al. (1989); Gilfedder et al. (1993); Ungar et al. (1993); Marañón (1998)) who have shown that seedbanks of perennial species do not closely reflect the dominant perennials aboveground.

Van Zyl (1998) also found that even though *A. junciformis* produced lots of seeds that landed in sites suitable for germination, few seedlings (1 – 4%) germinated. Moreover, the basal area of *A. junciformis* increased by more than 66% during the time of the study while other grass species generally increased only by 3% (Van Zyl, 1998). It may well be that *A. junciformis* produces a lot of seeds to compensate for the low seed viability (Venter, 1968). This is supported by Wellstein et al. (2007) who found that species with high seed accumulation are less likely to become extinct, which is ultimately the aim of a seedbank (Andersen, 1989; Kalisz, 1991).

In the field study, the most common species that emerged were also forbs (92%). Furthermore, more grass species were seen emerging from the field study, particularly because these could be identified on site since they mostly grew in close proximity of the parent tuft (Hopfensperger, 2007). These grasses included *T. triandra*, *T. leucothrix*, *S. pyramidalis*, *S. sphacelata, E. curvula, C. caesius* and *C. gayana*. Similar results were obtained by Uys (2006) who observed high levels of forb emergence in the field in the mesic grasslands of Highmoor and Midmar.

A possible explanation for the high forb emergence in both the seedbank and field study may be the available space to grow in, due to the absence of vegetation in the seedbank study and in the field as a result of the burn and the HDG (Collins, 1987) and the reduction in competition as a result thereof. A study by (Collins, 1987) in which the Tallgrass prairie was burned and grazed, also found an increase in the cover composition of forbs and C3 grasses. A similar observation was made in this study - more forbs and grasses emerged from the HDG initially, which had more bare soil and thus more open spaces to colonise than the control (Everson, 1994).

The second most dominant seedling species to emerge were *A. junciformis* seedlings (4%) which is surprising since no *A. junciformis* were recorded in the seedbank study. This could again confirm that *A. junciformis* and most grass species reproduce vegetatively rather than by seed. This is supported by the fact that fire stimulates tillering (Everson et al., 1985) and by the suggestion that sexual reproduction for perennial grasses may only be necessary after a disturbance (Everson, 1994), where disturbances could have had an effect on tiller production and thus on the vegetative reproduction.

The results obtained from this study also indicate the shift in species and cover composition one could expect if HDG and herbicide treatments are applied, in relation to a burned control.

A reduction in bare soil (53.05% - 34.51%) was observed, coupled with an increase in vegetation cover of forbs, grasses and in *A. junciformis*. Similar results were obtained by Tainton (1972b) and Botha (2006) who found an increase in the relative abundance of forbs after implementing a HDG and after applying herbicide respectively, though no mention is made of the effect the treatments had on the cover composition of *A. junciformis*. Botha (2006) also noticed that the forbs which emerged after *A. junciformis* was killed by herbicide application, were replaced by a number of grass species in the following seasons, which could also occur in Ukulinga but would require further research. Tainton (1972b) also noticed a reduction in the bare soil cover, as was also observed in this study, and an increase in the relative abundance of weeds, which could occur in the study site at Ukulinga but would require further research since the study by Tainton (1972b) was conducted over 12 years.

After 12 years of HDG, Tainton (1972b) found that the veld condition of the site had been altered by up to 70%, *A. junciformis* also having become dominant. After a single HDG, all the '*mtshiki*' grass species (*E. curvula, E. plana, S. africanus, S pyramidalis, T. leucothrix*) increased. Most of the other grass species increased after the treatment from not being present before the treatment to being present (e.g. *C. dactylon, D. amplectens, E. plana*, *P. natalense*). Some species e.g. *B. pilosa*, *C. gayana* and *Vachellia* trees decreased in relative abundance from being present to being absent after the treatment. This indicates how necessary the burn really was since it reduced *B. pilosa*, an exotic weed, *C. dactylon*, an exotic grass that is also considered a persistent weed though of fairly high grazing value (Van Oudtshoorn, 2012) and several *Vachellia* trees which are prone to encroach grasslands.

