OPTIMIZING THE USE OF PRE-EMERGENT HERBICIDES IN WHEAT PRODUCTION, UNDER CONSERVATION AGRICULTURE PRACTICES IN THE SOUTH-WESTERN CAPE REGION

by

BONGANI NKOSINATHI NTOMBELA

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Supervisor: Dr P.J. Pieterse

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DECLARATION

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ABSTRACT

The interception of herbicide by residue cover can result into poor weed management, leads to more weed seeds reaching the soil seed bank, which results in higher weed pressure in the following seasons and, in the long-term, these sub-lethal doses can lead to the development of non-target site herbicide resistance. Therefore, the aim of this study was to investigate possible dosage rate/application rate combinations that can result in the required amount of selected pre-emergent herbicides to reach the soil surface at different levels of residue cover. The efficacy of pyroxasulfone herbicide when applied on increased amounts of residue cover was executed in a field trial, discussed in Chapter 3 and a glasshouse trial, discussed in Chapter 4. For field trials at Langgewens residue cover were arranged to 0, 6 and 12 t ha^{-1} and to 0, 4.5 and 9 t ha^{-1} at Tygerhoek. Pyroxasulfone's treatment were as follows; recommended and 1.5 times the recommended dosage rates and recommended and double the recommended application rates. Weed and crop counts were made at seven weeks after planting and at crop anthesis. Vegetative growth parameters were determined at anthesis. Yield components were determined just before harvesting. After harvesting; yield, thousand kernel mass and hectolitre mass were determined. For the glasshouse trial, 50 commercial ryegrass seeds and five wheat seeds were planted per pot. Wheat residue cover was arranged as 0, 1.5, 3, 4.5 and 6 t ha^{-1}. Pyroxasulfone was applied at similar dosage rates and application rates as in Chapter 3. After the herbicide was applied, 5 mm of clean water was used to wash off the herbicide. Ryegrass counts was made at 7 weeks after planting (WAP). After harvesting; vegetative growth parameters and yield were determined. Doubling of recommended application rate had a little impact compared to increasing the dosage rate. A field trial comparing the effectiveness of weed control of pyroxasulfone, prosulfocarb plus triasulfuron and triallate when applied on increased amounts of residue cover is discussed in Chapter 5. The study was executed at Tygerhoek and Langgewens with residue cover arranged to result in 0, 5.5 and 11 t ha^{-1} and 0, 4.8 and 9.6 t ha^{-1} respectively. At both sites, herbicide dosage rates and application rates were arranged as in Chapter 3. Data was collected as in Chapter 3. Pyroxasulfone at increased dosage rates, controlled weeds better than other herbicides followed by prosulfocarb plus triasulfuron. Triallate treatment performed poorly across residue cover levels, even on an increased dosage rate. The results showed similar trends to the previous two chapters indicating that an increase in dosage rate was more effective than an increase in application rate to improve the efficacy of pre-emergence herbicides under high residue conditions.

UITTREKSEL

Die onderskepping van vooropkoms onkruiddoders deur oesreste kan lei tot swak onkruidbeheer wat kan lei tot meer onkruidsaad wat die saadbank bereik en ‘n hoër onkruiddruk in die volgende seisoen en op die lang duur kan dit lei tot die ontwikkeling van nie-teikensetel onkruiddoderweerstand. Die doel van die studie was dus om verskillende dosis- en watertoedieningshoeveelhede te ondersoek wat kan bydra om die korrekte hoeveelheid vooropkoms onkruiddoder te laat kontak maak met die grondoppervlakte by verskillende hoeveelhede oesreste. Die effektiwiteit van pyroxasulfone as dit op verhoogde oesresvlakke toegedien word is in ‘n veldproef wat in Hoofstuk 3 beskryf is en ‘n glashuisproef, wat in Hoofstuk 4 beskryf word, getoets. Vir die veldproewe op Langgewens is die oesreste gemanipuleer tot 0, 6 en 12 t ha^{-1} en op Tygerhoek tot 0, 4.5 en 9 t ha^{-1}. Pyroxasulfone behandelings was as volg: die onkruiddoderdosis was die geregistreerde dosis en 1.5 keer die geregistreerde dosis terwyl die watertoedingsvlak die aanbevole vlak was en dubbel die aanbevole vlak. Onkruid en gewastellings is gedoen sewe weke na plant en op antesestadium van die koring. Vegetatiewe groeiparameters is bepaal met antese. Opbrengskomponente is net voor oes bepaal en na oes is opbrengs, duisendkorrelmassa en hektolitermassa bepaal. In die glashuisproef is 50 raaigrassade van ‘n kommersiële kultivar asook vyf koringsade per pot gesaai. Oesreste is gemanipuleer tot 0, 1.5, 3, 4.5 en 6 t ha^{-1}. Pyroxasulfone is toegedien teen dieselfde dosisse en watertoedieningshoeveelhede as in Hoofstuk 3. Na toediening is 5 mm skoon water op elke pot toegedien om die onkruiddoder in te was. Raaigrastellings is gedoen sewe weke na plant. Na oes is die vegetatiewe groeiparameters en die oesopbrengs bepaal. Verdubbeling van die watertoedieningshoeveelheid het min impak gehad vergeleke met ‘n hoë onkruiddoderdosis wat effektiwiteit oor alle oesresvlakke in beide die veld- en glashuisproef veroorsaak het. ‘n Veldproef wat die effektiwiteit van pyroxasulfone met prosulfocarb plus triasulfuron en ook triallate vergelyk het, word in Hoofstuk 5 bespreek. Die veldproef is uitgevoer op Tygerhoek met oesresvlakke van 0, 5.5 en 11 t ha^{-1} en op Langgewens met oesresvlakke van 0, 4.8 9.6 t ha^{-1}. Die onkruiddoders is toegedien teen dieselfde dosisse en watertoedieningshoeveelhede soos beskryf in Hoofstuk 3. Data is versamel soos beskryf in Hoofstuk 3. Pyroxasulfone teen verhoogde dosisse het die beste onkruidbeheer tot gevolg gehad, gevolg deur prosulfocarb plus triasulfuron. Triallate het oor alle behandelings swak resultate gelewer. Resultate was oor die algemeen (met uitsondering van triallate) dieselfde as in die vorige hoofstukke met verhoogde onkruiddoderdosisse wat beter beheer by hoë oesresvlakke tot gevolg gehad het as verhoogde watertoedieningshoeveelhede

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TABLE OF CONTENT

PREFACE

This thesis consists of 6 chapters. Chapter 1 deals with the background for the study and further outlines the research question, research goal and overall research objectives. Chapter 2 unpacks the literature review that is relevant to this study. Chapters 3 outlines the field trial on the effectiveness of weed control with increased pyroxasulfone application and dosage rates when applied on increased amounts of residue cover. Chapter 4 outlines the glasshouse trial on the effectiveness of weed control with increased pyroxasulfone application and dosage rates when applied on increased amounts of residue cover. Chapter 5 outlines the field trial comparing the effectiveness of weed control with pyroxasulfone, prosulfocarb plus triasulfuron and triallate at different application and dosage rates when applied on increased amounts of residue cover. Chapter 6 consists of the concluding statement based on overall findings from the experiments and further outlines limitations of the study and possible recommendations. All the relevant material that was consulted for discussion are outlined in the references at the end of each chapter

CHAPTER 1

GENERAL INTRODUCTION

1.1 Background to the research question

In agricultural production in general and in crop production, weeds are described as highly competitive plants that persistently adapt to cropping systems and thus lead to crop yield reduction and poor crop quality if not kept in check (Yaun et al. 2007). According to Zimdahl (2007), weeds are problematic in crop production because of adaptation mechanisms, such as the ability to reproduce when young, rapid seedling growth and quick maturation. There are many methods of weed control that have been developed, for example mechanical removal, but chemical control using herbicide application has been a major control mechanism in recent decades (Yaun et al. 2007).

In the Western Cape province of South Africa, wheat production is under pressure from weed competition and this is exacerbated by high incidences of herbicide resistance in weeds to post-emergent herbicides (Pieterse 2010). According to Cook (2011), pre-emergent herbicides can play a critical role in mediating post-emergent herbicide resistance in weeds.

These concerns about weed control in the Western Cape are accompanied by the adoption of conservation agriculture (CA) by farmers in the region (du Toit 2007). Conservation agriculture is explained by Nichols et al. (2015) as consisting of three components, namely crop rotation; continuous minimum soil disturbance, due to reduced tillage; and permanent organic soil cover. As much as CA has both short- and long-term benefits, such as improved soil moisture retention, organic matter retention and the prevention of soil erosion, these benefits are counterbalanced by the negative effects of increased weed competition in this cropping system (Giller et al. 2009).

According to Schmitz et al. (2015), the main reason for increased weed density is the absence of tillage in conservation agriculture, which plays a crucial role for weed control in conventional agriculture. Tillage has been used as a mechanical intervention to mediate or control weeds in agriculture. This suggests that the introduction of CA may unintentionally present a challenge with an environment that allows weeds to grow and flourish because of the absence of mechanical removal of weeds in this cropping system (Chauhan et al. 2012).

Conservation agriculture practices, such as reduced tillage, may thus result in an increase in weed occurrence and may prompt crop production to be highly reliant on herbicides, which can lead to increased herbicide resistance (Haskins 2012). New ways to manage weeds successfully under conservation agriculture cropping system are therefore required (Chauhan et al. 2012).

The retainment of the permanent organic soil cover, which forms a major part of the principles of CA, creates challenges when it comes to the effective application of pre-emergent herbicides and the ability of these to reach the soil surface in sufficient amounts. According to Farooq et al. (2011), the failure of herbicides to reach the soil surface is caused by the fact that herbicides become intercepted by the residue cover and sometimes react with the residue that is used as an organic soil cover. This can lead to reduced amounts of herbicides reaching the soil surface (Farooq et al. 2011). The failure of herbicides to reach the soil surface may lead to poor weed management, which may lead to more weed competition and lower yield in the short term. In the medium term, it can lead to more seeds reaching the soil seed bank, which results in higher weed pressure in the following planting seasons and, in the long-term, there is the possibility of non-target site herbicide resistant development. According to Neve and Powles (2005), applying herbicides at sub-lethal rates or reduced doses can lead to weeds developing resistance towards that herbicide; this resistance is described as non-target site herbicide resistance. This type of resistance is diverse and complex, with a possibility of not only affecting that specific herbicide but also extending to other herbicides with different modes of action (Busi et al. 2014). Due to abovementioned characteristics, the non-target site herbicide resistance can develop an effect on herbicides that have not yet entered the market, thus affecting the utility of new herbicides in the long term (Yang et al. 2016). It is therefore important to ensure that the required dosage of herbicides reaches the soil surface for effective weed control to be realised where there is retention of residue cover.

1.2 Research question:

This research seeks to address the following research question; "At what dosage rates, application rates and levels of residue cover can pre-emergent herbicide efficiently reach the soil surface and be able to control weeds effectively in wheat production?"

1.3 Research aim:

The primary aim of this study was to investigate the possible adaptations to application methods that can assist in obtaining the required amount of pre-emergent herbicide to reach the soil surface where there is retention of residue cover.

1.4 Study objectives

In order to achieve the abovementioned research aim and address the research question, the following objectives form the basis of this study:

i. To assess the effectiveness of weed control with increased pre-emergent herbicide application and dosage rates when applied on increased amounts of residue cover;
ii. To determine vegetative growth parameters of wheat with increased pre-emergent herbicide application and dosage rates when applied on increased amounts of residue cover;
iii. To evaluate the yield components of wheat with increased pre-emergent herbicide application and dosage rates when applied on increased amounts of residue cover; and
iv. To analyse the quality parameters of wheat with increased pre-emergent herbicide application and dosage rates when applied on increased amounts of residue cover.

1.5 Hypothesis

The null hypothesis (H_o) of this study states that, increasing pre-emergent herbicide application and dosage rates when applied to increased amounts of residue cover will not increase the efficacy of the herbicides.

The alternative hypothesis (H_1) of this study states that, increasing pre-emergent herbicide application and dosage rates when applied to increased amounts of residue cover will increase the efficacy of the herbicides.

REFERENCES

Busi R, Gaines TA, Vila-Aiub MM, Powles SB. 2014. Inheritance of evolved resistance to a novel herbicide (pyroxasulfone). *Plant Science* 217-218: 127-134.

Chuahan BS, Singh RG, Mahajan G. 2012. Ecology and management of weeds under conservation agriculture: A review. *Crop Protection* 38: 57-65.

Cook T. 2011. Options for using more residual herbicides in northern no-till systems. https://www.grdc.com.au/Research-and-Development/GRDC-Update-Papers/2011/03/Options-for-using-more-residual-herbicides-in-northern-notill-systems . Accessed on 2016/02/26.

du Toit G. 2007. Promoting conservation agriculture in South Africa: a case study among commercial grain producers in the North-West province. *Bureau for Food and Agricultural Policy*. BAFP Report no. 2007-4.

Farooq M, Flower KC, Jabran K, Wahid A, Siddique KHM. 2011. Crop yield and weed management in rainfed conservation agriculture. *Soil & Tillage Research* 117: 172-183.

Giller KE, Witter E, Corbeels M, Tittonell P. 2009. Conservation agriculture and smallholder farming in Africa: The heretics' view. *Field Crops Research*. 114: 23-34.

Haskins B. 2012. Using pre-emergent herbicides in conservation farming systems. http://www.dpi.nsw.gov.au/agriculture/farm/conservation/information/pre-emergent-herbicides . Accessed on 2016/02/27.

Neve P, Powles S. 2005. High survival frequencies at low herbicide use rates in populations of *Lolium rigidum* result in rapid evolution of herbicide resistance. *Heredity* 95: 485-492.

Nichols V, Verhulst N, Cox R, Govaerts B. 2015.Weed dynamics and conservation agriculture principles: A review. *Field Crops Research* 183: 53-68.

Pieterse PJ. 2010. Herbicide resistance in weeds – a threat to effective chemical weed control in South Africa. *South African Journal of Plant and Soil* 27: 66-73.

Schmitz PM, Puran MAL, Hesse JW. 2015. The importance of conservation tillage as a contribution to sustainable agriculture: A special case of soil erosion. *Institut für Agribusiness* 33.

Yaun J, Tranel PJ, Stewart Jr CN. 2007. Non-target-site herbicide resistance: a family business. *Trends in Plant Science* 12: 1-42.

Yang, Q., Deng, W., Li, X., Yu, Q., Bai, L., & Zheng, M. 2016. Target-site and non-target-site based resistance to the herbicide tribenuron- methyl in flixweed (*Descurainia sophia L.*). *BMC Genomics* 17: 1–13.

Zimdahl RL. 2007. *Fundamentals of Weed Science* (3rd edn). Burlington: Academic Press.

CHAPTER 2

LITERATURE REVIEW

2.1 Weed competition and yield reduction

A weed is defined by Walton (1988) as a plant that has detrimental effects on agricultural activities, as opposed to being beneficial. The competition between weed and crop for resources results in crop yield reduction and impairment of crop quality, which leads to financial loss in agricultural production. It is estimated that, on a global scale, weeds are responsible for reducing crop yield by almost 10% (Naylor 2002). Kerr (2016), more recently, puts this figure as high as 20% globally. Between 1988 and 90, there was an estimated 16.5% loss in crop production in Africa due to weeds (Cobb and Reade 2010). The cash value of the losses incurred because of weeds is much greater than the combined loss due to insect pests and diseases (Walton 1988). It has been calculated that for every kilogram of weed growth, farmers lose a kilogram of crops produced (Kerr 2016).

There are several reasons as to why losses due to weeds are so high. These include the fact that weeds compete with crop plants for environmental resources, such as nutrients, water, pollinators and light, these resources are crucial in crop life and are usually in limited supply (Naylor 2002; Sheafer and Moncada 2012). Weeds also recover more easily if there are limited resources, compared to crops (Zimdahl, 2007). Furthermore, weeds are one of the well-known competitive ruderals; these are plant species that are first to colonize disturbed soil (Cobb and Reade 2010).

Other factors that confer a competitive advantage to weeds over crops plants include rapid seedling growth, the development of a large exploitative root system, rapid growth and a short vegetative period before flowering and the ability to complete seed production rapidly compared to the crop with which the weed is interfering (Zimdahl 2007). According to Walton (1988), weeds are usually hardy, vigorous plants and have extensive, efficient roots and prolific seed production. Weeds have an ability to form soil seed banks, where weed seeds are stored and wait for favourable conditions for germination; these seed banks then become a reservoir for the perpetuation of weed populations (Sheaffer and Moncada 2012). Weeds also have a competitive edge over crops because of characteristics such as having a high photosynthetic rate, a high light saturation intensity, a low carbon dioxide (CO_2) compensation point, and the ability to grow and survive under adverse climatic and soil conditions (Zimdahl 2007).

According to Naylor (2002), interactions between weeds and crops can be categorised as either direct or indirect interference. Indirect interference is when weeds and crops demand the same resources, which are in limited supply, while direct interference is when the weed releases phytotoxic chemicals that have detrimental effects on the other, a process known as allelopathy (Naylor 2002). Allelopathic weeds have the potential to reduce crop seed germination ability and can also affect seedling growth (Sheaffer and Moncada 2012). Other weeds are parasitic and survive by obtaining nutrients directly from the crop's vascular system (Sheaffer and Moncada 2012). The effect of weeds on crop growth is severe during crop establishment (Sheafer and Moncada 2012).

According to Cobb and Reade (2010), at least four major crops and weeds share certain characteristics, plant families and even origins. The success of some weeds is thus linked to similarity with a crop, which includes sharing identical life cycles. Weed seed maturation coincides with crop harvest, which increases the likelihood of weed seed spread (Cobb and Reade 2010). This has been confirmed by Sheaffer and Moncada (2012), who have noted that sometimes there are similarities between weed seeds and crop seeds, and that this has the potential to cause grain contamination during harvest. Weeds that are still active during harvesting time can tamper with harvesting mechanisms, thereby making harvesting difficult (Sheaffer and Moncada 2012).

2.2 The principles of conservation agriculture

Sustainable agriculture is defined by Fowler and Rockstrom (2001) as the implementation of agricultural practices that conserve water and soil, do not degrade the environment and are technically appropriate, economically viable and socially acceptable. Conservation Agriculture (CA) is one of the various concepts that fall under the umbrella of sustainable agriculture; other notions include Low Input Sustainable Agriculture and Regenerative, Biological and Organic Farming (United States Department of Agriculture, 1999).

Conservation agriculture (CA) consists of three principles, namely: (i) minimum tillage or no soil disturbance; (ii) permanent organic soil cover; and (iii) diversified crop rotation (Nichols et al. 2015). These principles complement each other, and it is thus advisable to implement all three simultaneously (du Toit 2007). The adoption of CA has the potential to play a crucial role in increasing agricultural productivity (ARC 2014). Other specific benefits of implementing CA include an increase in yield, a decrease in labour requirements, improvement in soil fertility, efficiency in soil moisture retention and reduction in soil erosion (Giller et al. 2009). Overall the adoption of conservation agriculture seeks to achieve efficient and better use of agricultural resources compared to conventional practices, through the integrated management of available soil, water and various biological resources (Knowler and Bradshaw 2007)

2.2.1 Minimum tillage

In the 18th and 19th centuries, the development of the plough as a tool for conventional tillage presented a breakthrough in the production of grains and, since then, the plough has been used widely for soil preparation and weed control (du Toit 2007). However, over the years, there have been concerns about the negative effect of intensive ploughing on soil moisture retention, because as the plough turns the soil, whatever moisture that is preserved at the top layer of soil dries out (du Toit 2007). It has been established that tilling of soils by plough have led to concern about its effect on soil productivity and wider environmental implications in a number of regions worldwide (Knowler and Bradshaw 2007). Other negative effects of ploughing include its destruction of soil structure; it leaves soil bare, which makes it prone to erosion (du Toit 2007). Mrabet (2002) has also suggested that there is a direct relationship between conventional tillage and erosion because intensive tillage by mechanical equipment generally results in intensified soil disturbance to a greater depth. According to Fowler and Rockstrom (2001), approximately 70% of the 5.2 billion hectares (ha) in global dryland crop production are degraded. This leads to 24 billion tons of top soil being lost annually and 1 billion ha (71%) of Africa's dryland crop production being severely affected by erosion (Fowler and Rockstrom 2001). The use of conventional cultivation tools, such as the mouldboard plough, by African farmers is the major contributor to that soil erosion (Fowler & Rockstrom 2001).

Instead of conventional ploughing and sowing, there has more recently been a move towards using mechanisms where the disturbance of the soil is minimised as much as possible (ARC 2014). Non-inversion tillage systems, for example, non-tillage and reduced tillage, are regarded as sustainable methods of cultivation in crop production (du Toit 2007). Conservation tillage has the potential to increase the organic matter content of soil, enhance soil aggregation and create a fertile soil layer that is an important buffer to soil erosion (Mrabet 2002). Conservation tillage can also slow surface water flow by increasing soil roughness, decrease evaporation through decreasing soil disturbance and increase soil macropores that assist in maintaining soil water holding capacity (Fowler & Rockstrom 2001).

The optimum form of conservation tillage is non-tillage, where no turning of the soil takes place at any stage of the production cycle (du Toit 2007). The non-tillage system entails using one pass seeding with narrow or knife point seed planters with less than 30% soil disturbance without any pre-season tillage taking place (D'Emden et al. 2008). The disturbed area must be less than 15 cm wide or less than 25% of the cropped area (Friedrich et al. 2012). The benefits of non-tillage include reduced soil erosion, lower fuel costs, higher long-term productivity, greater moisture retention and water infiltration (D'Emden et al. 2008). The other form of conservation tillage is known as reduced tillage, where tillage can be used, but at a minimal rate for primary tillage. Implements such as tillers, chisels and discs are then used for cultivation of the soil instead of the mouldboard plough (du Toit 2007).

2.2.2 Permanent organic soil cover

Permanent organic soil cover includes retention of plant stubble or plant residue after the planting season. The stubble acts as a cover to prevent soil erosion by wind as well as water erosion (ARC 2014). With the use of CA, a decrease in water evaporation from the soil due to the residual cover increases the soil water content in comparison with conventional tillage, especially in dry seasons or during drought (Mas and Verdú 2003). Stubble cover also forms a buffer that lowers soil temperature and preventing the destruction of bio-organisms in the soil (ARC 2014). According to Giller et al. (2009), permanent soil cover has the potential to reduce soil erosion by 80% and greater soil cover would suppress erosion even further.

The cover can be grouped into three categories, namely 30-60%, 60-90% and >90% ground cover. Anything less than 30% of organic soil cover is not deemed as CA (Friedrich et al. 2012). Farmers therefore need to leave as much post-harvest plant residues on the land as possible, avoid burning or removing excess plant remains, since most farmers try to burn or remove stubble to ease planting operation in the next season, and avoid using farming land as grazing area for livestock, because this also reduces stubble cover availability on the soil (du Toit 2007).

2.2.3 Crop rotation

Monoculture entails the planting of one crop species on the same land, season after season (Thierfelder & Wall 2010) . It can be more convenient and easier to operate as a cropping system, but it becomes a threat in long-term crop production and not sustainable (du Toit 2007; Thierfelder & Wall 2010). Occurrences such as higher soil losses, deterioration in soil structure, the presence of weeds, crop specific pests and diseases are synonymous with monoculture systems (du Toit 2007). Correspondingly Ahmed et al. (2004) mentions that cultivating the same crop on the same land for consecutive years leads to reduction in soil fertility, it alters soil structure and causes crops to be vulnerable or be exposed to common pests and diseases. On the other hand, crop rotation as an alternative cropping system has benefits in both crop yield and crop quality (du Toit 2007). Crop rotation refers to the cultivation of different crops, alternating these on the same piece of land; the same crop will not be cultivated every year and by rotating the crops, the soil will not be exhausted and can recover (ARC 2014).

It is recommended that rotation should involve at least three different crops (Friedrich et al. 2012). In the case of perennial crops, crop diversity can be achieved through intercropping, which involves a balanced mix of legume and non-legume crops (Friedrich et al. 2012). According to Lok et al. (2018) the advantage of diversity of crop species include the fact that it increases the number of ecological niches, which can further increase the number of associated species in that environment.

Incorporating the rotation system with crop species with deep root system result positive returns such as; improved soil structure aggregation, improved soil porosity, better infiltration and better water holding capacity (Thierfelder & Wall 2010). Crop rotation can also promote better nutrients distribution in the soil profile by alternating crop species with different root depth, because different root depths exploit nutrients at different root zones (Thierfelder & Wall 2010). Through diversifying crops they plant the farmer can also be able to diversify their income and stabilise their financial returns because planting different crops mitigate the effects that may be caused by failure of certain crops (Thierfelder & Wall 2010).

2.3 An overview on the adoption of CA in South Africa

Conservation agriculture is regarded as a remedy for the problems of poor agricultural productivity and soil degradation in sub-Saharan Africa (Giller et al. 2009). Mrabet (2002) has noted that traditional conservation tillage, for example hand or animal traction-based tillage, have been used by African farmers for years. These farmers have traditionally been using water and soil conservation methods while producing their food needs. Conservation tillage systems are thus not new techniques in Africa, but need to be improved through new technologies that promote large scale farming (Fowler and Rockstrom 2001). Fowler and Rockstrom (2001), further pointed out that conservation tillage in Africa originated many centuries ago because farmers began to realise the damage of soil degradation and to seek sustainable ways of farming.

Soil degradation in Africa is caused by factors such as overgrazing, the extensive cultivation of marginal lands, the widespread clearing of vegetation for agriculture, deforestation, the exploitation of unsuitable agricultural technologies, the mismanagement of arable lands and frequent droughts (Mrabet 2002). South Africa is one of the countries that are known to have soils that are susceptible to degradation because of poor management due to inadequate information among communities (du Toit 2207). According to Van Zyl et al. (1996), South Africa has been losing approximately 300-400 tons of soil annually due to degradation.

However currently there is no policy in South Africa that has been promulgated specifically for CA. There are only some related policies available, for example the Policy on Agriculture in Sustainable Development and the Organic Production Policy, which have the potential to influence farmers to adopt CA (Mudavanhu 2015). Over the years, there has been a legislative framework that has been developed as a legal basis for curbing soil degradation in South Africa (Mudavanhu 2015). This framework includes the Forest and Veld Conservation Act of 1941, the Soil Conservation Acts of 1946 and 1969, the Conservation of Agricultural Resources Act of 1983 and the Environment Conservation Act of 1989 (Mudavanhu 2015). However, these acts were not applied in the homeland areas and were only created to be implemented in the other farming areas thus excluding the other significant part of the country's farming land (Mudavanhu 2015).

Globally, over 95 million ha of farming land were cultivated in accordance with the principles of CA in 2005 (Derpsch 2005) and, according to Friedrich et al. (2012), this figure has been expanding at an average rate of approximately 7 million ha per year. Around the year 2012, CA production systems were used on about 125 million ha of farming land around the world. In South Africa, there has been a noticeable move towards CA among grain and sugar-cane growers in the Western Cape, KwaZulu-Natal and Free State provinces; adoption of the concept is still slow in other production areas (du Toit 2007). The ARC (2014) has noted that wheat farmers of the Western Cape traditionally planted wheat commercially using a monoculture system, but many have now adopted CA. In KwaZulu-Natal, there has been substantive adoption and success of CA due to favourable rainfall conditions and soils with high clay content. This has led to the formation of the KwaZulu-Natal No-till Club, which has been actively conducting research on CA since 1997 (du Toit 2007).

In the Western Cape province of South Africa, it is reported that the adoption of CA by farmers in grain production areas has markedly increased from less than 5% in 2000 to approximately 60% in 2011 (ARC 2014). The success of CA adoption in the Western Cape has been due to many factors, one of which has arguably been the use of benchmarking and adopting technology interventions from Australia, which has similar climatic conditions to the Western Cape. These technologies include pre-emergent herbicides that can be used to counter herbicide resistance and the development of non-till planters that could be used on the stony soils in the Western Cape region (ARC 2014). There is limited information and statistics about CA in South Africa. A possible reason for this is that the country's agricultural production regions are heterogenous in terms of precipitation, temperature and soils; therefore, technological comparison between one region and another might be complex and unrealistic (du Toit 2007; Mudavanhu 2015).

Around 2012, in South Africa there was approximately 368 000 ha of farming land that was practising CA (Friedrich et al. 2012). This makes South Africa a leading country in Africa, followed by Zambia at 200 000 ha, Mozambique at 152 000 ha and Zimbabwe at about 139 000 ha. However, South Africa's figure is not even a quarter of what the USA has achieved. The USA is the global leader in the adoption of CA, with CA being used on 26,5 million ha (Friedrich et al. 2012), as shown in Table 1 below.

Table 2. 1: Global outlook on the adoption of CA, with countries listed in descending order (Friedrich et al. 2012)

Country	**CA area (ha)**
USA	26,500,000
Argentina	25,553,000
Brazil	25,502,000
Australia	17,000,000
Canada	13,481,000
Russia	4,500,000
China	3,100,000
Paraguay	2,400,000
Kazakhstan	1,600,000
Bolivia	706,000
Uruguay	655,100
Spain	650,000
Ukraine	600,000
South Africa	368,000
Venezuela	300,000
France	200,000
Zambia	200,000
Chile	180,000
New Zealand	162,000
Finland	160,000
Mozambique	152,000
United Kingdom	150,000
Zimbabwe	139,300
Colombia	127,000
Others	409,440

Overall adoption of CA in South Africa has been hindered by factors such as land tenure complications, uncontrolled communal grazing, insufficient soil cover, as well as the socio-economic standing of the farmers (Mudavanhu 2015). There is thus an urgent need for research and the development of relevant policy initiatives and interventions to address these challenges, so that the concept of CA becomes an attractive alternative for farmers in South Africa and the entire sub-Saharan Africa (Mudavanhu 2015).

2.4 The challenges of weed control in CA

Besides the benefits of CA, which have been discussed above in section 2.2 there are also negative implications. These include an increase in weed competition because of greater weed infestation, which leads to increased requirement of herbicides when compared to conventional agricultural methods (Schmitz et al. 2015). The main cause of the increase in weed density is the absence of tillage in CA compared to conventional agriculture, which relies on tillage (Schmitz et al. 2015). Mas and Verdú (2003), have also considered that weed control is one of the major limiting factors that affect farmers during the adoption of CA. Weed control is therefore considered a serious challenge in CA because of the absence of tillage, which can be used as a primary tool for the control of weeds (Valentin, 2008).

It has been an accepted practice in conventional agriculture that tillage has been used as one of the main mechanisms to mediate or control weeds in crop production (Chuahan et al. 2012). Tillage has got the ability to separate weeds' shoots from roots, desiccate shoots and exhaust the carbohydrate reserves of perennial weeds (Zimdahl 2007). Perennial weeds tend to increase in conservation agriculture because rhizomes and stolons are left less disturbed in the conservation tillage system (Nakamoto et al. 2006). Deep tillage also assists in burying weeds seed deep enough to prevent any further successful germination (Rao 2015). This is why the density of the weed population may increase under CA, because weed seeds tend to accumulate on the topsoil (Nakamoto et al. 2006). Tillage also prevents the build-up of annual and perennial weed species in the seed bank by exposing them, thus stimulating the germination of weed seeds (Rao 2015). Even though the removal of tillage in CA can present challenges, the positive consequence of no-tillage systems is that there is an increase in the richness and diversity in weed communities. This is important because in weed management, the situation where weed flora are dominated by a few species must be prevented (Mas & Verdú 2003). Mas and Verdú (2003) have concluded that primary tillage and no-tillage practices can both have major effects on weed dynamics and crop-weed interference.

Since weed control through tillage is not possible in CA, this is likely to lead to changes in weed communities and the growth dynamics of these compared to conventional tillage systems (Nichols et al. 2015). Therefore, the implementation of reduced tillage conservation practices has often caused a loss in crop production, because the reduced tillage did not adequately control weeds (Nichols et al. 2015). The high level of weed incidence in CA is also caused by the fact that the permanent organic cover on the soil surface keeps the soil cooler and moist, resulting in the increased survival of germinating small seeded weeds compared to conventional agriculture (Valentin 2008). For CA to be successful, it needs to incorporate other effective weed control methods (Valentin 2008).

Since CA does not utilize tillage, the use of herbicides becomes greater (Nakamoto et al. 2006), and dependence on the use of herbicides can lead to an increased likelihood of herbicide resistance (D'Emden et al. 2008). According to Valentin (2008), post-emergent herbicides have been used as a weed control mechanism in conservation non-till agriculture, and this has been highly successful, resulting in increased yields and less crop loss due to weeds. However, there have been high incidences of herbicide resistance in weeds towards post-emergent herbicides in the Western Cape region, and this has caused some difficulties with weed control in the region (Pieterse 2010). In countries such as Australia, pre-emergent herbicides have become an important component of weed management in CA systems and the reliance on pre-emergent herbicides in that country has grown from 1 million ha of land in 1990 to approximately 7 million ha in 2003 (D'Emden et al. 2008). Pre-emergent herbicides therefore play a crucial role in replacing and minimising the effects of post-emergent herbicide resistance in weed control (Cook 2011). Nichols et al (2015) have emphasised that the adoption of CA changes weed dynamics and therefore there is an urgent need to adjust weed control methods.

However, the permanent organic soil cover that forms a major part of CA creates challenges when it comes to the efficient application of pre-emergent herbicides and the ability of these to reach the soil surface (Farooq et al. 2011). According to Farooq et al. (2011), the herbicides can be intercepted by the residue cover and sometimes herbicides react with residue that is used as an organic soil cover, which can lead to reduced amounts of herbicides reaching the soil surface. When reduced amounts or sub-lethal rates of herbicides are repeatedly applied in the long term, this can lead to weeds developing resistance towards that herbicide (Neve and Powles 2005). Such resistance can also extend to other herbicides with different modes of action (Busi et al. 2014). The herbicide resistance phenomenon is discussed in more details below.

2.5 Herbicide resistance

Herbicide resistance is the inherited ability of a weed to survive a rate of herbicide that in normal circumstances would have resulted in effective weed control; this survival take place in successive populations over a period and not in an individual (Naylor 2002). Yang et al (2016) define herbicide resistance as an evolutionary adaptation of weeds to herbicide selection. The populations of weeds that develop special traits, such as herbicide resistance, are called biotypes (Sheaffer &Moncada, 2012). According to Pannell et al. (2016), herbicide resistance poses a threat to the sustainability of herbicide-tolerant crops, can cause environmental risks due to the increased use of alternative weed-control treatments, hinders public and private research and development programs, necessitate new approaches to manage such resistance and jeopardises food security for both developed and developing countries.

There are two primary mechanisms of herbicide resistance in weeds, namely: (i) resistance that arises because of mutations in the target site of the herbicide which is called target-site resistance (TSR) (Yaun et al. 2007) and (ii) the other occur as a result of mechanisms which reduce herbicide concentration reaching the target-site and the latter is known as non-target site resistance (NTSR) (Yang et al. 2016). According to Yuan et al. (2006) herbicide dose does have direct effect in herbicide resistance development, where the use of very high dose over a period of time may promote target-site resistance development, and the use of very low dosage may lead to the development of non-target-site herbicide resistance. Each of these mechanisms is discussed in more detail below.

2.5.1 Target-site herbicide resistance (TSR)

Preston (2014a) describes target-site resistance as an alteration to the protein that binds the herbicide, resulting in a lack of inhibition of the biochemical pathway. Yang et al. (2016), meanwhile, has suggested that TSR is due to gene mutations in target enzymes. These enzymes include acetolactate synthase, acetyl-CoA carboxylase, protoporphyrinogen IX oxidase,4-hydroxyphenylpyruvate dioxygenase and 5-enolpyruvylshikimate-3-phosphate synthase (Yang et al. 2016).

Scarabel et al. (2015) goes further and describe TSR as herbicide resistance that fall under the category of monogenic resistance. Target site resistance is referred to as monogenic resistance, because it supply alleles of the gene encoding the herbicide target that carry mutations resulting in structural and functional changes at the herbicide binding site (Scarabel et al. 2015).

2.5.2 Non-target site herbicide resistance (NTSR)

The non-target site (NTSR) mechanism is when weeds develop herbicide resistance through increased herbicide detoxification (Sheaffer and Moncada 2012). On the other hand, Preston (2014b) describes the non-target site resistance mechanism as the eventuality that allows weeds to survive the application of the herbicide by not allowing enough herbicide to reach the target site at which the weed may be initially affected. Instead, the weed will survive and produce seed. In this resistance mechanism, there is more rapid breakdown of the herbicide inside the weed, which results in less of the active herbicide reaching the target site to kill the weed (Preston, 2014a). According to Scarabel et al. (2015) , NTSR it is prevalent among grass weeds.

Yang et al. (2016) have highlighted that NTSR occurs due to mechanisms reducing herbicide concentrations reaching target-sites. When herbicides are applied at inefficient rates to weeds, there is the possibility of weeds accumulating minor genes that can cause a slight increase in weeds fitness and therefore provide significant levels of resistance (Rao 2015). Therefore, repeated exposure of weed populations to the sub-lethal doses of herbicides may, over time, cause an accumulation of a gene pool with resistance and can also allow target weed species to develop biochemical mechanisms of herbicide detoxification (non-target resistance) (Rao 2015).

When compared to TSR, NTSR poses a greater threat to crop production because it is more complex and diverse, and for these reasons it is less well understood (Yang et al. 2016). On top of that, NTSR may cause weeds to evolve unpredictable resistance to a wide range of herbicides of different modes of action, including herbicides that have not yet entered the market and thus affecting the utility of new herbicides (Yang et al. 2016). Scarabel et al. (2015) further allude that unlike TSR, NTSR can be either be polygenic or mono- genic and that results in a very unpredictable resistance to herbicides with different chemical structure and target proteins. On top of that the molecular genetic identification of specific enzymes that carries resistance that leads to non-target-site resistance remains largely unclear (Busi et al. 2014)

This is echoed by Preston (2014a), by pointing out that NTSR mechanisms can be highly complicated because its outcome can lead to cross-resistance to herbicides with the same modes of action but different chemical composition. Cross-resistance patterns are known to be highly variable and unpredictable, suggesting that there are numerous types of enhanced herbicide detoxification occurring (Busi et al. 2014). Furthermore, there is the possibility of multiple resistance against herbicides with different mode of action (Busi et al. 2014). Even the resistance management strategies of herbicide mixtures and rotations, which may be effective to manage target site resistance, may have little or no effects on metabolic resistance that comes with non-target site resistance (Yang et al. 2016).

Other herbicides are applied as pro-herbicides and rely on the weed plant metabolising the herbicide to the active compound (Preston 2014a). If the plant fails to metabolise the herbicide, it will never work in killing that plant. This type of NTSR been observed in pre-emergent herbicides, such as triallate, which has been used in Canada (Preston 2014a). Conversely, plants may also have NTSR where they develop means where metabolism can be used to detoxify herbicide into nontoxic molecule before it reaches the target cells (Goggin et al. 2016;Yuan et al. 2006).

