THE EFFECTS OF CHLORMEQUAT CHLORIDE AND ETHEPHON ON SELECTED SMALL GRAIN CEREALS IN SOUTH AFRICA

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DECLARATION

I hereby declare that the information contained in the following dissertation is the result of my own research unless otherwise stated.

Signed:.............................

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I, Peter Greenfield supervised the above candidate in the conduct of his dissertation study.

Signed:............................. P. S. Greenfield

Peter Greenfield

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ABSTRACT

Lodging poses a serious limitation to successful economic production of small grain cereals and can lead to extensive yield and quality losses. Plant growth regulators (PGR's) that reduce plant height and lodging have been employed in management systems in Europe and the United States, however, these compounds have not been evaluated on commercial cultivars of wheat, barley and oats in South Africa. Current recommendations to reduce lodging include limiting N inputs, seeding rates and critical irrigations, all of which may also limit yield potential and grain quality. The objectives of this study were to assess the effects of two common stem-elongation-inhibiting PGR's (chlormequat chloride and ethephon) on the growth, development, and agronomic characteristics of wheat, barley and oats. The aim of the study was to introduce an additional component of intensive cereal management in the form of PGR's, and to allow producers to implement intensive production practices without incurring losses due to lodging.

Field trials were conducted with each of the three cereal crops in the 2003 and 2004 seasons at Vaalharts and Bethlehem. The PGR's were applied separately and in combination with each other to lodging-tolerant and -susceptible cultivars (wheat and oats) at different stages of development (tillering, elongation, flag leaf stage). The PGR's were also tested in combination with different levels of N (barley) applied at the haulm elongation stage, the flag leaf stage, or both. The PGR chlormequat produced negligible effects on plant height, lodging, yield, or quality components in all of the tested cultivars. Ethephon and the PGR combination successfully reduced plant height (by 120 to 150mm) and lodging (by 25 to 94%) when applied to the lodging susceptible cultivars of wheat and oats at the flag leaf stage or as a split application to the barley cultivar "Puma" (plant height and lodging reduced by 180 to 230mm and 83 to 92% respectively). Effects on grain yield were variable, ranging from occasional reductions (by 3 t ha^{-1}) and improvements (by 1 t ha^{-1}) with the barley, and no effects with the wheat and oats. Wheat quality parameters such as protein content and hectolitre mass were improved by 2 and 4% respectively. However, the nature of the responses was highly dependent on the times of application with later applications producing the greatest positive effects on quality, yield and lodging reductions. Additionally, ethephon and the PGR combination allowed higher levels of N to be employed without increases in lodging of barley. Generally, ethephon and the PGR combination applied at the flag leaf stage of growth are suitable anti-lodging tools for small grain cereal production and should be employed as an insurance measure against lodging in intensive management systems.

INTRODUCTION

Small grain cereals dominate world agricultural production as they directly or indirectly provide a major portion of human nutrition. They are considered to be some of the most important and widespread food crops in the world with more than 590 million tons of wheat produced globally in the past decade (Anon, 2004). The most important areas of small grain production in the world include China, as well as areas within Europe, where more than 95% of the rye, 60% of the oats, about 50% of the barley and wheat, and approximately 1% of the rice are produced (Gooding & Davies, 1997). In South Africa, a significant proportion of agricultural land is dedicated to small grains with production figures for the 2003/04 season being 1.4, 0.23, and 0.015 Mt for wheat, barley, and oats, respectively (Anon, 2004).

Small grain production under irrigation in South Africa contributes a significant proportion to total small grain productivity. Wheat produced under irrigation constitutes approximately 20% of total wheat production (Barnard *et al.*, 2005). Some of the major irrigation areas in South Africa include parts of the Free State, Northern Cape, North West, Mpumalanga and Kwa-Zulu Natal with most of the emphasis being placed on wheat, barley and oat production. The management strategies employed in these regions differ and are primarily dependent on the environment, the producer and the crop. In an attempt to achieve higher harvestable yields in cereals there has been a tendency to increase nitrogen inputs and seeding rates (Mohamed *et al.*, 1990). This is a trend that is evident in South Africa and internationally. Unfortunately the generous use of nitrogenous fertilizers, higher seeding rates and irrigation, which is necessary to produce high yields of good quality grain, can lead to excessive vegetative growth which predisposes the plant to weakening of mechanical tissue and consequently, to lodging. These practices have therefore simultaneously increased incidences of lodging, thereby enhancing potential yield losses (Herbert, 1982).

Lodging occurs when plant mechanical tissue has been weakened by certain factors such as adverse weather conditions, crown and stem diseases, poor or excessive plant nutrition, and management practices such as high seeding rates (Gooding & Davies, 1997). Additionally, high spike masses created by high yields cannot be sustained by existing stem strength. These factors often result in the bending or falling over of the crop which causes loss in harvesting efficiency (a lodged crop takes longer to harvest than a standing crop and has greater harvest losses), reduction in yield, preharvest sprouting losses, increased disease incidence, reduction in quality, and poor canopy display (Paulsen, 1987). Yield reductions of up to 40% have been reported when lodging occurs at anthesis (Herbert, 1982).

Plant breeding programs have, to a certain extent, developed lodging-tolerant cultivars with short, stiff straw and high harvest indexes, however, the problem of lodging has not been eliminated (Cox & Otis, 1989). This is especially true in the irrigation areas of South Africa where some cultivars of wheat, barley and oats are still prone to lodging. Lodging losses have been reported with taller, older cultivars as well as modern, shorter cultivars (Fischer & Stapper, 1987). An option, which has not been investigated in South Africa, is the use of plant growth regulators (PGR's) on the lodging-susceptible irrigation cultivars produced in this country.