Aristida junciformis increased (29.3% – 33.27%) after treatment application indicating that overgrazing and selective grazing promote its encroachment (Morris et al., 1993; Tainton, 1972b) and that it persists under a burn and rest regime (Morris et al., 1996). The increase in *A. junciformis* was, however, not as significant as the change of the relative abundance of *T. triandra* which contributed the most to the species composition change, decreasing from 11.50% to 4.60%. This may be the result of *A. junciformis* altering the environment for its encroachment, to replace other species (Morris et al., 1993).

These results are surprising, especially since *A. junciformis* seemed to be more dominant than the statistics show which may be related to its umbrella-like canopy that reduce visibility of other species that are clearly present. This umbrella-like canopy creates high levels of competition as the area under it is often clear of other plant species indicating its high competitiveness (Van Zyl, 1998). The canopy of *A. junciformis* and its so-called circle of influence prevents other species from establishing, though seedling forbs can be seen grow within this circle (pers. obs). This is probably because their roots are small enough to be unaffected by the competition. Unfortunately this area is also prone to soil erosion due to the high percentage of bare soil present (Edwards et al., 1979).

In terms of the species composition of the seedlings that emerged after treatment application, specifically after HDG, an increase was also noted in *A. junciformis*, *A. amplectens*, *T leucothrix* and the forbs, though these changes were not statistically significant. Concerning was that a decrease in *T. triandra* was observed as was a decrease in the '*mtshiki*' species (*E. capensis* and *E. curvula*) and sedges of which no seedlings emerged. This may be the result of the effect HDG has on the palatable species as described in section 7.2 of this discussion. These results are not surprising considering the substantiation of literature of the effect of HDG on the veld condition and species composition of the grasslands in southern Africa.

Morris et al. (1996) discovered that long rests between grazing, HDG or the interruption of a HDG did not improve the productivity of the plants and did not improve the veld condition. Instead they observed that the sites which had been grazed at a high stocking rate displayed the greatest departure from the original botanical composition than the sites where rotational grazing was implemented. Furthermore, they discovered that interrupting a HDG resulted in a species composition change from being *T. triandra* dominant to an increase in *S. africanus* which was finally dominated by *A. junciformis* (Morris et al., 1996). However, a rest and burn resulted in a shift in which the relative abundance of *T. triandra* increased (Morris et al., 1996).

Factors that may have affected the species and cover composition include the fact that different soil types exist within Ukulinga which were not analysed in this study and may affect the aboveground species composition. It is suggested that further studies be conducted incorporating the role of soil into the eradication of *A. junciformis*.

7.4 Recommendations for rehabilitating and managing *A. junciformis* dominated grasslands

Eradicating *A. junciformis* once it has established, is harder than it seems (Wiseman et al., 2002), mainly because the mesic grasslands are susceptible to encroachment by *A. junciformis* (Tainton, 1972b; Morris et al., 1996) and because *A. junciformis* has such unfavourable characteristics. Its tough, unpalatable leaves (Tainton et al., 1976; Fish et al., 2015) that create an umbrella-like canopy and its strong, deep roots (Johnson, 1989) allow it to remain dominant and capable of modifying the environment in which it establishes itself (Van Zyl, 1998) such that its high competitive ability (McKenzie, 1982) enables it to become dominant (Van Zyl, 1998).

The aim of this study was to identify a management technique that is successful in controlling and managing *A. junciformis*. Of critical importance to the management technique implemented is the level of infestation by *A. junciformis* into the veld and the size of the veld, since this would affect intensity of labour required, costs involved and success rate. Management techniques are suggested for *A. junciformis* infested veld and veld prone to infestation below, based on the results provided in this study and available literature:

***Aristida junciformis* infested veld**

Based on the results obtained from this study:

a. A burning regime should be used to ensure that moribund material is removed and to maintain species diversity and reduce bare soil cover as was observed in this study;
b. A HDG is not a solution because it weakens palatable species at the expense of unpalatable species which exploit their position to promote their dominance;
c. It is suggested that the grazing patterns as described by Daines (1980) be used to ensure that livestock are removed from the veld before a HDG is implemented, specifically in areas where resting is not a feasible option;
d. Since the herbicide application had a better success rate in this and in the study by Botha (2006) it is suggested that further research be conducted investigating the effect of a second herbicide application or by use of different applicator tools as described by Terry et al. (1996) and Botha (2006), especially for veld that consists of larger areas than those in which this study was conducted.