According to Yuan et al. (2006), herbicide detoxification in a plant undergoes four phases, which are explained in details below. Firstly, Phase I herbicide molecules are activated in order for particular functional groups are exposed to Phase II (Yuan et al. 2007). In Phase II is where conjugation of bulky hydrophilic molecule to the xenobiotic using thiols or sugars takes place and that ensures that end product of the phase is recognised by Phase III. In Phase III, through active transport conjugated molecule is transported into vacuole or extracellular space and ABC transporters are the main mode of transportation involved in this phase. Lastly, Phase IV the conjugated molecule that was transported in vacuole or extracellular space undergoes further degradation at this phase (Yuan et al. 2006)

Another possible mechanism for non-target site resistance is that when there are changes to the translocation of herbicides within the plant, the herbicide becomes trapped in the leaf tips and reduced amounts are present in the meristem and other parts of the plant, which leads to reduced concentrations of the herbicides in these tissues, thus decreasing the possibility of being killed by the herbicide (Preston 2014a). This is further alluded by Goggin et al. (2016) where it is accentuated that leaf cuticle and different structural barrier impede the absorption of the herbicide into the plant's mesophyll which results in the absorption of sub-lethal dosages into the cells. The herbicide is removed from target site and be is transported where it has no effect and that process is called herbicide sequestration (Ge et al. 2018). The example of herbicide sequestration is where herbicide or its conjugates are moved into plant's vacuole or the apoplast, thus taken away from both the vascular system and the site of herbicide action (Goggin et al. 2016).

2.6 Pre-emergent herbicides

Pre-emergent herbicides are those herbicides that are applied just after planting, before the crop or weed emerges. This contrasts with post-emergent herbicides, which are applied after the weeds have emerged (Zimdahl 2007). According to Preston (2014b), pre-emergent herbicides are applied before the weeds germinate. Since these herbicides are applied before weeds emerge, it is imperative to have a record of the species of weeds that are expected, so that the correct herbicide can be chosen; records for each field must thus be kept (Preston 2014a). Pre-emergent herbicides are advantageous compared to post-emergent herbicides because of the former’s ability to kill weeds at the early growth stages (Awan et al. 2016). Controlling weeds at a later stage of growth becomes more expensive if pre-emergent herbicides were not applied (Awan et al. 2016).

Pre-emergent herbicides usually have lower application rates and thus lower water volumes per hectare compared to post-emergent herbicides (Preston 2014b). Most pre-emergent herbicides are volatile, and they require immediate soil incorporation after application. This incorporation can be through rainfall or irrigation (Zimdahl 2007).

After it has been applied, the pre-emergent herbicide may either be adsorbed or absorbed by weed seeds present in the soil (Awan et al. 2016). Adsorbed herbicides remain on the outer surface of the seed with the possibility of being absorbed by the weed seedlings as these emerge, while absorbed herbicides enter the weed seeds through mass flow or diffusion (Awan et al. 2016).

Pre-emergent herbicides have more factors or variables that affect efficacy than post-emergent herbicides (Preston 2014b). The efficiency and effectiveness of pre-emergent herbicides for weed control depend on factors such as doses, soil tilth, soil moisture, the composition of weed flora, environmental conditions and also the application rate of the herbicide (Awan et al. 2016). Soil moisture is the most important factor as it can influence both herbicide efficacy and crop phytotoxicity by altering herbicide absorption, translocation or metabolism (Awan et al. 2016). Therefore, all pre-emergent herbicides need at least some soil moisture or ideally rainfall following application to become activated and available to weed seeds (Haskins 2012).

Since pre-emergent herbicides must be absorbed or adsorbed by weed seeds, there is a need for herbicides to have some solubility in water to be absorbed by emerging shoots (Preston 2014b). Even those herbicides, such as trifluralin, that are absorbed by seedlings in a gas form still need adequate moisture to be released from the soil as a gas (Preston 2014b). Weed control with pre-emergent herbicides will therefore always be lower or inefficient under dry conditions (Preston 2014b).

The application of pre-emergent herbicides in non-till systems presents numerous challenges. This is due to the high possibility of herbicides such as trifluralin, pendimethalin and triallate binding or being retained to organic matter or stubble residues; the herbicide thus does not reach the soil surface or reach it in insufficient amounts (Preston 2014b). Haskins (2012) has noted that permanent organic matter affects the application of pre-emergent herbicides in the following two ways: (i) it becomes a physical barrier that impedes the herbicide from reaching the soil surface; and (ii) it can also tie up some herbicides, making these unavailable for weed control.

Increasing the application rate of herbicides is recommended to allow the required dose to reach the soil surface (Preston 2014b). According to Haskins (2012), using higher water rates (>80 L. ha^{-1}) with coarse, larger non-air inducted droplets can aid in getting more herbicide to the soil. Leaving the stubble standing can also reduce the occurrence of this problem (Haskins 2014). There is the possibility of selecting herbicides that are more suitable to situations where there are high stubble loads because other herbicides intercepted and bind into stubble and some herbicides, for example atrazine, simazine, Balance® (isoxaflutole) and Boxer® Gold (prosulfocarb) can wash off the stubble into the soil, maintaining efficacy for weed control (Haskins 2014).

2.7 CONCLUSION

Even though there is low adoption of conservation agriculture (CA) in the rest of Africa, South Africa is one of the leading adopters of CA with Western Cape as a leading province in the adoption of CA in the country. Although CA presents a lot of opportunities equally it presents some challenges. One of those challenges is the behaviour of different pre-emergent herbicides which become intercepted by organic cover which is retained on the field to satisfy CA protocol. This has short term and long-term implications, such as poor weed control and exposing weeds to sub-lethal dosages which can lead into weeds developing non-target site herbicide resistance. Because of these challenges outlined above then there is a gap in developing techniques that will assist into ensuring that the required amount of herbicides does reach the soil surface even in the presence of residue cover on the surface.

REFERENCES

Ahmed S, Akbar W, Riaz, MA. 2004. Effect of crop rotation and intercropping on Subterranean termites in wheat at Faisalabad. *Pakistan Entomology* 26 : 25-30.

ARC-Small Grain Institute & the Western Cape Department of Agriculture, 2014. Assessing the impact of conservation practices on wheat production in the Western Cape. *ARC Economic & Biometrical Services Report.*1–40.

Awan TH, Cruz PC, Chuahan BS. 2016. Effect of pre-emergence herbicides and timing of soil saturation on the control of six major rice weeds and their phytotoxic effects on rice seedlings. *Crop Protection* 83: 37-47.

Busi R, Gaines TA, Vila-Aiub MM, Powles SB. 2014. Inheritance of evolved resistance to a novel herbicide (pyroxasulfone). *Plant Science* 217:127-218

Chuahan BS, Singh RG, Mahajan G. 2012. Ecology and management of weeds under conservation agriculture: A review. *Crop Protection* 38: 57-65.

Cobb HC, Reade JPH. 2010. *Herbicides and Plant Physiology*. (2nd edn). Oxford: Wiley-Blackwell.

Cook T. 2011. Options for using more residual herbicides in northern no-till systems. https://www.grdc.com.au/Research-and-Development/GRDC-Update-Papers/2011/03/.Options-for-using-more-residual-herbicides-in-northern-notill-systems. Accessed on 2016/02/26.

Derpsch R. 2005.The extent of conservation agriculture adoption worldwide: implications and impacts. Paper presented at the third World Congress on Conservation Agriculture, October 2005, Nairobi, Kenya.

D'Emden FH, Llewellyn RS, Burton MP. 2008. Factors influencing adoption of conservation tillage in Australian cropping regions. *Australian Journal of Agricultural and Resource Economics* 52:169–182.

du Toit G. 2007. Promoting conservation agriculture in South Africa: a case study among commercial grain producers in the North-West province. *Bureau for Food and Agricultural Policy*. *BAFP Report* no. 2007-4.

Farooq M, Flower KC, Jabran K, Wahid A, Siddique KHM. 2011. Crop yield and weed management in rainfed conservation agriculture. *Soil & Tillage Research* 117:172-183.

Fowler R, Rockstrom J. 2001. Conservation tillage for sustainable agriculture: An agrarian revolution gathers momentum in Africa. *Soil and Tillage Research* 61:93–107.

Friedrich T, Derpsch R, Kassam A. 2012. Overview of the global spread of conservation agriculture. *Field Actions Science Reports*. *The Journal of Feld Actions* Special Issue 6:60–7.

Giller KE, Witter E, Corbeels M, Tittonell P. 2009. Conservation agriculture and smallholder farming in Africa: The heretics' view. *Field Crops Research* 114: 23-34.

Haskins B. 2012. Using pre-emergent herbicides in conservation farming systems.

http://www.dpi.nsw.gov.au/agriculture/farm/conservation/information/pre-emergent-herbicides. Accessed on 2016/02/27

Kerr B. 2016. Watch out for the weeds.

URL available: whttp://ww.farmersweekly.co.za/article.aspx?id=85622&h=Watch-out-for-new-weed. Accessed 2016/09/12

Knowler D., Bradshaw B. 2007. Farmers ' adoption of conservation agriculture : A review and synthesis of recent research. *Food Policy* 32: 25–48.

Lok C, Liu C, Kuchma O, Krutovsky KV, 2018. Mixed-species versus monocultures in plantation forestry : Development , benefits , ecosystem services and perspectives for the future. *Global Ecologyand Conservation* 15: 1-13.

Mas MT, Verdú AMC. 2003. Tillage system effects on weed communities in a 4-year crop rotation under Mediterranean dryland conditions. *Soil and Tillage Research* 74: 15–24.

Mrabet R. 2002. Stratification of soil aggregation and organic matter under conservation tillage systems in Africa. *Soil and Tillage Research* 66:119–128.

Mudavanhu S. 2015. The impact of economic policies and instruments on conservation agriculture in South Africa.

Master of Science in Agriculture (Agricultural Economics), Stellenbosch University, Stellenbosch.

Nakamoto T, Yamagishi J, Miura. 2006. Effect of reduced tillage on weeds and soil organisms in winter wheat and summer maize cropping on Humid Andosols in Central Japan. *Soil and Tillage Research* 85: 94–106.

Naylor R. 2002. *Weed Management Handbook*. (9th edn). Oxford: Blackwell Science Ltd.

Neve P, Powles S. 2005. High survival frequencies at low herbicide use rates in populations of *Lolium rigidum* result in rapid evolution of herbicide resistance. *Heredity* 95: 485-492.

Nichols V, Verhulst N, Cox R, Govaerts B. 2015.Weed dynamics and conservation agriculture principles: A review. *Field Crops Research* 183: 53-68.

Pannell DJ, Tillie P, Rodríguez-cerezo E, Ervin D, Frisvold GB. 2016. Herbicide resistance: economic and environmental challenges. *AgBioForum* 19: 136–155.

Pieterse PJ. 2010. Herbicide resistance in weeds – a threat to effective chemical weed control in South Africa. *South African Journal of Plant and Soil* 27: 66-73.

Preston C. 2014a. The mechanisms of herbicide resistance: what are we selecting for and why? URL available: https://www.grdc.com.au/Resources/Publications/2014/02/GRDC-Grains-Research-Update-Coonabarabran-Feb-2014. Accessed on 2016/03/03.

Preston C. 2014b. Understanding pre-emergent cereal herbicides; how they work, interactions with seeder type, soil, weed kill and crop safety. URL available: https://www.grdc.com.au/Resources/Publications/2014/02/GRDC-Grains-Research-Update-Coonabarabran-Feb-2014. Accessed on 2016/03/02.

Rao VS. 2015. *Transgenic Herbicide Resistance in Plants*. New York: CRC Press.

Scarabel L, Pernin F, Délye C. 2015. Occurrence, genetic control and evolution of non-target-site based resistance to herbicides inhibiting acetolactate synthase (ALS) in the dicot weed *Papaver rhoeas*. *Plant Science* 238 :158–169.

Sheaffer CC, Moncada KM. 2012. *Introduction to Agronomy: Food, Crops and Environment*. (2nd edn). New York: Delmar Cengage Learning.

Schmitz PM, Puran MAL, Hesse JW. 2015. The importance of conservation tillage as a contribution to sustainable agriculture: A special case of soil erosion. *Agribusiness-Forschung* 33 Institut für Agribusiness.

United States Department of Agriculture.1999. Sustainable Agriculture: Definitions and Terms. URL available: https://www.nal.usda.gov/afsic/sustainable-agriculture-definitions-and-terms. Accessed on 2017/03/13.

Valentin BM. 2008. Weed control in conservation agriculture. Govaerts B and Castellanos-Navarrete A (Eds). Compendium of deliverables of the conservation agriculture course 2008. CIMMYT URL available http://repository.cimmyt.org/xmlui/bitstream/handle/10883/549/93381.pdf. Accessed 2016/02/25.

Van Zyl J, Kirsten JF, Binswanger HP. 1996. *Agricultural Land Reform in South Africa: Policies, Markets and Mechanisms*. Cape Town: Oxford University Press.

Walton PD. 1988. Principles and Practices of Plant Science. New Jersey: Prentice Hall.

Yaun J, Tranel PJ, Stewart Jr CN. 2007. Non-target-site herbicide resistance: a family business. *Trends in Plant Science* 12: 1-42.

Yang Q, Deng W, Li X, Yu Q, Bai L, Zheng M. 2016). Target-site and non-target-site based resistance to the herbicide tribenuron- methyl in flixweed (*Descurainia sophia* L). *BMC Genomics*, 1–13.

Zimdahl RL. 2007. Fundamentals of Weed Science (3rd edn). Burlington: Academic Press.

CHAPTER 3

DOES INCREASING APPLICATION AND DOSAGE RATES OF PYROXASULFONE INCREASE CONTROL OF RYEGRASS UNDER CONSERVATION AGRICULTURE CONDITIONS?

ABSTRACT

Field experiments were conducted at Langgewens and Tygerhoek Research Farms in 2016 where residue cover was manipulated in three different residue cover treatments, viz. high, medium and low. After sowing of wheat, pyroxasulfone (Sakura®) was applied at dosage rate/application rate combinations of 125 g ha^{-1} in 200 L H_2O ha^{-1}, 125 g ha^{-1} in 400 L H_2O ha^{-1}, 187.5 g ha^{-1} in 200 L H_2O ha^{-1} and 187.5 g ha^{-1} in 400 L H_2O ha^{-1}. A control treatment with no herbicides applied was also included resulting in five herbicide treatments. Split-plots were arranged in a completely randomized block design replicated four times. Herbicide treatments formed the main plots with residue cover forming the split plot treatments. Weed and crop count was made at seven weeks after planting (WAP) and at anthesis. Vegetative growth parameters were determined at anthesis. Yield components were determined just before harvesting. After harvesting; yield, thousand kernel mass and hectolitre mass were determined. Increasing the dosage rate from 125 g ha^{-1} to 187.5 g ha^{-1} improved the efficacy of pyroxasulfone, across all residue covers. The doubling of recommended application rate to 400 L ha^{-1} improved the efficacy when it was applied on an increased residue cover in some limited instances but overall it was the increase in registered dosage rate that consistently improved pyroxasulfone's efficacy across all levels of residue covers.

Keywords

Application rate, conservation agriculture, dosage rate, pre-emergent herbicides, pyroxasulfone, residue cover.

3. 1INTRODUCTION

For many years tillage has been used as one of the means for weed control and any possible change in tillage system will have significant impact on the composition of weed communities. That is why it is imperative to study any phenomenon that may affect weed control in conservation agriculture (Arshad et al. 1994). According to Arshad et al. (1994), a high levels of crop residues is one of the phenomena that leads to poor performance of pre-emergent herbicides in conservation agriculture.

The effectiveness of pre-emergence weed control in residue retained cropping systems such as conservation agriculture, can be compromised when the residue intercept the herbicide and prevent it from reaching the desired target, or the herbicide is tightly bound to organic matter or residue (Cook et al. 2016). Some weed species can escape the application of pre-emergent herbicides in conservation agriculture systems where residue can bind soil-applied herbicides and result in lower efficacy (Chauhan and Abugho 2012). Although crop residue retention has both positive and negative effects, efforts must be employed to enhance positive effects over the negative ones (Farooq et al. 2011).

According to Cook et al. (2016) different types of pre-emergent herbicides differ in the degree of binding to residue cover or organic material and it depends on the composition of the herbicides. Beside the fact that the herbicide bind tightly or loosely on the residue cover, there are other factors that may influence the efficacy of pre-emergent herbicides (Cook et al. 2016). These factors that affect pre-emergent herbicides includes chemical considerations such as how prone herbicide is to volatility, sensitivity to sunlight degradation (photo degradation), water solubility of the herbicides, and prevailing environmental conditions at the time of application namely; rainfall, soil moisture levels, temperature levels during time of application and just after application (Haskins 2012). It is therefore important to ensure where there is an increase in residue that the required dosage of pre-emergent herbicides reaches the soil surface for effective weed control to be realised in an environment where there is retention of residue cover.

The aim of this study was to determine the dosage rate and application rates that can be utilised on an increased residue cover for effective weed control. Therefore, the objectives that formed the basis of this study comprised the following; to assess the effect of increased pyroxasulfone application and dosage rates on (i) the effectiveness of weed control, (ii) the vegetative growth parameters of wheat plants, (iii) wheat grain yield and yield components of wheat, and (iv) the quality parameters of wheat grain. The null hypothesis (H_0) of this study was therefore that, increasing application and dosage rates of pyroxasulfone under increased amounts of residue cover will not influence the parameters listed above.

3. 2 MATERIALS AND METHOD

3.2.1. Experimental Site

The first experiment was carried out in 2016 in the Western Cape Province of South Africa, at the Langgewens research farm near Moorreesburg in Swartland area, West Coast region The site is located at 33°17´ S 18°40´ E at an altitude of 137 m above sea level .The region get rain in winter which is distinctly Mediterranean-type climate with an average annual rainfall of approximately 400 mm. Its soil characteristics consists of 0.59% carbon, 77% sand, 14% silt, and 9% clay, and high stone presence. The soils are derived from Malmesbury and Bokkeveld shales.

The second experiment was also carried out in 2016 at Tygerhoek research farm near Riviersonderend, Overberg region. This site is located at 31°54'0"S 23°19'0" E at an altitude of 1,188 m above sea level. The region gets both summer and winter rainfall with an average annual rainfall of 450 mm of which 68% occurs between April and October. The soils characteristic in area is dominated poorly developed, shallow shale-derived soils with a high stone presence. The Oakleaf, Glenrosa and Swartland are the main soils forms in the area.

The rainfall data for 2016 at Langgewens and Tygerhoek research farms are given in Table 3.1 and 3.2 respectively.

Table 3. 1: Rainfall for Langgewens research farm during the year 2016 (mm)

Date	January	February	March	April	May	June	July	August	September	October	November	December
1							9		4			
2							4					
3								23				
4												
5							8		1.5			
6									4			
7												
8									3	1		
9												
10						25						
11										5		
12												
13					0.5							
14						6		11				
15						22	5.5	1				
16						19			4.5	1		
17									2,5			
18												
19			2									
20		6				26	3					
21				4		3	20					
22				13			8	15	1.5			
23				22	Herbicide		2	3				
24												
25	5,5											
26	8		1									
27			26			8	5		20			
28						5	4		3			
29				10			20					
30			6	5,5								
31												
Total	13.5	6	35	54.5	0,5	114	88.5	53	44	7	0	0

Table 3.2: Rainfall for Tygerhoek research farm during the year 2016 (mm)

Date	January	February	March	April	May	June	July	August	September	October	November	December
1							0.4					25
2						2.2	3.2		5.6			20,7
3		9				1.2		11.2	54.6			32,7
4		7.1										15,8
5												1,7
6							4.2					42
7	13.3		2						0.5			105,7
8		3.3	0.5									29,8
9							1.6		1.7	4.1		
10						25			0.7			
11			6.1									0
12							2.3					0
13												
14	4.4					2						
15					Herbicide	1						
16		0.7				2.2	2.5					
17									1.7	1.3		
18												
19			5.8		1.4							
20						5.6						
21			2.2			2.5	6.5					
22		0.6						18.6	3.3			
23				6.8								
24			5				10.7					
25			4.3		0.3							
26	7.3						69.5					
27			6.8						2.1			
28						0.3			3.3			
29							3.4					
30				9			1.4					
31												
Total	25	20.7	32.7	15.8	1.7	42	105.7	29.8	73.5	5.4	0	273.4

3.2.2. Treatments and experimental design

The treatments and experimental design were identical both at Langgewens and Tygerhoek. The experimental layout was arranged in a randomized block design arranged as a 5x3 factorial replicated 4 times. The experiment consisted of the following factors: five herbicide treatments (pyroxasulfone applied at 125 g ha^{-1} in 200 L ha^{-1} water (recommended dosage and application rate), 125 g ha^{-1} in 400 L ha^{-1} water, 187.5 g ha^{-1} in 200 L ha^{-1} water, 187.5 g ha^{-1} in 400 L ha^{-1} water and a control treatment where no herbicide was applied (**Table 3.3**) and three residue cover treatments (low, medium and high). To investigate the interactions between residue cover, dosage rate and application rate in more detail, a subset of data that exclude the control treatment, was analysed as a 2x2x3 factorial design with two herbicide dosage rates (recommended registered dosage rate (125 g ha^{-1}) and 1.5 times the recommended dosage rate (187.5 g ha^{-1})), 2 herbicide application rates (recommended registered application rate (200 L ha^{-1}) and double the recommended application rate (400 L ha^{-1}) and three residue cover treatments (low, medium and high).

On both rsearch farms the trial was laid out in a wheat monoculture field that formed part of the long-term rotational trials managed by the Department of Agriculture: West Cape. The transect method was used to determine the amount of residue cover (Dickey et al 1986, Wollenhaupt, & Pingry 1991). At both farms the plot sizes were 1.5 m wide by 7.5 m long. The 7.5 m plots were split into three 2.5 m split-plots where the residue treatments were applied resulting into split-plots with area of 1.5 m x 2.5 m each and then residue treatments were applied on them.

The wheat residue cover both at Langgewens and Tygerhoek were manipulated to result in three different residue cover treatments namely 100% (high), 50% (medium) and 0% (where negligible small amount of residue was left on the soil surface) residue cover. The amount of wheat residue cover in kg m-^{2}, was only determined at Langgewens by randomly collecting as much as possible residues on fifteen 0.5 m^2 rectangular sample plots on the field and drying the residues for 7 days in an empty greenhouse without temperature control to become air-dry. The air-dry mass of the residues was then correlated with the cover percentage determined in each subplot by means of the transect method. By making use of the regression coefficient, the cover dry mass on the different residue treatments were then arranged as follows; in Langgewens; 100% (high = 12 t ha^{-1}) which is double to what is found on commercial farms, 50% (medium = 6 t ha^{-1}) which is approximately what is found on commercial farms and 0% (low = negligible small amount of residue left on the soil surface) (See **Figure 3.1**). Residues from neighbouring wheat plots were used to get enough residue to attain the specific dry masses on the plots.

At Tygerhoek no specific amount of the residues was put onto the plots as at Langgewens since there were relatively low wheat residues on the soil. An attempt was made to manipulate the residues into relatively high, medium and low levels by raking all the residues from one 2.5 m subplot (low residue cover) onto the adjacent plot (high residue cover) while the third plot remained undisturbed (medium residue cover). Residue cover of plots were randomly determined by means of the transect method to get an estimate of the residue cover on the plots in Tygerhoek and the approximate amount of residues was estimated as follows; high = 9 t ha^{-1}, medium= 4.5 t ha^{-1} and low = negligible small amount of residue cover left on the soil surface.

The herbicide was applied immediately before planting on 23rd May 2016 and 10th May 2016 at Langgewens and Tygerhoek respectively by means of a knapsack sprayer equipped with a flat fan nozzle (**Table 3.3**).

Table 3.3: Herbicide treatments applied on the trial

Treatment	Herbicide	Dosage Rate (g ha^{-1})	Application Rate (L ha^{-1})
1	Pyroxasulfone	125	200
2	Pyroxasulfone	125	400
3	Pyroxasulfone	187.5	200
4	Pyroxasulfone	187.5	400
5	Control	No Herbicide	No herbicide


(a)


(b)


(c)

Figure 3. 1: Different residue cover levels in the Langgewens trial where different application and dosage rates of pyroxasulfone were tested on increased residue levels. (a) low residue cover, (b) medium residue cover,(c) high residue cover

3.2.3. Planting and seeding

A disc planter was used during planting to fulfil the non-till or reduced tillage principle as one of the conservation agriculture practices both at Langgewens and Tygerhoek.

3.2.4. Plant management

The fertilizer, pesticides and fungicides were applied according to best practice principles in the field trials in both trials.

3.2.5. Data collection

At different stages after planting, the following parameters were measured and recorded both at Langgewens and Tygerhoek:

i. Weed and crop count

Seven weeks after planting (WAP) weed (mainly ryegrass & wild oats) and crop counts were conducted. On each treatment, counts were randomly carried out inside three 30 cm x 30 cm quadrats and two 30 cm x 30 cm quadrats for weeds and crops respectively. At anthesis weed and crop counts were carried out in the same fashion as above but additionally, both weeds and crops were cut at soil surface and put in plastic bags to be transported to the laboratory for the assessment of the vegetative growth parameters. The values obtained from the quadrats were adjusted to weed and plant population per m^2.

ii. Vegetative growth parameters

Five wheat plants were sampled in each plot and the number of wheat spikelets per head of the wheat plant were counted and the average number of spikelets per head was recorded. The wheat ears, wheat plants and weeds were then put in an oven and dried at 60 ºC for 72 hours. The wheat plants and weeds were then weighed on an electronic scale balance to determine biomass for each. The average number of kernels per ear was recorded.

iii. Yield and yield components

At harvest the plots were harvested by means of a plot harvester (Hege 140) and yield was then determined for each treatment by weighing the wheat grains on an electronic scale balance. Immediately before harvest, five wheat ears were randomly picked from each plot and the yield components on each were determined i.e. number of spikelets per ear, number of kernels per spikelet, number of kernels per ear and weight of kernels per ear.

iv. Quality parameters

Hectolitre mass (HLM)/specific weight was analysed using a two-level HLM apparatus. Thousand kernel weight (TKW) was determined by weighing one thousand kernels using the electronic scale balance.

3.2.6 Statistical analysis

The STATISTICA 12 program was used to conduct analysis of variance. Means of significance and interactions were separated using Fisher's least significance (LSD) test at 5% level of significance. Two-way ANOVA and three-way ANOVA were used to analyse interaction between the two factors (herbicide treatment and residue cover) and the three factors (residue cover, dosage rate and application), respectively. Where the Levene's test showed severe non-homogeneity of variances, the Games-Howell multiple comparison procedure was used instead of the LSD intervals.

3. 3 RESULTS

Two-way ANOVA analysis with factors herbicide treatments and residue levels

3. 3.1 Weeds population

Weed population counted 7 weeks after planting (WAP):

At Tygerhoek there was no significant interaction between herbicide treatment and residue cover, only herbicide treatment had significant effect ($p \leq 0.05$) on the number of weeds (**Table 3.6**). Herbicide Treatments 2, 3 and 4 resulted in the lowest number of weeds that were significantly different from herbicide Treatment 5 (highest number of weeds) and herbicide treatment 1 with second lowest number of weeds (**Table 3.4**). At Langgewens there was significant interaction between herbicide treatment and residue cover ($p \leq 0.05$) (**Table 3.6**). Even though there were no significant differences in the number of weeds between all herbicide Treatments 1, 2, 3 and 4 applied across residue cover levels, Treatment 5 recorded significantly higher number of weeds. In Treatment 1 there were significantly more weeds at the high residue cover level than at the medium and low residue cover levels. In Treatment 5 however, the lowest residue cover level resulted in significantly higher number of weeds than the other two residue cover levels (**Figure 3. 2**). Another observation at herbicide Treatment

5 is that the higher the residue cover the number of weeds declined.The number of weeds in Treatment 5 (unsprayed control) was generally significantly higher than in Treatments 2, 3 and 4 over all residue levels.

Weeds population counted at anthesis:

At Tygerhoek there was significant interaction between herbicide treatment and residue cover ($p \leq 0.05$) (**Table 3.6**). Even though were no major differences between treatments across residue cover level, Treatments 3 and 4 recorded the lowest number of weed infestation. Due to high variation in the occurrence of weeds there were no significant differences between treatment combinations, but trends show much higher weed numbers in Treatment 5 and very low number of weeds in Treatments 3 and 4. (**Figure 3.3**). Although no significant differences occurred, trends were generally the same as at Langgewens at 7 WAP (**Figure 3.2**).

At Langgewens, there was no significant interaction between treatment and residue cover and only herbicide treatment had significant effect ($p \leq 0.05$) on the number of weeds (**Table 3.6**). Treatments 3 and 4 resulted in the lowest number of weeds, but were not significantly lower than in Treatments 1 and 2. However all sprayed treatments (1 – 4) were significantly different from Treatment 5 which resulted in the highest weed infestations (**Table 3.5**).

3. 3.2 Wheat plants population

Wheat population counted 7 weeks after planting (WAP):

At Tygerhoek there was no significant interaction between treatment and residue cover or any significant differences within factors (**Table 3.6**). At Langgewens there was significant interaction between treatment and residue cover ($p \leq 0.05$) (**Table 3.6**). Treatments 3 and 4 resulted in the highest number of wheat plants at low and medium residue cover but were not significantly different from wheat numbers obtained in Treatment 1 applied at low and medium residue cover (**Figure 3.4)**. In Treatments 1, 2 and 4 the high residue cover levels resulted in significantly lower numbers of wheat plants than the low and medium residue cover levels at the corresponding dosage rates. In contrast Treatment 5 recorded the lowest number of wheat plants across all residue cover levels. The other important observation is that number of wheat plants was low on high residue covers when compared to low and medium residue cover across all treatments (**Figure 3. 4)**.

Wheat population counted at anthesis:

At Tygerhoek there was no significant interaction between treatment and residue cover or any significant differences within factors (**Table 3.6**). At Langgewens there was no significant interaction between treatment and residue cover, only treatment had significant effect ($p \leq 0.05$) on the number of wheat plants (**Table 3.6**). At Langgewens Treatments 3 and 4 resulted in the highest number of wheat plants and were not significantly different from other treatments except Treatment 5 (unsprayed control) which resulted in the lowest number of wheat plants compared to the herbicide treatments (**Table 3.5**).

3. 3.3 Weeds biomass

Both at Tygerhoek and Langgewens there were no significant interactions between treatment and residue cover, and in both cases only treatment had significant effect ($p \leq 0.05$) on weed biomass **(Table 3.6).** At Tygerhoek, Treatments 3 and 4 resulted in the lowest weed biomass and but were not significantly different from Treatments 1 and 2, while Treatment 5 resulted in significantly higher weeds dry mass than the herbicide treatments (**Table 3.4**). At Langgewens similar trend was observed where Treatments 3 and 4 resulted in the lowest weed biomass and were not significantly different from Treatments 1 and 2, while Treatment 5 resulted in significantly higher weed dry mass than the herbicide treatments (**Table 3.5**).

3. 3.4 Wheat plants biomass

At Tygerhoek there was no significant interaction between treatment and residue cover or any significant differences within factors (**Table 3.6**). At Langgewens there was no significant interaction between treatment and residue cover, and only treatment had significant effect ($p \leq 0.05$) on the wheat plants dry mass (**Table 3.6**). At Langgewens, Treatment 1 obtained significantly higher wheat plant dry mass than Treatments 2, 3 and 5 but was not significantly different from Treatment 4. Conversely, Treatment 5 resulted in the lowest wheat plant dry mass but was not significantly lower than Treatments 2 and 3 (**Table 3.5**).

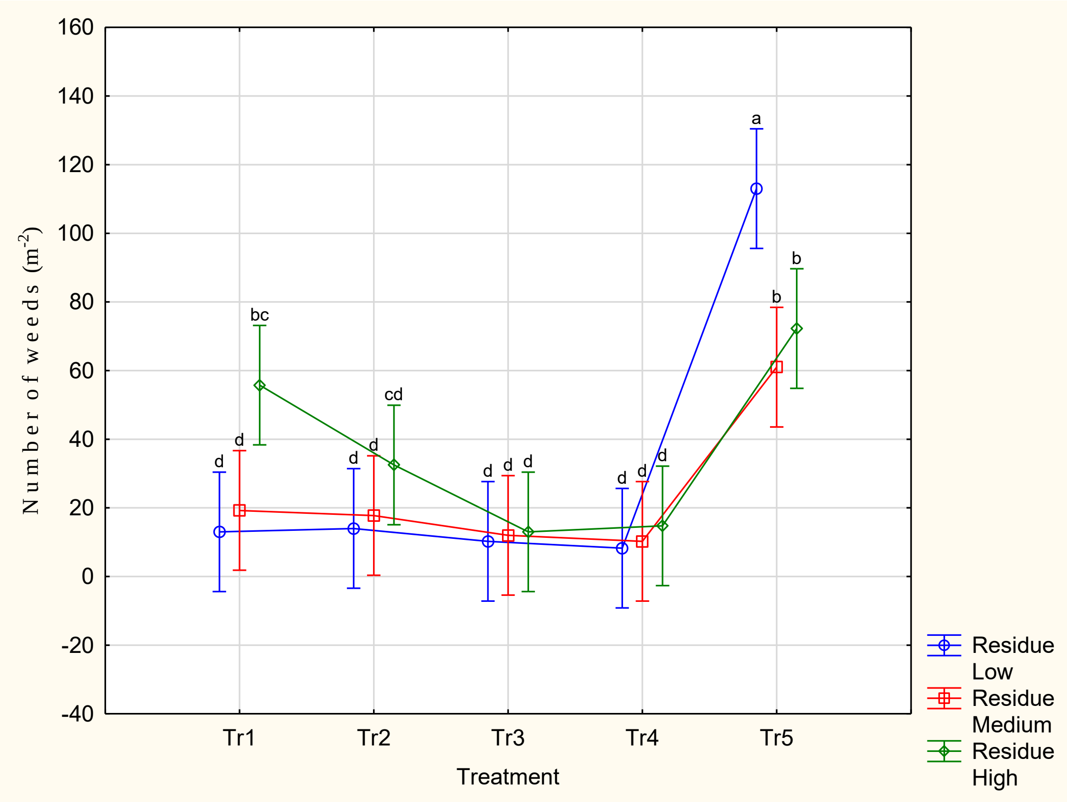

Figure 3. 2: Weeds population that was recorded at 7 WAP at Langgewens, illustrating interaction between herbicide treatment and residue cover. Different letters denote means which differed significantly at $p \leq 0.05$ as per Fishers LSD. Vertical bars indicate 0.95 confidence intervals.

Table 3.4: The vegetative growth, quality parameters that was influenced by treatments as main factor in a trial at Tygerhoek where efficiency of pyroxasulfone applied at different application and dosage rates on various residue levels in a wheat field was investigated

Treatment	Weeds population 7 WAP (m^{-2})	Weed biomass (g)	No. of spikelets (per ear)	1000 kernel mass (g)
1	28b	10,7ab	18b	42,2ab
2	17bc	1,4b	19a	40bc
3	5c	1.7b	19a	43a
4	3c	0,7b	19a	43,5a
5	66a	35.8a	17c	38.3c

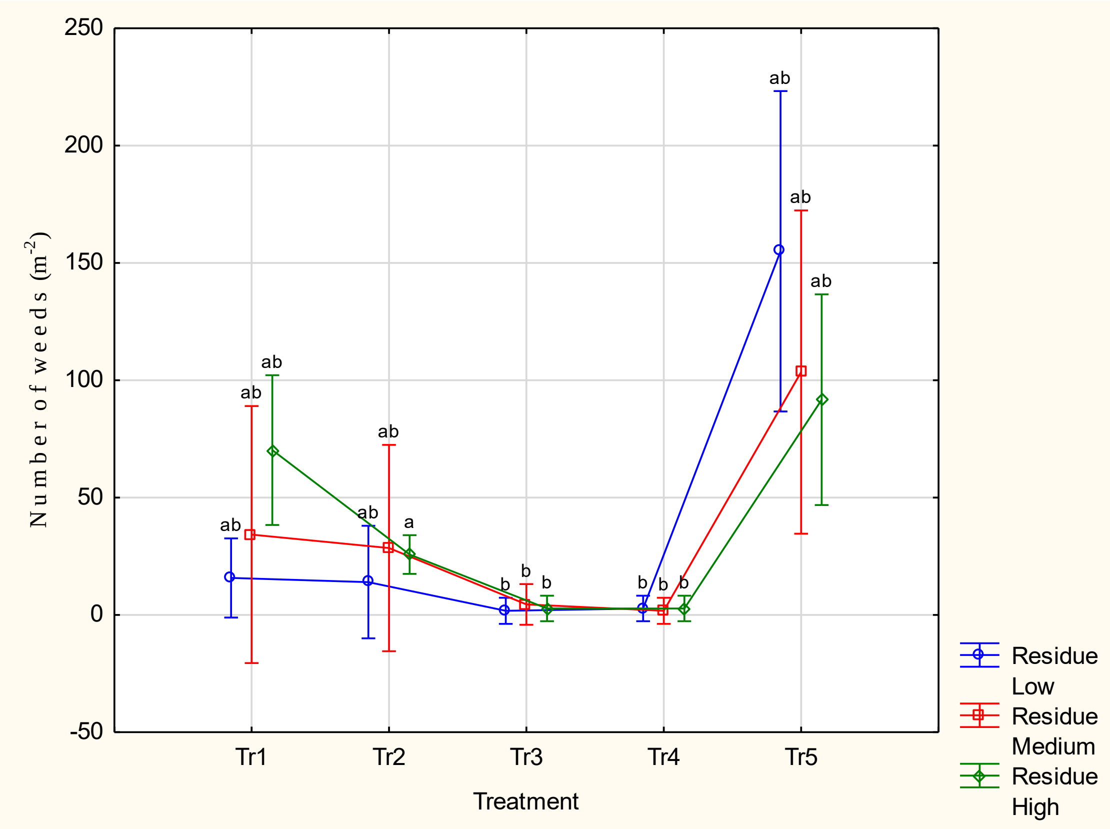

Figure 3.3: The number of weeds that were recorded at anthesis at Tygerhoek, illustrating interaction between treatment and residue cover. Different letters denote means which differed significantly at $p \leq 0.05$ as per Fishers LSD. Vertical bars indicate 0.95 confidence intervals

3. 3.5 Number of spikelets per ear

Both at Tygerhoek and Langgewens there was no significant interaction between treatment and residue cover and only treatment had significant effect ($p \leq 0.05$) on the number of spikelets per ear (**Table 3.7**). At Tygerhoek, Treatments 2. 3 and 4 recorded the highest amount of spikelets per ear that were significantly higher than Treatment 1 that in turn was significantly higher than Treatment 5 that resulted the lowest number of spikelets per ear (**Table 3.4**). At Langgewens, Treatments 3 and 4 resulted in the highest number of spikelets per ear and were significantly higher than the other treatments with Treatments 1 and 2 resulting in the second highest number of spikelets per ear and Treatment 5 producing the lowest number of spikelets per ear (**Table 3.5**).