Plant growth regulators are used in certain countries in Europe, the United States of America and Canada as part of an Intensive Cereal Management (ICM) strategy (Wiersma *et al.*, 1986). Other components of such a strategy include irrigation, high nitrogen inputs, high seeding rates and extensive disease control. The ultimate aim of ICM is to improve yield potential while at the same time eliminating the risks of lodging through the application of PGR's. These products primarily work by reducing internode elongation of plants thereby creating a shorter plant that is more tolerant to lodging (Dahnous *et al.*, 1982). The subsequent effects on souce-sink relations, assimilate transport, canopy architecture and growth rate may lead to beneficial effects on yield and quality as demonstrated by most of the researchers that have investigated these products (Cox & Otis, 1989; Khan & Spilde, 1992; Webster & Jackson, 1993; Stahli *et al.*, 1995). There has been extensive work done in other countries, and to a lesser extent in South Africa, on the effects of PGR's on cereal growth and development. The beneficial effects of these products were identified forty years ago when much of the initial research was conducted (Tolbert, 1960). Following the initial research, these products are currently being implemented in management systems around the world (Rajala *et al.*, 2002). Research done in South Africa during that period (from 1960 until now) produced inconsistent results; consequently no sound recommendations were made (Barnard & Burger, 2003).

As a result of inconsistencies in the trial data, no follow up research was conducted and the commercial use of PGR's in South Africa is limited. Producers that did include these PGR's as part of their management strategies were doing so using recommendations from research done in other countries on completely different cultivars. At present, local producers do not have any scientific data or recommendations suited to South African conditions to assist them in the choice or implementation of such products. Additionally, much of the previous research was done on older cultivars with lower yield potentials. With the introduction of modern, higher yielding cultivars, the risks that are involved in production have increased. This situation is evident in the irrigation areas of South Africa where significant lodging losses with modern cultivars have been reported (Barnard &Burger, 2003).

It is therefore necessary to re-visit PGR research in South Africa as the possible advantages and applications of these products may have been overlooked in the past. Local producers may possibly be unaware of the potential use of PGR's as valuable chemicals to inhibit lodging. What is therefore needed is a thorough investigation into the use of PGR's as a solution to the problem of small grain lodging in South Africa. In addition to this the possible beneficial effects on yield and quality may improve income for producers. Such research may ultimately allow local producers to make use of intensive management practices to improve yield and quality without incurring potential losses from lodging. This study aims to investigate some of the issues concerning the use of PGR's as a tool to prevent lodging in South African irrigated small grains. Aspects such as type of PGR, times of application, and cultivar responses were investigated in order to optimize the use of PGR, and to introduce a potential component of an intensive small grain cereal management strategy.

CHAPTER 1

LITERATURE REVIEW

1.1 Plant growth regulators (PGR's) in the cereal industry

The primary active ingredients that are utilized as stem shortening agents in cereal production are ethephon [(2-chloroethyl) phosphonic acid] and chlormequat chloride[(2-chloroethyl) trimethylammonium chloride] (Nafziger *et al.*, 1986). These ingredients may either be used individually or in combination with each other or with other chemicals to produce a range of commercial products currently available for lodging control in cereals. The discussions in this chapter as well as chapters to follow will therefore focus on these two active ingredients instead of the individual commercial products of which there are numerous variations.

1.1.1 Development and mode of action

The development of stem elongation-restricting PGR's for cereals began in the early 1960's when Tolbert (1960) summarized the basic properties of the compound chlormequat. It was shown that the most characteristic growth change after application of chlormequat was a reduction in the height of plants accompanied by an increase in stem diameter. Also, the effects of this compound were found to be contrary to those obtained with gibberellins, and in addition, its effects were reversed by gibberellin treatments. It was therefore concluded that the actions of gibberellins and chlormequat were mutually antagonistic (Tolbert, 1960).

Following Tolbert's (1960) findings, it was later discovered that chlormequat acts by inhibiting gibberellin biosynthesis through blocking one of the pathways to its synthesis rather than interfering with gibberellin action in the cell (Paleg *et al.*, 1965). The findings of Paleg *et al.* (1965) were further supported by other researchers (Lowe & Carter, 1972). The gibberellin hormones act by stimulating and promoting cell elongation in plants. Chlormequat works by blocking gibberellin synthesis thereby preventing normal elongation of the plant's haulms. This ultimately produces a shorter plant, which is more tolerant to lodging.

Research on the PGR ethephon began in the late 1960's and early 1970's when it was discovered that its application from the early boot to the late boot stages of plant development reduced plant height and lodging in wheat and oats (Warner, 1969). Much of this work led to the commercial use of ethephon for lodging prevention in wheat. With the introduction of intensive management practices, the use of ethephon gained wide agronomic acceptance, and it was later identified as an ethylene-releasing compound (Brown & Earley, 1973).

The compound ethephon is spontaneously hydrolyzed in water to produce ethylene (Lurssen, 1982). This reaction is base-catalyzed, requiring no enzymatic activity (Caldwell *et al.*, 1988). Ethephon is therefore a source of ethylene, and has also been shown to stimulate further ethylene production in the plant (Caldwell *et al.*, 1988). Ethylene inhibits the synthesis and movement of indolylacetic acid (IAA, auxin) in stem tissues, thereby reducing auxin's ability to promote stem elongation (Danhous *et al.*, 1982). The result is similar to that obtained with application of chlormequat i.e. a reduction in stem elongation thereby creating a shorter plant that is more tolerant to lodging.

Following the success of the use of chlormequat and ethephon as valuable tools against lodging, development then began on products that contained combinations of these active ingredients (Herbert, 1983). There are presently many products currently on the market that contain chlormequat and ethephon as active ingredients. These products either mimic the effects of either active ingredient or they produce completely different effects.