Prone to infestation

Goodall et al. (1998) states that, "control programmes should strive for maintenance because total eradication is impossible and unrealistic". This is certainly applicable to *A. junciformis* infested veld. It is therefore suggested that if veld is not yet dominated by *A. junciformis* or if no *A. junciformis* is present on site, that correct management be maintained to prevent its establishment and its spread (Venter, 1968). Poisoning individual *A. junciformis* tufts may be a consideration, if these are present, or simply implementing management techniques that maintain the vigour and competitive ability of all plant species (Johnson, 1989; Tainton, 1972b), e.g. mowing, fire and other non-selective techniques, to ensure that these are not outcompeted by *A. junciformis*. Burning and grazing regimes should also not be disrupted as this promotes *A. junciformis* invasion (Morris et al., 1996).

7.5 Research suggestions for future research

A school of thought has put forward the idea that *A. junciformis* may be adaptable to any situation (Ghebrehiwot et al., 2014; Johnson, 1989) and that it may spread, even under good management practices (Van Zyl, 1998; Venter, 1993; Venter, 1968). Further research is required to better understand this relatively understudied grass. Studies should be conducted to better understand the roots of *A. junciformis*, which seem to be the key to the resistance and resilience of *A. junciformis*, allowing it to alter the environment to its own competitive advantage. It is also suggested that further studies be conducted determining the effect of mechanical control on *A. junciformis* by ploughing and reseeding , slashing, tillering or suppression (Terry et al., 1996), though these will probably be more feasible for areas with lower *A. junciformis* densities (Goodall et al., 1998).

Other studies that could be conducted include studies that aim to improve our understanding of how *A. junciformis* flowers, by answering questions such as what triggers flowering? What triggers tillering? What triggers seed shed? and What promotes germination? as these will also improve our understanding of how it establishes, spreads and persists.

Studies like the one conducted by Terry et al. (1996) and Phillips (2000), which tested different herbicides to eradicate an unfavourable grass and replace it with favourable plant or grass species could be repeated in the mesic grasslands of South Africa. Some have already been conducted in South Africa (e.g. Wiseman et al. (2002)) but unfortunately with very little or no success (Johnson, 1989). The effectiveness of different surfactants in combination with different herbicides could also be tested.

It is also recommended that the seedling emergence studies from this study be repeated in different seasons and under different treatments, not just under a control and HDG, to determine if emergence would be different in different seasons after different treatments and to determine if this would reduce the output of *A. junciformis* seedlings emerging in the field. The seedbank study should also be repeated to determine if *A. junciformis* does emerge at all or if its non-existence in this study is the result of it not being present in the seedbank or because it reproduces vegetatively rather than by seed. It is also suggested that both the seedbank and seedling study from this study are repeated to determine why so many forbs emerged and how many survive into the following season.

Further research could also be conducted to find alternative uses for *A. junciformis* e.g. using it as a biofuel, using its fibre to make paper. A final suggestion for future research is to determine the effect climate change may have on the establishment, spread and competitive ability of *A. junciformis*, since climate change may bring about some severe weather changes that may not only affect *A. junciformis* but also other species that are necessary for agriculture and thus livestock production.

8 Chapter Eight: Conclusion

Three objectives were defined to help meet the main aim of the study, namely to identify a practical, focused management technique that is successful in controlling and managing *A. junciformis*.