Table 3.5: The vegetative growth, yield and quality parameters that was influenced by treatments as main factor in a trial at Langgewens where efficiency of pyroxasulfone applied at different application and dosage rates on various residue levels in a wheat field was investigated.. Different letters denote means that differed significantly at $p \leq 0.05$ as per Fishers LSD

Treatment	Weed Population at anthesis (m^{-2})	Wheat plant population at anthesis (m^{-2})	Weed biomass (g)	Wheat plants biomass (g)	Wheat grain yield ($t\ ha^{-1}$)	No. of spikelets (per ear)	No. of kernels (per ear)	Thousand kernel mass (g)
1	16b	85a	3b	86a	4,6a	18b	52ab	40.7c
2	17b	88a	2.5b	63bc	4.4a	18b	51b	40.3c
3	6b	96a	1.4b	62bc	4.5a	19a	58a	44b
4	3b	88a	0.8b	74ab	4.9a	19a	58a	47.8a
5	67a	61b	17.7a	53c	2.4a	14c	38c	39.2c

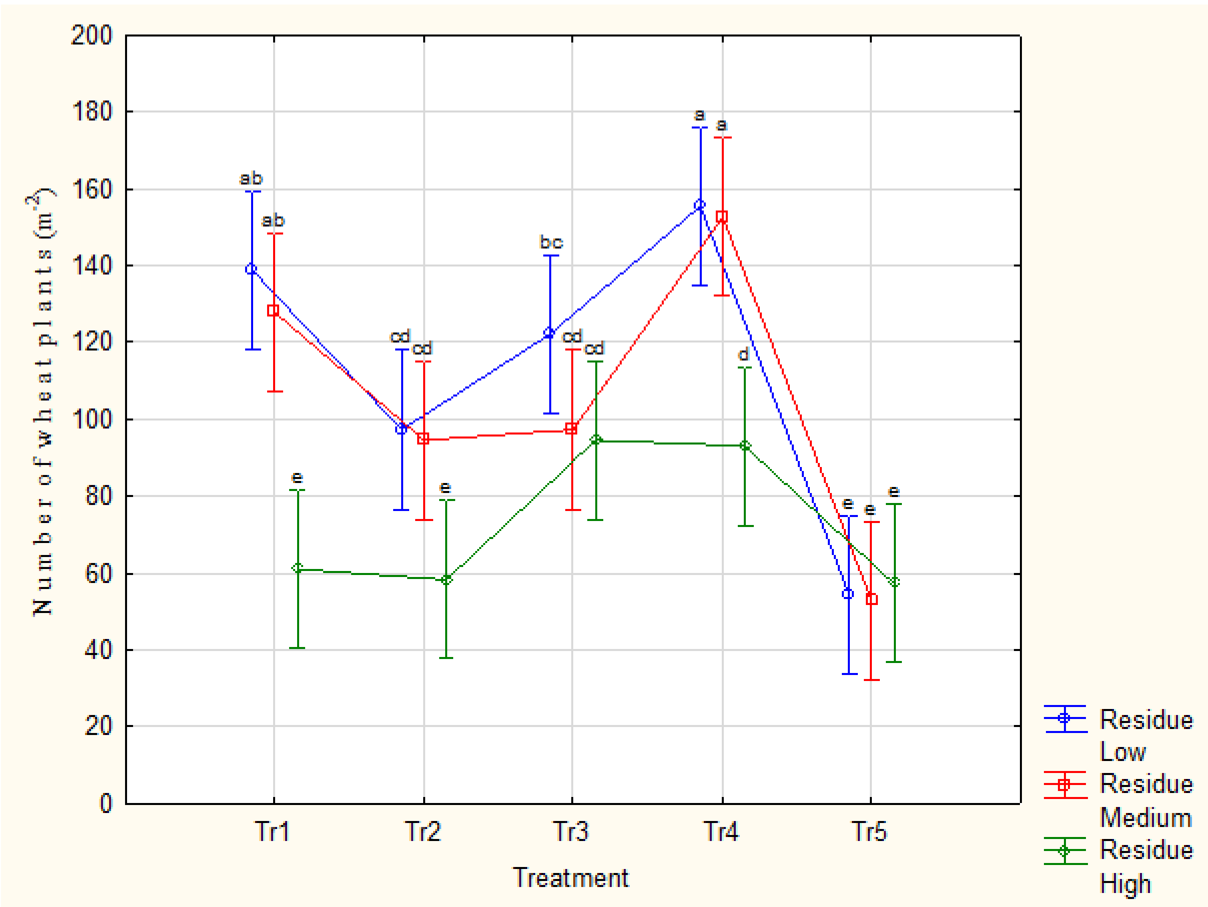

Figure 3.4: The number of wheat plants that were recorded at 7 WAP at Langgewens, illustrating interaction between t treatment and residue cover. Different letters denote means which differed significantly at $p \leq 0.05$ as per Fishers LSD. Vertical bars indicate 0.95 confidence intervals

3. 3.6 Number of kernels per ear

At Tygerhoek there was no significant interaction between treatment and residue cover or any significant differences within factors (**Table 3.7**). At Langgewens there was no significant interaction between treatment and residue cover and only treatment had significant effect ($p \leq 0.05$) on the number of kernels per ear (**Table 3.7**). Treatments 3 and 4 resulted in the highest number of kernels per ear and were significantly different from Treatment 2 whilst Treatments 1 and 2 produced significantly more kernels per ear than Treatment 5 (**Table 3.5).**

Table 3.6:. Analysis of variance (ANOVA) table on vegetative growth parameters at Langgewens and Tygerhoek.

Factors at Tygerhoek	Weeds population 7 WAP (m^{-2})	Weeds population anthesis (m^{-2})	Wheat plants population 7 WAP (m^{-2})	Wheat plants population anthesis (m^{-2})	Weed biomass (g)	Wheat biomass (g)
Treatment	*	ns	ns	ns	*	ns
Residue	ns	ns	ns	ns	ns	ns
Treatment *Residue	ns	*	ns	ns	ns	ns
Factors at Langgewens						
Treatment	*	*	*	*	*	*
Residue	*	ns	*	ns	ns	ns
Treatment *Residue	*	ns	*	ns	ns	ns

*= denotes significant interaction between respective factors ($p \leq 0.05$), ns denotes no significant interaction between respective factors ($p > 0.05$)

Table 3.7: Analysis of variance (ANOVA) table on yield parameters at Langgewens and Tygerhoek.

Factors at Tygerhoek	No. of spikelets (per ear)	No. of kernels (per ear)	Wheat grain yield (t. ha^{-1})	Thousand kernel mass (g)	Hectolitre mass (kg. hL^{-1})
Treatment	*	ns	ns	*	ns
Residue	ns	ns	ns	ns	ns
Treatment *Residue	ns	ns	ns	ns	ns
Factors at Langgewens					
Treatment	*	*	*	*	ns
Residue	ns	ns	ns	ns	ns
Treatment *Residue	ns	ns	ns	ns	ns

*=denotes significant interaction between respective factors ($p \leq 0.05$), ns denotes no significant interaction between respective factors ($p > 0.05$)

3. 3.7 Wheat grain yield

Both at Tygerhoek and Langgewens there was no significant interaction between treatment and residue on wheat grain yield (**Table 3.7**). At Langgewens treatment had significant effect on wheat grain yield ($p \leq 0.05$) (**Table 3.7**). All the herbicide treatments resulted in about equal grain yields of about 4.4 to 4.9 t ha^{-1} (**Table 3.5**) which was significantly better than the grain yield in Treatment 5 (2.4 t ha^{-1}). At Tygerhoek no significant differences ($p \geq 0.05$) between treatments or residue cover levels occurred (**Table 3.7**).

3. 3.8 Thousand kernel mass

Both at Tygerhoek and Langgewens there was no significant interaction between treatment and residue cover, with only treatment that had significant effect ($p \leq 0.05$) on the thousand kernel mass. (**Table 3.7**). At Tygerhoek treatments Treatments 3 and 4 resulted in the highest 1000 kernel mass but was not significantly different from Treatment 1. Conversely Treatment 5 received resulted in the lowest thousand kernel mass and that was not significantly different from Treatment 2 (**Table 3.4**). At Langgewens Treatment 4 resulted in the highest amount of thousand kernel mass and that was significantly higher than Treatment 3 that was in turn significantly higher than the rest of the treatments that did not differ significantly from each other including treatment 5 with lowest 1000 kernel mass(**Table 3.5**).

3. 3.9 Hectolitre mass

Both at Tygerhoek and Langgewens there was no significant interaction between treatment and residue or any significant differences within factors in terms of hectolitre mass (**Table 3.7**).

Results for the investigation of the three-way interactions between residue cover, dosage rate and application rate.

3. 3.10 Weeds population

At Tygerhoek, there was no significant interaction between factors (residue cover, dosage rate and application rate) on the number of weeds, 7 weeks after planting (WAP), with only the herbicide dosage rate having significant effect ($p \leq 0.05$) on the number of weeds (**Table**

Table 3. 8: Analysis of variance (ANOVA) table on weeds population, wheat population and vegetative growth parameters at Langgewens and Tygerhoek

Factors at: Tygerhoek	Weeds population 7 WAP (m^{-2})	Weeds population at anthesis (m^{-2})	Wheat plants population 7 WAP (m^{-2})	Wheat plant population anthesis (m^{-2})	Weed biomass (g)	Wheat biomass (g)
Dose	*	*	ns	ns	*	ns
Application	ns	*	ns	ns	*	ns
Residue	ns	*	ns	ns	ns	ns
Dose*Application	ns	ns	n	ns	*	ns
Dose*Residue	ns	*	s	ns	ns	*
Application*Residue	ns	ns	ns	ns	ns	ns
Dose*Application*Residue	ns	ns	ns	ns	ns	ns
Langgewens						
Dose	*	*	*	ns	ns	ns
Application	ns	ns	ns	ns	ns	ns
Residue	*	ns	*	ns	ns	ns
Dose*Application	ns	ns	*	ns	ns	*
Dose*Residue	*	*	ns	*	ns	ns
Application*Residue	ns	ns	ns	ns	ns	ns
Dose*Application*Residue	ns	ns	*	ns	ns	ns

*= significant interaction between respective factors ($p \leq 0.05$), ns=no significant interaction between respective factors

3.8). An increase in dosage rate (Dose 1.5x) reduced the numbers of weeds significantly compared to the recommended dosage rate treatment (Dose 1x) (**Table 3.10**).

At anthesis there was significant interaction ($p \leq 0.05$) between two factors; dosage rate and amount of residue present on the field (**Table 3.8**). The number of weeds were low when the recommended dosage rate (Dose 1x) was applied on the low residue cover and as soon as the residue cover increased from low to medium and high, the number of weeds increased with significant differences between residue cover levels (**Figure 3.5**). Therefore, the recommended dosage rate applied on the high residue cover resulted in the highest number of weeds, followed by the medium residue cover with the second highest number of weeds and low residue with the lowest number of weeds. With the increased dosage rate (Dose 1.5x) there was a decrease in the number of weeds across all level of residue cover (low, medium, high) with no significant differences in the number of weeds among the three residue level covers. It is worth mentioning that there were no significant differences in the number of weeds between the normal dosage rate (Dose 1x) applied at low residue cover and increased dosage rate (Dose 1.5x) applied at medium and high residue cover levels. In addition, application rate on its own demonstrated some significant effect on the number of weeds according to the ANOVA results (**Table 3.8**). However, even though double the application rate resulted in the lowest number of weeds Fishers's LSD test showed no significant differences compared to the recommended application rate (**Table 3.9**).

Table 3.9: The effect of application on different on number of weeds seven weeks after planting (WAP) in the Tygerhoek trial. Different letters denote means that differed significantly at $p \leq 0.05$ as per Fishers LSD

Site	Application rate (L ha^{-1})	Number of weeds7 WAP (m^{-2})
Tygerhoek	200	22a
	400	14a

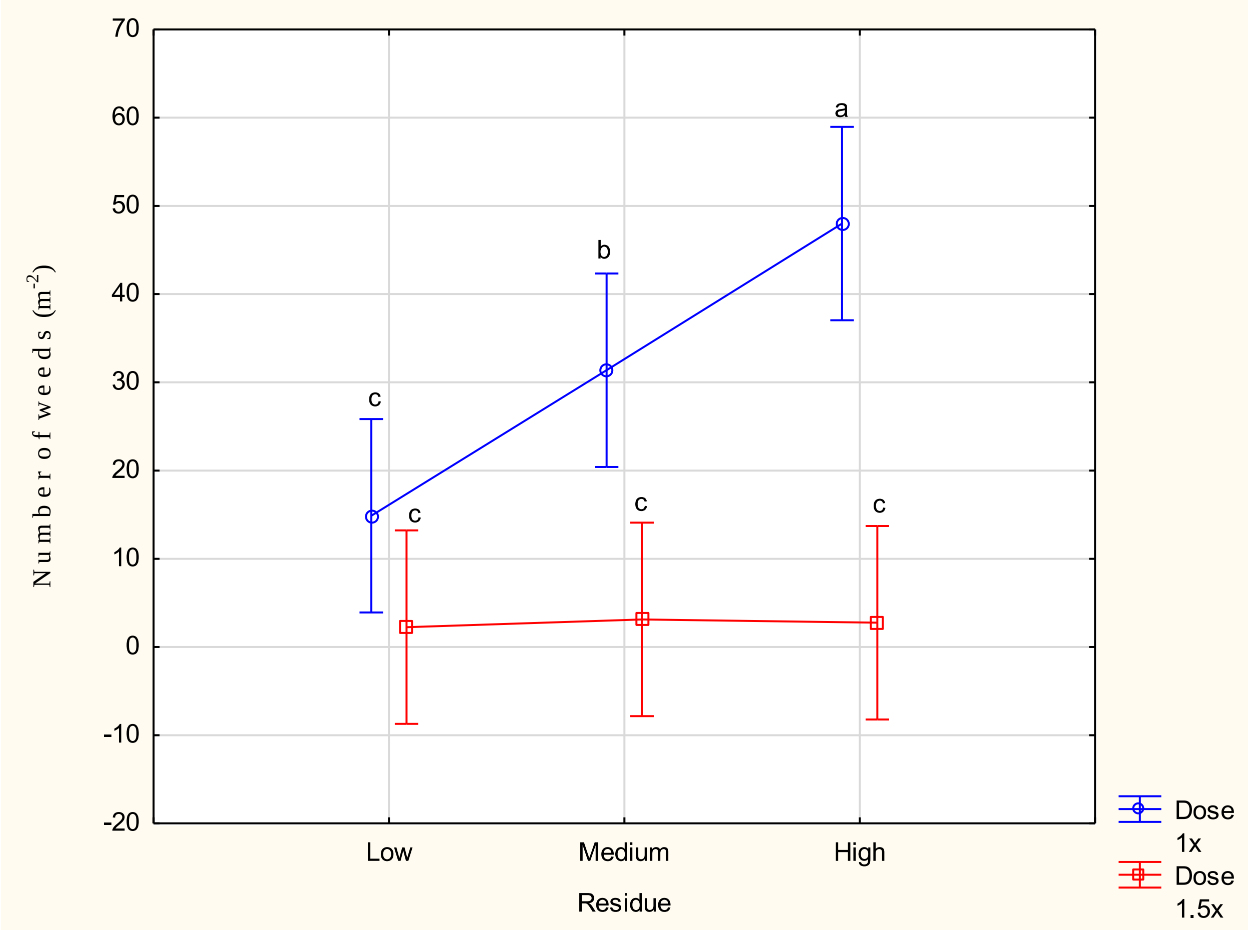

Figure 3.5: The number of weeds that were recorded during the wheat anthesis growth stage at Tygerhoek, illustrating interaction between dosage rate and residue cover. Different letters denote means which differed significantly at $P \leq 0.05$ as per Fishers LSD. Vertical bars indicate 0.95 confidence intervals.

At Langgewens, in terms of the number of weeds that were recorded 7 WAP, there was significant interaction ($p \leq 0.05$) between dosage rate and residue levels (**Table 3.8**).When the1x dosage rate was applied at high levels of residue cover, it resulted in the highest number of weed infestation that was significantly different from the rest of the treatment combinations (**Figure 3.6**). At anthesis there was also significant interaction ($p \leq 0.05$) between dosage rate and residue cover (**Table 3.8**). The 1x dosage rate applied at medium residue cover and high residue cover displayed the highest number of weeds with no significant differences between the two residue treatments (**Figure 3.7)**. The 1.5x dosage rate applied at medium residue cover and high residue cover were not significantly different from each other with lowest number of weeds, and equally they were not significantly different from the 1x dosage rate applied on low residue cover and medium residue cover.

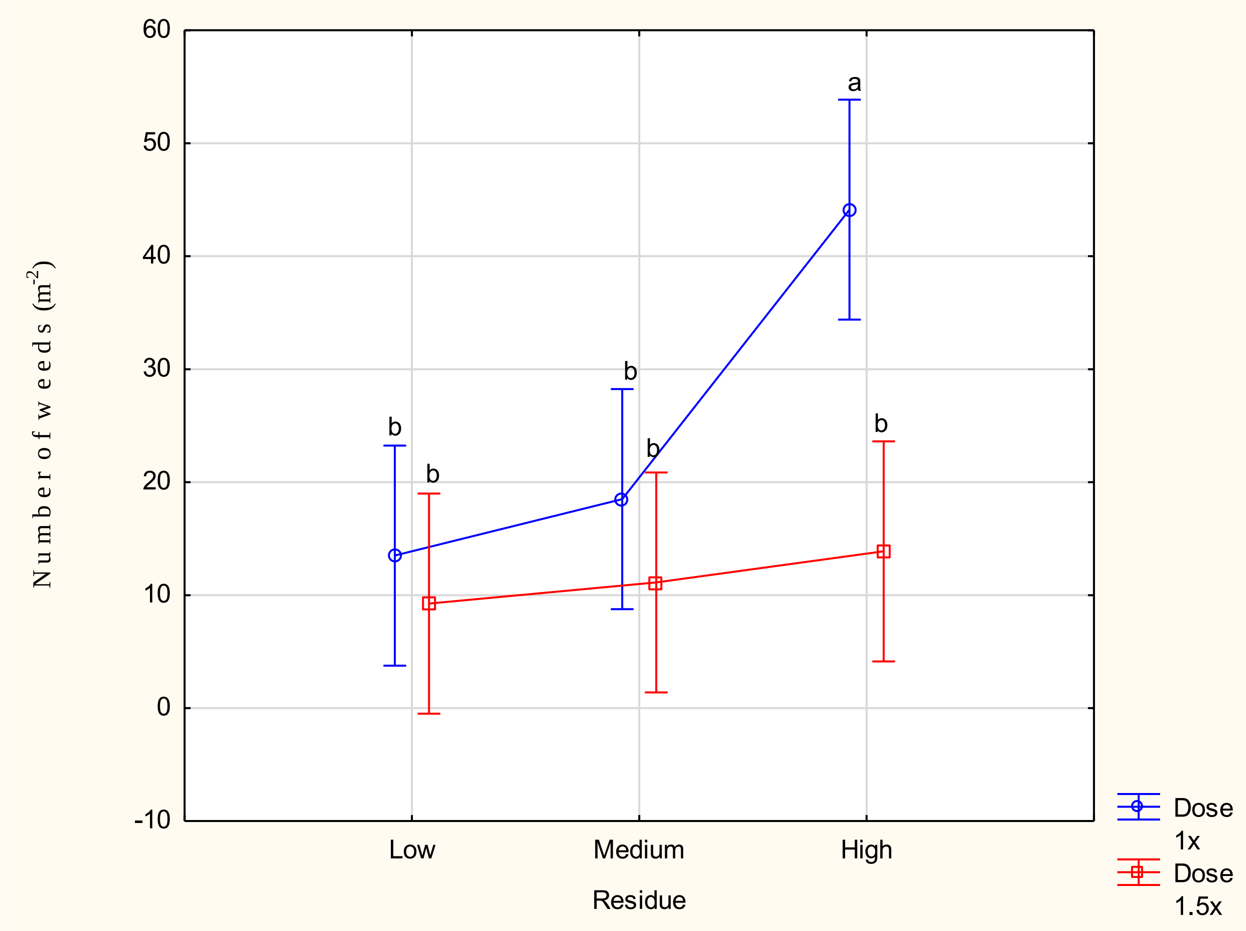

Figure 3. 6: The effect of dosage rate on different parameters in the Tygerhoek trial. Different letters denote means that differed significantly at $p \leq 0.05$ as per Fishers LSD

Table 3.10:The effect of dosage rate on different on number of weeds seven weeks after planting (WAP) in the Tygerhoek trial and kernel mass. Different letters denote means that differed significantly at $p \leq 0.05$ as per Fishers LSD

Site	Dosage rate	Weeds population 7 WAP (m^{-2})	Thousand kernel mass (g)
Tygerhoek	1x	22a	41 a
	1.5 x	4b	43a

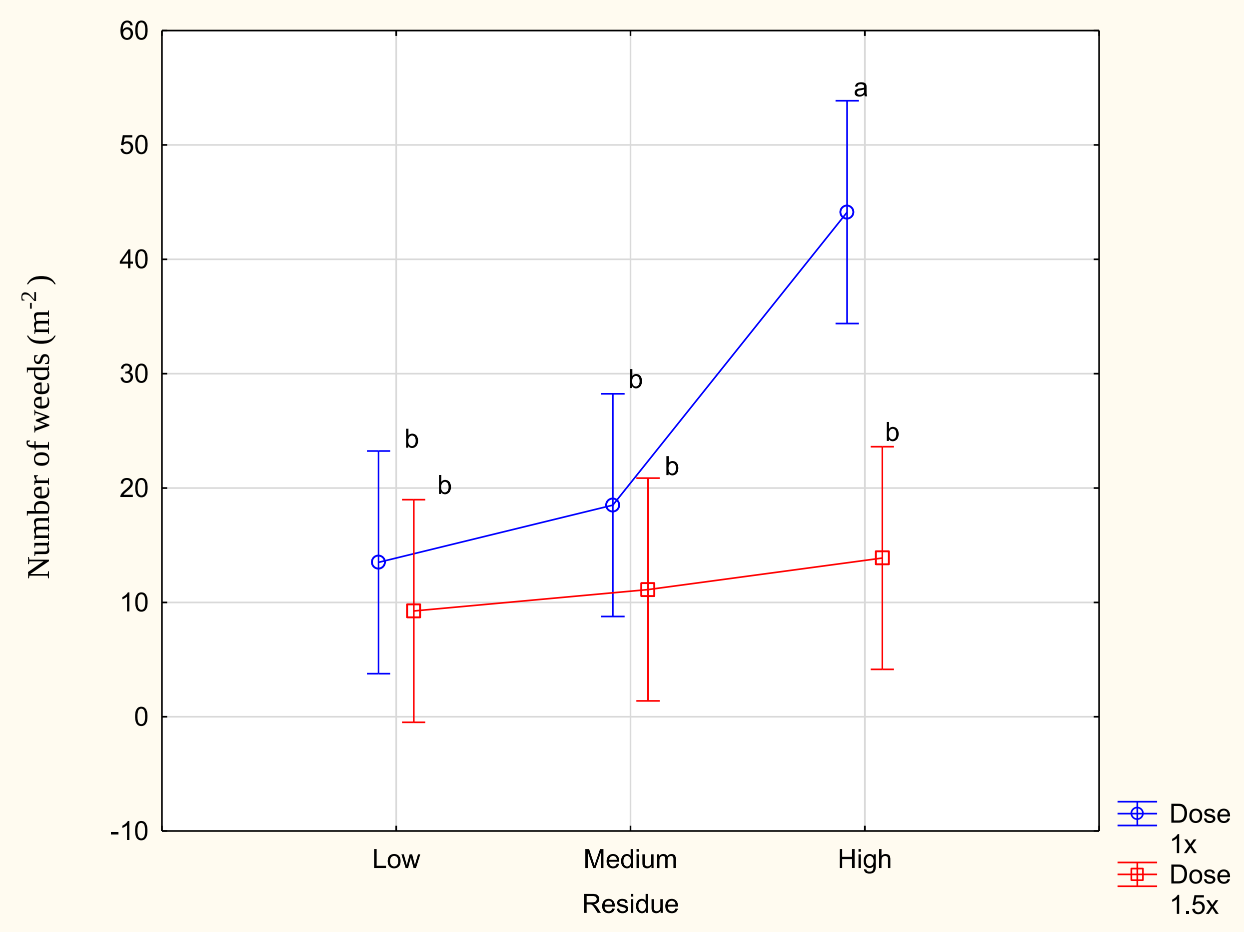

Figure 3.7: The number of weeds at seven weeks after planting at Langgewens, illustrating interaction between dosage rate and residue cover. Different letters denote means which differed significantly at $p \leq 0.05$ as per Fishers LSD. Vertical bars indicate 0.95 confidence intervals.

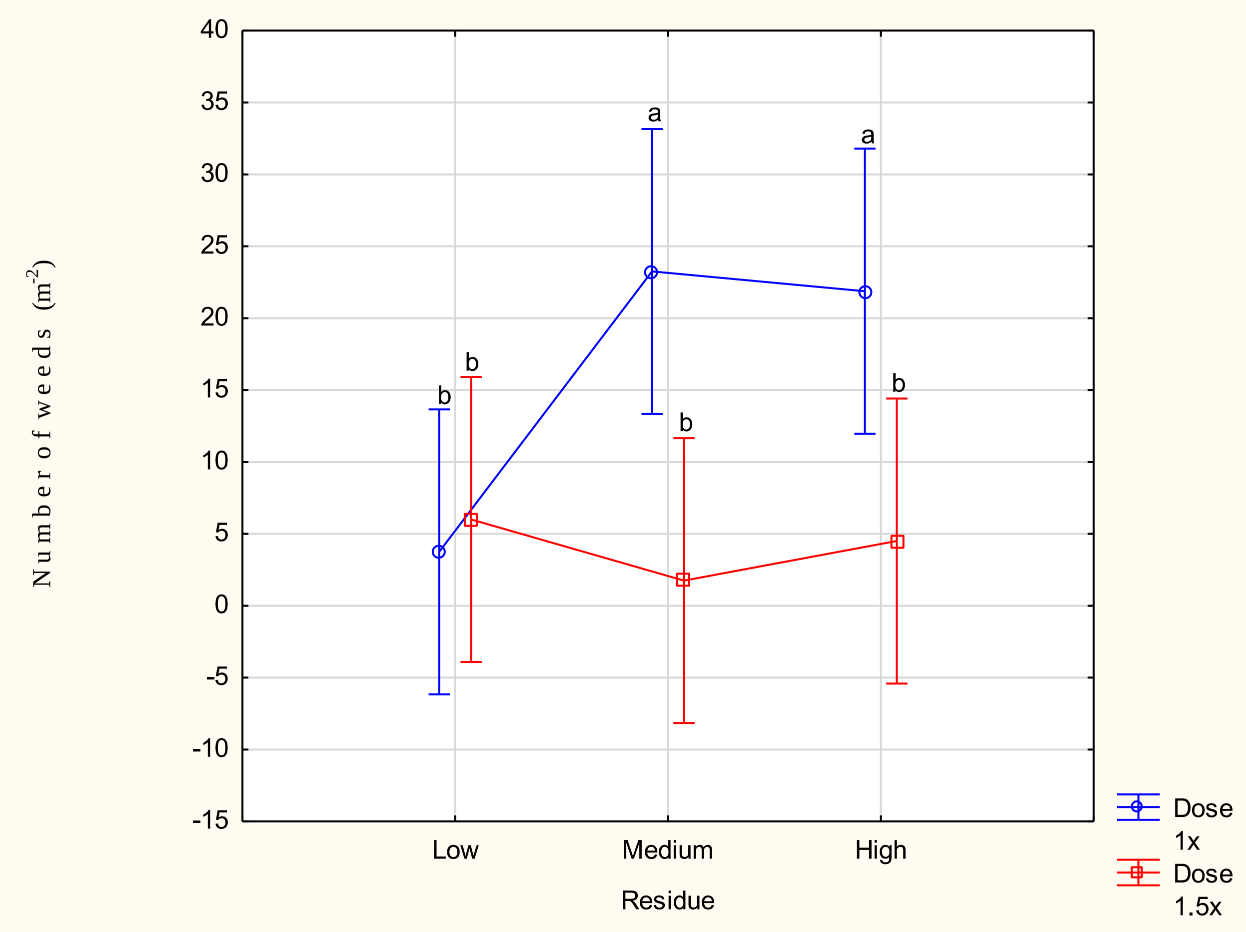

Figure 3.8: The number of weeds at wheat anthesis growth stage at Langgewens, illustrating interaction between dosage rate and residue cover. Different letters denote means which differed significantly at $p \leq 0.05$ as per Fishers LSD. Vertical bars indicate 0.95 confidence intervals.

3. 3.11 Wheat plants population

In terms of wheat numbers, there was no significant interaction between factors (dosage, application rate and residue cover) or significant differences within factors both at 7 WAP and at anthesis at Tygerhoek (**Table 3.8**). At Langgewens, there was significant interaction ($p \leq 0.05$) between dosage rate, application rate and residue cover in wheat numbers 7 WAP (**Table 3.8**). At an application rate of 200 L ha^{-1}, high residue levels significantly reduced the number of wheat plants where the recommended dosage rate of 1x was applied but this was not evident where a dosage rate of 1.5x was applied. At 400 L ha^{-1} application rate the same trend for the 1x dosage rate was visible but the 1.5x dosage rate resulted in unexpected results. In this case the wheat numbers also decreased significantly at the highest residue cover (**Figure 3.9)**.

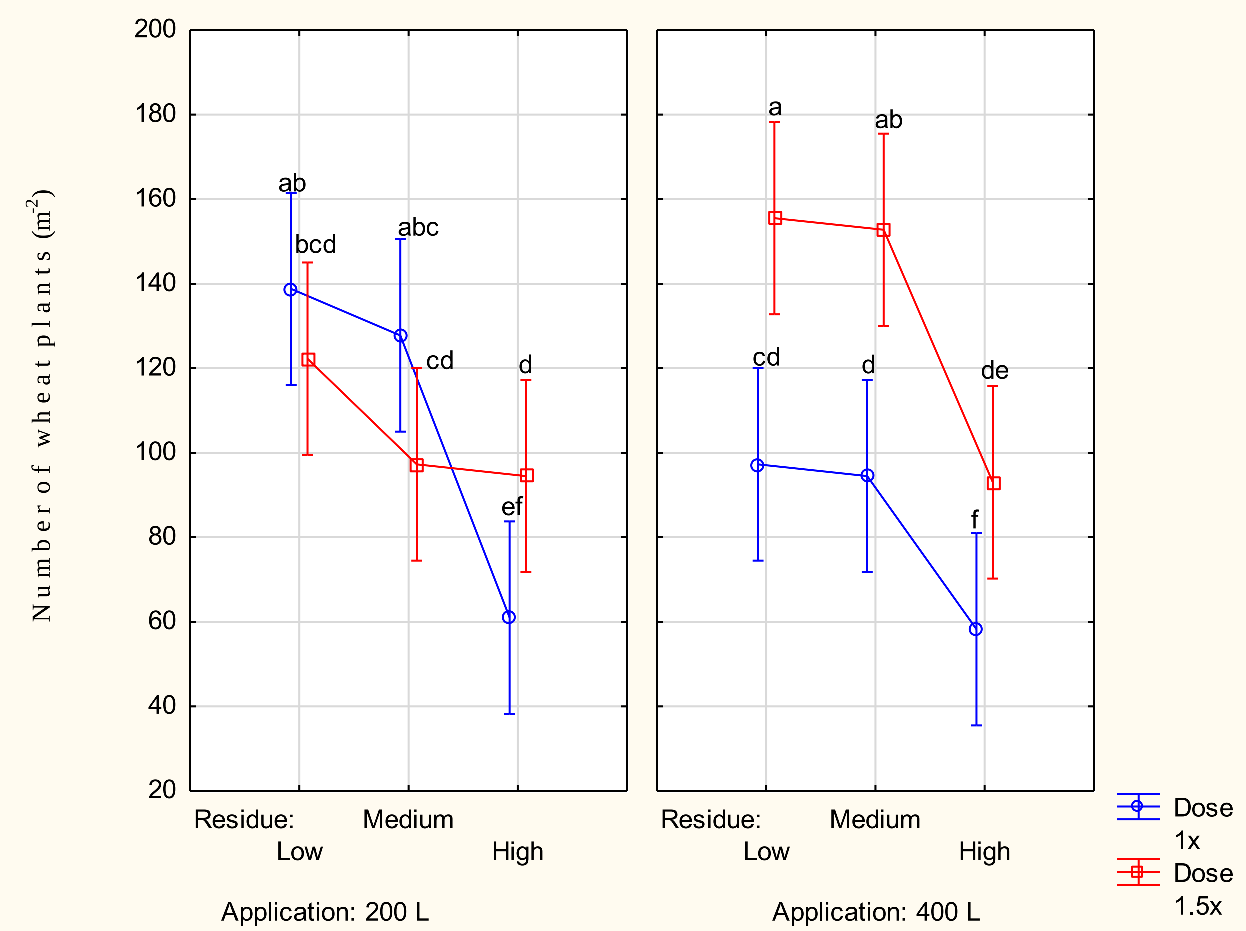

Figure 3.9: The number of wheat plants at 7 WAP at Langgewens, illustrating interaction between application rate, dosage rate and residue cover. Different letters denote means which differed significantly at $p \leq 0.05$ as per Fishers LSD. Vertical bars indicate 0.95 confidence intervals

On the other hand, at anthesis at Langgewens there was significant interaction ($p \leq 0.05$) only between dosage rate and residue cover on the numbers of wheat plants (**Table 3.8**). Again the wheat numbers declined significantly as residue cover increased in the 1x dosage rate (**Figure 3.10**). At the 1.5x dosage rate however, no decrease in wheat numbers occurred but they stayed relatively stable through all the residue cover levels.

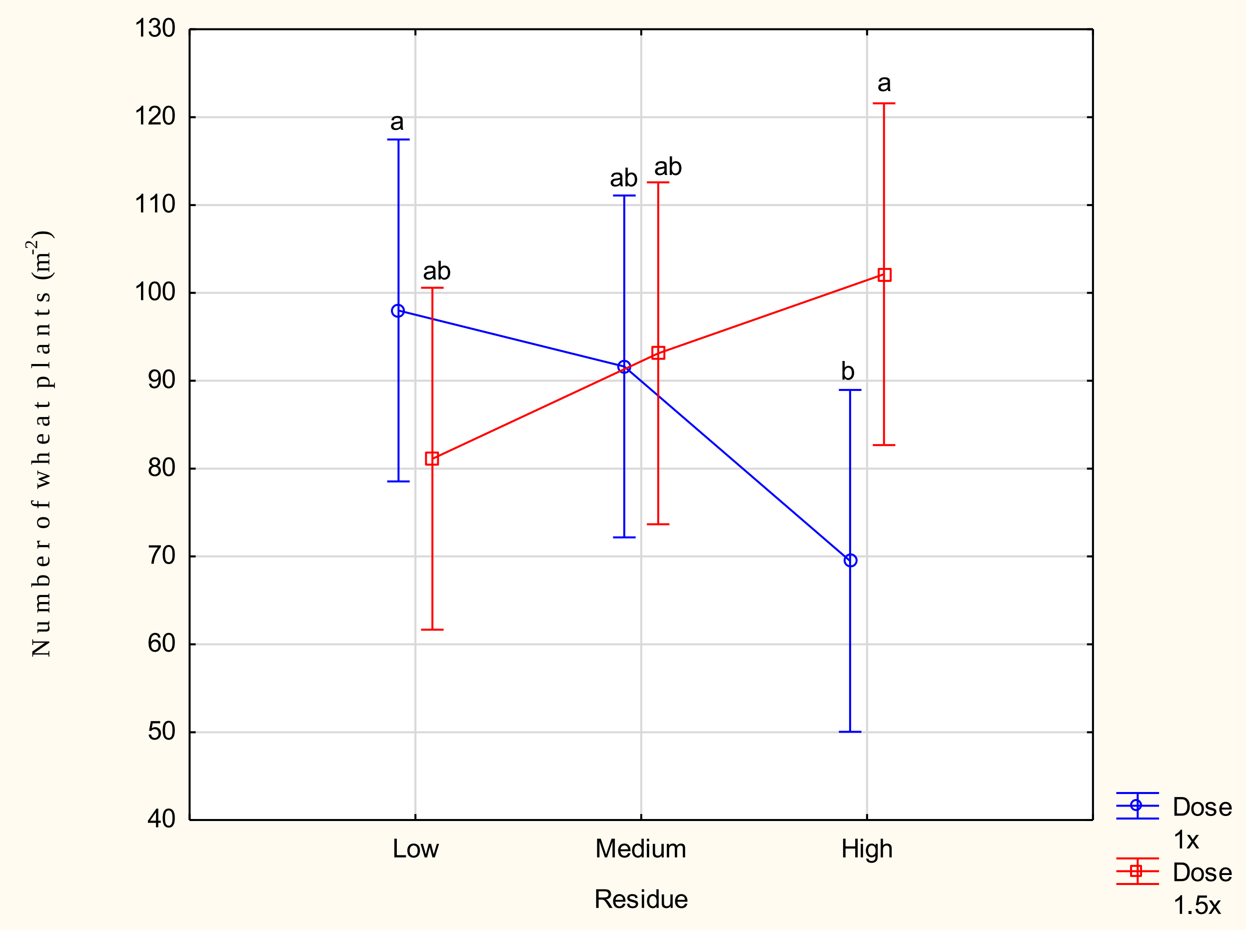

Figure 3.10: The number of wheat plant at wheat anthesis for Langgewens, illustrating interaction between dosage rate and residue cover. Different letters denote means which differed significantly at $p \leq 0.05$ as per Fishers LSD. Vertical bars indicate 0.95 confidence interval.

3. 3.12 Weed biomass

At Tygerhoek, the only significant interaction ($p \leq 0.05$) among factors was observed between herbicide dosage rate and application rate (**Table 3.8**). The weed biomass was significantly higher when the registered dosage rate (Dose 1x) and registered application rate (200 L ha-1) were applied (**Figure 3.11**). When the application rate was doubled (400 L ha-1) while dosage rate kept at registered rate (Dose 1x) there was a significant decline in biomass and that significant reduction of weed dry weight was also evident when the dosage rate was increased by 1.5 (Dose 1.5x) while registered application rate (200 L ha-1) was maintained. There was a further decline of weed dry weight when both dosage rate and application were increased to 1.5x and double, respectively.