1.1.2 Applications in the cereal industry

Plant growth regulators are primarily employed as growth retarding compounds in the cereal industry (Tripathi *et al.*, 2004). The commercial products are most often water-soluble formulations and can be applied as a foliar spray or seed treatment (Green, 1986). Greater success has been obtained with applications as foliar sprays compared with seed treatments (Tolbert, 1960), and foliar applications have therefore become more prevalent. However, there has been considerable controversy over the correct timing of applications of these compounds (Woolley *et al.*, 1991).

1.1.2.1 Time of application

After its discovery in the 1960's, chlormequat gained widespread usage as a foliar spray applied during the stem elongation stage of growth of wheat (Humphries *et al.*, 1965). It was later discovered that application during the three to five-leaf stage of growth produced similar and sometimes superior results in terms of lodging and yield compared with later applications (Kettlewell *et al.*, 1983). A substantial amount of research was conducted to identify the most beneficial time of application, however, no sound recommendations could be made due to contradictory results (Myhre *et al.*, 1973). Figure 1a and b demonstrate the effects of different times of application of chlormequat on yield and lodging of wheat. According to Figure 1a and b, applications at the tillering stage are most beneficial with regard to both lodging reduction and yield improvement.

Despite evidence that chlormequat application during the early stages of growth may lead to beneficial effects on yield and lodging, current recommendations for South African production state that applications should be made at the time of stem elongation (Vermeulen *et al.*, 2000). In addition, limited research has been conducted on the application of chlormequat at later stages of growth (e.g., flag leaf stage). It has been postulated that the later the spraying the more the inhibition of elongation shifts to the higher internodes where intercalary meristematic activity is prevalent at the time of application, and, because these are the longest internodes of the haulm, the total effect on plant height will be more pronounced. Bruinsma (1982) stated that applications at very early growth stages gives a strong stem base, but that a subsequent recovery response by the plant can reduce the overall shortening effect of the treatment. These contradicting conclusions clearly indicate the need to investigate the different times of application of chlormequat.

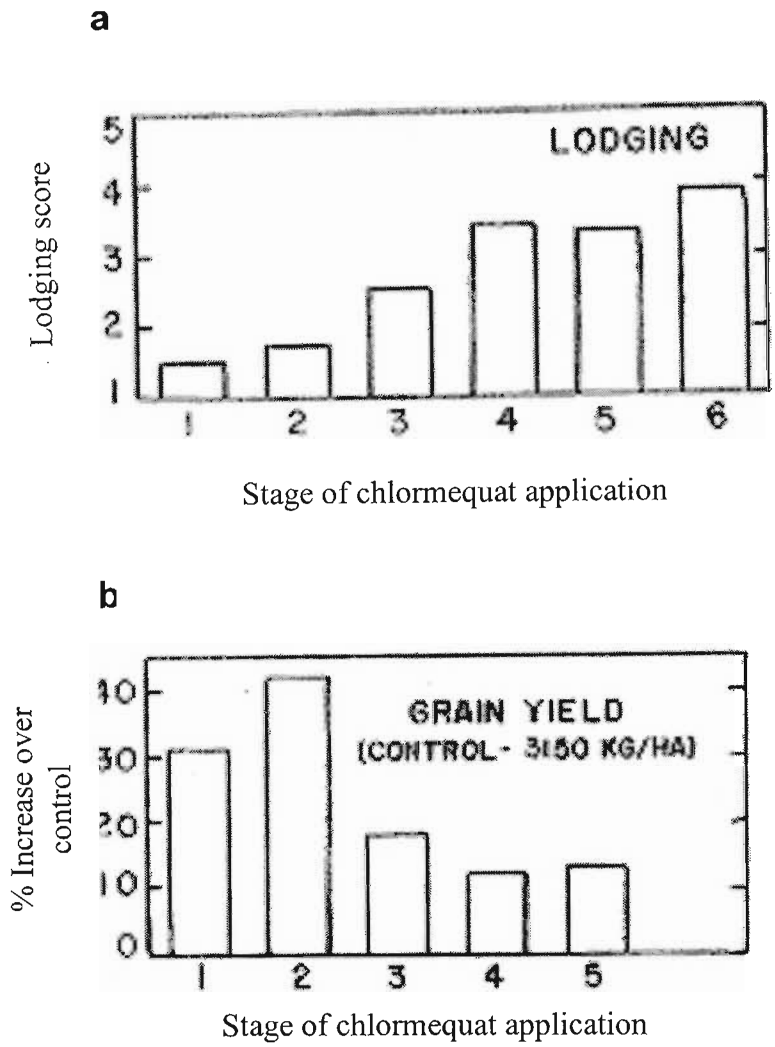

Fig. 1. The influence of single foliar applications (1-fifth leaf; 2-tillering; 3-spike emergence; 4-booting; 5-heading; 6-control) of chlormequat on lodging (1-no loding; 5-severe lodging) (a) and yield (b) of wheat (from Myhre *et al.*, 1973).

The compound ethephon is normally applied at the flag leaf stage of growth and exerts an extension-inhibitory effect on the upper internodes only (i.e. mainly the peduncle) (Brown & Earley, 1973). Reports have shown that applications of ethephon during stem elongation in barley have similar effects to the later applications and may in fact improve yield and lodging tolerance (Moes & Stobbe, 1991). Other researchers have also reported that application of ethephon to wheat during stem elongation is effective in reducing plant height and lodging (Caldwell *et al.*, 1988).