The first objective was to compare the effects of a selective technique (lenient graze followed by targeted herbicide application), a non-selective technique (HDG) and a control (only burned) on the mortality of *A. junciformis* and on the relative species composition in the sward to better understand how to reduce the abundance of *A. junciformis*. The findings of this study led to the conclusion that *A. junciformis* is difficult to kill because it is resistant to herbicide. More research is required to test different herbicides, different tools for herbicide application and to test the effect of surfactants. Long term studies are required to determine the changes that may occur while accommodating seasonal variability.

The second objective was to compare the effects of a HDG to an ungrazed control on the regrowth and productivity of *A. junciformis* and on the relative cover abundance in the sward to better understand how to reduce the abundance of *A. junciformis*. The findings of this study led to the conclusion that *A. junciformis* is resilient to a HDG. A HDG seems to work in favour of unpalatable species and should therefore be avoided.

In terms of the species and cover composition changes addressed in the first and second objective, the findings of this study indicate that implementing a burn and HDG may result in an alteration of the species cover and species composition of the veld in which they are implemented by increasing vegetative cover, mainly of forbs and *A. junciformis*.

The third objective was to compare seedbanks before and after treatment application in high, medium and low *A. junciformis* infestation levels. The findings of this study led to the conclusion that forbs are the most likely species to emerge from the seedbank or colonise bare areas in grasslands. Since few grass species emerged from the seedbank study with low survival rates post-transplanting, it is believed that most grass species reproduce vegetatively rather than by seed, including *A. junciformis*. This is substantiated by many literature sources but further research should be conducted to determine if this is really the case for *A. junciformis*.

In terms of management it is suggested that in grasslands or veld that has not yet been invaded by *A. junciformis* non-selective management should be implemented (e.g. fire or mowing) to maintain the competitive abilities of all species present thereby preventing *A. junciformis* from becoming dominant. In grasslands and veld where *A. junciformis* has become dominant it should be treated with herbicide, since this has had the highest success rate in eradicating *A. junciformis* to date.

Considering all the research that has been done in the past and in this study, it is evident that *A. junciformis* is and remains a persistent, indigenous weed that is understudied and difficult to eradicate. However, drastic measures need to be taken to eradicate this grass as it spreads easily, especially under selective overgrazing or fire exclusion, persists once established and alters the environment it has manifested itself in by drastically reducing the forage production and plant species diversity of grassland and thus its economic potential for livestock production (Van Zyl, 1998; Venter, 1968).

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Appendices

Appendix 1: Raw GLMM results for Survivorship of *A. junciformis* tufts before and after treatment application

Survivorship

Summary table:

Generalized linear mixed model fit by maximum likelihood (Laplace Approximation) ['glmerMod']

Family: binomial (logit)

Formula: survive ~ treatment * time + (1 | paddock)

Data: aj_mortality

AIC	BIC	logLik	deviance	df.resid
555.6	592.8	-270.8	541.6	1493

Scaled residuals:

Min	1Q	Median	3Q	Max
-10.9973	0.1391	0.1391	0.1391	0.8853

Random effects:

Groups	Name	Variance	Std.Dev.
paddock	(Intercept)	0.2522	0.5022

Number of obs: 1500, groups: paddock, 15

Fixed effects:

	Estimate	Std. Error	z value	Pr(>|z|)	
(Intercept)	3.972e+00	5.036e-01	7.887	3.10e-15	***
treatmentH	-2.079e-05	7.108e-01	0.000	1.000	
treatmentP	1.018e-01	7.149e-01	0.142	0.887	
timePost	-1.441e-05	6.319e-01	0.000	1.000	
treatmentH:timePost	4.896e-05	8.937e-01	0.000	1.000	
treatmentP:timePost	-3.203e+00	7.905e-01	-4.052	5.08e-05	***

Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Anova table

Analysis of Deviance Table (Type II Wald chisquare tests)

Response: survive

	Chisq	Df	Pr(>Chisq)	
treatment	29.564	2	3.804e-07	***
time	21.323	1	3.880e-06	***
treatment:time	24.118	2	5.793e-06	***

Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Post-hoc comparisons

$emmeans

time = Pre:

treatment	prob	SE	df	asymp.LCL	asymp.UCL	z.ratio	p.value
C	0.982	0.00914	Inf	0.952	0.993	7.887	<.0001
H	0.982	0.00914	Inf	0.952	0.993	7.886	<.0001
P	0.983	0.00841	Inf	0.956	0.994	7.974	<.0001

time = Post:

treatment	prob	SE	df	asymp.LCL	asymp.UCL	z.ratio	p.value
C	0.982	0.00914	Inf	0.952	0.993	7.887	<.0001
H	0.982	0.00914	Inf	0.952	0.993	7.886	<.0001
P	0.705	0.05584	Inf	0.585	0.802	3.243	0.0012

Confidence level used: 0.95

Intervals are back-transformed from the logit scale

Tests are performed on the logit scale

$contrasts

time = Pre:

contrast	odds.ratio	SE	df	asymp.LCL	asymp.UCL	z.ratio	p.value
C / H	1.000	0.711	Inf	0.189	5.29	0.000	1.0000

```
 C / P        0.903  0.646 Inf     0.169      4.82 -0.142  0.9889
 H / P        0.903  0.646 Inf     0.169      4.82 -0.142  0.9889

time = Post:
 contrast odds.ratio     SE  df asymp.LCL asymp.UCL z.ratio p.value
 C / H        1.000  0.711 Inf     0.189      5.29  0.000  1.0000
 C / P       22.224 12.650 Inf     5.854     84.37  5.449  <.0001
 H / P       22.225 12.651 Inf     5.854     84.38  5.448  <.0001

Confidence level used: 0.95
Conf-level adjustment: tukey method for comparing a family of 3 estimates
Intervals are back-transformed from the log odds ratio scale
P value adjustment: tukey method for comparing a family of 3 estimates
Tests are performed on the log odds ratio scale
```

Appendix 2: Raw LMM results for Height of *A. junciformis* tufts before and after treatment application

Summary table:

```
Linear mixed model fit by REML. t-tests use Satterthwaite's method ['lmerModLmerTest']
Formula: log(height) ~ as.factor(time) * treatment + (1 | paddock)
   Data: aj_height

REML criterion at convergence: 85.1

Scaled residuals:
    Min      1Q  Median      3Q     Max
-3.8469 -0.5126  0.1280  0.5827  2.6208

Random effects:
 Groups   Name        Variance Std.Dev.
 paddock  (Intercept) 0.04511  0.2124
 Residual             0.07515  0.2741
Number of obs: 200, groups:  paddock, 10

Fixed effects:
                           Estimate Std. Error        df t value Pr(>|t|)
(Intercept)                 2.74942    0.10259   9.27533  26.801 4.19e-10 ***
as.factor(time)2            1.59268    0.05483 188.00000  29.050  < 2e-16 ***
treatmentH                 -0.78515    0.14508   9.27533  -5.412 0.000384 ***
as.factor(time)2:treatmentH   0.70742    0.07754 188.00000   9.124  < 2e-16 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

Anova table:

```
Analysis of Deviance Table (Type II Wald chisquare tests)

Response: log(height)
                          Chisq Df Pr(>Chisq)
as.factor(time)           2520.6462  1  < 2.2e-16 ***
```

treatment 9.5235 1 0.002029 **

as.factor(time):treatment 83.2439 1 < 2.2e-16 ***

Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Post hoc comparrisons

$emmeans

time	treatment	emmean	SE	df	lower.CL	upper.CL	t.ratio	p.value
1	C	2.75	0.103	9.28	2.52	2.98	26.801	<.0001
2	C	4.34	0.103	9.28	4.11	4.57	42.326	<.0001
1	H	1.96	0.103	9.28	1.73	2.20	19.147	<.0001
2	H	4.26	0.103	9.28	4.03	4.50	41.568	<.0001

Degrees-of-freedom method: kenward-roger

Results are given on the log (not the response) scale.

Confidence level used: 0.95

$contrasts

contrast	estimate	SE	df	lower.CL	upper.CL	t.ratio	p.value
1,C - 2,C	-1.5927	0.0548	188.00	-1.735	-1.451	-29.050	<.0001
1,C - 1,H	0.7851	0.1451	9.28	0.335	1.235	5.412	0.0018
1,C - 2,H	-1.5150	0.1451	9.28	-1.965	-1.065	-10.442	<.0001
2,C - 1,H	2.3778	0.1451	9.28	1.928	2.828	16.390	<.0001
2,C - 2,H	0.0777	0.1451	9.28	-0.372	0.528	0.536	0.9481
1,H - 2,H	-2.3001	0.0548	188.00	-2.442	-2.158	-41.953	<.0001

Results are given on the log (not the response) scale.

Confidence level used: 0.95

Conf-level adjustment: tukey method for comparing a family of 4 estimates

P value adjustment: tukey method for comparing a family of 4 estimates

Appendix 3: Raw LMM results for Biomass of *A. junciformis* tufts after treatment application