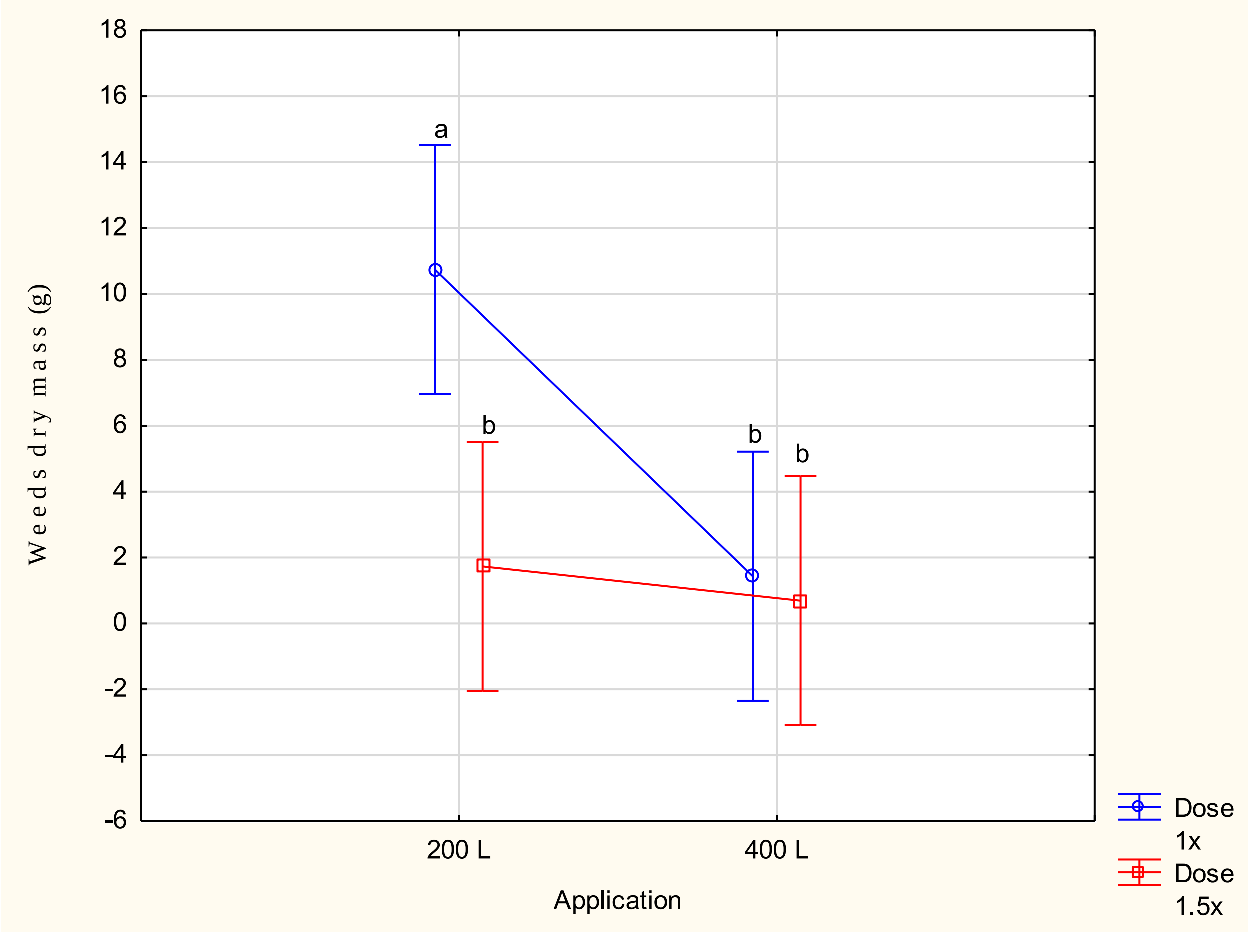

Figure 3.11: The weed biomass for the Tygerhoek trial**,** depicting interaction between dosage rate and application rate**.** Different letters denote means which differed significantly at $p \leq 0.05$ as per Fishers LSD. Vertical bars indicate 0.95 confidence intervals.

At Langgewens the weed biomass displayed no significant interaction between all three factors that were analysed (dosage rate, application and residue cover) (**Table 3.8**).

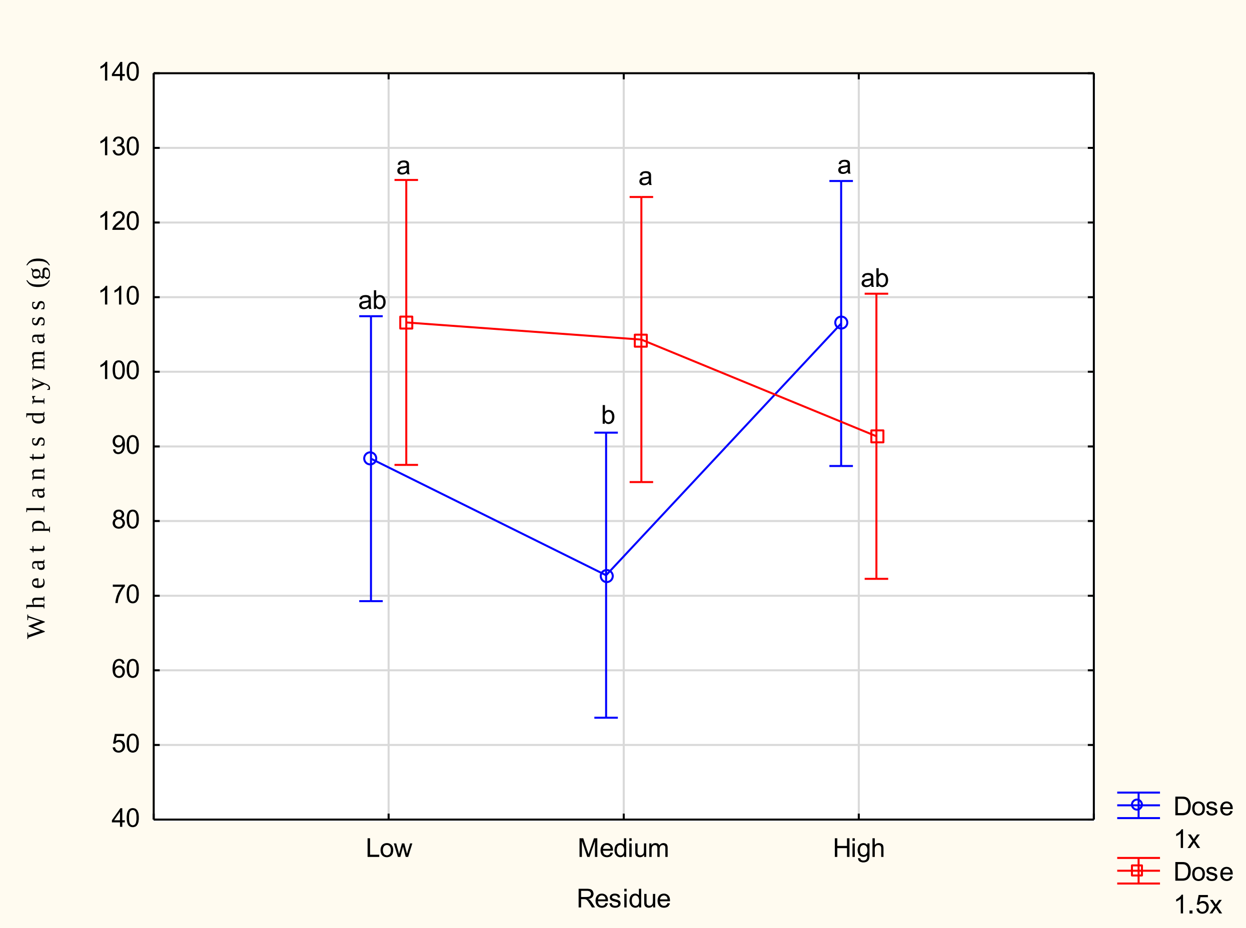

Figure 3.12: The wheat dry mass in the Tygerhoek trial, illustrating interaction between dosage rate and residue cover. Different letters denote means which differed significantly at $p \leq 0.05$ as per Fishers LSD. Vertical bars indicate 0.95 confidence intervals.

3. 3.13 Wheat biomass

For wheat dry weight analysis, significant interaction ($p \leq 0.05$) was only observed between herbicide dosage rate and residue levels at Tygerhoek (**Table 3.8**). Wheat plants produced a higher dry mass at the recommended dosage rate (1x) under high residue levels than under medium residue levels (**Figure 3.12**). At the higher dosage rate of 1.5x there was no significant differences in wheat dry mass production between the different residue levels.

At Langgewens, significant interaction ($p \leq 0.05$) was recorded between dosage rate and application rate (**Table 3.8**). Wheat dry weight produced at the recommended dosage rate (1x) significantly reduced when application rate was doubled from 200 to 400 L ha^{-1} (**Figure 3.13**). At the higher dosage rate of 1.5x however there was no significant differences between wheat dry mass produced at the two different application rates.

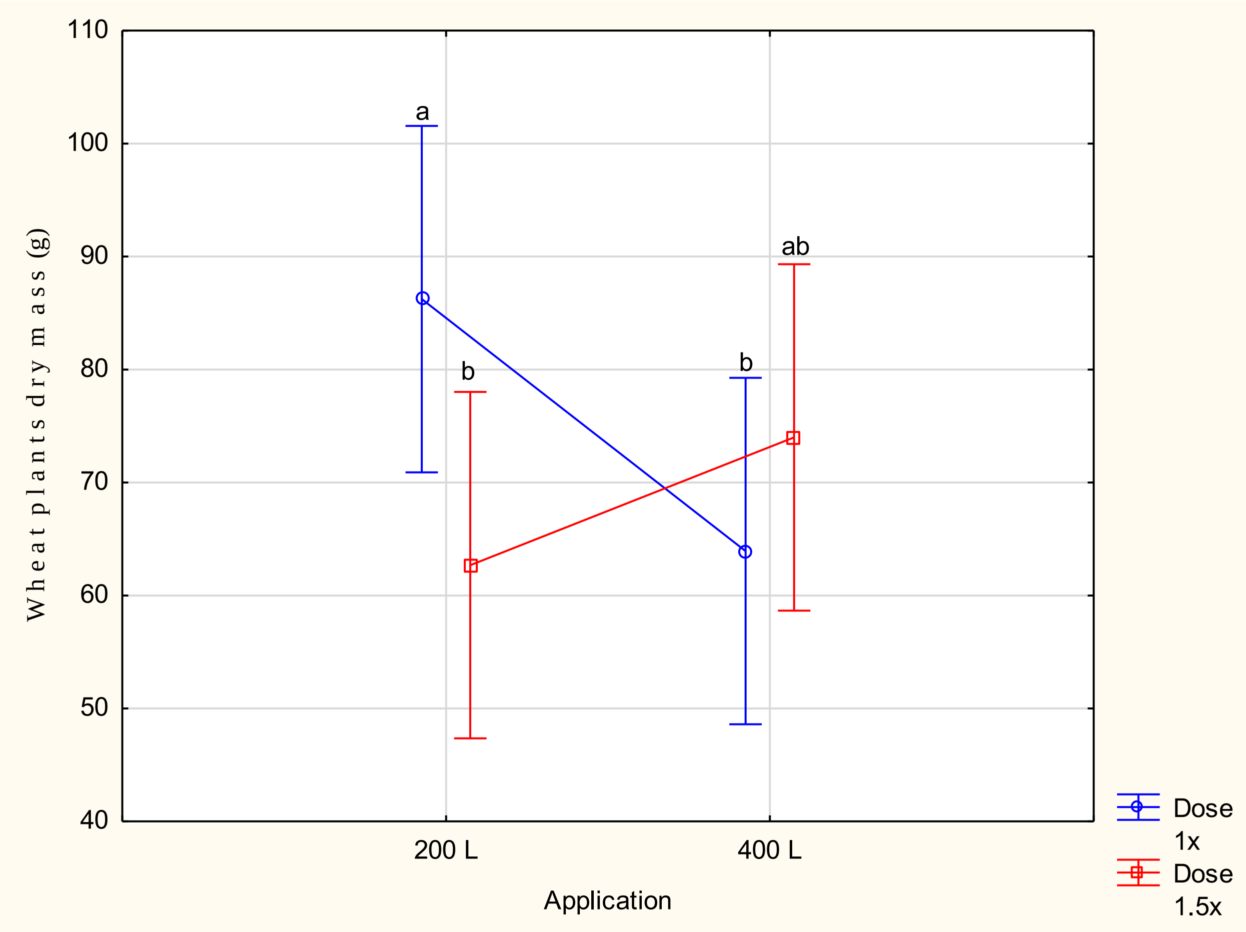

Figure 3.13: The wheat plants dry mass at Langgewens, illustrating interaction between application rate and dosage rate. Different letters denote means which differed significantly at $p \leq 0.05$ as per Fishers LSD. Vertical bars indicate 0.95 confidence intervals.

Table 3.11: Analysis of variance (ANOVA) table on yield components, yield and quality parameters at Langgewens and Tygerhoek.

Factors at Tygerhoek	No. of spikelets (per ear)	No. of kernels (per ear)	Wheat grain yield ($t.\ ha^{-1}$)	Thousand kernel mass (g)	Hectolitre mass ($kg.\ hL^{-1}$)
Dose	*	ns	ns	*	*
Application	ns	ns	ns	ns	ns
Residue	ns	ns	ns	ns	ns
Dose*Application	ns	ns	ns	ns	ns
Dose*Residue	ns	ns	ns	ns	*
Application*Residue	*	ns	ns	ns	ns
Dose*Application*Residue	ns	ns	ns	ns	ns
Factors at Langgewens					
Dose	*	*	ns	*	*
Application	ns	ns	ns	*	ns
Residue	ns	ns	ns	ns	ns
Dose*Application	ns	ns	ns	*	ns
Dose*Residue	ns	ns	ns	ns	ns
Application*Residue	ns	ns	ns	ns	ns
Dose*Application*Residue	ns	ns	ns	ns	ns

*= significant interaction between respective factors ($p \leq 0.05$), ns=no significant interaction between respective factors

3. 3.14 Number of spikelets

At Langgewens there was no interaction between all three factors in terms of number of spikelets per ear, however the dosage rate did have some influence (**Table 3.11**). An increase in dosage rate recorded a slight increase in number of spikelets per ear, but it was not significantly different from the one recorded at recommended dosage rate according to the Fisher LSD test (**Table 3.12**).

However, there was interaction between application rate and residue cover in Tygerhoek (**Table 3.11**). At an application rate of 200 L ha^{-1} there was significantly less spikelets per ear at the medium residue level compared to the low residue level (**Figure 3.14**). At the 400 L ha-1 application rate however there were no significant differences between residue levels in terms of spikelets per ear.

3. 3.15 Number of kernels per ear

At Tygerhoek, there were no significant interactions between factors or significant differences within factors, but at Langgewens, dosage rate did have some effect on the number of kernels per ear (**Table 3.11**) An increase in dosage rate demonstrated significantly higher number of kernels per ear compared to the recommended dosage rate (**Table 3.12**).

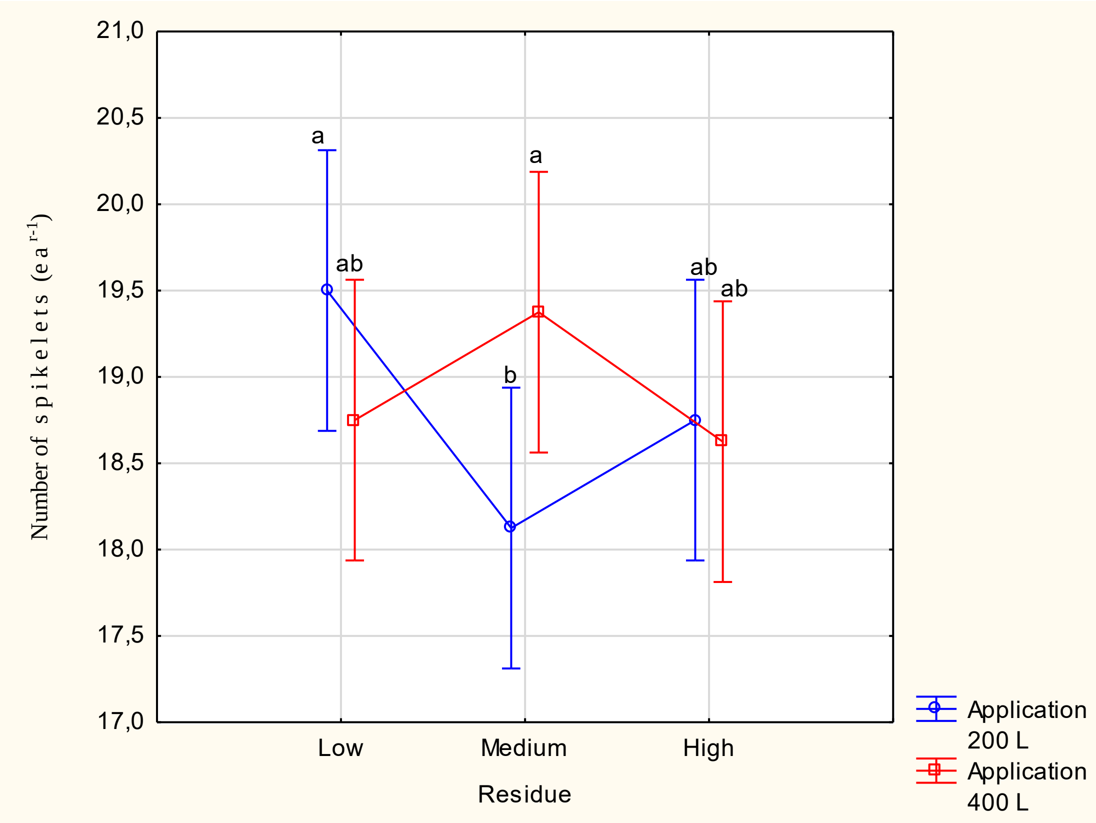

Figure 3.14: The number of spikelets per wheat ear at Tygerhoek, depicting interaction between application rate and residue cover. Different letters denote means which differed significantly at $p \leq 0.05$ as per Fishers LSD. Vertical bars indicate 0.95 confidence intervals.

3. 3.16 Wheat grain yield

At both Tygerhoek and Langgewens there was no significant interaction between factors or significant differences within factors in terms of yield (Results not shown) (**Table 3.11**).

3. 3.17 Thousand kernel mass

At Tygerhoek, there was no significant interaction between the three factors but the dosage rate did have some influence on thousand kernel mass (**Table 3.11**). An increase in dosage rate recorded a slight increase in thousand kernel weight, but it was not significantly different from the one recorded at recommended dosage rate according to Fisher's LSD test (**Table 3.10**).

At the Langgewens trial, 1000 kernel weight analysis demonstrated significant interaction between dosage rate and application rate (**Table 3.11**). At the higher dosage rate of 1.5x, both application rates resulted in a higher 1000 kernel mass compared to the recommended dosage rate (1x) (**Figure 3.15**). At the lower (1x) dosage rate, no significant differences at the different application rates could be ascertained.

Table 3.12: The effect of dosage rate on different parameters in the Langgewens trial. Different letters denote means that differed significantly at $p \leq 0.05$ as per Fishers LSD

Site	Dosage rate	No. of spikelets (per ear)	No of kernels (per ear)	Hectolitre mass (kg. hL^{-1})
Langgewens	1x	18a	52b	72b
	1.5 x	19a	58a	76.5a

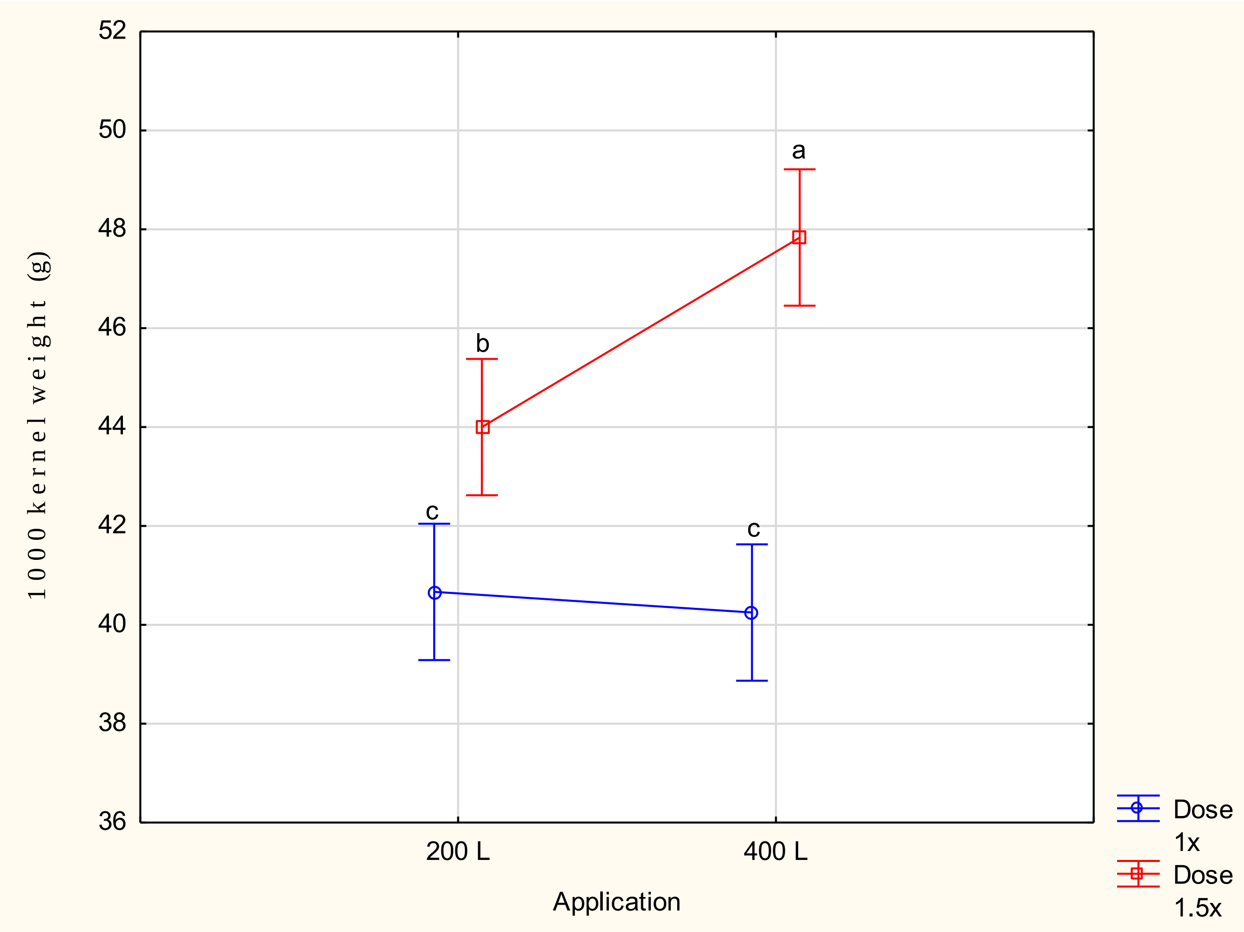

Figure 3.15: The thousand kernel weight at Langgewens, illustrating interaction between application rate and dosage rate. Different letters denote means which differed significantly at $p \leq 0.05$ as per Fishers LSD. Vertical bars indicate 0.95 confidence intervals.

Table 3.13: The hectolitre mass at Tygerhoek, illustrating the effect of dosage rate at different residue cover levels. Different letters denote means that differed significantly at $p \leq 0.05$ as per Fishers LSD.

Dosage	Residue cover	Hectolitre mass (kg. hL-1)
1x	Medium	65.5 c
1x	High	69.7 b
1x	Low	76.5a
1.5x	High	76.9a
1.5x	Medium	77.7a
1.5x	Low	77.8a

3. 3.18 Hectolitre mass

At Langgewens, there was no significant interaction among the three factors, but dosage rate did have some effect on the hectolitre mass (**Table 3.11**). An increase in dosage rate led to a significant increase in hectolitre mass compared to the recommended dosage rate (**Table 3.12**). On the other hand, at Tygerhoek significant interaction was observed between residue cover and dosage rate (**Table 3.11**). At the recommended dosage rate the hectolitre mass differed significantly between residue cover treatments (**Table 3.13**). Conversely, at the higher 1.5x dosage rates no significant differences occurred between the different residue levels.

3.3 DISCUSSION

Application of pyroxasulfone increased wheat yield at Langgewens irrespective of the dosage or application rate. No differences in yield between the four herbicide treatments could be ascertained, even though the higher dosage rates generally resulted in significantly lower weed numbers and biomass compared to the lower dosage rates. Since ryegrass was the dominant weed on Langgewens it is maybe an indication that ryegrass needs large numbers to successfully compete with wheat. In the control treatments the ryegrass numbers were over 60 ryegrass plants per square meter which significantly suppressed wheat numbers and wheat yield. Within the herbicide treatments weed numbers varied between approximately three and 30 plants per square meter and that did not suppress wheat yield significantly. It is inexplicable why wheat yield was not suppressed in the control treatment at Tygerhoek since similar weed numbers occurred in the control treatments there. Tygerhoek received about 47 mm of rain less than Langgewens so competition for moisture should have been fiercer at Tygerhoek (**Tables 3.2,3.1**).

The more detailed analyses of the data excluding the control data revealed similar trends as the first analysis including the control data. Even though there was no significant interaction between factors in some of the variables, in terms of weed numbers there was interaction between residue and dosage rate. That interaction was observed in the Tygerhoek trial, when the registered dosage rate was applied on 0% residue, effectiveness of pyroxasulfone was high. The same trend was also observed both at 7 WAP weeks after planting and at anthesis in the Langgewens trial with pyroxasulfone's registered dosage rate showing good control only at 0% residue cover. Efficacy was subsequently reduced when the registered dosage rate was sprayed on an increased residue cover with 50% (6 t ha^{-1}) and 100% (12 t ha^{-1}) residues resulting in the highest weeds infestation in an ascending order. This is concurring with previous studies where the effectiveness of pre-emergent herbicides applied at the registered dosage rate decrease as the residue cover increases (Khalil 2017). In some instances the increase in residue cover caused a decline in number of weeds where no herbicide was applied which signifies that increasing residue cover has potential to suppress weeds (Khaliq et al. 2011; Brandsæter et al. 2012; Chauhan et al. 2012; Shirtliffe and Johnson 2012).

When registered dosage rate was applied on 50% and 100% residue, the efficacy of pyroxasulfone was reduced, with 100% residue cover resulting in the highest weeds infestation. There is a possibility that even though pyroxasulfone does not bind tightly on organic matter, it still needs at least 5 mm of rainfall for it to be washed off from the residue cover (Khalil 2017). At Tygerhoek only 1.4 mm of rainfall occurred 4 days after spraying, 0.3 mm of rainfall 10 days and another 1.2 mm of rainfall 19 days after spraying (**Table 3.2**). It was only at 26 days after application that 25 mm of rainfall was recorded. Conversely when the registered dosage rate was increased by 1.5 (Dose × 1.5) pyroxasulfone's effectiveness increased across all three residue cover levels (0%, 50%. 100%). At Langgewens the first rain was measured 10 days after spraying (**Table 3.1**) which relates to an even longer dry period after spraying than at Tygerhoek but at least the rains were substantial.

Correspondingly at Langgewens, pyroxasulfone was only effective across all residue cover levels (0 residue cover, 6 t ha^{-1} and 12 t ha^{-1}), when the registered dosage rate was increased by 1.5 times. Generally, increasing the dosage rates of herbicide has a positive impact on the effectiveness of the herbicide because better persistence of the herbicide can be achieved in different environments (Preston 2014). Previous studies also showed that increases in dosage rates of pre-emergent herbicides or soil applied herbicides provided adequate weed control even in an environment where there were increased residue cover (Haskins 2012 ; Chauhan and Abugho 2012).

In terms of wheat dry weight at Tygerhoek, the interaction between dosage rate and residue cover depicted that registered dosage rate sprayed on medium residue cover (50% cover) produced the lowest dry weight. According to Singh et al. (2013) a wheat crop finds it difficult to compete with weeds because weeds have faster growth rates and higher dry-matter accumulation rate compared to wheat. In contrast when a similar dosage rate was applied on high residue cover (100%

cover) it resulted in the highest wheat dry weight with a possible explanation that the increase in residue cover presented an environment that is conducive for vigorous plant growth rate even in the presence of weed infestation. An increase in dosage rate by 1.5 caused an increase in wheat dry weight when it was sprayed across all residue cover levels. At Langgewens the dry weight analysis showed interaction between application rate and dosage rate but the trends displayed makes no sense at all. It is possible that the higher dosage rate might have had phytotoxic effects on the wheat thereby reducing the dry mass production but it does not explain then why it the wheat dry mass increased at 400 L ha^{-1} and why it decreased at 400 L ha^{-1} at the registered dosage rate.

At Langgewens, wheat numbers seven weeks after planting (WAP) demonstrated interaction between residue cover, dosage rate and application rate. When registered dosage rate and application rate was sprayed on the field with no residue cover it recorded the highest number of wheat plants compared to medium residue cover and higher residue cover. Weed infestation and spatial distribution affects the distribution and growth of wheat crops (Patterson 1995). Other studies have proven that wheat crop mortality can occur where there is weed infestations (Stougaard and Xue 2004). On the other hand, 1.5 times the dosage rate at registered application rate resulted in a higher number of wheat plants compared to registered dosage rate and application when both combinations were sprayed on a high residue cover. The 1.5 times dosage rate and doubled application rate combination resulted in higher wheat numbers when it was sprayed across all three levels of residue covers compared to registered dosage rate and application rate combination. Generally, the wheat numbers decreased when the residue levels increased. This could be a result of high residue levels hampering the establishment of wheat seedlings (Wuest et al. 2000).

It is surprising that wheat yield yield was not influenced by any of the factors at any of the localities. The low weed numbers and high wheat numbers at low residue covers should have resulted in higher wheat yields (Arshad et al. 1994, Ali et al. 2008). However, the negative effect of the higher numbers of weed plants at higher residue levels could have been counteracted by the better microclimate conditions under the higher residue levels.

The interaction between dosage and application rate when 1000 kernel weight was analysed, showed that the lowest values were attained at both registered application and dosage rate with the possibility of weeds affecting the size of wheat grains. In previous studies it has been proven that the presence of weeds can lead to the reduction of quality parameters such as wheat thousand kernel weight and grain yield (El-Metwally et al. 2015, Khan et al 2003) An increase in dosage rate by 1.5 demonstrated an increase in 1000 kernel weight. Likewise, the combination of 1.5 times dosage rate and doubled application rate recorded the highest 1000 kernel weight. Even an increase in dosage rate with recommended application rate (200 L ha^{-1}), resulted in increased thousand kernel weight.

Overall the highest thousand kernel weight was recorded where both dosage rate and application rate were increased.

3. 4 CONCLUSION

Pyroxasulfone's registered dosage rate (125 g ha^{-1}) and recommended application rate (200 L ha^{-1}) demonstrated poor weed control when it was sprayed on increased amounts of residue cover. Increasing the dosage rate from 125 g ha^{-1} to 187.5 g ha^{-1} improved the efficacy of pyroxasulfone, across all residue covers. The doubling of recommended application rate to 400 L ha-[1] improved the efficacy when it was applied on an increased residue cover in some limited instances but overall it was the increase in registered dosage rate that consistently improved pyroxasulfone's efficacy across all levels of residue covers. More importantly, increased pyroxasulfone dosage rates did not negatively influence the growth and yield of wheat.

REFERENCES

Ali M, Zand E, Soufizadeh S, Beheshtian M. 2008. Study on the efficacy of weed control in wheat (*Triticum aestivum* L.) with tank mixtures of grass herbicides with broadleaved herbicides. *Crop Protection* 27:104–111.

Arshad MA, Gill KS, Coy GR . 1994. Wheat yield and weed population as influenced by three tillage systems on a clay soil in temperate continental climate. *Soil Till age Res* 28:227–238.

Brandsæter LO, Goul Thomsen M, Wærnhus K, Fykse H . 2012. Effects of repeated clover undersowing in spring cereals and stubble treatments in autumn on Elymus repens, Sonchus arvensis and Cirsium arvense. *Crop Protectio*n 32:104–110.

Chauhan BS, Abugho SB . 2012. Interaction of rice residue and pre-herbicides on emergence and biomass of four weed species. *Weed Technol* 26: 627–632.

Chauhan BS, Singh RG, Mahajan G . 2012. Ecology and management of weeds under conservation agriculture: A review. *Crop Protection* 38:57–65.

Cook A, Bates A, Shepperd W, Richter I .2016. Herbicide efficacy in retained stubble systems https://grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-updatepapers/2016/08/herbicide-efficact-in-retained-stubble-systems. Accessed on 2017/11/02.

Dickey EC, Jasa PJ, Shelton DP. 1986. Estimating residue cover.

https://digitalcommons.unl.edu/cgi/viewcontent.cgi?article=1256&context=biosysengfacpub.Accessed 2016/05/10

El- l-Metwally IM, Abdelraouf RE, Ahmed MA, Mounzer O, Alarcon JJ, Abdelhamid MT. 2015. Response of wheat (*Triticum aestivum L.*) crop and broad-leaved weed to different water requirements and weed management in sandy soils. *Agriculture* 61(1): 22-32.

Farooq M, Flower KC, Jabran K, Wahid A, Siddique KHM. 2011. Crop yield and weed management in rainfed conservation agriculture. *Soil and Tillage Research* 117:172-183.

Haskins B. 2012. Herbicides in conservation farming systems using pre-emergent : Top tips for using pre-emergent herbicides.
http://www.dpi.nsw.gov.au/agriculture/farm/conservation/information/pre-emergent-herbicide.
Accessed on 2017/010 /27.

Khalil Y. 2017. Herbicides and stubble – some wash off, some don't. https://ahri.uwa.edu.au/herbicides-and-stubble-some-wash-off-some-dont/.Accessed 2018/12/3

Khaliq A, Matloob A, Farooq M, Mushtaq MN. 2011. Effect of crop residues applied isolated or in combination on the germination and seedling growth of horse purslane (*Trianthema portulacastrum*). *Planta Daninha* 29(1):121-128

Khan MH, Hassan G, Khan N, Khan M. 2003. Efficacy of different herbicides for controlling broadleaf weeds in wheat. *Asian J PLant Sc*i 2:254–256.

Patterson DT. 1995. Effects of environmental stress on weed / crop interactions. *Weed Science* 43:483–490.

Preston C. 2014. Understanding pre emergent cereal herbicides. https://grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2014/03/understanding-pre-emergent-cereal-herbicides.Accessed on 2018/11/20.

Shirtliffe SJ, Johnson EN. 2012. Progress towards no-till organic weed control in western Canada. *Renew Agric Food Syst* 27:60–67.

Singh V, Singh H, Raghubanshi AS . 2013. Competitive interactions of wheat with Phalaris minor or Rumex dentatus: A replacement series study. *Int J Pest Manag* 59:245–258.

Stougaard RN, Xue Q . 2004. Spring wheat seed size and seeding rate effects on yield loss due to wild oat (*Avena fatua*) interference. *Weed Science* 52:133–141

Wollenhaupt NC, Pingry J.1991. Estimating residue using line-transect.
https://learningstore.uwex.edu/Assets/pdfs/A3533.pdf. Accessed 2016/05/10

Wuest SB, Albrecht SL, Skirvin KW. 2000. Crop residue position and interference with wheat seedling development. *Soil and Tillage Research* 55:175–182

CHAPTER 4

THE EFFECTIVENESS OF RYEGRASS CONTROL WITH VARYING PYROXASULFONE APPLICATION AND DOSAGE RATES UNDER VARYING RESIDUE COVER LEVELS IN A GLASSHOUSE ENVIRONMENT

ABSTRACT

A glasshouse pot experiment was conducted at Welgevallen Experimental Farm, Stellenbosch in 2017. Approximately fifty seeds of ryegrass and five wheat seeds were directly sown in plastic pots filled with field soil; with an area of 188.6 cm^2 each. After sowing, dried wheat residue cover was manipulated into five different treatments, viz. 100% (11.3 $g.cm^{-2}$ equal to 6 t. ha^{-1}), 75% (8.5 g.-cm^{-2} equal to 4.5 $t.ha^{-1}$), 50% (5.7 $g.cm^{-2}$ equal to 3 $t.ha^{-1}$), 25% (2.8 $g.cm^{-2}$ equal to 1.5 $t.ha^{-1}$) and 0% (with no residue cover). A pre-emergent herbicide (pyroxasulfone – Sakura®) was applied at dosage rate/application rate combinations of 125 g ha^{-1}/200 L ha^{-1}(the recommended rates), 125 g ha^{-1}/400 L ha^{-1}, 187.5 g ha^{-1}/200 L ha^{-1}, 187.5 g ha^{-1}/400 L ha^{-1} and control with no herbicide. After the herbicide was applied, 5 mm of clean water was applied to each pot by means of herbicide sprayer to wash off the herbicide from the residue cover. Ryegrass counts was made at seven weeks after planting (WAP). At harvesting; wheat dry mass, ryegrass dry mass and yield were determined. High = 6 t ha^{-1} residue cover levels reduced the efficacy of pyroxasulfone. Increasing the dosage rate of pyroxasulfone to 187.5 g ha^{-1} however improved the ryegrass control. Increasing the application rate to double the application rate (400 L ha^{-1}) did not significantly improve efficacy of pyroxasulfone.

Keywords

Application rate, conservation agriculture, residue cover, pre-emergent herbicides, pyroxasulfone dosage rate,.

4.1. INTRODUCTION

There have been a growing concern about the negative effect of intensive tillage on soil productivity and wider environmental implications and there is a need to reduce intensive tillage

(Knowler and Bradshaw 2007). On the other hand, for many years tillage has been used as one of the means for weed control and any possible change in tillage system will have significant impact on the composition of weed communities - that is why it is imperative to study any phenomenon that may affect weed control in conservation agriculture (Arshad et al. 1994). According D'Emden et al. (2008) the removal of tillage as one of the measures to control weeds populations results in a greater dependence on chemical weed control and that present possible risks of herbicide resistance.

According to Arshad et al. (1994), a high level of crop residues is one of the phenomena that leads to poor performance of conservation agriculture. The effectiveness of weed control in residue retained cropping systems such as conservation agriculture, can be compromised when the residue intercepts the herbicide and prevent it from reaching the desired target, or the herbicide is tightly bound to organic matter or residue (Cook et al. 2016). Some weed species can escape the application of pre-emergent herbicides in conservation agriculture systems in which increased residue levels can result in lower efficacy (Chauhan and Abugho, 2012). According to Khalil et al. (2018) decayed and aged crop residue increase the interception of pre-emergent herbicides because compounds such as cellulose decompose, leaving the more recalcitrant lignin, which has been associated with the retention of herbicides. Although crop retention has both positive and negative effects, efforts must be employed to enhance positive effects over the negative ones (Farooq et al. 2011).

These problems occur during a period where the prevalence of post-emergent herbicide resistance is on an increase and pre-emergent herbicides are becoming more important alternatives for weed control (Preston 2014). However, the challenge is that pre-emergent herbicides have several factors that can affect their efficacy compared to post-emergent herbicides (Preston 2014).

According to Cook et al. (2016) different types of pre-emergent herbicides differ on the degree of binding to residue cover or organic matter and it depends on the herbicide's composition. Beside the fact that the herbicide binds tightly or loosely on the residue cover, there are other factors that may influence the efficacy of pre-emergent herbicides (Cook et al. 2016). These factors that affect pre-emergent herbicides includes chemical considerations such as; the herbicide is prone to volatility, some are sensitive to sunlight degradation (photo degradation), herbicides water solubility and prevailing environmental conditions at the time of application, namely; rainfall, soil moisture levels, temperature levels during time of application and just after application (Haskins 2012). It is therefore important to ensure where there is an increase in residue that the required dosage of pre-emergent herbicides reaches the soil surface for effective weed control to be realised in an environment where there is retention of residue cover.