Ethephon acts by releasing ethylene in the plant by a slow release mechanism (Lurssen, 1982). Taking this into consideration, one would therefore expect ethylene evolution to continue slowly and constantly even if ethephon is applied at an earlier stage of growth. This would imply that if the compound is applied at earlier stages in plant growth there could be possible growth retarding effects on both lower and upper internodes thereby having a greater effect on final plant height. Further investigations are necessary to test this theory.

1.1.2.2 Dosages and additives

The effects of rates of application of PGR's are highly variable and are dependent on factors such as cultivar, environment, type of active ingredient and time of application. Specific dosage rates may have variable effects on different plant characters. Brown & Earley (1973) found no differences in yield after ethephon application at different rates (0.28, 0.56, 1.12, and 2.24kg ha^{-1}), however, plant height was significantly reduced at the higher rates of application. In contrast to this, Foster & Taylor (1993) found simultaneous reductions in height and lodging as well as improvements in yield as increasingly higher rates of ethephon (0.1, 0.28, and 0.5kg ha^{-1}) were applied to a barley cultivar. Tolbert (1960) showed that plant height was reduced progressively as increasing concentrations of chlormequat were applied to wheat.

The recommended dosages of lodging controlling PGR's in South Africa are 2.1L ha^{-1}, 1-1.25L ha^{-1} and 2-2.5L ha^{-1} for chlormequat, ethephon and mixtures of chlormequat and ethephon, respectively (Vermeulen *et al.*, 2000). The slow release of ethylene by ethephon and the inhibition of gibberrellin by chlormequat result in similar effects on plant growth, irrespective of the dosages employed. However, there are implications that the magnitude of the effects are greater with higher dosages (Tolbert, 1960).

Many researchers have reported the use of various mixtures and additives together with PGR's. Woolley *et al.* (1991) reported that addition of an acidified soy lecithin adjuvant to chlormequat further improved the shortening effect of the treatment by 8% averaged over three cultivars of wheat. Kettlewell *et al.* (1983) made use of sticking and wetting agents to improve chlormequat uptake in wheat trials. Stahli *et al.* (1995) reported that the addition of the herbicide imazaquin to chlormequat led to improvements in wheat flag leaf surface area, net CO_2 assimilation rate and grain yield by 6.3%, 2%, and 2.3% respectively, as compared to the standard chlormequat treatment. There is a limited amount of research done on the inclusion of additives in PGR's (Kettlewell *et al.*, 1983; Stahli *et al.*, 1995). However, the reports mentioned, and others give an indication of possible benefits of using additives and further research is therefore necessary to test the effects on a larger scale.

1.2 Effects of PGR's on vegetative growth

Endogenous levels of phytohormones control many aspects of plant growth and development. Synthetic PGR's either mimic the effects of phytohormones or they interfere with the biosynthesis, translocation, or metabolic conversion of phytohormones (Bruinsma, 1982), and are thus used to manipulate plant form and development. The PGR's chlormequat and ethephon exert their effects by changing the levels of the phytohormones gibberrellin and ethylene, respectively. The plant hormones direct various aspects of growth from germination until seed maturation.

1.2.1 Tiller production and survival

Tillering is an important process that contributes greatly to the attainment of optimal yields in small grain cereals. Tillering is responsible for the capacity of cereals to compensate for fluctuations in plant population (different seeding rates or uneven emergence) and hence produce stable yields (Hutley-Bull & Schwabe, 1982).

Most reports on the effects of chlormequat on tillering indicate that the product may be beneficial in enhancing tiller production and survival. Tolbert (1960) first reported enhanced and earlier tillering of young wheat plants treated with chlormequat within a few days after treatment with the compound. The improvement in tillering also led to the production of bushier plants, which has implications in terms of dense canopy production. Humphries *et al.* (1965) showed that application of chlormequat to wheat at the sixth leaf stage improved tillering in general and this was the main reason for the 5% increase in grain yield observed. Kettlewell *et al.* (1983) found that chlormequat had no effect on the number of tillers per plant, however, the number of ears m^{-2} was increased by 12% on average at harvest. It was suggested that the chlormequat treatment probably enhanced tiller survival.

The impact of chlormequat on tiller production and tiller survival is dependant on the time of application of the compound. It seems plausible that application after the tillering phase is completed may improve tiller survival (Kettlewell *et al.*, 1983), while application before or during tillering may improve tiller production (Green, 1986).

There are numerous hypotheses that outline the methods by which chlormequat affects tiller production and survival. It has been suggested that the reduction in growth and elongation of the main shoot after chlormequat application (due to it's anti-gibberellin properties) allows greater assimilate availability for tiller production and survival (Green, 1986). Alternatively, smaller plants with shorter and hence more upright leaves may lead to better light penetration into the canopy. This may allow more efficient light interception by developing tiller leaves, consequently improving assimilate supply and tiller survival (Bruinsma, 1982). Craufurd & Cartwright (1989) reported that chlormequat had a similar effect to imposing short days i.e. a reduction in the rate of development. They suggested that the application of chlormequat slows down the primordial developmental rate thereby allowing more time for tiller primordia to be initiated and this ultimately improves tiller number. It is also possible that chlormequat improves tiller production and survival through a combination of the above processes and further investigations are necessary to determine the exact mechanism.

Ethephon has also been reported to improve tiller production in cereals. Rajala & Peltonen-Sainio (2001) reported that the application of ethephon at the three-leaf stage led to significant improvements in tiller number of 26, 32 and 39% in wheat, barley and oats, respectively. Woodward & Marshall (1988) recorded a 40% increase in the number of tillers produced in barley plants after treatment with ethephon. It was also found that elongation of these tiller buds generally increased with ethephon application.