```
Summary table:
Linear mixed model fit by REML. t-tests use Satterthwaite's method ['lmerModLmerTest']
Formula: log(biomass) ~ treatment + (1 | paddock)
   Data: aj_biomass

REML criterion at convergence: 170.5

Scaled residuals:
     Min       1Q   Median       3Q      Max
-2.33334 -0.73731  0.01945  0.78365  1.97886

Random effects:
 Groups   Name        Variance Std.Dev.
 paddock  (Intercept) 0.05208  0.2282
 Residual             0.28789  0.5366
Number of obs: 99, groups:  paddock, 10

Fixed effects:
            Estimate Std. Error      df t value Pr(>|t|)
(Intercept)  4.55618    0.12717 7.98964  35.827 4.12e-10 ***
treatmentH   0.07064    0.18019 8.04911   0.392    0.705
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Anova table:
Analysis of Deviance Table (Type II Wald chisquare tests)

Response: log(biomass)
           Chisq Df Pr(>Chisq)
treatment 0.1537  1      0.695

Post hoc comparrisons:
$emmeans
```

```
 treatment emmean    SE   df lower.CL upper.CL
 C           4.56 0.127 7.94     4.26     4.85
 H           4.63 0.128 8.06     4.33     4.92

Degrees-of-freedom method: kenward-roger
Results are given on the log (not the response) scale.
Confidence level used: 0.95

$contrasts
 contrast estimate   SE df t.ratio p.value
 C - H     -0.0706 0.18  8 -0.392  0.7053

Results are given on the log (not the response) scale.
```

Appendix 4: Raw GLMM results for Seedling Emergence after treatment application

Total Seedling emergence

Summary table:

```
Generalized linear mixed model fit by maximum likelihood (Laplace Approximation) ['glmerMod']
 Family: poisson  ( log )
Formula: total ~ treatment + (1 | paddock)
   Data: aj_seedling

     AIC      BIC   logLik deviance df.resid
   668.9    673.1   -331.5    662.9       27

Scaled residuals:
    Min      1Q  Median      3Q     Max
-7.0886 -2.0528 -0.7689  1.9424 14.0104

Random effects:
 Groups  Name        Variance Std.Dev.
 paddock (Intercept) 0.2428   0.4928
Number of obs: 30, groups:  paddock, 10

Fixed effects:
            Estimate Std. Error z value Pr(>|z|)
(Intercept)   3.5958     0.2247  16.000   <2e-16 ***
treatmentH   -0.3078     0.3193  -0.964    0.335
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

Anova table:

```
Analysis of Deviance Table (Type II Wald chisquare tests)

Response: total
           Chisq Df Pr(>Chisq)
treatment 0.9292  1     0.3351
```