The aim of this study was to determine the most efficient dosage rate and application rate of pyroxasulfone that can be utilised on an increased residue cover for effective ryegrass control. Therefore, the objectives that form the basis of this study are as follows; (i) to assess the effectiveness of ryegrass control, (ii) to determine vegetative growth parameters of wheat and (iii) to determine wheat grain yield with increased pyroxasulfone application and dosage rates when applied on increased levels of residue cover.

The null hypothesis (H_0) of this study was then that, increasing pyroxasulfone's application and dosage rates when applied to increased amounts of residue cover will not increase the efficacy of the herbicide.

4.2. MATERIALS AND METHOD

4.2.1. Experimental Site

The experiment was carried out in 2017 in the Western Cape Province of South Africa, Stellenbosch University's Welgevallen experimental farm in a glasshouse. The site is located at 33° 56´33" S and 18° 51´56" E at an altitude of 136 m above sea level. The temperature in the glasshouse ranged from 15 ºC at night to 25 ºC during the day.

4.2.2. Treatments and experimental design

Fifty seeds of ryegrass and 5 wheat seeds were sown directly into plastic the pots with a surface area of 188.6 cm^2 each. The pots contained about 3 kg of soil obtained from a field on the Welgevallen Experimental Farm. After sowing, dried wheat residue cover was manipulated in five different residue cover treatments, using the field ratio that was obtained through a transect method , viz. 100% (11.3 $g.cm^{-2}$ or 6 t. ha^{-1}), 75% (8.5 $g.\text{-}cm^{-2}$ or 4.5 $t.ha^{-1}$), 50% (5,7 $g.cm^{-2}$ or 3 $t.ha^{-1}$), 25% (2.8 $g.cm^{-2}$ or 1.5 $t.ha^{-1}$) and 0% (with no residue cover) cover (**Figure 4.2**). The pre-emergent herbicide pyroxasulfone – (Sakura®) was applied in the pots at three different dosage rates, two different application rates (water applied per hectare) and a control treatment as described in **Table 4.1**. After applying herbicides each pot was immediately treated with the equivalent of 5 mm of rain to wash the herbicide off the residue cover, using the laboratory spraying cabinet (**Figure 4.1).**

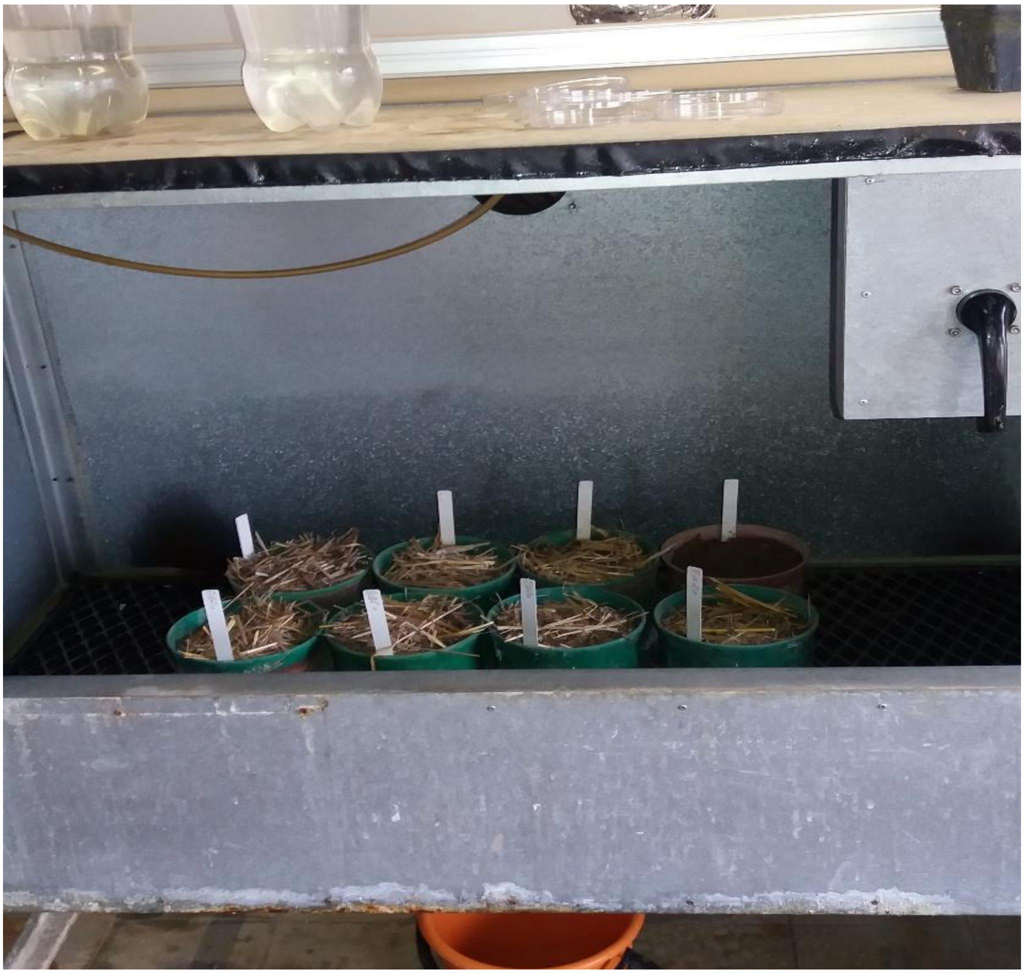

Figure 4. 1: The laboratory spraying cabinet used to apply simulated rainfall as well as the herbicide treatments.

Table 4. 1: Dosage rate and application rate combinations of pyroxasulfone applied to the pots containing wheat and ryegrass

Treatment number	Herbicide	Dosage Rate (g ha^{-1})	Application Rate (L ha^{-1})
1	Pyroxasulfone	125	200
2	Pyroxasulfone	125	400
3	Pyroxasulfone	187.5	200
4	Pyroxasulfone	187.5	400
5	Pyroxasulfone	0 (No herbicide)	200
6	Pyroxasulfone	0 (No herbicide)	400

The experimental layout was arranged in a randomized block design arranged as a 5x3x2 factorial replicated four times, inclusive of one control (0x dosage rate). The experiment consisted of the following factors: five residue covers (0%, 25%,50% 75%, 100%), three pyroxasulfone dosage rates (zero (control), recommended registered dosage rate (1x – 125 g ha^{-1}) and 1.5 times the recommended dosage rate (1.5x – 187.5 g ha^{-1})) and two herbicide application rates (recommended registered application rate (200 L ha^{-1}) and double the recommended application rate (400 L ha^{-1}).

(a) 

 (b)

(c) 

 **(d)**

(e) 

Figure 4. 2: Different levels of residue cover treatments, (a) 0%, (b) 25 %, (c) 50%, (d),75%, and (e)100% in the pot trial evaluating the effect of different pyroxasulfone dosage and application rates on wheat and ryegrass.

4.2.3. Planting

Fifty seeds of a commercial ryegrass cultivar (*Lolium multiforum* cv. Energa) and five wheat seeds (cv. SST027) were directly sown into the pots with an area of 188.6 cm^2 each.

4.2.4. Plant management

For nutritional requirements, 00.2 g cm^{-2} of LAN per pot was applied during different stages as per standard practices. Irrigation was done by a self-regulating system which ensured moisture requirements were maintained at optimum level.

4.2.5. Data collection

i. Ryegrass

Seven weeks after planting a once off ryegrass count was conducted because of the controlled environment of the pot system as compared to field experiments where more than one count is usually necessary. The number of ryegrass plants per pot was converted to plant population m^{-2}.

ii. Vegetative growth parameters

At wheat physiological maturity, the wheat and ryegrass plants were harvested by means of cutting the stems at the soil surface, after that wheat plants and weeds were put into an oven and dried at 60 ºC for 72 hours. The dried wheat and ryegrass plants were then weighed on an electronic scale balance to determine dry mass for each.

iii. Wheat grain yield

After harvesting yield was then determined for each treatment by weighing the wheat grains on an electronic scale balance.

No quality analyses were carried out on the wheat seed due to very small amounts of grain produced per pot.

4.2.6. Statistical analysis

The STATISCA 12 program was used to conduct analysis of variance. Means of significance and interactions were separated using Fisher’s least significance (LSD) test at 5% level of significance. Three-way ANOVA was used to analyse possible interaction of the three factors (residue cover, dosage rate and application). Where the Levene’s test showed severe non-homogeneity of variances, the Games-Howell multiple comparisons procedure was used instead of the LSD intervals

4.3. RESULTS

4.3.1. Ryegrass population

There was significant interaction between residue cover and dosage rate on the number of ryegrass plants, 7 weeks after planting (WAP) ($p \leq 0.05$) (**Table 4.2**). The recommended pyroxasulfone dosage rate (1x) and increased dosage (1.5 x) both resulted in significantly lower number of ryegrass plants compared to the control (0x). There were no significant differences in the number of ryegrass plants between the recommended dosage rate (1x) and increased dosage rate (1.5 x) across all residue cover levels, except at the 100% residue level, where the increased dosage rate resulted in a significantly lower number of ryegrass plants compared to the recommended dosage rate (**Figure 4.3**).

Table 4. 2: Analysis of variance (ANOVA) table of parameters measured in a pot experiment investigating the effect of different pyroxasulfone application and dosage rates under different residue cover levels

Factors	Ryegrass population (m^{-2})	Ryegrass biomass (g)	Wheat biomass (g)	Wheat grain yield ($t\ ha^{-1}$)
Dose	*	*	*	*
Application	ns	ns	ns	ns
Residue	*	*	ns	ns
Dose*Application	ns	*	ns	ns
Dose*Residue	*	*	ns	ns
Application*Residue	ns	*	ns	ns
Dose*Application*Residue	ns	ns	ns	ns

*= denotes significant interaction between respective factors ($p \leq 0.05$), ns= denotes no significant interaction between respective factors

)

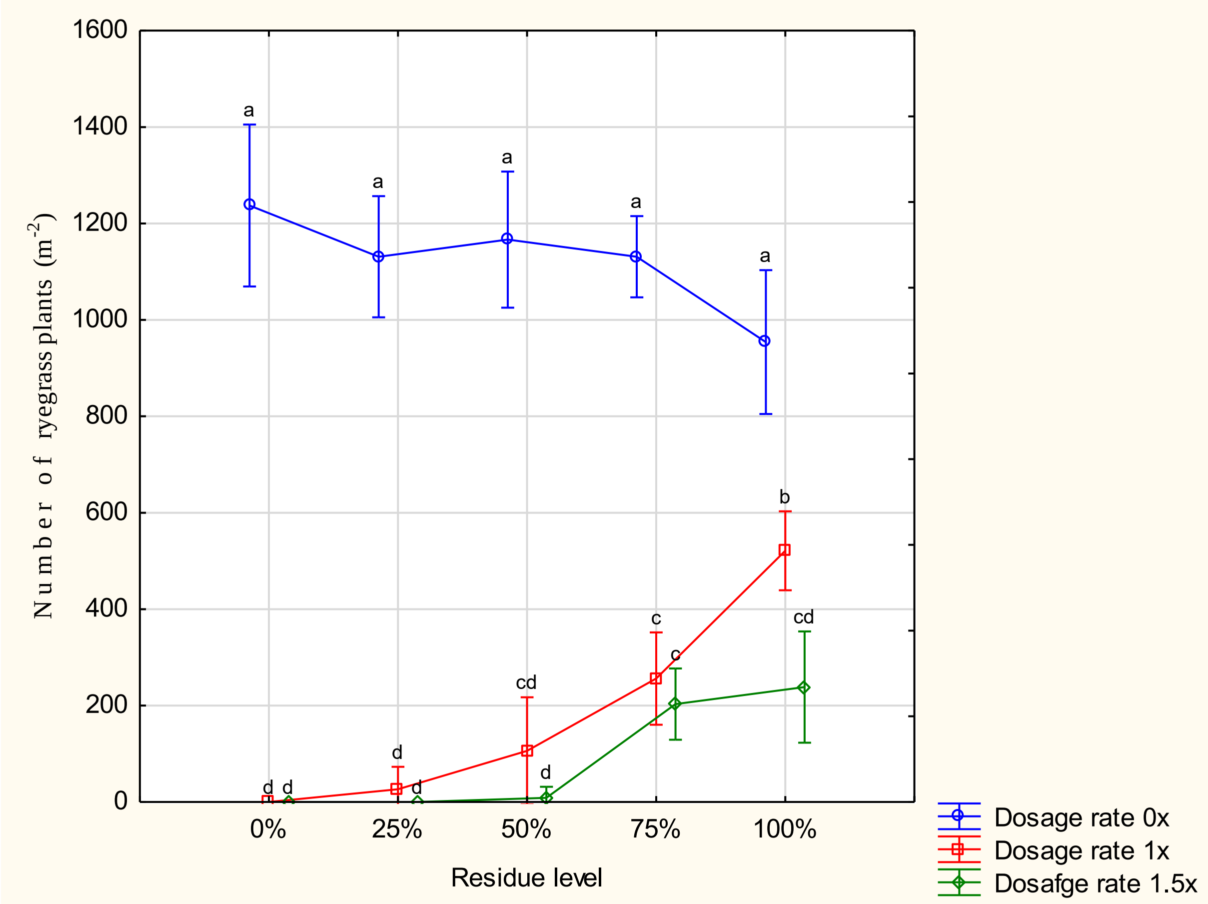

Figure 4. 3: Population of ryegrass recorded seven WAP illustrating the interaction between residue cover and dosage rate in a pot experiment investigating the effect of different pyroxasulfone application and dosage rates under different residue cover levels. Different letters denote means that differed significantly at $p \leq 0.05$ as per Fishers LSD. Vertical bars indicate 0.95 confidence intervals.

4.3.2. Ryegrass biomass

There were significant two-way interactions between dosage rate and residue cover, application rate and residue cover and dosage rate and application rate in terms of ryegrass dry mass ($p \leq 0.05$) (**Table 4.2**). In terms of interaction between dosage rate and residue cover, trends were similar to the ryegrass plant numbers parameter (**Figures 4.3, 4.4**). However, no significant differences were observed between recommended dosage rates and increased dosage rates across all residue covers. The control treatment generally resulted in significantly higher ryegrass dry mass production (**Figure 4.4**).

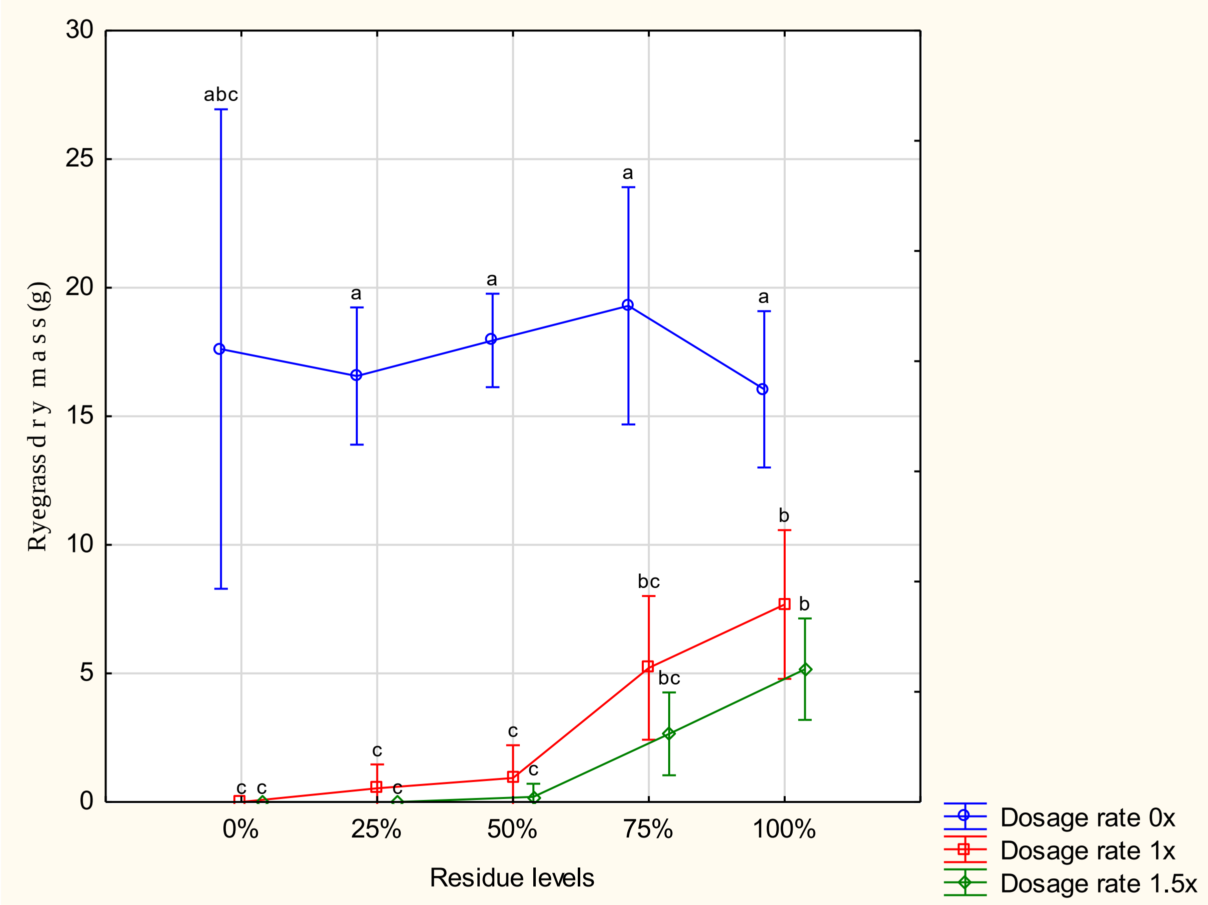

Figure 4. 4: Ryegrass dry mass recorded after harvesting illustrating the interaction between residue cover and dosage rate in a pot experiment investigating the effect of different pyroxasulfone application and dosage rates under different residue cover levels. Different letters denote means that differed significantly at $p \leq 0.05$ as per Fishers LSD. Vertical bars indicate 0.95 confidence intervals.

In terms of application rate and residue cover, the only significant differences between the two application rates were at the 0% and 100% residue levels (**Figure 4.5**)

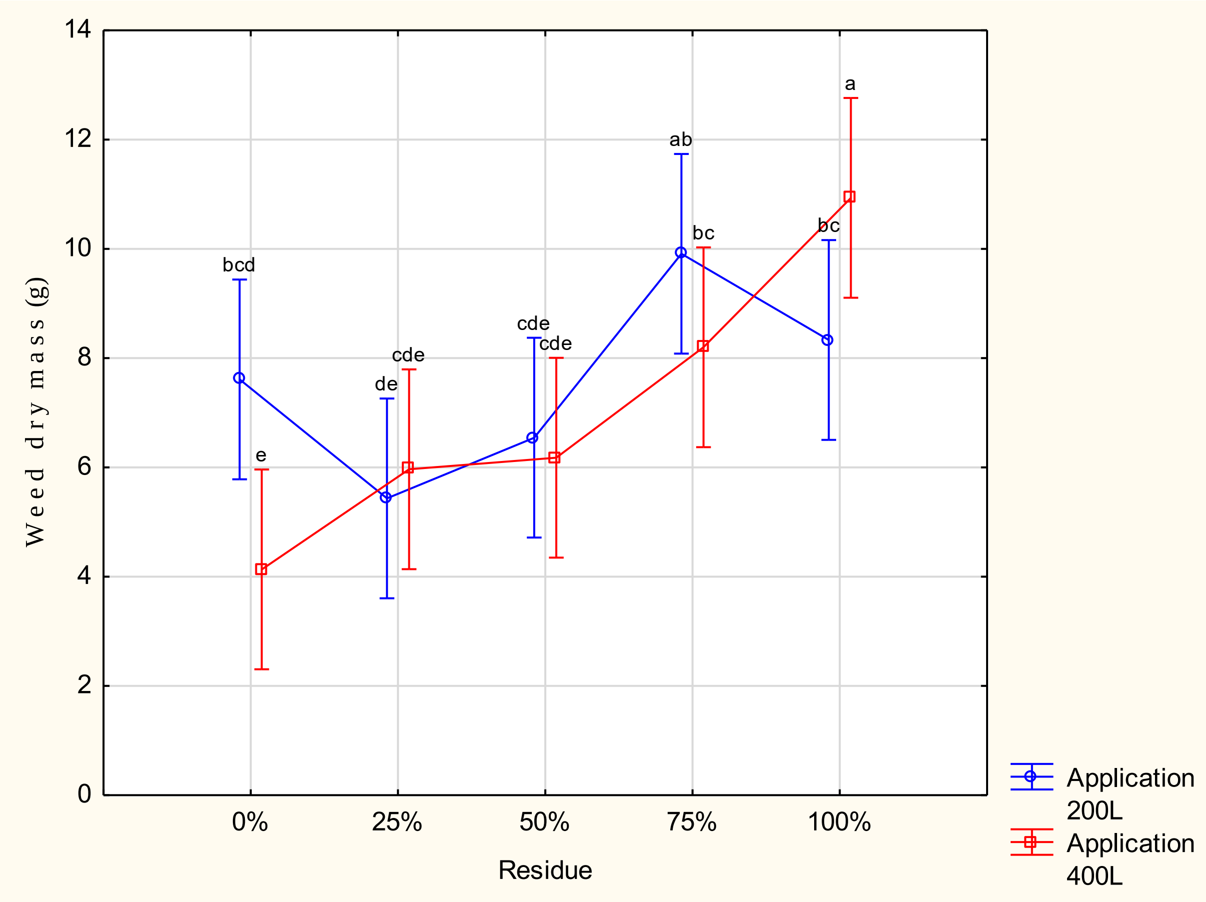

Figure 4. 5: Ryegrass dry mass recorded at harvesting illustrating the interaction between residue and application rate in a pot experiment investigating the effect of different pyroxasulfone application and dosage rates under different residue cover levels. Different letters denote means that differed significantly at p ≤ 0.05 as per Fishers LSD. Vertical bars indicate 0.95 confidence intervals.

In terms of dosage rate and application, there were no significant differences between the two application rates except at the control dosage rate where the doubled application rate resulted in significantly lower ryegrass dry mass compared to the recommended application rate (**Figure 4.6**).

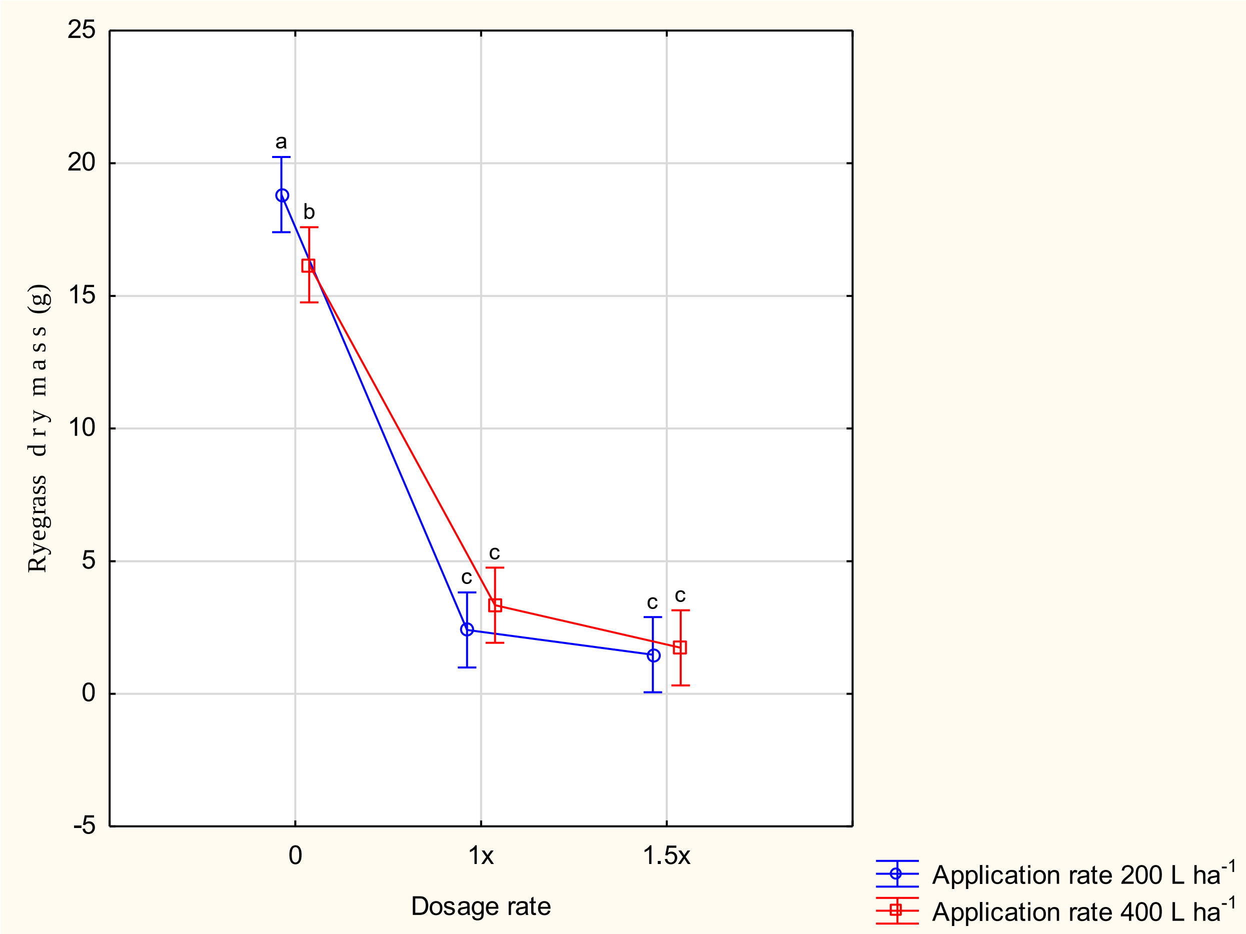

Figure 4. 6: Ryegrass dry mass observed at harvesting illustrating the interaction between dosage and application rate in a pot experiment investigating the effect of different pyroxasulfone application and dosage rates under different residue cover levels. Different letters denote means that differed significantly at $p \leq 0.05$ as per Fishers LSD. Vertical bars indicate 0.95 confidence intervals.

4.3.3. Wheat biomass

There was no significant interaction between factors in terms of wheat dry mass, with only the herbicide dosage rate having significant effect ($p \leq 0.05$) (**Table 4.2**). Both the 1x and 1.5x dosage rates resulted in significantly higher wheat dry mass compared to the 0x control dosage rate (**Table 4.3**).

Table 4. 3: The effect of pyroxasulfone dosage rate on the wheat dry mass production and yield in a pot experiment investigating the effect of different pyroxasulfone application and dosage rates under different residue cover levels. Different letters denote means which differed significantly at $p \leq 0.05$ as per Fishers LSD

Dosage rate	Wheat biomass (g)	Wheat grain yield ($t\ ha^{-1}$)
0 (Control)	7.2b	2.8c
1x	15.7a	4.8b
1.5x	16.6a	5.6a

4.3.4. Wheat grain yield

There was no significant interaction between factors (residue cover, dosage rate and application rate) in terms of wheat grain yield, with only the herbicide dosage rate having a significant effect ($p \leq 0.05$) (**Table 4.2**). The 1.5x dosage rate resulted in the highest yield, which was significantly better than the yield from the recommended dosage rate, and both treatments' yields were significantly higher than the 0x (control) dosage rate that resulted in the lowest yield **(Table 4.3**).

4.4. DISCUSSION

Both the recommended dosage rate and increased dosage rate of pyroxasulfone showed almost similar patterns in ryegrass control, both resulting in significantly lower ryegrass numbers than the control treatment. There were no significant differences over all residue levels between the two dosage rates in terms of ryegrass numbers and ryegrass dry mass, except at the 100% residue level where the higher dosage rate resulted in significantly lower ryegrass numbers compared to the recommended dosage rate. This could be attributed to the possibility that varying amounts of herbicide was washed off at different residue cover levels and reached the soil surface in adequate amounts for it to put necessary stress on the ryegrass. According to previous research pyroxasulfone is not intercepted easily by residues because of its chemical composition, so it can easily reach the soil surface (Preston 2014). That is however also dependent on other factors such as the availability and timing of rainfall after the application which assist in washing off the herbicide from the residue cover to soil surface (Khalil 2017).

In this study, the application of water equal to 5 mm of rain immediately (within 3 hours) after applying the herbicide, is demonstrating the same patterns than in cases where the rainfall after herbicide application influenced washing off the residue and the herbicide's ability to reach the soil surface (Khalil 2017). Additionally, the residue in this study was dry before herbicide application and it has been proven in recent research that dry residues intercept less herbicide compared to wet residues (Khalil 2017).

Another trend observed in the number of ryegrass plants and ryegrass biomass, is that where herbicide was not applied (control), the number of ryegrass plants decreased as the amount of residue cover increased even though there were no significant differences among different residue cover levels. This is in line with previous research where it has been proven that the presence of residue cover does suppress and reduce the number of weeds in crop production (Teasdale et al. 2004, Brandsæter et al. 2012, Carr et al. 2012, Shirtliffe and Johnson 2012). The reduction in the number of weeds has a positive impact because it reduces the use of herbicides, makes chemical control easier and less expensive, and in the long term reduces the risk of herbicide resistance development (Norsworthy et al. 2012).

In terms of ryegrass biomass, it was observed that both recommended and increased dosage rates had an impact on ryegrass dry mass that was significantly lower than those in the control treatment even at high residue cover levels. This reduction in ryegrass biomass is most probably due to the fact there are much lower numbers of ryegrass where pyroxasulfone was applied. However, it is possible that the reduction in number of ryegrass plants does not always correlate with the reduction in ryegrass dry mass. It concurs with previous research which has proven that pyroxasulfone, even applied on high residue levels, does lead to shoot and root-length inhibition which leads to stunted growth and ultimately reduce the weed dry mass without killing the weeds (Khalil et al. 2018).

In terms of wheat grain yield, dosage rate of pyroxasulfone did have some significant effects on yield with increased dosage rates resulting in the highest yield that was significantly higher than the yield obtained with the recommended dosage rate that in turn was significantly higher than the control treatment that resulted in the lowest yield. The higher grain yields obtained after application of pyroxasulfone is attributed to the efficiency of pyroxasulfone that was able to reach the soil surface and reduce weed growth thus leaving resources in the soil available for growth of the wheat plants. This is supported by Khan et al. (2003) and El-Metwally et al. (2015) concluded that increase in yield in herbicide treated plots is most probably attributed to efficient weed control.

4.5. CONCLUSION

This study has shown that high (100% = 6 t ha^{-1}) residue cover levels can negatively influence the efficacy of pyroxasulfone on ryegrass. Increasing the application rate from the recommended 200 L ha^{-1} of water to double the application rate (400 L ha^{-1}) did not improve efficacy of pyroxasulfone significantly. It seems to be a waste of a scarce commodity such as water to increase the application rate when applying pyroxasulfone. Increasing the dosage rate of pyroxasulfone to 187.5 g ha^{-1} however resulted in significantly better ryegrass control and significantly higher wheat yields at high residue cover levels. This work proves that higher dosage rates increase the ability of pyroxasulfone to reach the soil in sufficient amounts to control ryegrass but, importantly, is not phytotoxic to wheat at that dosage rate and it might be a solution for farmers struggling with inefficient ryegrass control under CA conditions.

REFERENCES

Arshad MA, Gill KS, Coy GR. 1994. Wheat yield and weed population as influenced by three tillage systems on a clay soil in temperate continental climate. *Soil and Tillage Research* 28:227–238.

Brandsæter LO, Goul TM, Wærnhus K, Fykse H. 2012. Effects of repeated clover undersowing in spring cereals and stubble treatments in autumn on Elymus repens, Sonchus arvensis and Cirsium arvense. *Crop Protection* 32:104–110.

Carr PM, Anderson RL, Lawley YE, Miller PR , Zwinger SF. 2012. Organic zero-till in the northern US Great Plains Region: Opportunities and obstacles. *Renewal Agricultural Food System* 27:12–20.

Chauhan BS, Abugho SB. 2012. Interaction of rice residue and pre Herbicides on emergence and biomass of four weed species. *Weed Technology* 26:627–632.

Cook A, Bates A, Shepperd W, Richter I. 2016. Herbicide efficacy in retained stubble systems https://grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-updatepapers/2016/08/herbicide-efficact-in-retained-stubble-systems. Accessed on 2017/11/02.

D'Emden F, Llewellyn RS, Burton MP. 2006. Adoption of conservation tillage in Australian cropping regions : An application of duration analysis. *Technological Forecasting and Social Change* 73(6):630–647.

El-Metwally IM, Abdelraouf RE, Ahmed MA, Mounzer O, Alarcon JJ, Abdelhamid MT. 2015. Response of wheat (Triticum aestivum L.) crop and broad-leaved weed to different water requirements and weed management in sandy soils. *Agriculture* 61(1):22-32

Farooq M, Flower KC, Jabran K, Wahid A, Siddique KHM. 2011. Crop yield and weed management in rainfed conservation agriculture. *Soil and Tillage Research* 117:172-183.

Haskins B. 2012. Herbicides in conservation farming systems using pre-emergent : Top tips for using pre-emergent herbicides.

http://www.dpi.nsw.gov.au/agriculture/farm/conservation/information/pre-emergent-herbicide.Accessed on 2017/010 /27.

Khalil Y. 2017. Herbicides and stubble – some wash off, some don't. https://ahri.uwa.edu.au/herbicides-and-stubble-some-wash-off-some-dont/.Accessed 2018/12/3

Khalil Y, Siddique KHM, Ward P, Piggin C, Bong SH, Nambiar S, Trengove R, Flower K. 2018. A bioassay for prosulfocarb, pyroxasulfone and trifluralin detection and quantification in soil and crop residues. *Crop Pasture Science* 69:606–616.

Khan MH, Hassan G, Khan N, KM. 2003. Efficacy of different herbicides for controlling broadleaf weeds in wheat. *Asian Journal of Plant Science* 2:254–256

Knowler D, Bradshaw B. 2007. Farmers ' adoption of conservation agriculture : A review and synthesis of recent research. *Food Policy* 32:25–48

Norsworthy JK, Ward SM, Shaw DR, Llewellyn RS, Nichols RL, Webster TM, Bradley KW, Frisvold G, Powles SB, Burgos NR, Witt WW, Barrett M. 2012. Reducing the Risks of Herbicide Resistance : Best Management Practices and Recommendations. *Weed Science* 60:31–62.

Preston C. 2014. Understanding pre emergent cereal herbicides. https://grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2014/03/understanding-pre-emergent-cereal-herbicides.Accessed on 2018/11/20.

Shirtliffe SJ, Johnson EN. 2012. Progress towards no-till organic weed control in western Canada. *Renawable Agrictural Food System* 27:60–67.

Teasdale JR, Mangum RW, Radhakrishnan J, Cavigelli MA. 2004.Weed seedbank dynamics in three organic farming crop rotations. *Agronomy J*ournal 96:1429–1435.

CHAPTER 5

THE EFFICACY OF DIFFERENT PRE-EMERGENT HERBICIDES AT DIFFERENT DOSAGE AND APPLICATION RATES APPLIED ON INCREASED RESIDUE COVER IN THE 2017 GROWING SEASON

ABSTRACT

Permanent organic soil cover in conservation agriculture creates a barrier that impedes sufficient amounts of pre-emergent herbicides to reach the soil surface for effective weed control. The failure of herbicides to reach the soil surface is caused by the fact that herbicides become intercepted by the residue cover and sometimes react with the residue cover. In the short term this can result in poor weed management and more competition to crops. In the medium term, it can lead to more weed seeds reaching the soil seed bank, which results in higher weed pressure in the following planting seasons and, in the long-term, these sub-lethal doses can lead to the development of non-target site herbicide resistance. Therefore, the aim of this study was to investigate the possible dosage rate/application rate combination that can assist in obtaining the required amount of pre-emergent herbicides to reach the soil surface at different levels of residue cover. the study was executed at Tygerhoek with residue cover arranged to result in the following levels;11 t ha^{-1}, 5.5 t ha^{-1} and 0 and Langgewens, with residue cover arranged as follows; 9.6 t ha^{-1}, 4.8 t ha^{-1} and 0. At both sites, herbicides treatments were applied as follows: pyroxasulfone, prosulfocarb plus triasulfuron and triallate at recommended dosage rate and 1.5 times the recommended rate dosage rate, and at recommended application rate and doubled the recommended application rate. Vegetative growth parameters of wheat and weeds were determined at anthesis. Weed and crop counts were conducted at 7 weeks after planting (WAP) and at anthesis. After harvesting; yield, 1000 kernel mass and hectolitre mass of the wheat was determined. Pyroxasulfone at increased dosage rates, controlled weeds better than other herbicides followed by prosulfocarb plus triasulfuron. Triallate treatment performed poorly across residue cover levels, even on an increased dosage rate. The results showed similar trends to the previous two chapters indicating that an increase in dosage rate was more effective than an increase in application rate to improve the efficacy of pre-emergence herbicides under high residue conditions.

Keywords

application rate, dosage rate, pre-emergent herbicides, residue cover, weed control, wheat yield.

5.1 INTRODUCTION

For many years tillage has been used as one of the means for weed control and any possible change in tillage system will have significant impact on the composition of weed communities, that is why it is imperative to study any phenomenon that may affect weed control in conservation agriculture (Arshad et al. 1994). The implementation of reduced soil tillage or minimal cultivation practices has led to increased weed infestation in winter wheat production (Knežević et al. 2010) According to Arshad et al. (1994), high levels of crop residues is one of the phenomena that leads to poor performance of conservation agriculture The retention of organic residues to soil to increase its organic matter content, to mitigate degradation and erosion is considered as a viable option in sustainable agricultural practices (Barba and Ordax 2018) . Barba and Ordax (2018) further alluded that the retention of residues in agricultural soils needs to be monitored because they can influence the behaviour of herbicides when they are applied.

The effectiveness of weed control in residue retained cropping systems such as conservation agriculture can be compromised when the residue intercepts the pre-emergent herbicide and prevent it from reaching the desired target, or the herbicide is tightly bound to organic matter or residue (Cook et al. 2016). Some weed species can escape the application of pre-emergent herbicides in conservation agriculture systems in which residue can bind soil-applied herbicides and result in lower efficacy (Chauhan and Abugho, 2012). Although crop residue retention has both positive and negative effects, efforts must be employed to enhance positive effects over the negative ones (Farooq et al. 2011).

According to Cook et al. (2016) different types of pre-emergent herbicides differ in the degree of binding to residue cover or organic matter and it depends on the composition of the herbicides. Beside the fact that the herbicide binds tightly or loosely on the residue cover, there are also other factors that may influence the efficacy of pre-emergent herbicides (Cook et al. 2016). These factors that affect pre-emergent herbicides includes chemical considerations such as; some herbicides are prone to volatility, some are sensitive to sunlight degradation (photo degradation), water solubility of the herbicides and prevailing environmental conditions at the time of applications, namely; rainfall, soil moisture levels, temperature levels during time of application and just after application (Haskins 2012). That influence the amount of herbicides that reach the soil surface and for herbicides such as pyroxasulfone there is potential of non-target site herbicide resistance when the weeds are exposed to recurrent low dosage overtime (Busi et al. 2012, Hern et al. 2017). It is therefore important to ensure where there is an increase in residue that the required dosage of pre-emergent herbicides reaches the soil surface for effective weed control to be realised.