Ethephon is most often applied to small grain cereals at the flag leaf stage and one would therefore expect very little effect on tillering. However, Foster *et al.* (1991) found that ethephon, applied at 0.6 kg ha^{-1}, stimulated late tillering in barley by 85% after application at the flag leaf stage. Unfortunately, these tillers did not mature in time to contribute to grain yield, and in general, grain yields were unaffected. It was suggested that ethephon application earlier in the season may be a means of promoting tillering and giving the newly initiated tillers time to fully develop and contribute to yield.

The improved tiller growth after ethephon application may be due to the availability of more assimilate for tiller growth following retarded meristematic growth and reduced sink activity in the main shoot (Rajala & Peltonen-Sainio, 2001). Alternatively, the response could be similar to that observed with chlormequat i.e. better light interception by developing tillers, may also be responsible for enhanced tillering. However, the most widely accepted explanation is that ethylene stimulates the breakdown of apical dominance (Harrison & Kaufman, 1982). In this explanation the ethylene released from ethephon inhibits auxin biosynthesis and transport from the main shoot apex. The weakened effect of apical dominance, which is dependant on auxin, allows lateral buds to develop hence improving tillering. Once again it is possible that the compound could act through a combination of these mechanisms thereby improving tiller production and survival.

1.2.2 Biomass accumulation

Both chlormequat and ethephon are known to reduce plant height and they are therefore expected to reduce biomass accumulation. This may be true, however, there have been some reports of increases in plant biomass after PGR application. Lowe & Carter (1972), in an experiment testing chlormequat activity at different temperatures, reported significant reductions in plant dry matter in chlormequat treated plants as compared to controls (Fig. 2). The major differences between the no application control and chlormequat treated plants occurred in the flag leaves and the internodes of the stems. It was suggested that the weight of the flag leaf and its sheath was reduced by chlormequat application due to the shorter length of the leaf. Humphries *et al.* (1965) also reported significant reductions in dry matter ranging from 11 to 16% for chlormequat treated plants compared with no application control plants at three different harvest dates. In contrast to Humphries *et al.* (1965), Myhre *et al.* (1973) reported significant increases of approximately 35, 43 and 7% in chaff, grain and straw dry matter, respepectively, after chlormequat application at either the fifth leaf or tillering stages. Koranteng & Matthews (1982) applied chlormequat to spring barley plants when three leaves had fully emerged and found that chlormequat increased final plant dry matter by 8.5%.

The influence of chlormequat on canopy size, leaf orientation, longevity and optical properties, together with its effects on photosynthesis and respiration, may combine to express a response in dry matter accumulation compared to normal crop growth (Green, 1986). The reduction in dry matter accumulation after chlormequat application may be due to it characteristically reducing stem length, and with the stem being one of the heaviest plant components, the effect of stem length change on total plant dry matter would be substantial. Alternatively, reports of increases in plant dry matter may be attributed to an increase in production of tillers following chlormequat treatment at early growth stages. The differential responses in dry matter accumulation following chlormequat may be due to variations in time of application, cultivars, and environmental influences.

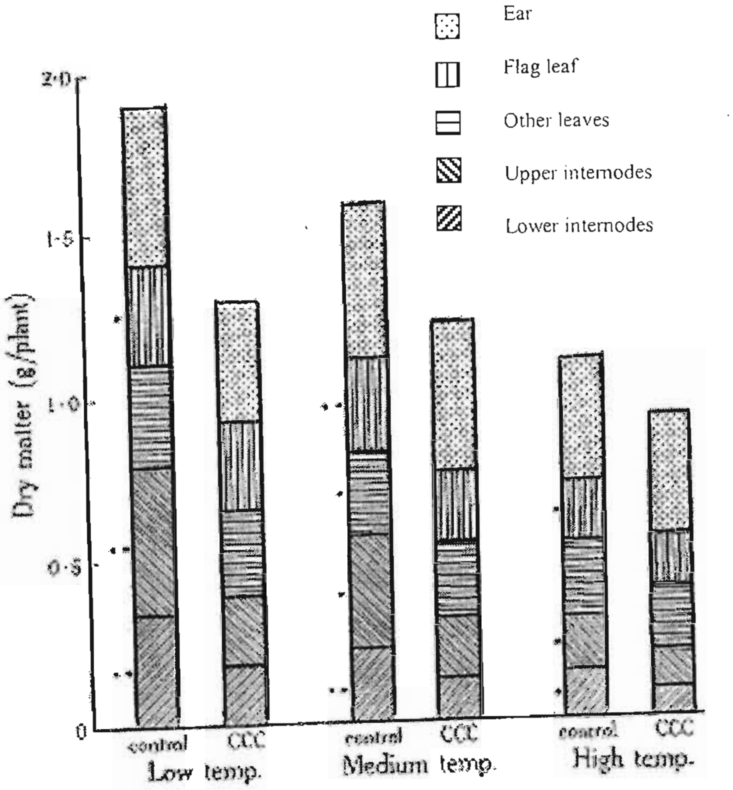

Fig. 2. Effect of chlormequat (CCC) on dry matter distribution in wheat plants grown in three different (fluctuating) temperature regimes. Significance of difference between corresponding parts of the control and sprayed plants are indicated by one (P<0.05) or two (P<0.01) asterisks, and no significance by none (after Lowe & Carter, 1972).

The effects of ethephon on dry matter accumulation have been more consistent compared to chlormequat. Cox & Otis (1989) reported significant plant biomass reductions of 7 and 13% at heading compared to controls when ethephon was applied to wheat prior to flag leaf emergence in the two years that the study was conducted. Rajala & Peltonen-Sainio (2001) applied ethephon to wheat at tillering and found significant reductions in dry matter of 39 mg plant^{-1} 14 days after application. Simmons *et al.* (1988) reported reductions in plant dry matter at maturity ranging from 1.8 to 2.4% as increasing rates of ethephon (0.28 to 0.42 kg a.i. ha^{-1}) were applied to both wheat and barley just before the flag leaf stage. The consistent reductions in plant biomass with ethephon application may be due to ethephon being normally applied in most studies at later stages of growth, after tillering is completed. Consequently, there may be no improvement in tillering (as it is already completed) and therefore no contribution to dry matter, while the opposite may be true for chlormequat application. In addition, the release of ethylene by ethephon may lead to early senescence, thereby preventing further biomass production.