Grass

Summary table:

```
Generalized linear mixed model fit by maximum likelihood (Laplace Approximation) ['glmerMod']
 Family: poisson  ( log )
Formula: grass ~ treatment + (1 | paddock)
   Data: aj_seedling

     AIC      BIC   logLik deviance df.resid
    95.8    100.0    -44.9     89.8       27

Scaled residuals:
    Min      1Q  Median      3Q     Max
-1.2402 -0.7266 -0.5718  0.3724  2.3743

Random effects:
 Groups  Name        Variance Std.Dev.
 paddock (Intercept) 0.6586   0.8116
Number of obs: 30, groups:  paddock, 10

Fixed effects:
            Estimate Std. Error z value Pr(>|z|)
(Intercept)   0.1765     0.4424   0.399    0.690
treatmentH   -0.6482     0.6695  -0.968    0.333
```

Anova table:

```
Analysis of Deviance Table (Type II Wald chisquare tests)

Response: grass
           Chisq Df Pr(>Chisq)
treatment 0.9373  1      0.333
```

Forbs

```
Summary table:
Generalized linear mixed model fit by maximum likelihood (Laplace Approximation) ['glmerMod']
 Family: poisson  ( log )
Formula: forb ~ treatment + (1 | paddock)
   Data: aj_seedling_forb

     AIC      BIC   logLik deviance df.resid
   248.0    251.7   -121.0    242.0       22

Scaled residuals:
    Min      1Q  Median      3Q     Max
-3.2923 -1.4782 -0.2866  1.3320  3.6805

Random effects:
 Groups  Name        Variance Std.Dev.
 paddock (Intercept) 0.2107   0.459
Number of obs: 25, groups:  paddock, 9

Fixed effects:
            Estimate Std. Error z value Pr(>|z|)
(Intercept)   3.3202     0.2361  14.060   <2e-16 ***
treatmentH   -0.1670     0.3185  -0.524      0.6
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Anova table:
Analysis of Deviance Table (Type II Wald chisquare tests)

Response: forb
           Chisq Df Pr(>Chisq)
treatment 0.2747  1     0.6002
```

Aristida

Summary table:

```
Generalized linear mixed model fit by maximum likelihood (Laplace Approximation) ['glmerMod']
 Family: poisson  ( log )
Formula: aristida ~ treatment + (1 | paddock)
   Data: aj_seedling

     AIC      BIC   logLik deviance df.resid
   114.3    118.5    -54.1    108.3       27

Scaled residuals:
    Min      1Q  Median      3Q     Max
-2.1342 -0.5576 -0.5033  0.1087  3.2728

Random effects:
 Groups  Name        Variance Std.Dev.
 paddock (Intercept) 1.183    1.088
Number of obs: 30, groups:  paddock, 10

Fixed effects:
            Estimate Std. Error z value Pr(>|z|)
(Intercept)  -0.4742     0.5999  -0.790    0.429
treatmentH    0.4100     0.8262   0.496    0.620
```

Anova table:

```
Analysis of Deviance Table (Type II Wald chisquare tests)

Response: aristida
           Chisq Df Pr(>Chisq)
treatment 0.2463  1     0.6197
```

Appendix 5: Raw calculation of average seedling density in field study

Total Seedlings emerged (all weeks)		
	per 3 m^2	**per m^2**
C1	118	39.3
C7	97	32.3
C9	200	66.7
C14	65	21.7
C15	62	20.7
H2	74	24.7
H3	150	50.0
H5	128	42.7
H12	37	12.3
H13	38	12.7
Mean	96.9	32.3
sd	52.37	17.46
CV%	54.04	

Appendix 6: Image 1 - Ukulinga grasslands before the burn

Appendix 7: Image 2 - Ukulinga after the burn

Appendix 8: Image 3 - Ukulinga grasslands before the cattle were brought in

Appendix 9: Image 4 - Ukulinga grasslands after the selective graze before herbicide application

Appendix 10: Image 5 - Ukulinga grasslands after the HDG

Appendix 12: Image 6 - Ukulinga grasslands after the HDG

Appendix 13: Image 7 – An *A. junciformis* tuft grazed short after the HDG

Appendix 14: Image 8 – Poisoned *A. junciformis* tufts that are considered alive because they have the potential to generate new tillers; note how green the center and how grey the surrounding vegetation is

Appendix 15: Image 9 – A poisoned *A. junciformis* tuft after herbicide application