The aim of this study was to determine the pre-emergent herbicide dosage rates and application rates that can be utilised on an increased residue cover for effective weed control. Therefore, the objectives that formed the basis of this study comprised of the following; (i) to assess the effectiveness of weed control with increased pre-emergent herbicide application and dosage rates when applied on an increased amount of residue cover, (ii) to determine vegetative growth parameters of wheat with increased pre-emergent herbicide application and dosage rate when applied on increased amounts of residue cover; (iii) to evaluate the yield of wheat with increased pre-emergent herbicide application and dosage rates when applied on increased amounts of residue cover, and (iv) to analyse the quality parameters of wheat with increased pre-emergent herbicides application and dosage rates when applied on increased amounts of residue cover. The null hypothesis (H_0) of this study was then: increasing pre-emergent herbicide application and dosage rates when applied to increased amounts of residue cover will not increase the efficacy of the herbicide.

5.2 MATERIALS AND METHOD

5.2.1. Experimental Site

The first experiment was carried out in 2017 in the Western Cape Province of South Africa, at the Langgewens research farm near Moorreesburg in Swartland area, West Coast region. The site is located at 33°17´ S 18°40´ E at an altitude of 137 m above sea level .The region get rain in winter which is distinctly Mediterranean-type climate with an average annual rainfall of approximately 400 mm. Its soil characteristics consist of 0.59% carbon, 77% sand, 14% silt, and 9% clay, and high stone presence. The soils are derived from Malmesbury and Bokkeveld shales.

The second experiment was also carried out in 2017 at Tygerhoek research farm near Riviersonderend, Overberg region. This site is located at 31°54'0"S 23°19'0" E at an altitude of 1,188 m above sea level. The region gets both summer and winter rainfall with an average annual rainfall of 450 mm of which 68% occurs between April and October. The soils characteristic in the area is dominated by poorly developed, shallow shale-derived soils with a high stone presence. The Oakleaf, Glenrosa and Swartland are the main soils forms in the area.

Table 5. 1 Rainfall for Langgewens research farm during the year 2017 (mm)

Date	**January**	**February**	**March**	**April**	**May**	**June**	**July**	**August**	**September**	**October**	**November**	**Date**
1				1	1							1
2								2			2	2
3								3.5		1,5	4.5	3
4					Herbicide	5				10		4
5									2			5
6									4			6
7						13						7
8						8	9		1			8
9												9
10												10
11					4	16		2				11
12						3		5				12
13				7								13
14												14
15			2			2.5				1		15
16							13	7		4.5		16
17						7				7		17
18												18
19										1.5		19
20			2.5			2						20
21												21
22						7		10				22
23						2						23
24	3							2				24
25					1		1		8	1		25
26				5	4.5		7					26
27												27
28						4.5						28
29								4				29
30	1.5					1.5						30
31												31
Total	**4.5**	**0**	**4.5**	**13**	**10.5**	**71.5**	**30**	**35.5**	**15**	**26.5**	**6.5**	**Total**

Table 5. 2: Rainfall for Tygerhoek research farm during year 2017 (mm)

Date	**January**	**February**	**March**	**April**	**May**	**June**	**July**	**August**	**September**	**October**	**November**	**December**
1					0.4		1.5					
2												
3		7.6			0.5							
4						2.4				2.2		
5								5.1				
6												
7						3.7						
8				1.8		14.9						
9						0.6						
10							19.6					
11					4.5			3.8				
12				1.6	0.3							
13		0.6		0.4				2.7				
14											30.9	
15					Herbicide	0.3					18	
16							14.5	4.7			2.8	
17						0.1		10.5	2.6	2.9		
18												
19												
20												
21												
22								5.7				
23						0.9		3				
24			0.3									
25	1.2				0.4			6.1				
26					2.3.		1.4		3	1.2		
27	21			3.6								
28												
29						2						
30												
31								5.2				
Total	**22.1**	**7.6**	**0.3**	**5.6**	**8.4**	**26.2**	**37**	**46.8**	**15.6**	**6.3**	**51.7**	**0**

5.2.2. Treatments and experimental design

The treatments and experimental design were identical both at Langgewens and Tygerhoek. The experimental layout was arranged in a randomized block design arranged as a 13x3 factorial replicated 4 times. The experiment consisted of the following factors: thirteen herbicide treatments which is described in **Table 5.3.** The herbicides applied were as follows: (i) Pyroxasulfone (Sakura®), (ii) Prosulfocarb + Triasulfuron (Boxer® and Logran®), (iii) Triallate (Avadex®). The dosage rates were arranged as follows; (i) the recommended registered dosage rate, (ii) 1.5 times the recommended dosage rate. The application rates were applied as follows, (i) the recommended application rate (200 L ha^{-1}) and (ii) double the application rate (400 L ha^{-1}) and three residue cover treatments (low, medium and high).

To investigate the interactions between residue cover, dosage rate and application rate in more detail, a subset of data that excluded the control treatment, was analysed as a 2x2x3 factorial design for each herbicide separately. The factors consisted of two herbicide dosage rates (recommended registered dosage rate and 1.5 times the recommended dosage rate, two herbicide application rates (recommended registered application rate (200 L ha^{-1}) and double the recommended application rate (400 L ha^{-1}) and three residue cover treatments (low, medium and high).

On both experimental farms the trial was laid out in a wheat monoculture field that formed part of the long-term rotational trials managed by the Department of Agriculture: Western Cape. The transect method was used to determine the amount of residue cover (Dickey et al 1986, Wollenhaupt, & Pingry 1991) (**Figure 5.1**). At both farms the plot sizes were 1.5 m wide by 7.5 m long. The 7.5 m plots were split into three 2.5 m plots where the reside treatments were applied resulting into split-plots with area of 1.5 m x 2.5 m each and then residue treatments were applied on them (**Figure 5.2**).

Figure 5. 1: Estimation of residue cover levels using line transect method at Langgewens

Figure 5. 2 : Splits plots layout at Langgewens

The residue cover both at Langgewens and Tygerhoek were manipulated to result in three different residue cover treatments namely high, medium and low. The amount of residue cover in kg m^{-2} were then converted to t ha^{-1}. The residues were manipulated into relatively high, medium and low levels by raking all the residues from one 2.5 m subplot (low residue) onto the adjacent plot (high residue) while the third plot remained undisturbed (medium residue). Residue cover of plots were randomly determined by means of the transect method to get an estimate of the residue cover on the plots at Tygerhoek and then classified as follows; high = approximately 11 t. ha^{-1}, medium= approximately 5.5 t. ha^{-1} and low = negligible small amount of residues left on the soil surface); at Langgewens; high = approximately 9.6 t. ha^{-1}, medium = approximately 4.8 t. ha^{-1} and low = negligible small amount of residues left on the soil surface.

The herbicide was applied immediately before planting on 4th of May 2017 and 15th of May 2017 at Langgewens and Tygerhoek respectively. Application was done by means of a knapsack sprayer equipped with a flat fan nozzle. `

Table 5. 3: Dosage rate and application rates combination per treatment

Treatment	Herbicide	Dosage Rate (L or g ha^{-1})	Application Rate (L ha^{-1})
1	Pyroxasulfone	125 g ha^{-1}	200 L ha^{-1} water
2	Pyroxasulfone	125 g ha^{-1}	400 L ha^{-1} water
3	Pyroxasulfone	187.5 g ha^{-1}	200 L ha^{-1} water
4	Pyroxasulfone	187.5 g ha^{-1}	400 L ha^{-1} water
5	Triasulfuron plus prosulfocarb	3 L/30 g ha^{-1}	200 L ha^{-1} water
6	Triasulfuron plus prosulfocarb	3 L/30 g ha^{-1}	400 L ha^{-1} water
7	Triasulfuron plus prosulfocarb	4.5 L/45 g ha^{-1}	200 L ha^{-1} water
8	Triasulfuron plus prosulfocarb	4.5 L/45 g ha^{-1}	400 L ha^{-1} water
9	Triallate	3 L ha^{-1}	200 L ha^{-1} water
10	Triallate	3 L ha^{-1}	400 L ha^{-1} water
11	Triallate	4.5 L ha^{-1}	200 L ha^{-1} water
12	Triallate	4.5 L ha^{-1}	400 L ha^{-1} water
13	Control	No herbicide	No water

5.2.3. Planting and seeding

A disc planter was used during planting to fulfil the non-till or reduced tillage principle as one of the conservation agriculture practices both at Langgewens and Tygerhoek.

5.2.4. Plant management

The fertilizer, pesticides and fungicides were applied according to best practice principles in the field trials in both areas.

5.2.5. Data collection

At different stages after planting, the following parameters were measured and recorded both at Langgewens and Tygerhoek:

i. Weeds and crop count

Seven weeks after planting (WAP) weed (mainly ryegrass and wild oats) and crop counts were conducted. On each treatment, counts were randomly carried out inside three 30 cm x 30 cm areas and two 30 cm x 30 cm areas for weeds and crops respectively. At anthesis weed and crop counts were carried out in the same fashion as above but at this stage both weeds and crops were cut at soil surface and put in plastic bags for the assessment of the vegetative growth parameters.

ii. Vegetative growth parameters

Five plants were sampled from each plastic bag and the number of stems and number of ears per wheat plant were counted for each treatment. After that the total number of ears per sample was counted. The wheat ears, wheat plants and weeds were then put into an oven and dried at 60 ºC for 72 hours. The dried, wheat plants and weeds were then weighed on an electronic scale balance to determine dry weight for each.

iii. Yield and yield components

At harvest the plots were harvested by means of a plot harvester and yield was then determined for each treatment by weighing the wheat grains on an electronic floor scale balance.

iv. Quality parameters

Hectolitre mass (HLM)/specific weight was analysed using a two-level HLM apparatus. Thousand kernel weight (TKW) was weighed using the electronic scale balance to determine the grain size and density. Protein analysis was conducted using the near-infrared reflectance spectrophotometer method through an InfraAlyzer IA450 instrument.

5.2.6. Statistical analysis

The STATISCA 12 program was used to conduct analysis of variance. Means of significance and interactions were separated using Fischer's least significance (LSD) test at the 5% level of significance. The two-way ANOVA analysis was used to analyze the relationship between herbicide treatment and residue levels and factorial ANOVA were used to analyse the interaction of three factors (residue cover, dosage rate and application rate) for each herbicide. Where the Levene's test showed severe non-homogeneity of variances, the Games-Howell multiple comparison procedure was used instead of the LSD intervals.

5.3 RESULTS

5.3.1. Two-way ANOVA analysis between herbicide treatments and residue levels

5.3.1.1. Weed population

i. Weed population counted seven weeks after planting (WAP):

Both at Tygerhoek and Langgewens there were not significant interactions between treatments and residue cover. However, both treatment and residue individually significantly influenced the weeds population ($p \leq 0.05$) (**Table 5 .4)**. In terms of treatments, at Tygerhoek, Treatments 4 and 8 resulted in the lowest number of weeds but were not significantly different from Treatments 2, 3, 6 and 10 **(Table 5.5)**. On the other hand, Treatment 13 resulted in significantly higher numbers of weeds than all other treatments.

At Langgewens, Treatments 3 and 4 resulted in significantly lower weed numbers than all the other treatments **(Table 5.6)** Treatment 13 resulted in significantly higher numbers of weeds than all other treatments.

In terms of the effect of residue cover levels on the effectiveness of weed control, at both Tygerhoek and Langgewens, high residue cover recorded the highest number of weeds, that was not significantly different from the medium residue cover but differed significantly from the low residue cover level **(Table 5.7)**.

ii. Weeds population counted at anthesis

Both at Tygerhoek and Langgewens only the treatments had significant effect on the weeds population ($p \leq 0.05$) (**Table 5.4**). At Tygerhoek a similar trend was prevalent, with Treatment 4 resulting in the lowest weeds population but it was only significantly different from Treatments 9, 11, 12 and 13 **(Table 5.5)**. Treatment 13 still recorded highest number of weeds but was not significantly different from Treatments 9, 11 and 12.

At Langgewens, Treatment 3 and 4 still performed better than the rest of the treatments, but they didn't significantly differ from the weeds population observed in Treatments 1 and 2 **(Table 5.6)**. Treatment 13 resulted in the highest weed infestation, but it was not significantly different from Treatments 5, 6, 9, 11 and 12.

5.3.1.2. Wheat plants population

i. Wheat plants population counted seven weeks after planting (WAP):

At Tygerhoek there were no significant interaction between factors or differences within factors. However, at Langgewens both treatments and residue did have significant effect on the number of wheat plants ($p \leq 0.05$) (**Table 5.4**). In terms of treatments, only Treatment 13 resulted in significantly lower wheat plant population compared to all the other treatments (**Table 5.6**). In terms of residue cover, the low residue cover level resulted in significantly lower wheat plants population than observed at the high residue cover level **(Table 5.7)**.

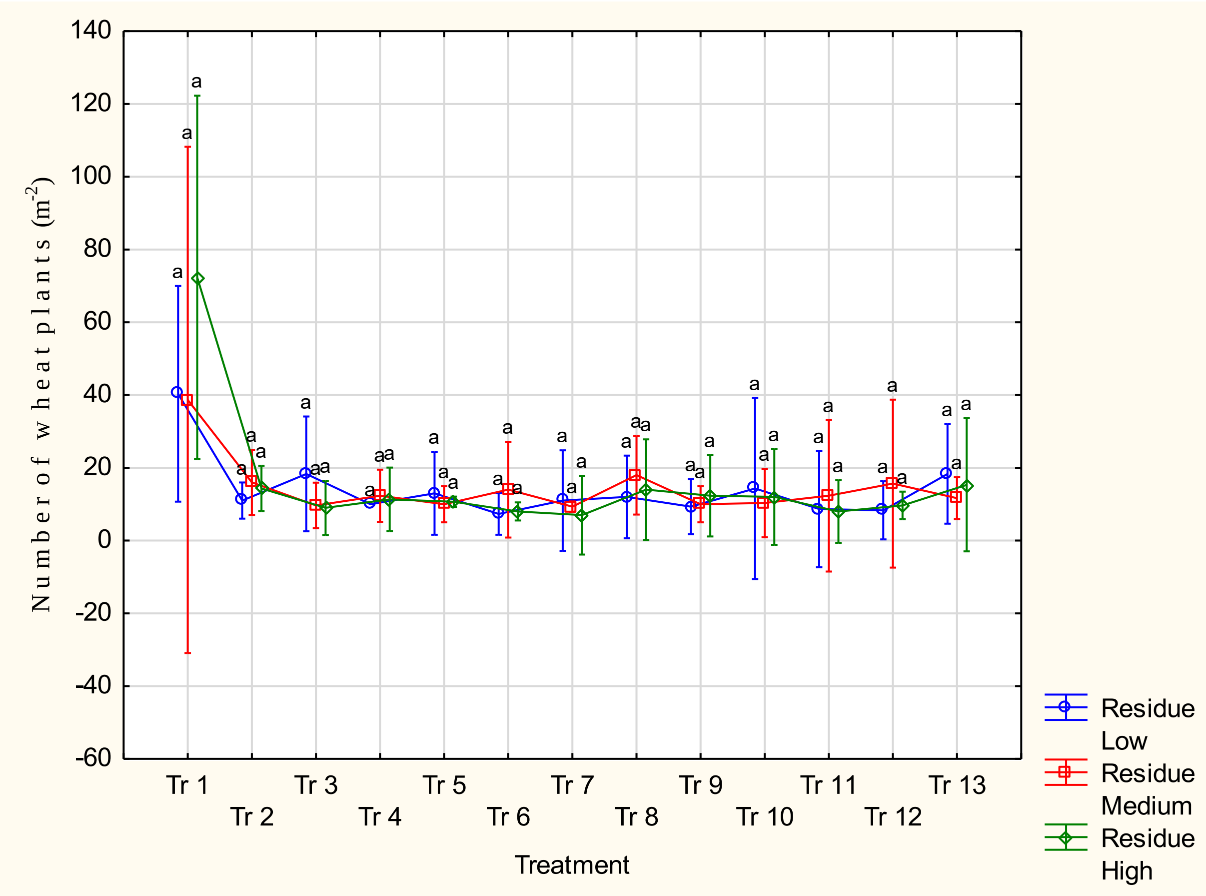

Figure 5. 3: Wheat plants population recorded at the anthesis stage at Tygerhoek where efficiency of different herbicides applied at different application and dosage rates on various residue levels in a wheat field was investigated, illustrating interaction between treatment of difference herbicides and residue cover. Different letters denote means that differed significantly at $p \leq 0.05$ as per Fishers LSD. Vertical bars indicate 0.95 confidence intervals.

i. Wheat plant population counted at anthesis

At Tygerhoek, there was significant interaction between herbicide treatments and residue and at Langgewens only herbicide treatments had significant effects on wheat plant population ($p \leq 0.05$) (**Table 5 .4**). In terms of the interaction between treatments and residue at Tygerhoek, there were no significant differences in the wheat plants population across all treatments (**Figure 5.3). ** In terms of the effect of treatments at Langgewens, Treatment 4 resulted in the highest number of wheat plants that was significantly higher than all other treatments except for Treatments 1 and 2 (**Table 5.6**).

5.3.1.3. Weed biomass

Both at Tygerhoek and Langgewens treatments had significant influence on the weed biomass (**Table 5.4**). At Tygerhoek, Treatment 4 resulted in the lowest weed biomass but was not significantly different from Treatments 1, 2, 3, 7 and 8 **(Table 5.5**). Treatment 13 had the highest weed biomass, but it was not significantly different from Treatment 12.

At Langgewens, Treatment 4 also resulted in the lowest weed biomass but it was not significantly different from Ttreatments 1, 2, 3, 7 and 8 (**Table 5.6**). Like at Tygerhoek, Treatment 13 resulted in the highest weed dry mass but it was not significantly different from Treatments 5, 6, 9, 10, 11 and 12.

5.3.1.4. Wheat biomass

Both at Tygerhoek and Langgewens only treatments had a significant effect on wheat biomass ($p \leq 0.05$) (**Table 5.4**). At Tygerhoek, Treatment 7 had the highest wheat biomass but it was not significantly different from Treatments 1, 2, 3, 4 and 8 **(Table 5.5**). Treatment 13 resulted in the lowest wheat biomass and was not significantly different from Treatments 5, 11 and 12.

At Langgewens, Treatment 7 resulted in the highest wheat biomass but it was not significantly different from Ttreatments 1, 2, 3, 4, 6, 8, 9 and 11 (**Table 5.6**). At Langgewens, Treatment 12 resulted in the lowest wheat biomass buit it was not significantly lower than Treatments 5, 6, 8, 9, 10, 11 and 13.

Table 5. 4: The vegetative growth, yield and quality parameters analysed through Two-way ANOVA at Tygerhoek and Langgewens where efficiency of different herbicides applied at different application and dosage rates on various residue levels in a wheat field was investigate denotes significant interaction between respective factors ($p \leq 0.05$)

Factors at Tygerhoek	Weeds population 7 WAP (m^{-2})	Weeds population at anthesis (m^{-2})	Wheat plants population 7 WAP (m^{-2})	Wheat plants population anthesis (m^{-2})	Weed biomass (g)	Wheat biomass (g)	Wheat grain yield ($t\ ha^{-1}$)	Thousand kernel mass (g)	Hectolitre mass ($kg.\ hL^{-1}$)	Protein Content (%)
Treatment	*	*	ns	*	*	*	*	ns	ns	*
Residue	*	ns	s	ns	ns	ns	ns	ns	ns	ns
Treatment*Residue	ns	ns	ns	*	ns	ns	ns	ns	ns	ns
Factors at Langgewens										
Treatment	*	*	*	*	*	*	*	*	ns	ns
Residue	*	ns	*	ns	ns	ns	ns	ns	ns	ns
Treatment*Residue	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns

*= denotes significant interaction between respective factors $p \leq 0.05$), ns= denotes no significant interaction between respective factors ($p > 0.05$)

Table 5. 5: The vegetative growth, yield and quality parameters that was influenced by treatments as main factor in a trial at Tygerhoek where efficiency of different herbicides applied at different application and dosage rates on various residue levels in a wheat field was investigated. Different letters denote means which differed significantly at $p \leq 0.05$ as per Fishers LSD

Treatment	Weeds population 7 WAP (m^{-2})	Weeds population at anthesis (m^{-2})	Weed biomass (g)	Wheat biomass (g)	Wheat grain yield ($t\ ha^{-1}$)	Protein Content (%)
1	15b	10bcd	15.3gh	95.3ab	1.9bcd	12.7a
2	7bc	9bcd	20.73efgh	77.5abcd	1.7cde	12.5a
3	9bc	6cd	17.1fgh	94.2ab	2.1ab	11.8ab
4	3c	3d	6.3h	100.9a	2.3a	12.6a
5	15b	8bcd	37.1cdef	62cde	1.2de	12.1a
6	8bc	7cd	33cdef	72.2bcd	1.6cde	12.5a
7	13b	6cd	16.3gh	102.2a	2abc	11.9ab
8	3c	5cd	19.3efgh	87.6abc	2.1ab	12.4a
9	13b	12abc	39.02cde	80.7bcd	1.7cde	11.6ab
10	7bc	9bcd	47.2bcd	76.3bcd	1.5cde	11.7ab
11	18b	17ab	54.5bc	54.1de	1.2de	10.7b
12	16b	25a	65.2ab	63.3cde	1.2de	11.3ab
13	61a	29a	81a	43.2e	0.9e	11.1ab

Table 5. 6: The vegetative growth, yield and quality parameters that was influenced by treatments as main factor in a trial at Langgewens where efficiency of different herbicides applied at different application and dosage rates on various residue levels in a wheat field was investigated. Different letters denote means which differed significantly at $p \leq 0.05$ as per Fishers LSD

Treatment	Weeds population 7 WAP (m^{-2})	Weeds population at anthesis (m^{-2})	Wheat plants population 7 WAP (m^{-2})	Wheat plants population anthesis (m^{-2})	Weed biomass (g)	Wheat biomass (g)	Wheat grain yield (t ha^{-1})	Thousand kernel mass (g)
1	46c	21cdef	106ab	150ab	2.5d	104.2ab	2.2ab	39.2a
2	39cd	17def	108ab	144ab	2.6d	110.2a	2.1ab	37.7abc
3	6d	6f	120a	138b	1.7d	106.4ab	2.4ab	38.6ab
4	3d	4f	129a	173a	0.7d	109.1a	2.5a	39.6a
5	44c	56abcd	107ab	90cd	19.5ab	69.8bc	1.6ef	37abc
6	58c	60abcd	101ab	106cd	12abc	84.3abc	2.4ab	38.1abc
7	32bc	28cde	135a	122bc	4cd	110.3a	2.4ab	38.2abc
8	29c	32bcde	127a	105cd	8.3bcd	87.9abc	2bcde	38.1abc
9	39bcd	70abc	140a	121bc	14.5abc	101.2abc	1.9cde	38.4ab
10	24c	47bcd	108ab	95cd	3.9abc	71bc	2.2ab	36.9c
11	57bc	95ab	125a	96cd	23.8ab	79.7abc	1.8def	36.7c
12	52c	69ab	101ab	80d	27a	62c	1.8def	37.9abc
13	106a	110a	47c	84d	27.1a	66.9bc	1.4f	36.7c

Table 5. 7: The effect of residue cover levels on the of number of weeds and wheat at Tygerhoek and Langgewens where efficiency of different herbicides applied at different application and dosage rates on various residue levels in a wheat field was investigated. Different letters denote means that means differed significantly at $P \leq 0.05$ as per Fishers LSD.

Residue cover levels	Weeds population 7 WAP (m^{-2}) Tygerhoek	Weeds population 7 WAP (m^{-2}) Langgewens	Wheat plants population 7 WAP (m^{-2}) Langgewens
Low	12b	37b	119a
Medium	14ab	45ab	110ab
High	18a	53a	107b

5.3.1.5. Wheat grain yield

Both at Tygerhoek and Langgewens, only herbicide treatments had significant effect on the wheat grain yield ($p \leq 0.05$) (**Table 5.4**). At Tygerhoek, Treatment 4 resulted in the highest wheat grain yield but it was not significantly different from Treatments 3, 7 and 8. (**Table 5.5**). At Langgewens, a similar pattern was observed, with Treatment 4 resulting in the highest wheat grain yield that was however not significantly different from Treatments 1, 2, 3, 6, 7 and 10 (**Table 5.6**). Treatment 13 recorded the lowest wheat grain yield and did not differ significantly from Treatments 5, 11 and 12.

5.3.1.6. Thousand kernel mass

At Tygerhoek there was no significant interactions between factors or significant differences within factors and at Langgewens only treatments did have significant effect on thousand kernel weight ($p \leq 0.05$) (**Table 5.4**). In terms of the effect of treatment on thousand mass weight at Langgewens, Treatment 4 resulted in the highest amount of thousand kernel mass that was however not significantly different from other treatments, except from Treatments 10, 11 and 13 which recorded slightly lower thousand kernel mass (**Table 5.6**)

5.3.1.7. Hectolitre mass

At both Tygerhoek and Langgewens there was no significant interactions between or significant differences within factors in terms of hectolitre mass (**Table 5.4**).

5.3.1.8. Protein content

At Langgewens there was no significant interactions between or significant differences within factors and at Tygerhoek treatments did have significant effect on wheat grain protein content ($p \leq 0.05$ (**Table 5.4**). At Tygerhoek, Ttreatments 1, 2, 4, 5, 6 and 8 resulted in significantly higher protein content than Treatment 11 (**Table 5.5**).

5.3.2. Interactions between residue cover, dosage rate and application rate for different herbicides

5.3.2.1. Weed population

Pyroxasulfone

At Tygerhoek, there was significant interaction between dosage rate and residue cover ($p \leq 0.05$), on the number of weeds, 7 weeks after planting (WAP) (**Table 5.18).** The number of weeds were low when the recommended dosage rate (Dose 1×) was applied on the low residue cover and as soon as the residue cover increased from low to medium and high, the number of weeds increased with significant differences between the two lowest residue cover levels and the highest residue cover level (**Figure 5.4**). With the increased dosage rate (Dose 1.5×) there were no significant differences in the number of weeds among the three levels of residue cover.

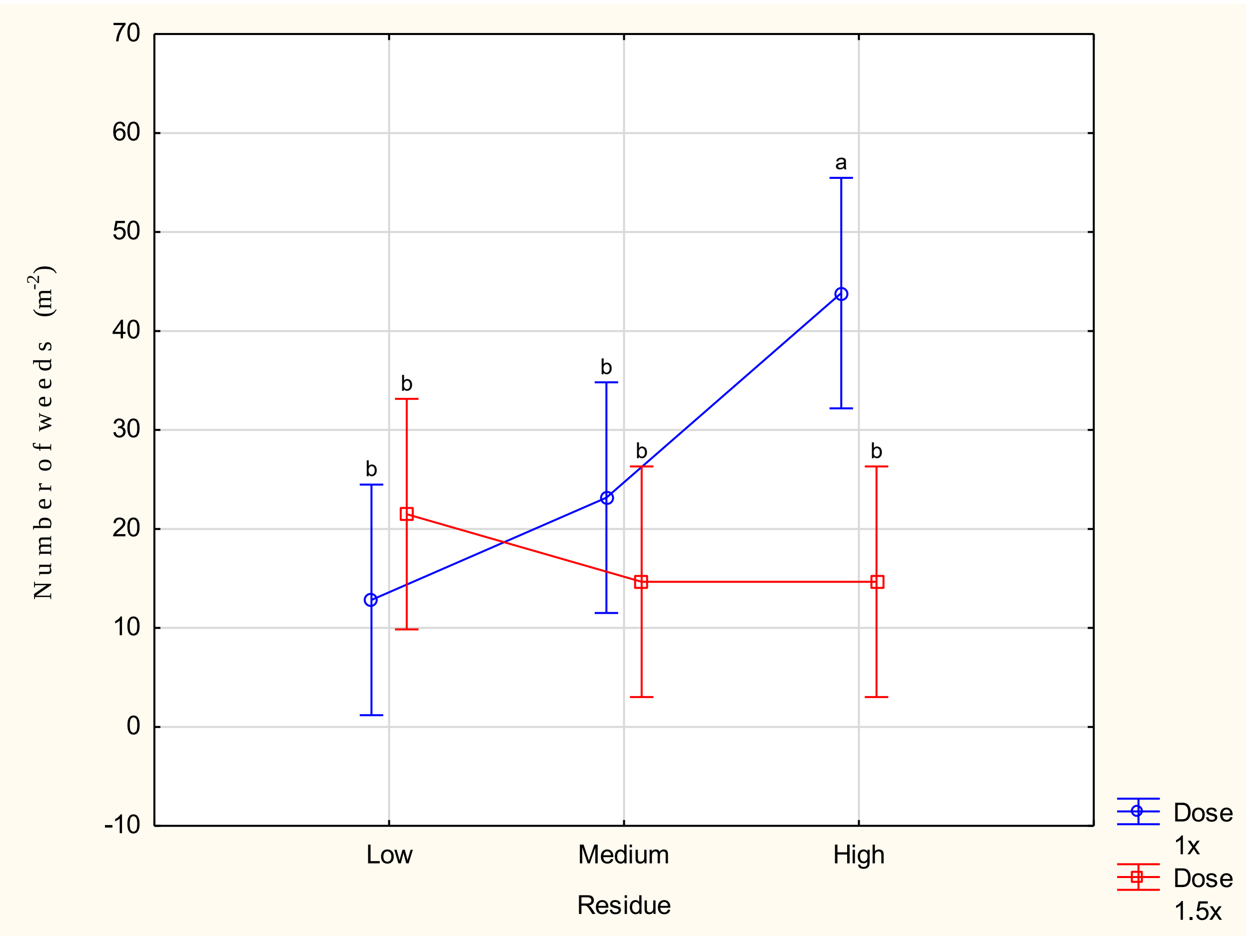

Figure 5. 4: The weeds population that were recorded seven weeks after plant (WAP) at Tygerhoek where pyroxasulfone was applied, illustrating interaction between dosage rate and residue cover. Different letters denote means which differed significantly at $P \leq 0.05$ as per Fishers LSD. Vertical bars indicate 0.95 confidence intervals.

At wheat anthesis growth stage, there was no significant interaction between the three factors (residue cover, dosage rate and application rate) on the number of weeds, with only the herbicide dosage rate having a significant effect ($p \leq 0.05$) on the number of weeds (**Table 5.18**). An increase in dosage rate to 1.5× recorded weed numbers which were significantly lower than the ones recorded at recommended dosage rate (**Table 5.8**)

At Langgewens, there was significant interaction between dosage rate and residue cover ($p \leq 0.05$), on the number of weeds, 7 weeks after planting (WAP) (**Table 5.18)** The number of weeds were low when the recommended dosage rate (Dose 1×) was applied on the low residue cover and as soon as the residue cover increased from low to medium and to high, the number of weeds increased with significant differences between residue cover levels (**Figure 5.5**). However increased dosage rate resulted in significantly lower number of weeds across all residue cover levels compared to the recommended dosage rate.

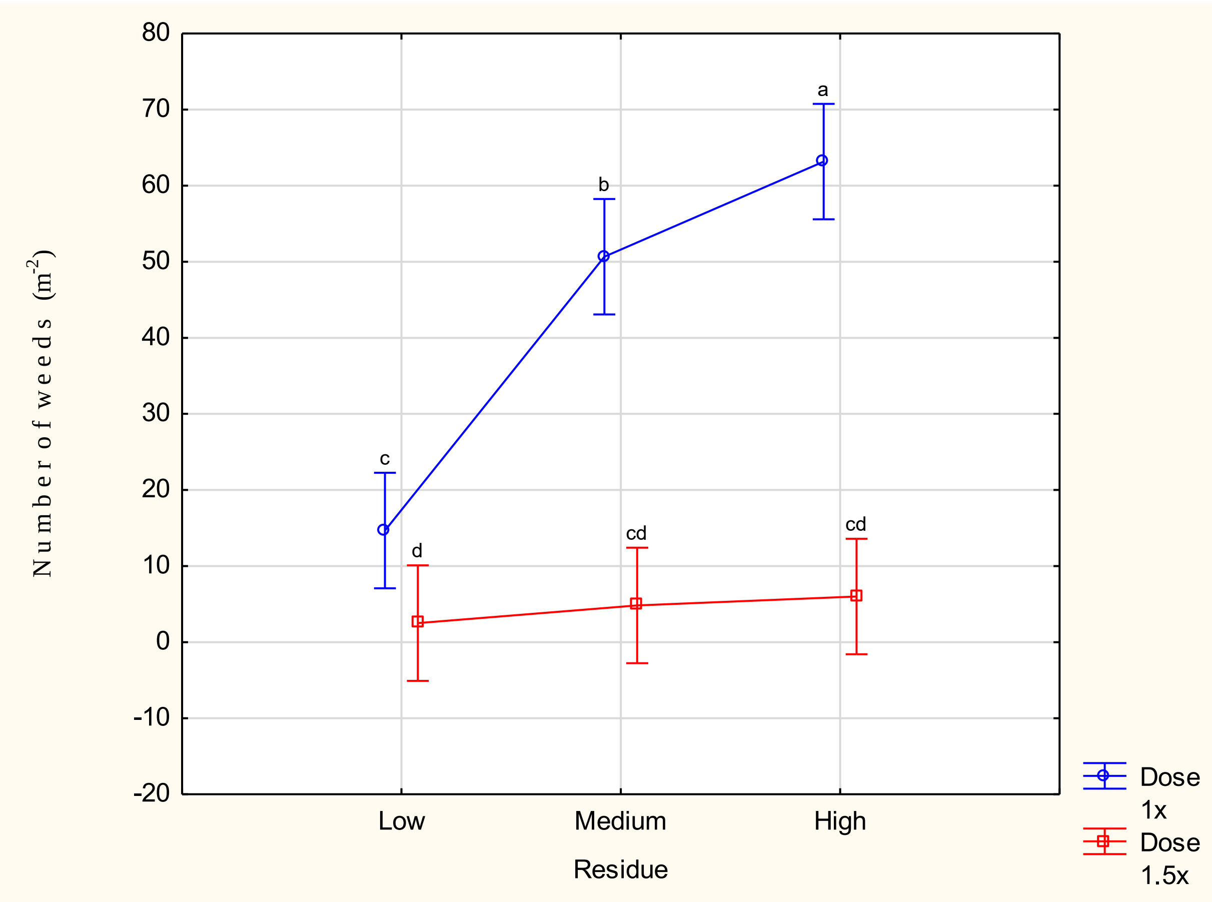

Figure 5. 5: The number of weeds that were recorded 7 WAP at Langgewens with pyroxasulfone treatments , illustrating interaction between dosage rate and residue cover. Different letters denote means which differed significantly at $P \leq 0.05$ as per Fishers LSD. Vertical bars indicate 0.95 confidence intervals

Table 5. 8: The effect of dosage rate on number of weeds at anthesis stage of the wheat at Tygerhoek in the pyroxasulfone. Different letters denote means that means differed significantly at P ≤ 0.05 as per Fishers LSD

Site	Dosage rate	Weed population anthesis (m^{-2})
Tygerhoek	1x	33a
	1.5 x	17b

At wheat anthesis growth stage, there was significant interaction (p ≤ 0.05) between application rate and residue cover (**Table 5.18).** There were no significant differences in the number of weeds between recommended application rate (200 L ha^{-1}) and double the application rate (400 L ha^{-1}) both at medium and high residue cover levels (**Figure 5.6)**. A significant difference in the number of weeds was recorded on the low residue cover where double the application rate resulted in the lowest number of weeds.

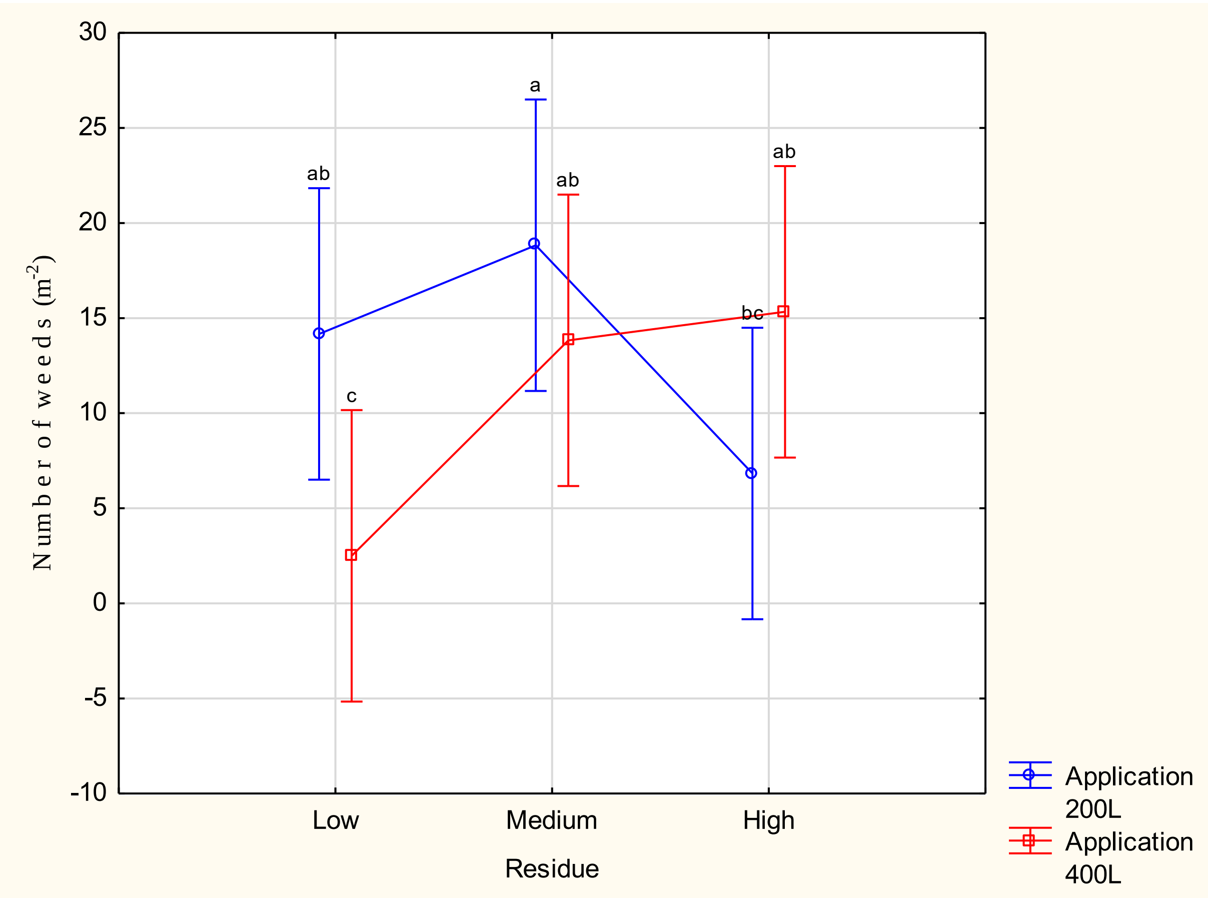

Figure 5.6: The number of weeds that were recorded at wheat anthesis stage at Langgewens where pyroxasulfone was applied, illustrating interaction between application rate and residue cover. Different letters denote means which differed significantly at P ≤ 0.05 as per Fishers LSD. Vertical bars indicate 0.95 confidence intervals

In addition, dosage rate on its own demonstrated significant effect ($p \leq 0.05$) on the number of weeds at the wheat anthesis stage (**Table 5.14**). An increase in dosage rate (1.5x) resulted in weed numbers which were significantly lower than the ones recorded at the recommended dosage rate treatment (**Table 5.9).**

Table 5. 9: The effect of dosage rate on different parameters at Langgewens in the pyroxasulfone treatment. Different letters denote means that means differed significantly at $P \leq 0.05$ as per Fishers LSD

Site	Dosage rate	Weed population anthesis (m^{-2})
Langgewens	1x	19a
	1.5 x	5b

Prosulfocarb plus triasulfuron

At Tygerhoek, there was no significant interaction between any of the factors (dosage rate, application rate and residue cover) on the number of weeds, 7 weeks after planting (WAP) (**Table 5.18).** However, each of the following factors i.e. dosage rate, application rate and residue cover, individually had significant effect ($p \leq 0.05$) on the number of weeds. An Increase in dosage rate (1.5x) resulted in numbers of weeds which were significantly lower than the ones recorded at recommended dosage rate treatment (**Table 5.10**). An increase in application rate (400 L ha^{-1}) resulted in numbers of weeds which were significantly lower than the ones recorded at recommended application rate (200 L ha^{-1}) (**Table 5.10**).