Biomass production may be regarded as an indication of photosynthetic activity. The reductions in biomass production following PGR treatment do not necessarily mean that photosynthesis is reduced. It could be possible that changes in source sink relations following PGR treatment lead to a greater translocation of assimilate to economically important plant parts (Cox & Otis, 1989). This implies that assimilate production may not be affected, however, assimilate translocation and distribution most probably is.

1.2.3 Root Growth

Any force that displaces a plant stem from a vertical position may be transmitted to the root system provided there is sufficient stem strength to prevent stem lodging. It is therefore imperative that a strong, well-developed root system is present to resist these forces and hence prevent root lodging. Applications of ethephon and chlormequat to small grain cereals have been shown to most likely reduce shoot elongation, however, reports on their effects on root growth have been inconsistent.

Application of chlormequat to wheat at the tillering stage significantly increased the number of coronal roots at anthesis by four compared with control treatments (Crook & Ennos, 1995). Rajala & Peltonen-Sainio (2001) reported improvements in root weight (by 3 mg plant^{-1}) and root:shoot ratios (by 27%) after early chlormequat applications. Similar reports of improvements in root biomass after chlormequat applications were made by Humphries *et al.* (1965). In contrast to these reports, Rajala *et al.* (2002) found no improvements in root growth after chlormequat application even when the dose was increased fifty times the recommended rate.

The observation that chlormequat reduces elongation growth in cereals may suggest that both root and shoot growth could be reduced. Rajala & Peltonen-Sainio (2001) reported parallel reductions in root and shoot growth resulting in unaltered root:shoot ratios. Another possibility could be that chlormequat-induced reductions in shoot growth may allow water, nutrients and photo-assimilates to be used for enhanced growth of roots thereby improving root:shoot ratios. There have been no reports of chlormequat reducing root:shoot ratios and this suggests that in commercial farming, applications of chlormequat are unlikely to have damaging effects on the root system.

The PGR ethephon acts by releasing the plant hormone ethylene, a compound known to stunt root elongation (Rajala *et al.*, 2002). Ethephon reduced root elongation by 10-30%, 40-70%, and 20-50% in wheat, barley and oats, respectively, when applied at and above the recommended rates (Rajala *et al.*, 2002). Woodward & Marshall (1988) also reported significant reductions (by approximately 45mm) in the length of root systems of wheat, fifteen days after treatment with ethephon. The consistent reductions in root growth following ethephon treatment may suggest negative impacts on water and nutrient uptake (due to lower surface areas for absorption) as well as lodging tolerance.

The effects of PGR's on root growth have to be considered in conjunction with shoot development. It is the root:shoot ratio that is of importance when considering factors such as assimilate partitioning, water usage and lodging tolerance. There is sufficient evidence that PGR's exert an influence on the root:shoot ratio, however, the nature of these effects are variable and require further investigation before valid conclusions can be made.

1.3 Effects of PGR's on agronomic characteristics

It is clear from section 1.2 that PGR's have definite effects on vegetative growth of cereals, however, it is the ultimate effect on agronomic characteristics such as yield and lodging that would benefit the cereal producer the most. The effects of growth retardants on agronomic characteristics will ultimately determine the profitability benefit to the farming enterprise.

1.3.1 Yield and yield components

Grain yield is the product of the number of spikes m^{-2}, grains $spike^{-1}$ (spikelets $spike^{-1}$ X grains $spikelet^{-1}$) and mass $grain^{-1}$. The effects of PGR's on tillering, partitioning of assimilate and general developmental processes would suggest significant modifications to all three of the above components. There have been many contradicting reports implying that these modifications may either be beneficial or detrimental to grain yield and its components.

Myhre *et al.* (1973) reported that the application of chlormequat to wheat at the fifth leaf and tillering stages increased the number of spikes m^{-2} by 20 and 30% respectively, thereby improving grain yield. Rowland (1973) who reported significant yield increases ranging from 3% to 7% after early chlormequat applications made a similar observation, stating that the improvement in yield was due to an increase in the number of spikes per unit area while the other yield components remained unchanged. In another study, Humphries *et al.* (1965), also attributed a 5% increase in yield after chlormequat application to an improvement in spikes m^{-2}, however, other components were also affected as mass $grain^{-1}$ decreased by 13% and the number of grains $spike^{-1}$ increased by 8%.

In the initial study involving chlormequat, Tolbert (1960) attributed yield increases in treated wheat plants to improvements in mass $grain^{-1}$ rather than grains $spike^{-1}$ or spikes m^{-2}. Similar results were obtained by Stahli *et al.* (1995) who accredited chlormequat induced yield increases of 16-20% in greenhouse grown wheat to improvements in mass $grain^{-1}$ rather than improvements in the other two components. These results contradicted those of Humphries *et al.* (1965), Myhre *et al.* (1973), and Rowland (1973) who attributed grain yield increases to improvements in spikes per unit area. In addition, there have been reports that chlormequat has no effect on grain yield or any of the components thereof (Kettlewell *et al.*, 1983). Meanwhile, some reports also indicated a decline in grain yield attributed to decreases in all three yield components (Green, 1986).

One of the main reasons for the improvement in spikes per unit area after chlormequat treatment may be related to the effect it has on tillering. One possibility is the reduction in the rate of tiller development, which therefore allows time for more tillers to develop and hence contribute to grain yield (Hutley-Bull & Schwabe, 1982). Alternatively, improved light penetration into a more upright leaf canopy could encourage tiller survival, or a reduction in growth of the main stem may allow greater assimilate supply to tillers.

Any improvements in grain number may be attributed to the effect of chlormequat on developmental rate. The reduction in growth rate may imply a longer duration of pre-anthesis growth (Green, 1986), and this could increase the duration of spikelet initiation, thereby improving grain number. Any improvements in mass grain^{-1} may be due to a longer duration of effective photosynthesis during grain filling, thereby enhancing mass grain^{-1}. With a slower growth rate there is an extended period during which the plants are capable of furnishing the seed with extra assimilate (Tolbert, 1960). In addition to this, any reductions in yield could be due to compensatory effects e.g. a larger number of grain sites could be competing for a similar supply of assimilate, leading to reduced grain weight and hence grain yield remains unchanged. It is clear that the responses of yield and yield components to chlormequat are variable and require further investigation.

The majority of reports on the effects of ethephon on cereal grain yield suggest that the compound reduces yield unless lodging is prevented. Wiersma *et al.* (1986) reported a yield increase of up to 6.4% in ethephon-treated plants averaged across environments and cultivars. The primary reason for this increase was that treated plots experienced less lodging. Similar results were obtained by Cox & Otis (1989), who found that under conditions that promote severe lodging, the PGR ethephon reduced lodging thereby preserving yield (5.7Mg ha^{-1}) as compared to control plots (5.3Mg ha^{-1}) that lodged, and hence produced lower yields. Dahnous *et al.* (1982), in an investigation into responses of wheat, barley and triticale to ethephon also reported that yield increases resulting from ethephon treatment were associated with reduced lodging.

Simmons *et al.* (1988), in a study of ethephon application rates, found that effects of ethephon on grain yields varied from significant reductions to significant increases, and that increases were most common when the control plots lodged. However, when lodging did not occur, ethephon treatments tended to produce less grain yield that could be attributed to reduced grain numbers and grain mass. Reports of ethephon reducing grain number per spike are common. Moes & Stobbe (1991) reported that a reduction of approximately 29 g m^{-2} in hand-harvested grain yield of ethephon treated barley plots was primarily due to a reduction in grains $spike^{-1}$ (by approximately 11.6 grains). Foster *et al.* (1991) reported that grain mass of barley was unaffected by ethephon treatment, however, grains $spike^{-1}$ decreased significantly by 26-36% at two different rates of ethephon. Similar results were obtained by Rowland (1973) who found that ethephon reduced the number of grains $spike^{-1}$ by 11 in one treatment through producing lower numbers of fertile spikelets per spike. In contradiction to these reports, Khan & Spilde (1992) reported a 5.4% increase in wheat grain yield after treatment with ethephon in the field. In this study, ethephon application tended to increase spikes m^{-2}, but had no effect on grain weight and grains $spike^{-1}$.

Most of the reductions in yield observed after ethephon application may be attributed to ethephon being an effective gametocide that induces male sterility in wheat (Rowell & Miller, 1971). This may be the primary reason for the commonly observed reductions in grains $spike^{-1}$ experienced by most of the researchers. Alternatively, the release of ethylene from ethephon (Lurssen, 1982) may enhance the developmental rate and the processes involved in senescence. The improved growth rate may ultimately result in the formation of fewer grain sites as well as shorten the duration of grain filling thereby negatively affecting grains $spike^{-1}$ and grain weight.

Moes & Stobbe (1991) reported that the production of late tillers after ethephon application may lead to competition for assimilate, since shoots which appeared after ethephon application would initially be dependent on assimilate from the main stem. It was concluded that this was the primary reason for the reduction in grain weight. Alternatively, any improvements in grain yield, such as that found by Khan & Spilde (1992), may actually be attributed to the production of more tillers that can contribute to yield. These interactions between tillering, grain number, and grain mass appear to be variable, and could be dependant on the environment, cultivar, and time of application of ethephon.

1.3.2 Plant height and lodging

The most consistent effect of PGR's on cereal growth and development is the reduction in plant height. If environmental conditions are conducive to lodging, the reductions in plant height are often accompanied by reduced lodging. However, these effects are extremely variable as lodging is dependant on a number of interacting factors such as cultivar, environmental conditions, soil nitrogen and water status and management practices. Both chlormequat and ethephon have consistently reduced plant height in most investigations, however, effects on lodging were variable.

In the initial study involving chlormequat, Tolbert (1960) reported significant height reductions in wheat ranging from 60mm to 180mm after soil applications of the compound at different concentrations. Woolley *et al.* (1991) observed a 5.8% reduction in mean height of wheat cultivars with a single chlormequat application at three different sites. The reduced height was also accompanied by a 30% reduction in lodging at one of the three sites.

In another experiment, Clark & Fedak (1977) reported reductions in height of 11.5%, 8.7% and 29% for barley, oats and wheat, respectively, after chlormequat application. In this experiment, lodging was delayed by one week by chlormequat treatment in those cultivars of the three crops that were reduced in height. Similar results were obtained by Humphries *et al.* (1965)

who reported average height reductions of 40% with chlormequat application to spring wheat in the field. It was also observed that the shortening caused by chlormequat persisted and was not confined to the period immediately after application. Similar reports of simultaneous reductions in height and lodging have been noted by other researchers (Myhre *et al.*, 1973; Berry *et al.*, 2000).