Table 5. 10: The effect of dosage rate, application rate and residue cover on the number of weeds 7 WAP at Tygerhoek in the prosulfocarb and triasulfuron treatment. Different letters denote means that differed significantly at $p \leq 0.05$ as per Fishers LSD

Site	Dosage rate	Weed population 7 WAP (m^{-2})
Tygerhoek	1x	42a
	1.5 x	19b
	Application rate	
	200 L	39 a
	400 L	21b
	Residue cover	
	Low	19b
	Medium	24b
	High	48a

In terms of residue cover, high residue cover resulted in the highest number of weeds which were significantly different from the low and medium residue covers (**Table 5.10**) which did not differ significantly from each other.

In terms of number of weeds counted at anthesis growth stage, there was no significant interaction between 3 factors (residue cover, dosage rate and application rate) nor any significant differences within factors (**Table 5.18**).

At Langgewens, weed numbers counted at 7 WAP and anthesis wheat growth stage, showed no significant interaction between 3 factors (residue cover, dosage rate and application rate), with only the herbicide dosage rate having significant effect ($p \leq 0.05$) on the number of weeds **(Table 5,18).** At both growth stages, an increase in dosage rate (1.5 L ha^{-1}) resulted in weed numbers significantly lower than the ones recorded at recommended dosage rate treatment (**Table 5.11**).

Table 5. 11: The effect of dosage rate on different parameters at Langgewens in the prosulfocarb plus triasulfuron treatment. Different letters denote means that differed significantly at $P \leq 0.05$ as per Fishers LSD

Site	Dosage rate	Weed populations at 7 WAP (m^{-2})	Weed population at anthesis (m^{-2})
Langgewens	1x	51a	58a
	1.5 x	30b	30b

Triallate

At Tygerhoek, there was no significant interaction between factors (dosage rate, application rate and residue cover) or significant differences within factors on the number of weeds, 7 weeks after planting (WAP) (**Table 5.19**).

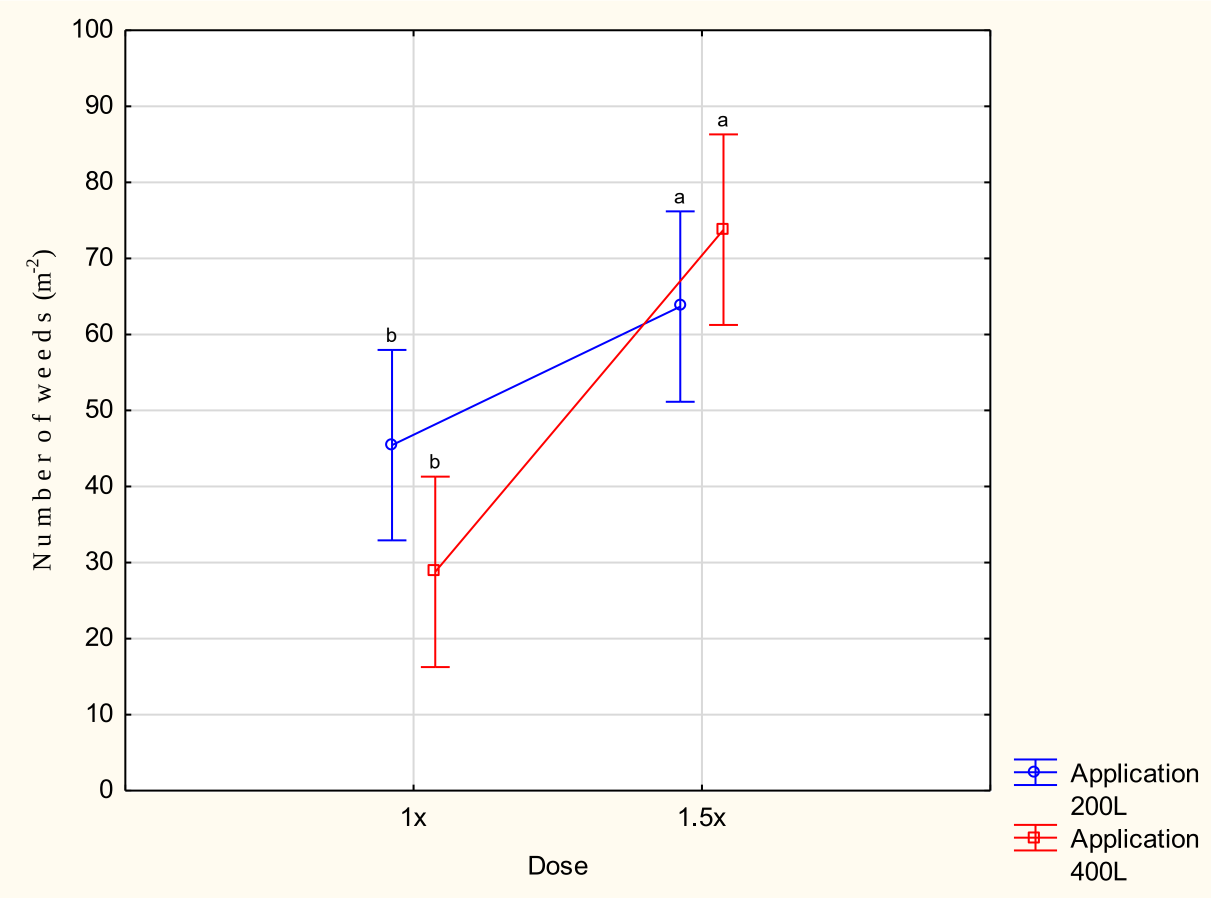

Figure 5. 7: The number of weeds that were recorded at anthesis at Tygerhoek where triallate was applied, illustrating interaction between dosage rate and application. Different letters denote means which differed significantly at $P \leq 0.05$ as per Fishers LSD. Vertical bars indicate 0.95 confidence intervals.

At anthesis growth stage, there was significant interaction ($p \leq 0.05$), between dosage rate and application rate (**Table 5.19**) in terms of weed numbers. There was no significant differences in the number of weeds when it comes to different applications rates (200 and 400 L ha^{-1}), both at recommended dosage rate (1x) and increased dosage (1.5x) **(Figure 5.7)**. Increased dosage rate (1.5x) however resulted in higher weed numbers than the registered dosage rate (1x) at both application rates.

At Langgewens, there was no significant interaction between factors (dosage rate, application rate and residue cover) on the number of weeds at 7 (WAP) with only dosage rate having a significant effect on the number weeds (**Table 5.20**)**.** Unlike the trend in pyroxasulfone and prosulfocarb plus triasulfuron treatments, with triallate an increase in dosage rate resulted in poor weed control with 1.5x dosage rate resulting in significantly higher number of weeds compared to the recommended dosage rate (1x) (**Table 5.12**).

In terms of number of weeds analysed at anthesis growth stage, there was no significant interaction between 3 factors (residue cover, dosage rate and application rate) (**Table 5.20**) and no other significant differences within treatments.

Table 5. 12: The effect of dosage rate on number of weeds 7 WAP at Langgewens, in the triallate treatment. Different letters denote means that differed significantly at $p \leq 0.05$ as per Fishers LSD

Site	Dosage rate	Weed population 7 WAP (m^{-2})
Langgewens	1x	31b
	1.5x	54a

5.3.2.2. Wheat plants population

Pyroxasulfone

At Tygerhoek, there was no significant interaction between 3 factors i.e. application rate, dosage rate and residue cover on the wheat plants population, 7 weeks after planting (WAP), however residue cover had significant effect ($p \leq 0.05$), on wheat plants population (**Table 5.18).** At high residue cover the lowest number of wheat plants were attained and were not significantly different from one attained at medium residue cover, however it was significantly different from the number of wheat plants attained at low residue cover (**Table 5.13**).

For the number of wheat plants counted at anthesis growth stage, there was significant interaction between application rate and residue cover (**Table 5.18)**. At low residue cover, doubled application rate resulted in the highest number of wheat plants and were significantly different from the ones attained at recommended application rate (**Figure 5.8**). At medium residue cover, the recommended application rate attained the highest number of wheat plants and was significantly different from the ones attained at double application rate. On the other hand, at high residue the recommended application rate attained the highest number of wheat plants, but it was not significantly different from the ones attained at double application rate.

Table 5. 13: The effect of residue cover on the number of wheat plants 7 WAP at Tygerhoek in the pyroxasulfone treatment. Different letters denote means that means differed significantly at P ≤ 0.05 as per Fishers LSD

Site	Residue cover level	Wheat plant population 7 WAP (m^{-2})
Tygerhoek	Low	91a
	Medium	76ab
	High	69b

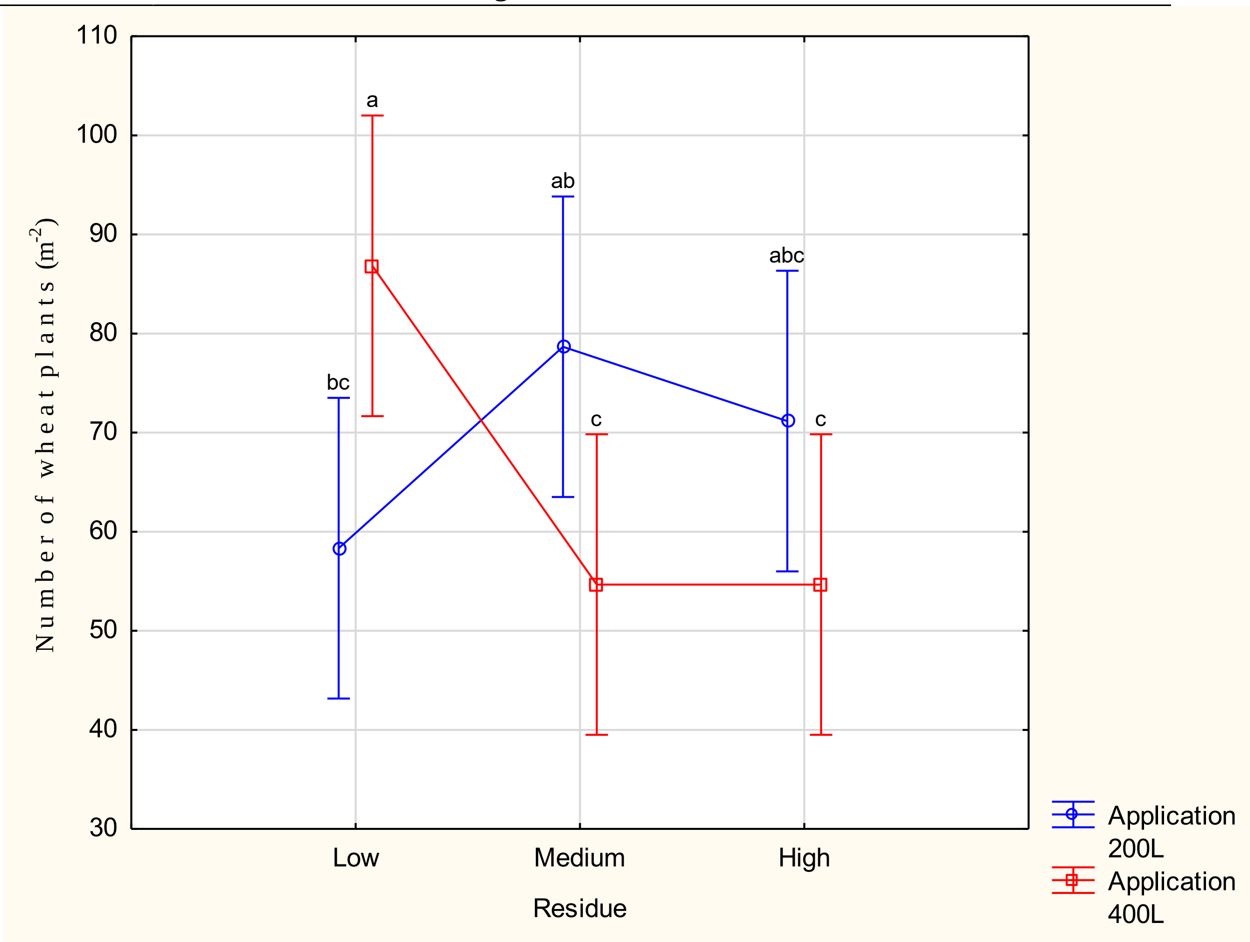

Figure 5. 8: The number of wheat plants that were recorded an anthesis in Tygerhoek in the pyroxasulfone treatment, illustrating interaction between application rate and residue cover. Different letters denote means which differed significantly at P ≤ 0.05 as per Fishers LSD. Vertical bars indicate 0.95 confidence intervals.

At Langgewens, there was significant interaction between dosage rate and residue cover ($p \leq 0.05$) on the number of wheat plants, 7 weeks after planting (WAP) (**Table 5.20).**

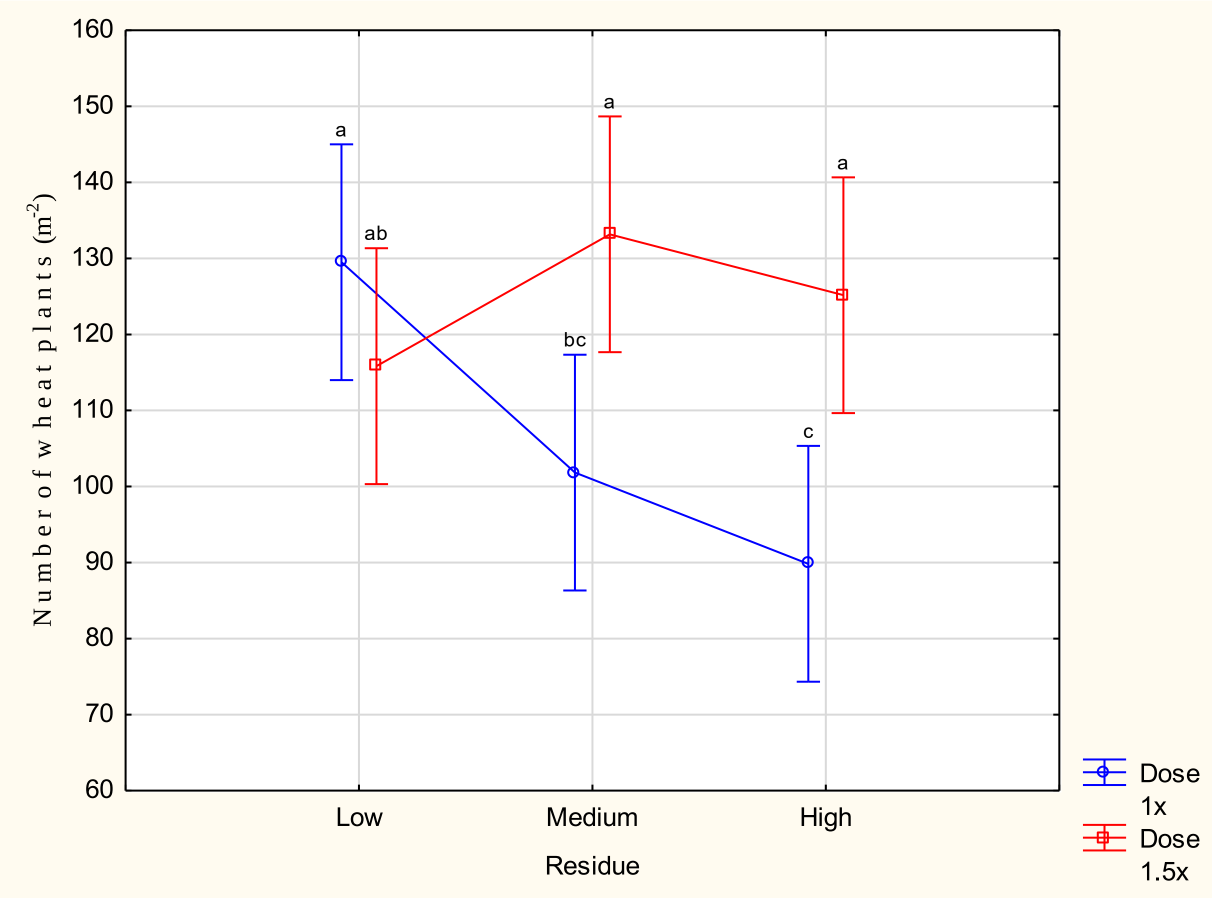

Figure 5. 9: The number of wheat plants that were recorded at 7 WAP in the Langgewens pyroxasulfone treatment, illustrating interaction between dosage rate and residue cover. Different letters denote means which differed significantly at P ≤ 0.05 as per Fishers LSD. Vertical bars indicate 0.95 confidence intervals

The number of wheat plants was high when the recommended dosage rate (1x) was applied on the low residue cover and as soon as the residue cover increased from low to medium and to high, the number of wheat plants decreased with significant differences between residue cover levels (**Figure 5.9**). On the other hand increased dosage rate resulted in significantly higher numbers of wheat plants across all residue cover levels. For number of wheat plants at anthesis, there was no significant interaction between all factors or within-treatment differences (**Table 5.20**).

Prosulfocarb plus triasulfuron

At Tygerhoek, there was no significant interaction between 3 factors (application rate, dosage rate and residue cover), on the number of weeds, 7 weeks after planting (WAP), however residue cover had significant effect ($p \leq 0.05$) on the number of weeds.(**Table 5.18).** At high residue cover the lowest number of wheat plants were attained and were not significantly different from one attained at medium residue cover, however it was significantly different from the number of wheat plants attained at low residue cover (**Table 5.14**).

Table 5. 14: The effect of residue cover on the number of wheat plants 7 WAP in the prosulfocarb plus triasulfuron treatment. Different letters denote means that means differed significantly at $P \leq 0.05$ as per Fishers LS

Site	Residue cover level	Wheat plants population 7 WAP (m^{-2})
Tygerhoek	Low	93a
	Medium	79ab
	High	72b

Regarding number of wheat plants counted at anthesis growth stage, there was no significant interaction between 3 factors (residue cover, dosage rate and application rate), however the dosage rate did have significant effect ($p \leq 0.05$) on the number of wheat plants (**Table 5.14**). An increase in dosage rate (1.5) resulted in significantly higher numbers of wheat plants than recorded at recommended dosage rate treatment (**Table 5.15**).

Table 5. 15: The effect of dosage rate on number of wheat plants at anthesis, Tygerhoek in the prosulfocarb plus triasulfuron treatment. Different letters denote means that means differed significantly at $P \leq 0.05$ as per Fishers LSD

Site	Dosage rates	Wheat plants population 7 WAP (m^{-2})
Tygerhoek	1x	49b
	1.5x	70a

At Langgewens, in terms of number of wheat plants analysed 7 WAP, there was no significant interaction between 3 factors (residue cover, dosage rate and application rate), but the dosage rate did have significant effect ($p \leq 0.05$) on the number of wheat plants (**Table 5.20**). An increase in dosage rate (1.5x) resulted in significantly higher numbers of wheat plants than at recommended dosage rate treatments (**Table 5.16**). At anthesis, there was no significant interaction between 3 factors (residue cover, dosage rate and application rate) or differences within treatments (**Table 5.20**).

Table 5. 16: The effect of dosage rate on number of wheat plants recorded 7 WAP at Langgewens in the prosulfocarb plus triasulfuron treatment. Different letters denote means that means differed significantly at $P \leq 0.05$ as per Fishers LSD

Site	Dosage rate	Wheat plants population 7 WAP (m^{-2})
Langgewens	1x	104b
	1.5 x	131a

Triallate

At Tygerhoek number of wheat plants counted at 7 WAP and anthesis growth stage, showed no significant interaction between 3 factors (residue cover, dosage rate and application rate) (**Table 5.19**) as well as no significant differences within factors**.**

At Langgewens, in terms of number of wheat plants analysed 7 WAP, there was no significant interaction between 3 factors (residue cover, dosage rate and application rate) but the application rate did have significant effect ($p \leq 0.05$) on the number of wheat plants (**Table 5.21**). Double application rate attained significantly lower numbers of wheat plants than in the recommended dosage rate **(Table 5.17)**. At anthesis, there was no significant interaction between 3 factors (residue cover, dosage rate and application rate) and no significant differences within treatments (**Table 5.21**).

Table 5. 17: The effect of application rate on number of wheat plants at Langgewens, Avadex treatment. Different letters denote means that means differed significantly at $P \leq 0.05$ as per Fishers LSD

Site	Application rate	Wheat plants population 7 WAP (m^{-2})
Langgewens	200L	133a
	400L	105b

Table 5. 18: Analysis of variance (ANOVA) table on different parameters at Tygerhoek

Herbicides	Tygerhoek	Weeds population 7 WAP (m^{-2})	Weeds population anthesis (m^{-2})	Wheat plants population 7 WAP (m^{-2})	Wheat plants population. anthesis (m^{-2})	Weed Bio mass (g)	Wheat bio mass (g)	Yield $t.ha^{-1}$	Thousand kernel mass (g)	Hectolitre mass ($kg.\ hL^{-1}$)	Protein Content (%)
Pyroxasulfone	Dose (D)	*	*	ns	ns	*	ns	*	*	ns	ns
	Application (A)	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
	Residue (R)	ns	ns	*	ns	ns	ns	ns	ns	ns	ns
	D*A	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
	D*R	*	ns	ns	ns	ns	ns	*	ns	ns	ns
	A*R	ns	ns	ns	*	ns	*	ns	ns	ns	ns
	D*A*R	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Prosulfocarb plus triasulfuron	Dose (D)	*	ns	ns	*	*	*	*	ns	ns	ns
	Application (A)	*	ns	ns	ns	ns	ns	ns	ns	ns	ns
	Residue (R)	*	ns	*	ns	ns	ns	ns	ns	ns	ns
	D*A	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
	D*R	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
	A*R	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
	D*A*R	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns

*= denotes significant interaction between respective factors ($p \leq 0.05$), ns= denotes no significant between respective factors p (>0.05)

Table 5. 19: Analysis of variance (ANOVA) table on different parameters at Tygerhoek

Herbicides	Tygerhoek	Weeds population 7 WAP (m^{-2})	Weeds population anthesis (m^{-2})	Wheat plants population 7 WAP (m^{-2})	Wheat plants population. anthesis (m^{-2})	Weed biomass (g)	Wheat biomass (g)	Yield $t.ha^{-1}$	Thousand kernel mass (g)	Hectolitre mass (kg. hL^{-1})	Protein Content (%)
Avadex	Dose (D)	ns	*	ns	ns	ns	*	ns	ns	ns	*
	Application (A)	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
	Residue (R)	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
	D*A	ns	*	ns	ns	ns	ns	ns	ns	ns	ns
	D*R	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
	A*R	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
	D*A*R	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns

*= denotes significant interaction between respective factors ($p \leq 0.05$), ns= denotes no significant between respective factors p (>0.05)

Table 5. 20: Analysis of variance (ANOVA) table on different parameters at Langgewens .

Herbicides	Langgewens	Weeds population 7 WAP (m^{-2})	Weeds population anthesis (m^{-2})	Wheat plants population 7 WAP (m^{-2})	Wheat plants population. anthesis (m^{-2})	Weed biomass (g)	Wheat biomass (g)	Yield $t.ha^{-1}$	Thousand kernel mass (g)	Hectolitre mass ($kg. hL^{-1}$)	Protein Content (%)
Pyroxasulfone	Dose (D)	*	*	*	ns	*	ns	ns	ns	*	*
	Application (A)	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
	Residue (R)	*	ns	ns	ns	ns	ns	ns	ns	ns	ns
	D*A	ns	ns	ns	ns	ns	ns	ns	*	ns	ns
	D*R	*	ns	*	ns	ns	ns	ns	ns	ns	ns
	A*R	ns	*	ns	ns	ns	ns	ns	ns	ns	ns
	D*A*R	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Prosulfocarb plus triasulfuron	Dose (D)	*	*	*	ns	*	*	ns	ns	ns	ns
	Application (A)	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
	Residue (R)	ns	ns	ns	ns	ns	*	ns	ns	ns	ns
	D*A	ns	ns	ns	ns	ns	*	*	ns	*	ns
	D*R	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
	A*R	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
	D*A*R	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns

*= denotes significant interaction between respective factors ($p \leq 0.05$), ns= denotes no significant between respective factors p (>0.05)

Table 5.21: Analysis of variance (ANOVA) table on different parameters at Langgewens and Tygerhoek.

Herbicides	Langgewens	Weeds population 7 WAP (m^{-2})	Weeds population anthesis (m^{-2})	Wheat plants population 7 WAP (m^{-2})	Wheat plants population. anthesis (m^{-2})	Weed biomass (g)	Wheat biomass (g)	Yield $t.ha^{-1}$	Thousand kernel mass (g)	Hectolitre mass ($kg. hL^{-1}$)	Protein Content (%)
Triallate	Dose (D)	*	ns	ns	ns	ns	ns	ns	ns	ns	ns
	Application (A)	ns	ns	*	ns	ns	*	ns	ns	ns	*
	Residue (R)	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
	D*A	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
	D*R	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
	A*R	ns	ns	ns	ns	ns	ns	ns	*	ns	ns
	D*A*R	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns

*= denotes significant interaction between respective factors ($p \leq 0.05$), ns= denotes no significant between respective factors p (>0.05)

5.3.2.3. Weed biomass

Pyroxasulfone

At Tygerhoek, there was no significant interaction between 3 factors (residue cover, dosage rate and application rate) on weed biomass, but the dosage rate did have significant effect ($p \leq 0.0$) (**Table 5.18**). An increase in dosage rate (1.5x) resulted in significantly lower weed biomass, compared to the recommended dosage rate treatment (**Table 5.22**)

Table 5.22: The effect of dosage rate on weed dry mass at Tygerhoek and Langgewens in the pyroxasulfone treatment. Different letters denote means that means differed significantly at $P \leq 0.05$ as per Fishers LSD.

Dosage rate	Weed biomass (g) Tygerhoek	Weed biomass (g) Langgewens
1x	18a	2.5a
1.5 x	3.9b	1.2a

Correspondingly, also in Langgewens there was no significant interaction between 3 factors (residue cover, dosage rate and application rate) on weed dry mass, but the dosage rate did have significant effect ($p \leq 0.0$) (**Table 5.20**). Dry mass recorded at an increased dosage rate (1.5x) was not significantly different from the one recorded at recommended dosage rate treatment (**Table 5.22**) although the ANOVA shows significant differences.

Prosulfocarb plus triasulfuron

At Tygerhoek, there was no significant interaction between 3 factors (residue cover, dosage rate and application rate) on weeds biomass, but the dosage rate did have significant effect ($p \leq 0.0$) (**Table 5.18**). An increase in dosage rate (1.5x) resulted in significantly lower weed biomass than at recommended dosage rate treatment (**Table 5.23**).

Correspondingly, also in Langgewens there was no significant interaction between 3 factors (residue cover, dosage rate and application rate) on weed biomass, but the dosage rate did have significant effect ($p \leq 0.0$) (**Table 5.20**). An increase in dosage rate (1.5x) resulted in significantly lower weeds biomass than at recommended dosage rate treatment (**Table 5.23**).

Table 5. 23: The effect of dosage rate on weeds bimass at Tygerhoek and Langgewens, Boxer and Logran trial treatment. Different letters denote means that means differed significantly at $P \leq 0.05$ as per Fishers LSD

Dosage rates	Weeds biomass (g) Tygerhoek	Weeds biomass (g) Langgewens
1x	35a	15.8a
1.5x	17.8b	6.2b

Triallate

Both at Tygerhoek and Langgewens, there was no significant interaction between 3 factors (residue cover, dosage rate and application rate) or significant differences within treatments on weed biomass, respectively (**Tables 5.19, 5.21).**

5.3.2.4. Wheat biomass

Pyroxasulfone

At Tygerhoek, there was significant interaction ($p \leq 0.05$) between application rate and residue cover on wheat biomass at anthesis (**Table 5.18**). Both at low and high residue covers there were no significant differences in the wheat dry mass attained at recommended application rate and double application rate (**Figure 5.10**). It was only at medium residue cover where wheat biomass recorded at recommended application rate was significantly higher than at double application rate.

On the other hand, at Langgewens, there was no significant interaction between 3 factors (residue cover, dosage rate and application rate) or significant differences within treatments on wheat biomass (**Table 5.20)**

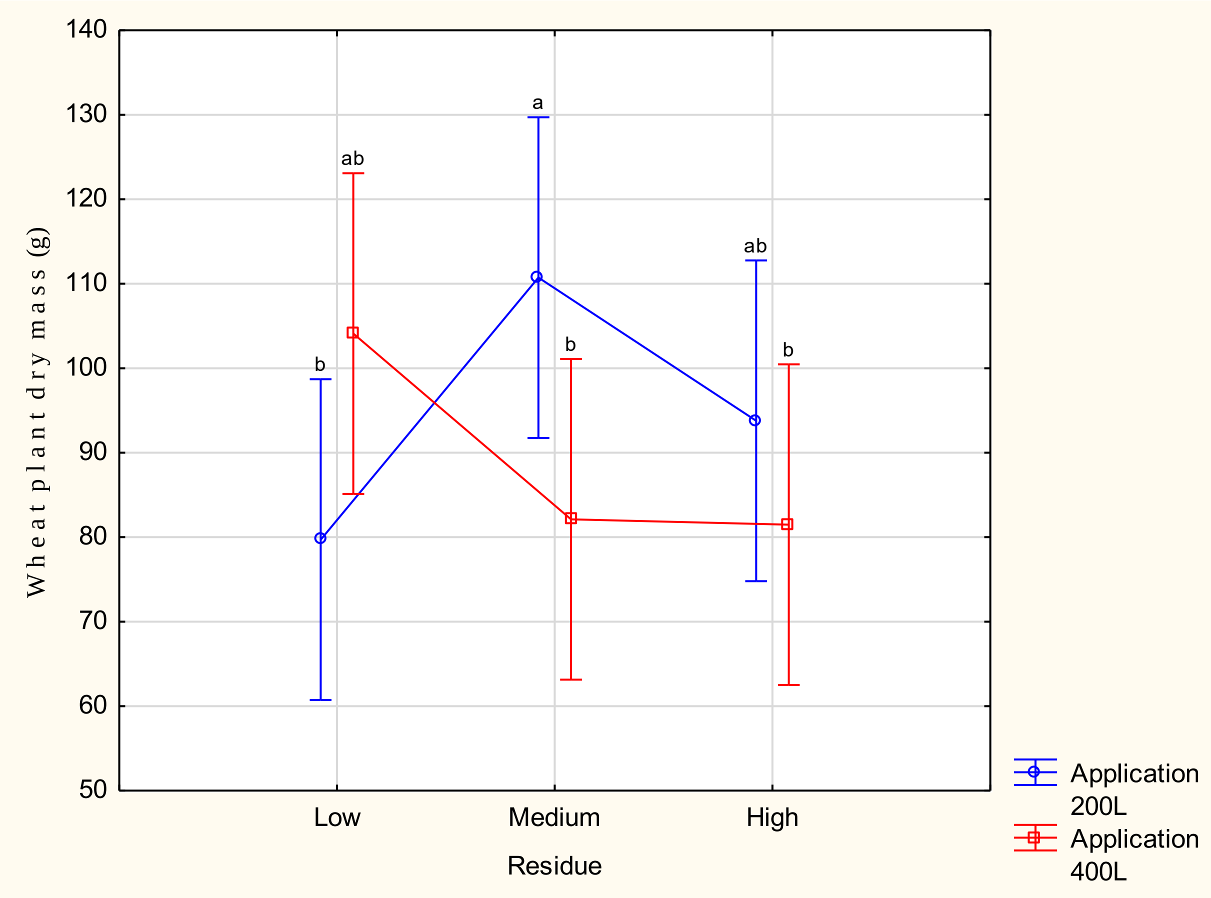

Figure 5. 10: Wheat biomass that were recorded in Tygerhoek in the pyroxasulfone treatment, illustrating interaction between application rate and residue cover. Different letters denote means which differed significantly at p ≤ 0.05 as per Fishers LSD. Vertical bars indicate 0.95 confidence intervals

Prosulfocarb plus triasulfuron

At Tygerhoek, there was no significant interaction between 3 factors (residue cover, dosage rate and application rate) on wheat biomass, but the dosage rate did have significant effect (p ≤ 0.0) (**Table 5.18**) An increase in dosage rate (1.5x) resulted in significantly higher wheat biomass, compared to the recommended dosage rate treatment (**Table 5.24**).

Table 5. 24: The effect of dosage rate on wheat biomass at Tygerhoek in the prosulfocarb plus triasulfuron treatment. Different letters denote means that means differed significantly at P ≤ 0.05 as per Fishers LSD

Site	Dosage rate	Wheat dry mass (g)
Langgewens	1x	67.1b
	1.5 x	94.9a

At Langgewens, there was significant interaction (p ≤ 0.05) between dosage rate and application rate on wheat biomass (**Table 5.20)**. At increased dosage rate the recommended application rate attained largest wheat dry mass and was significantly different from double application rate at increased dosage rate. At recommended dosage rate there were no significant differences in the wheat dry mass between recommended application rate and doubled application rate (**Figure 5.11**).

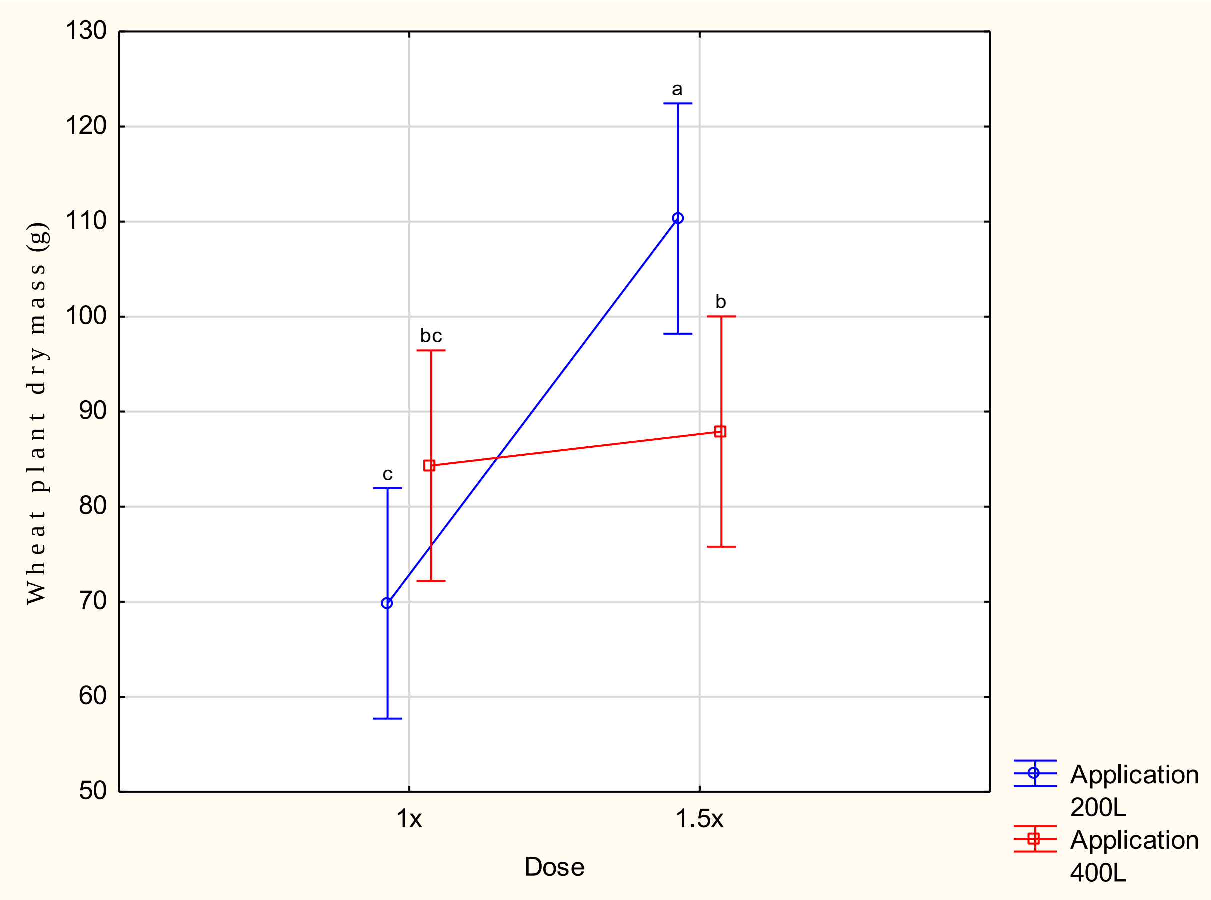

Figure 5. 11: Wheat biomass that was recorded at Langgewens prosulfocarb plus triasulfuron treatment, illustrating interaction between dosage rate and application rate. Different letters denote means which differed significantly at $P \leq 0.05$ as per Fishers LSD. Vertical bars indicate 0.95 confidence

Also, residue cover had significant effect on wheat biomass (**Table 5.20**). Medium residue cover resulted in the largest wheat biomass and was significantly higher than at low and high residue cover (**Table 5.25**). Wheat biomass that was recorded from low and high residue cover were not significantly different from each other.

Table 5. 25: The effect of residue cover on wheat biomass at Langgewens in the prosulfocarb plud triasulfuron treatment. Different letters denote means that means differed significantly at P ≤ 0.05 as per Fishers LSD

Site	Residue cover level	Wheat biomass (g)
Langgewens	Low	82.1b
	Medium	99a
	High	83.2b

Triallate

At Tygerhoek, there was no significant interaction between 3 factors (residue cover, dosage rate and application rate) on wheat biomass, but the dosage rate did have significant effect ($p \leq 0.0$) (**Table 5.19**). The wheat biomass attained at recommended dosage rate was greater and significantly different from the one attained at increased dosage rate (**Table 5.26**).

Table 5. 26: The effect of application rate, dosage on wheat biomass at Langgewens, Tygerhoek respectively, in the triallate treatment. Different letters denote means that means differed significantly at P ≤ 0.05 as per Fishers LSD

Site	Application rate	Wheat biomass (g)
Langgewens	200L	90.4a
	400L	66.5b
Tygerhoek	Dosage rate	Wheat biomass (g)
	1x	78.5a
	1.5 x	58.7b

At Langgewens, there was no significant interaction between 3 factors (residue cover, dosage rate and application rate) on wheat biomass, but the application rate did have significant effect ($p \leq 0.0$) (**Table 5.21)**. The recommended application rate attained largest wheat biomass and was significantly different from double application rate (**Table 5.26**).

5.3.2.5. Yield

Pyroxasulfone

At Tygerhoek, there was significant interaction ($p \leq 0.0$) between dosage rate and residue cover in terms of wheat grain yield (**Table 5.18**).

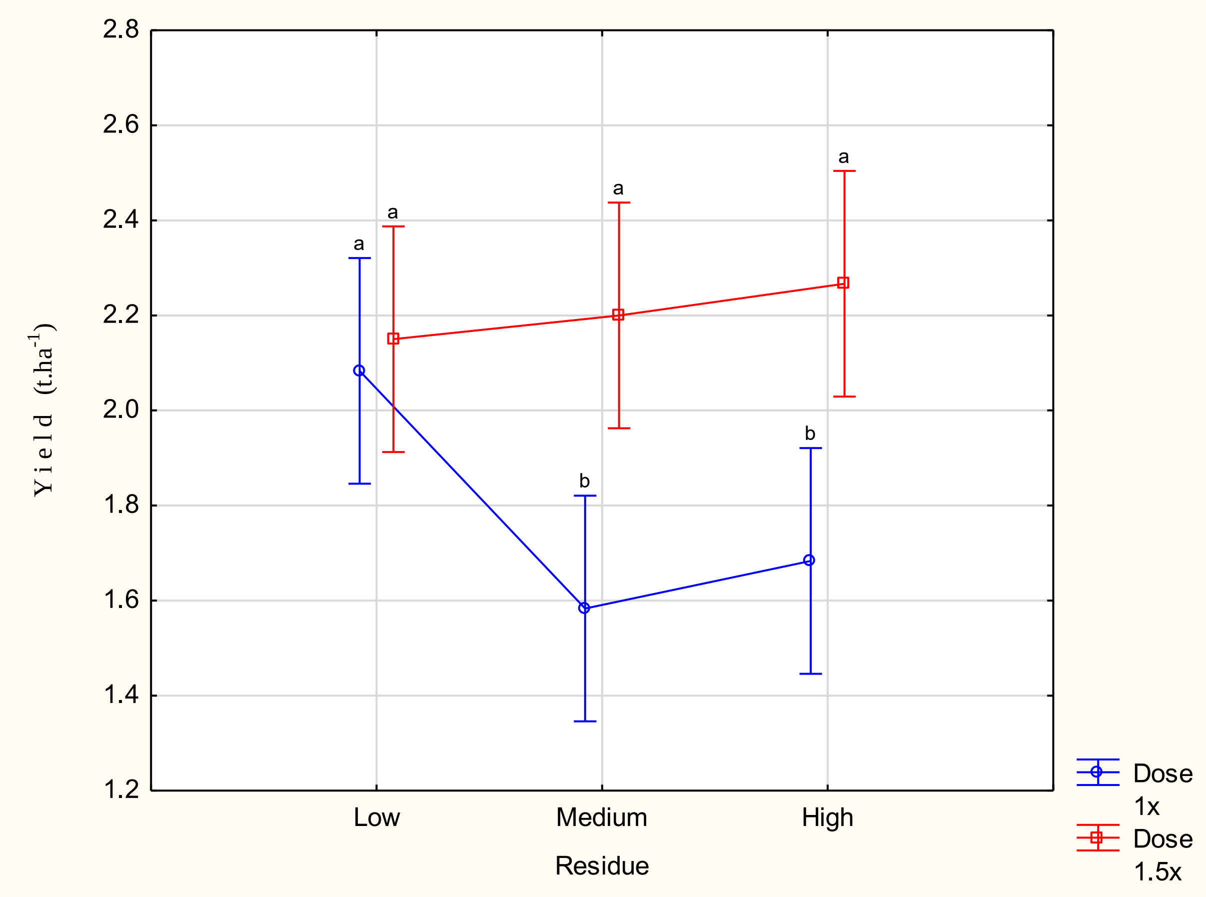

Figure 5. 12: Wheat grain yield that was recorded at Tygerhoek in the pyroxasulfone treatment, illustrating interaction between dosage rate and residue cover. Different letters denote means which differed significantly at $P \leq 0.05$ as per Fishers LSD. Vertical bars indicate 0.95 confidence intervals.

An increase in dosage rate increased the wheat grain yield across all residue covers but it was not significantly different from each other (**Figure 5.12)**. At recommended dosage rate however, an increase in residue cover caused a decline in wheat grain yield, with wheat grain yield recorded at medium and high residue cover significantly lower than the one recorded at low residue cover.

At Langgewens, there was no significant interaction between 3 factors (residue cover, dosage rate and application rate) or significant differences within factors in terms of wheat grain yield (**Table 5.20**).

Prosulfocarb plus triasulfuron

At Tygerhoek, there was no significant interaction between 3 factors (residue cover, dosage rate and application rate) on wheat grain yield but the dosage rate did have significant effect

($p \leq 0.0$) (**Table 5.18**). The wheat grain yield attained at increased dosage rate was greater and significantly different from the one attained at recommended dosage rate (**Table 5.27)**

Table 5. 27: The effect of dosage rate on yield at Tygerhoek in the prosulfocarb plus triasulfuron trial. Different letters denote means that means differed significantly at $P \leq 0.05$ as per Fishers LSD.

Site	Dosage rate	Wheat grain yield ($t\ ha^{-1}$)
Tygerhoek	1x	1.4b
	1.5x	2.1a

On the other hand, at Langgewens there was significant interaction ($p \leq 0.0$) between dosage rate and application rate in terms of wheat grain yield (**Table 5.20**). The higher dosage rate of 1.5x produced significantly higher wheat yield at the 200 L ha-1 application rate but at 400 l ha-1 application rate there was no significant difference between dosage rates (**Figure 5.13**)

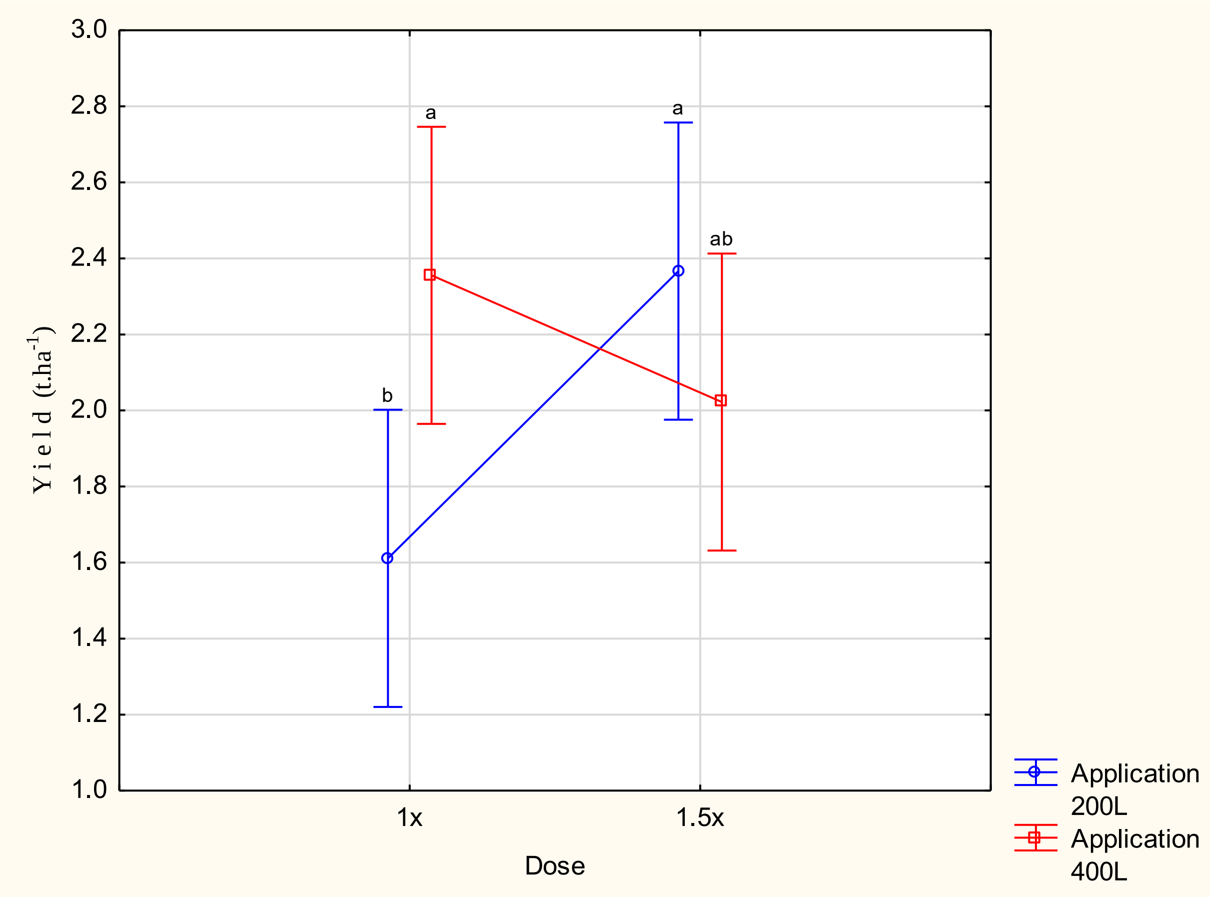

Figure 5. 13: Wheat grain yield that was recorded at Langgewens in the prosulfocarb plus triasulfuron treatment, illustrating interaction between dosage rate and application rate. Different letters denote means which differed significantly at P ≤ 0.05 as per Fishers LSD. Vertical bars indicate 0.95 confidence interval.

Triallate

Both at Tygerhoek and Langgewens, there was no significant interaction between 3 factors (residue cover, dosage rate and application rate) or any significant differences within factors in terms of wheat grain yield, respectively (**Tables 5.19, 5.21**).

5.3.2.6. Thousand kernel mass

Pyroxasulfone

At Tygerhoek, there was no significant interaction between 3 factors (residue cover, dosage rate and application rate) in terms of thousand kernel mass but the dosage rate did have a significant effect ($p \leq 0.0$) (**Table 5.18**). The thousand kernel weight attained at increased dosage rate was greater and significantly different from the one attained at recommended dosage rate (**Table 5.28**).

Table 5. 28: The effect of dosage rate on thousand kernel weight at Tygerhoek in the pyroxasulfone treatment. Different letters denote means that means differed significantly at P ≤ 0.05 as per Fishers LSD.

Site	Dosage rate	Thousand kernel mass (g)
Tygerhoek	1x	38.1b
	1.5 x	39.9a

At Langgewens, there was significant interaction (p ≤ 0.0) between dosage rate and application rate in terms of thousand kernel weight (**Table 5.20**). However, there was no significant differences on thousand kernel weight across all interactions (**Figure 5.14**).

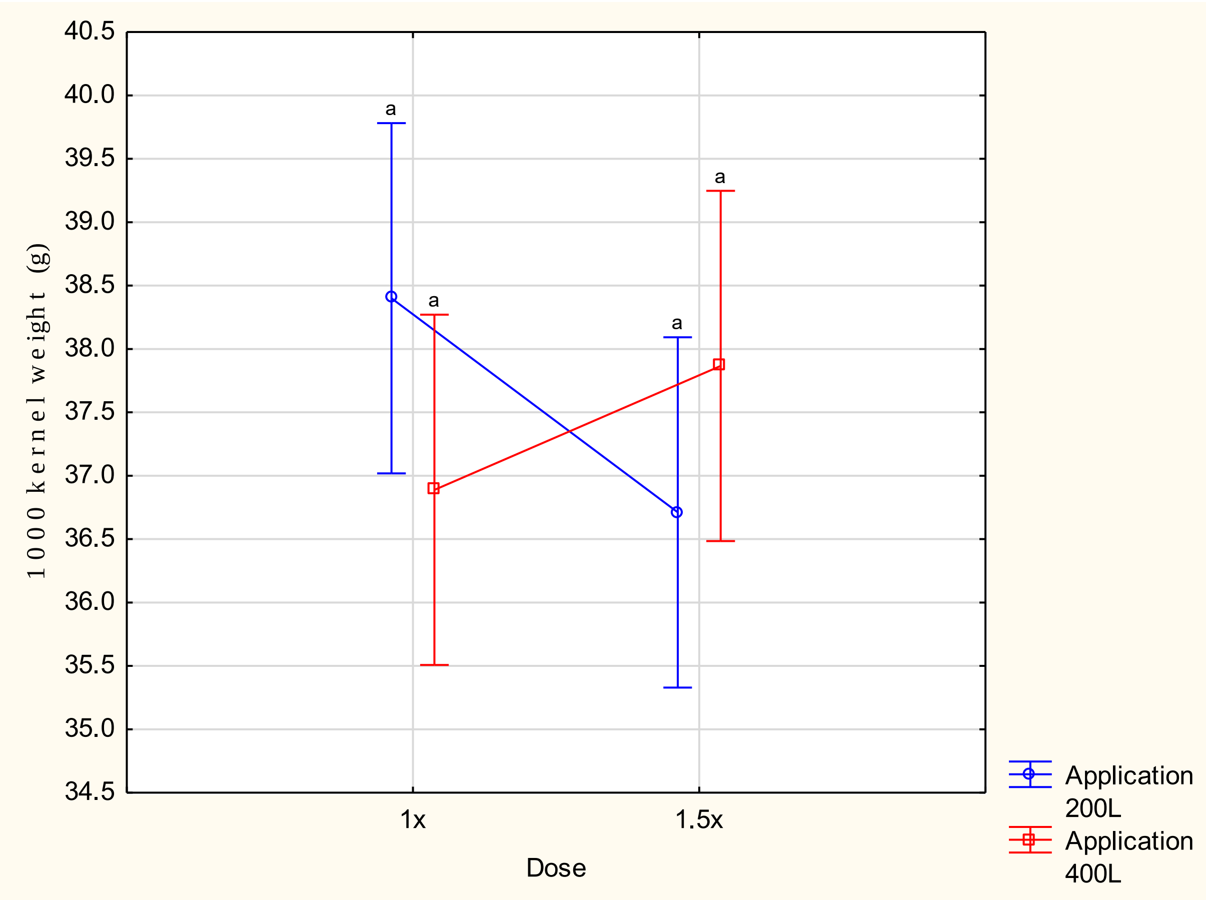

Figure 5. 14: Wheat thousand kernel weight that was recorded at Lanngewens in the pyroxasulfone treatment, illustrating interaction between dosage rate and application rate. Different letters denote means which differed significantly at P ≤ 0.05 as per Fishers LSD. Vertical bars indicate 0.95 confidence intervals.

Prosulfocarb plus triasulfuron

Both at Tygerhoek and Langgewens, there was no significant interaction between 3 factors (residue cover, dosage rate and application rate) or significant differences within factors in terms of thousand kernel mass, respectively (**Tables 5.18, 5.20.**

Triallate

Both at Tygerhoek and Langgewens, there was no significant interaction between 3 factors (residue cover, dosage rate and application rate) or significant differences within factors in terms of thousand kernel mass, respectively (**Tables 5.19, 5.21**).

5.3.2.7. Hectolitre mass

Pyroxasulfone

Both at Tygerhoek and Langgewens, there was no significant interaction between 3 factors (residue cover, dosage rate and application rate) or significant differences within factors in terms of hectolitre mass, respectively (**Table 5.18, 5.20**).

Prosulfocarb and triasulfuron

At Tygerhoek, there was no significant interaction between 3 factors (residue cover, dosage rate and application rate) or significant differences within factors in terms of hectolitre mass (**Table 5.18**).

On the other hand, at Langgewens there was significant interaction ($p \leq 0.0$) between dosage rate and application rate in terms of hectolitre mass (**Table 5.20). **At an application rate of 200 L ha^{-1} there was a significant increase in hectolitre mass when the dosage rate was increased to 1.5x. At the 400 L ha^{-1} application rate however there was no significant difference between the two dosage rates (**Figure 5.15**).

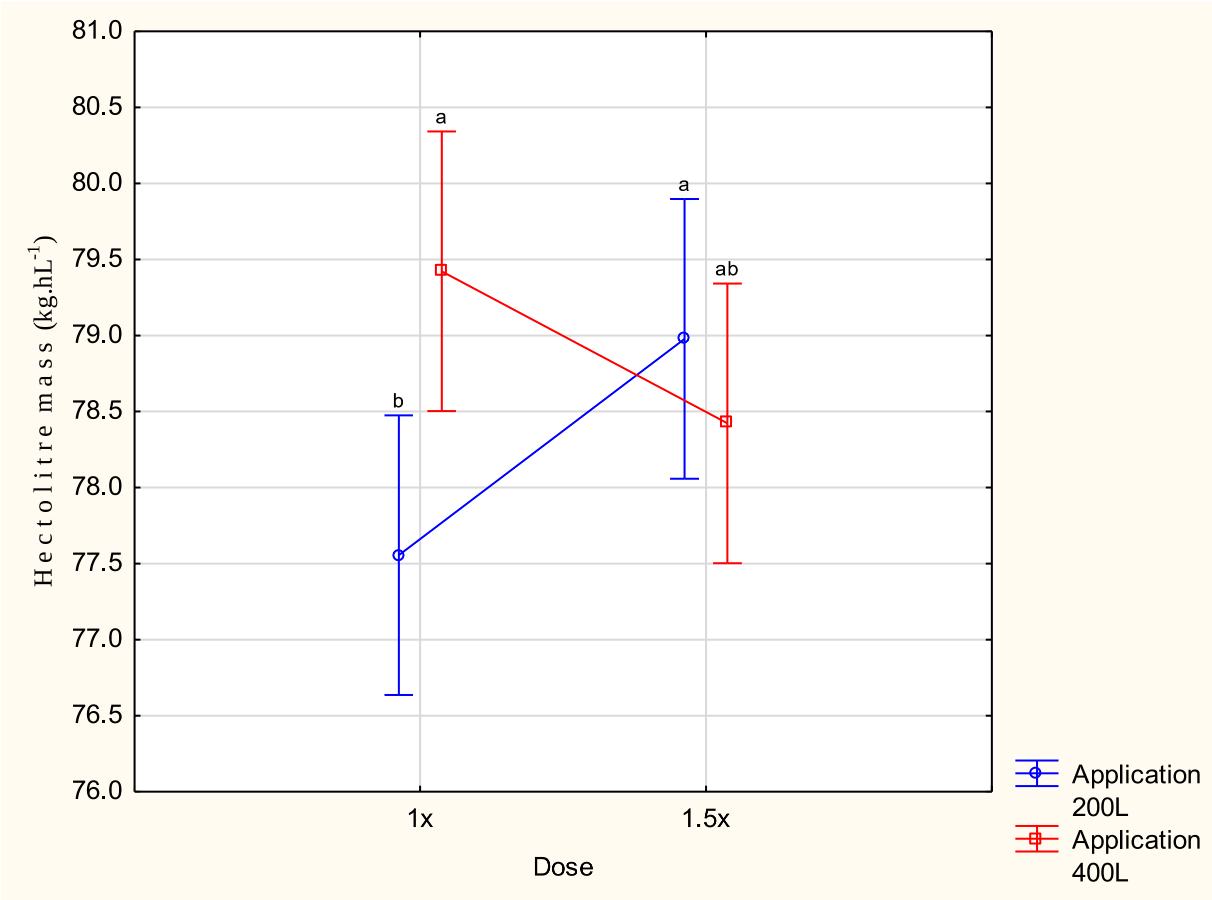

Figure 5. 15: Hectolitre mass that was recorded at Langgewens in the prosulfocarb plus triasulfuron treatment, illustrating interaction between dosage rate and application rate. Different letters denote means which differed significantly at $P \leq 0.05$ as per Fishers LSD. Vertical bars indicate 0.95 confidence intervals.

Triallate

Both at Tygerhoek and Langgewens, there was no significant interaction between 3 factors (residue cover, dosage rate and application rate) or significant differences within factors in terms of hectolitre mass, respectively (**Tables 5.19, 5.21**).

5.3.2.8. Protein content

Pyroxasulfone

Both at Tygerhoek and Langgewens, there was no significant interaction between 3 factors (residue cover, dosage rate and application rate) or significant differences within factors in terms of protein content, respectively (**Tables 5.18, 5.20).**

Prosulfocarb and triasulfuron

Both at Tygerhoek and Langgewens, there was no significant interaction between 3 factors (residue cover, dosage rate and application rate) or significant differences within factors in terms of protein content, respectively (**Tables 5.18, 5.20).**

Triallate

At Langgewens, there was no significant interaction between 3 factors (residue cover, dosage rate and application rate) in terms of protein content, however application rate did have a significant effect ($p \leq 0.0$) (**Table 5.21**). The protein content attained at recommended application rate was not significantly different from the one attained at doubled application rate according to Fischer's LSD test although the ANOVA showed significant differences (**Table 5.29**).

Table 5. 29: The effect of application rate, dosage on different parameters at Langgewens and Tygerhoek, in the triallate treatment. Different letters denote means that differed significantly at $P \leq 0.05$ as per Fishers LSD

Site	Application rate	Protein content (%)
Langgewens	200L	11.2a
	400L	11.3a
Tygerhoek	Dosage rate	Protein content (%)
	1x	11.6a
	1.5 x	10.9b

At Tygerhoek, there was no significant interaction between 3 factors (residue cover, dosage rate and application rate) in terms of protein content, but the dosage rate did have a significant effect ($p \leq 0.0$) (**Table 5.19**). Protein content attained at recommended dosage rate was greater and significantly different from the one attained at increased dosage rate (**Table 5.29**).

5.4 DISCUSSION

The application rate had a limited effect on the number of weeds and weeds biomass. Pyroxasulfone's ability to control weeds at the recommended dosage rate was reduced as the amount of residue cover increased but when dosage rate was increased the efficacy of weed control increased. Even though it may be be expensive for farmers to apply higher dosages but not increasing application rate might be positive in South Africa where we have water scarcity. These findings demonstrate that recommended dosage rates may achieve effective weed control up to the medium residue cover, 4.8 t ha^{-1} to 5.5 t ha^{-1}. However as recommended dosage rate was not able to achieve effective weed control at high residue cover, 9.7 t. ha^{-1} and 11 t. ha^{-1} at Langgewens and

Tygerhoek respectively, increased dosage rates may be needed though it will expensive for farmers.

The failure of pyroxasulfone at higher residue levels can be due to its chemical behaviour. According to Preston (2014) and Khalil (2017) pyroxasulfone has low ability to be intercepted by residue cover but it still needs a certain amount of rain immediately after being applied for it to be washed off the residue cover. During this study at Tygerhoek and Langgewens it took ten days and five days to rain after application, respectively (**Tables 5.2 and 5.1**). Prosulfocarb and triasulfuron also followed the same pattern since it has almost similar characteristics to pyroxasulfone, that are high solubility and it do not bind tightly to residue cover (Preston 2014). Of the three herbicides pyroxasulfone resulted in the best weed control, followed by prosulfocarb and triasulfuron with intermediate performance and triallate that was least effective to control weeds and, in some cases, did not result in significantly less weeds than the unsprayed control treatment. The performance of these herbicides can be attributed to their chemical abilities and their behaviour when they are in contact with organic cover on the soil (Preston 2014). According to Preston (2014), triallate have low water solubility (Yates 2006) and bind tightly on organic cover because it has higher K_{oc}, the soil organic carbon-water partitioning coefficient, compared to pyroxasulfone, prosulfocarb and triasulfuron. The higher the K_{oc} values, the higher the possibilities of herbicide to be bound to organic matter thus reduced amounts of herbicide will be available to reach the soil surface. That can also pose a risk in a near future because as more herbicides is held up on the organic residue it has a potential to injure susceptible crops in following growing seasons (Curran 2001). Preston (2014) further alludes that pre-emergent herbicides have to be absorbed by the germinating seedling from the soil and these herbicides need to have some solubility in water and be in a position in the soil to be absorbed by the roots or emerging shoot.

Triallate has a high half-life (82 days) compared to pyroxasulfone with a medium half-life (22 days) and prosulfocarb and triasulfuron with low to medium half-lives (12-23 days) and it can be present in the soil for long periods of up to 6 months. However it is highly volatile and that is one of its limitations (Atienza et al. 2001, Yates 2006, Preston 2014). The volatility of triallate due to its high vapour pressure means that it can easily dissipate and do not stay in the soil due to lack of moisture in the soil (Müller et al. 1998,Yates 2006, Zhao et al. 2015). In this study it took several days to rain after application in both research sites and that had the potential to have exposed herbicides such as triallate to volatility .Previous studies argued that the binding of herbicides to organic material has a potential to reduce volatility and leaching of herbicides after application (Curran 2001), however that still does not assist in the improvement of herbicide efficacy because that binding effect reduce the amount of herbicide that reach he soil to kill weeds (Preston 2014).

The disc seeder used in this study also does influence the efficacy of pre-emergent herbicides. According to Preston (2014) pre-emergent herbicides with high water solubility such as pyroxasulfone, prosulfocarb and triasulfuron performs very well under disc seeder conditions compared to triallate which performs very well under conventional practices.

In terms of the effect of herbicides on the wheat plans population and wheat biomass the effect of pyroxasulfone at high dosage rates did not differ significantly from prosulfocarb and triasulfuron at high dosage rates. On the other hand, triallate resulted in the lowest number of wheat plants and wheat dry mass and in most cases, it was not significantly different from the unsprayed control. According to previous studies wheat growth parameters such as number of wheat plants and dry mass give an indication of the effect of weeds on plant growth rate (Khan et al 2003, El-Metwally1 et.al 2015). The improvement of wheat growth or the lack thereof is attributed to the reduction or increase of weed competition with wheat plants that influence efficient use of resources needed by the crop to improve their growth (El-Metwally1 et al. 2015).

The wheat grain yield was below the long-term average yield of 3.4 t ha^{-1} for Langgewens and 3.6 t ha^{-1} for Tygerhoek due to erratic rainfall in the 2017 season (Kriel 2018). However, there were some significant differences among herbicide treatments with increased dosage rates of pyroxasulfone and prosulfocarb plus triasulfuron performing better at around 2.1-2.5 t ha^{-1} compared to triallate at increased dosage rate and control which ranged from 1.4-1.9 t ha^{-1} on both farms. Wheat grain yield for increased dosage rates of pyroxasulfone and prosulfocarb plus triasulfuron were above 2 t. ha^{-1} that was almost similar to the average yield that was obtained at Langgewens farm (2.4 t. ha^{-1}) and Tygerhoek farm (2.4 t. ha^{-1}) for the 2017 season (Kriel 2018).

The wheat plants population, wheat biomass and wheat grain yield indicate increasing dosage rates of pyroxasulfone and prosulfocarb plus triasulfuron did not have any phytotoxic effects on the wheat crop. This is in contrast with other research findings which find that increasing the dosage rates of herbicides increases the potential of their phytotoxicity to the crop (El-nahhal and Hamdona 2017). Other previous research argues that it needs to be monitored how increases in dosage overtime have effect on crops planted on the following seasons Curran (2001). However due to chemical behaviour of pyroxasulfone and prosulfocarb plus triasulfuron such as high solubility and short half- life (Preston 2014), phytotoxicity is less likely.

5.5 CONCLUSION

Pyroxasulfone at increased dosage rates (1.5 times the recommended rate) was the best performing herbicide compared to the other two treatments and improved the control of weeds across all residue covers. On the other hand, application rate had minimal impact on the efficacy of all herbicides across all residue cover levels. Prosulfocarb plus triasulfuron at the increased dosage rate was the second-best performing herbicide in terms of weed control. So the farmers practising conservation agriculture can still use recommended dosage rates as long as residue cover is less than 4.8 -5.5 $t.ha^{-1}$ but soon as residue cover is increased to 9.6-11 t.ha, 1.5 times dosage rate is the effective dosage rate for pyroxasulfone in particular That will be an economically viable option for farmers who cannot afford increasing dosage rates, giving them options to stick to certain level of residue cover where they will continue using recommended dosage rates while still achieving conservation agriculture principles. On the other hand triallate performed poorly across residue cover levels, even when the dosage rate was increased its weed control remained poor and, on many occasions, similar to treatment where no herbicide was applied. The other important factor is that even though increase in dosage rate may be expensive to farmers, it has a potential of avoiding more pressure on water resources because there is no need to increase application rate because it has minimal effect. This is critical because of frequent droughts that have been experienced recently, already putting pressure on water usage in agricultural production.

Thus, for conservation agriculture practices (in particular where disc seeders are used for sowing) pyroxasulfone and prosulfocarb plus triasulfuron at 1.5 times the recommended dosage rate should be recommended to be used by farmers where residue levels are increased.

REFERENCES

Arshad MA, Gill KS, Coy GR. 1994. Wheat yield and weed population as influenced by three tillage systems on a clay soil in temperate continental climate. *Soil and Tillage Research*. 28:227–238.

Atienza J, Tabernero MT, Sanz M. 2001. Volatilisation of triallate as affected by soil texture and air velocity. *Chemosphere* 42: 257–261.;

Barba V, Ordax JM. 2018. Recycling organic residues in soils as amendments : Eff ect on the mobility of two herbicides under different management practices. *Journal of Environmental Management* 224: 172–181.

Busi R, Gaines TA, Walsh MJ, Powles SB. 2012.Understanding the potential for resistance evolution to the new herbicide pyroxasulfone : field selection at high doses versus recurrent selection at low doses.*Weed Research* 52: 489–499.

Chauhan BS, Abugho SB. 2012. Interaction of rice residue and pre Herbicides on emergence and biomass of four weed species. *Weed Technology*. 26:627–632.

Cook A, Bates A, Shepperd W, Richter I. 2016. Herbicide efficacy in retained stubble systems https://grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-updatepapers/2016/08/herbicide-efficact-in-retained-stubble-systems. Accessed on 2017/11/02.

Curran WS. 2001. Persistence of herbicides in soil. https://extension.psu.edu/downloadable/download/sample/sample_id/162/. Accessed 2018/12/16

Dickey EC., Jasa PJ.; Shelton DP. 1986. Estimating residue cover. https://digitalcommons.unl.edu/cgi/viewcontent.cgi?article=1256&context=biosysengfacpub.Accessed 2016/05/10

El-Metwally IM, Abdelraouf RE, Ahmed MA, Mounzer O, Alarcon JJ, Abdelhamid MT. 2015. Response of wheat (*Triticum aestivum L.*) crop and broad-leaved weed to different water requirements and weed management in sandy soils. *Agriculture* 61(1): 22-32.

El-nahhal Y, Hamdona N. 2017. Adsorption , leaching and phytotoxicity of some herbicides as single and mixtures tosome crops. *Journal of the Association of Arabian University of Basic and Applied Sciences* 22: 17–25.

Farooq M, Flower KC, Jabran K, Wahid A, Siddique KHM. 2011. Crop yield and weed management in rainfed conservation agriculture. *Soil and Tillage Research* 117: 172-183.

Haskins B. 2012. Herbicides in conservation farming systems using pre-emergent : Top tips for using pre-emergent herbicides.

http://www.dpi.nsw.gov.au/agriculture/farm/conservation/information/pre-emergent-herbicide.Accessed on 2017/010 /27.

Hern E, Gonz L, Chueca C. 2017. Current status in herbicide resistance in Lolium rigidum in winter cereal fields in Spain : Evolution of resistance 12 years after. *Crop Protection* 102:10-18

Khalil Y. 2017. Herbicides and stubble – some wash off, some don't. https://ahri.uwa.edu.au/herbicides-and-stubble-some-wash-off-some-dont/.Accessed 2018/12/3

Khan MH, Hassan G, Khan N, Khan Ma. 2003. Efficacy of different herbicides for controlling broadleaf weeds in wheat. *Asian Journal of Plant Sc*ience 2: 254–256.

Knežević M, Antunović M , Renata Baličević L, Ranogajec L. 2010.Weeed control in winter wheat as afffected by tillage and post-emergence herbiicides. *Herbologia* 11 (2).

Kriel G. 2018**.** Conservation agriculture pays off in drought.

. https://www.farmersweekly.co.za/crops/conservation-agriculture-pays-off-drought/.Accessed 2018/12/10

Preston C. 2014. Understanding pre emergent cereal herbicides. https://grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2014/03/understanding-pre-emergent-cereal-herbicides.Accessed on 2018/11/20.

Wollenhaupt NC, Pingry J. 1991. Estimating residue using line-transect**.**

https://learningstore.uwex.edu/Assets/pdfs/A3533.pdf. Accessed 2016/05/10

Yates SR. 2006. Measuring herbicide volatilization from bare soil. *Environ Sci Technol* 40:3223–3228.

Zhao P, Huang B, Gu K, Zou N, Pan C. 2015. Analysis of triallate residue and degradation rate in wheat and soil by liquid chromatography coupled to tandem mass spectroscopy detection with multi-walled carbon nanotubes. *Int J Environ Anal Chem* 95 (15) : 1413–1423.

CHAPTER 6

GENERAL CONCLUSION AND RECOMMENDATIONS

6.1. CONCLUSION

Retaining of a permanent organic soil cover, which forms a major part of the principles of conservation agriculture (CA), creates challenges when it comes to the effective application of pre-emergent herbicides and the ability of these to reach the soil surface in sufficient amounts. According to Farooq et al. (2011), the failure of herbicides to reach the soil surface is caused by the fact that herbicides become intercepted by the residue cover and sometimes react with the residue that is used as an organic soil cover. This can lead to reduced amounts of herbicides reaching the soil surface (Farooq et al. 2011). This may lead to poor weed management, which may lead to more weed competition and lower crop yields in the short term. In the medium term, it can lead to more seeds reaching the soil seed bank, which results in higher weed pressure in the following planting seasons and, in the long-term, there is the possibility of development of non-target site herbicide resistance.

Therefore, there is a need to develop mechanisms that will improve ability of the herbicide to reach the soil surface. This study aimed to determine at what dosage- and application rates can pre-emergent herbicides efficiently reach the soil surface to control weeds effectively in wheat production systems in the presence of increased levels of residue cover.

Pyroxasulfone's registered dosage rate (125 g ha^{-1}) and recommended application rate (200 L ha^{-1}) demonstrated poor weed control when applied on increased amounts of residue cover. Increasing the dosage rate from 125 g ha^{-1} (1x) to 187.5 g ha^{-1} (1.5x) improved the efficacy of pyroxasulfone, across all residue cover levels. The doubling of the recommended application rate to 400 L ha-^{1} improved the efficacy when applied on an increased residue cover in some limited instances but overall increases in registered dosage rate consistently improved pyroxasulfone efficacy across all levels of residue covers. The prosulfocarb plus triasulfuron treatment at an increased dosage rate (1.5x) was the second-best performing herbicide treatment in terms of weed control. More importantly, increased pyroxasulfone as well as prosulfocarb plus triasulfuron dosage rates did not negatively influence the growth and yield of wheat that is a positive step since increases in dosage rate has potential to damage the crop and impede on its growth.

The application of these herbicides at increased dosage rates had a positive impact on wheat yield as well as some quality parameters such as hectolitre mass and thousand kernel weight. The good performance of these herbicides on increased levels of residue cover can be attributed to their chemical abilities such as high solubility and the fact that they do not bind tightly when in contact with organic cover on the soil. On the other hand, triallate performed poorly across all residue cover levels. Even at increased dosage rates weed control remained poor and, on many occasions, did not result in significantly better crop yields than the untreated control. This is probably due to its chemical composition such as low solubility, high volatility and high ability to bind to the residue cover.

6.2. LIMITATIONS OF THE STUDY

The amount of residues on the different fields that was available for the trials varied considerably. Only at Langgewens in the pyroxasulfone trial was it possible to obtain enough wheat straw to manipulate the amount of residue cover accurately to specific levels. In the other trials on Tygerhoek in 2016 and 2017 and on Langgewens in 2017 there was not access to large amounts of residue to do proper manipulation. However, manipulation was done by arranging the available residue into available amount of cover, followed by low amounts of cover and then double the amount of available cover. These residue amounts therefore varied between trials and also within trials and meaningful conclusions regarding the effect of the herbicides on accurately known amounts of residue cover was not possible. However, the different amounts of residue cover in the different fields more accurately resemble the situation on commercial farms where variable amounts of residue cover occur. The overall conclusions in the trials with the variable cover levels however did not differ from the conclusions of the trial with the accurately manipulated levels of residue cover. It is therefore probably safe to say that the main trends observed in these trials are applicable to different commercial farm conditions.

Another limitation was the weather conditions over the two years. In both years rainfall at both localities was under-average with 2017, at Langgewens in particular, one of the driest years in history. Probably more important from the perspective of this study, is that little and late rains in the sowing season was experienced in both years at both localities. Therefore, in all trials the wheat was sown in dry soil, and hence the herbicides were applied in dry soil. The fact that several days or even weeks passed after sowing and herbicide application before it rained might have influenced results. If the herbicides were applied under moist conditions, or if it rained within a day of application, triallate might have performed better due to less volatilisation and the other two herbicides might have performed poorer due to stronger binding of the chemicals to the residues

(Preston 2014). With the perceived trend of lower and later precipitation during sowing time in the winter rainfall areas, these results however are applicable to wheat production systems, but needs to be tested under moist sowing conditions.

6.3. RECOMMENDATIONS

The most important conclusion of this study is that it is not necessary to apply more pressure on scarce water resources because an increase in application rate has minimal effect on the efficacy of the herbicides. This is critical because of frequent droughts experienced recently already putting pressure on water usage in agricultural production.

Farmers practising conservation agriculture can still use recommended dosage rates as long as residue cover level is below 4.8 - 5.5 t. ha^{-1}. However, as soon as residue cover is increased to 9.6-11 t ha^{-1}, then 1.5 times the recommended dosage rate is needed for pyroxasulfone in particular. Farmers who cannot afford increasing the dosage rate, have the option to manage residues to stay below a certain level (*ca* 5 t ha^{-1}).

As was mentioned above, these results were obtained under conditions of dry sowing and herbicide application. It is important that these investigations be repeated under moist sowing conditions to determine if the results will be constant. The use of disc or tine planters may also play a role, because in these trials only disc planters were used, and it is advisable to also look at the performance of the herbicides when applied when planting is done with a time planter. The higher dosage rates should also be tested on different soil types, since more sandy soils may result in crop damage if the registered dosage rates of the herbicides are exceeded.

REFERENCES

Farooq M, Flower KC, Jabran K, Wahid A, Siddique KHM. 2011. Crop yield and weed management in rainfed conservation agriculture. *Soil & Tillage Research* 117: 172-183

Preston C. 2014. Understanding pre emergent cereal herbicides. https://grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2014/03/understanding-pre-emergent-cereal-herbicides.Accessed on 2018/11/20.