The responses to ethephon are similar to those observed with chlormequat with regards to plant height and lodging. Foster *et al.* (1991) reported significant reductions in plant height ranging from 160mm to 270mm with increasing dosages of ethephon averaged over three cultivars of spring barley. Danhous *et al.* (1982) also reported significant reductions in plant height after ethephon application on both wheat and barley, however, the responses were cultivar specific for both crops. Schwartz *et al.* (1983) reported simultaneous reductions in plant height and lodging in wheat, barley and rye. This is in keeping with the work of Wiersma *et al.* (1986) who found that a 50mm reduction in plant height after ethephon treatment led to a subsequent 31% reduction in the lodging score of winter wheat. In this investigation plant height and lodging were significantly correlated indicating that management practices that promote vigorous vegetative growth and greater plant height, will increase lodging. In general, the effects of ethephon and chlormequat on plant height are similar, however, the subsequent effects on lodging are dependent on a number of other factors.

One of the most influential factors affecting plant height and lodging is the time of application of the compounds. Work done by Myhre *et al.* (1973) suggested that the greatest reduction in plant height and lodging occurs when chlormequat is applied at around the fifth leaf stage of development. Woolley *et al.* (1991) reported that application of chlormequat to wheat at the beginning of stem elongation reduced plant height (by 51mm) and lodging (by 5 to 8%) to a greater extent than earlier applications. Clark & Fedak (1977) also reported reductions in height (by 29, 11.5 and 8.7%) and a general reduction in lodging following early chlormequat applications in wheat, barley and oats, respectively.

It is apparent that chlormequat is suited to early applications, but it is possible that a subsequent recovery response by the plant later in the growth stages would render the treatment ineffective (Bruinsma, 1982). However, if the elongation-inhibiting effects of chlormequat persist in the plant (Humphries *et al.*, 1965), one would expect the effect to be transferred to the longer, later formed internodes thereby having a greater effect on total plant height.

Applications of ethephon seem to be more suited to later stages of growth with reductions in plant height being primarily due to reductions in peduncle length. The exact timing of application at the later growth stages also makes a difference, as shown by Danhous *et al.* (1982), who found that applications at the late boot stage reduced height by approximately 50mm more than applications at early heading. Ethephon has also been reported to increase the activities of two of the enzymes involved in lignin synthesis: phenylalanine ammonia lyase and peroxidase (Blomquist *et al.*, 1973). It is therefore possible that the reduction in plant height combined with increased straw strength from ethephon application may contribute to reduced lodging in cereals.

The effects of chlormequat and ethephon on plant height and subsequently lodging are variable and dependant on times of application. Other elements such as cultivar, environment, nitrogen fetilization and management also play important roles in ensuring that reductions in height are accompanied by reductions in lodging.

1.4 The use of PGR's in crop management

1.4.1 PGR's and intensive cereal management

Plant growth regulators form an integral part of intensive cereal management (ICM) strategies. Use of ICM attempts to control some of the limiting factors in cereal production by altering several management practices. These include planting dates, to avoid diseases and pests; narrow row spacings to improve yield; additional N fertilization and precise timing of the N to promote reproductive development rather than vegetative growth; and fungicide applications to control diseases (Harms *et al.*, 1989). In an attempt to protect the yield produced by these management practices, PGR's may be necessary to decrease lodging, which may have negative effects on grain filling and harvesting. The PGR's must interact with all elements of an ICM system in order to be totally efficient in protecting potential yield.

In an experiment comparing recommended and intensive management practices Harms *et al.* (1989) concluded that PGR's are necessary together with high seeding and N fertilization rates as well as disease control in order to enhance yields in an ICM system. Nafziger *et al.* (1986) reported that while most PGR treatments were effective in decreasing plant height and lodging in an ICM system, these favorable results must be weighed against occasional yield decreases. These reports seem to support the idea that PGR's are necessary in an ICM system, however, there are other researchers who do not concur. Mohamed *et al.* (1990) reported that intensification of cultural practices and the use of PGR's were not effective in increasing grain yield and quality in wheat grown in the United States. They attributed this to the fact that management practices in the Western irrigated regions of the USA were already optimized. A similar conclusion was made by Foster & Taylor (1993) who investigated management strategies for barley production.

The greatest effects of PGR's were observed when lodging was a factor (Nafziger *et al.*, 1986; Harms *et al.*, 1989; Webster & Jackson, 1993). This observation suggests that PGR's should only be used in management systems when lodging is a potential problem, however, lodging is a factor that cannot be predicted with certainty. One could therefore conclude that PGR's should form part of ICM systems as an insurance against the possibility of lodging.

1.4.2 PGR's and nitrogen fertilization

Most of the studies relating to the interactions between N application and PGR's have produced inconsistent results. The theory behind the investigations is that in an ICM system, a PGR is used to allow higher levels of N fertilization, which eventually results in greater grain yields. However, this effect is not always observed, due to the interactions between other factors such as cultivar, environment and type of PGR (Mohamed *et al.*, 1990).

Nafzinger *et al.* (1986), in an experiment involving chlormequat and two levels of N application, found no interaction between N level and PGR in the first year of the study. In the second year of the study, it was found that chlormequat had no effect on yield at the low N level (84 kg ha^{-1}), however, it reduced yields by 11% at the high level (168 kg ha^{-1}). Similar results were obtained by Knapp & Harms (1988), who found that grain yields were not increased when N applications were increased above the normal recommended rates while combined with chlormequat to control lodging. These results are in contrast to that of Herbert (1983), who found that grain yields of wheat increased with increasing N application until a maximum point, after which yields were reduced. However, with the use of chlormequat, grain yields increased above the normal maximum point of inflection (Figure 3). This was the expected effect of chlormequat application as reported by other authors (Hofner & Kuhn 1982; Van Sanford *et al.*, 1989; Webster & Jackson, 1993).

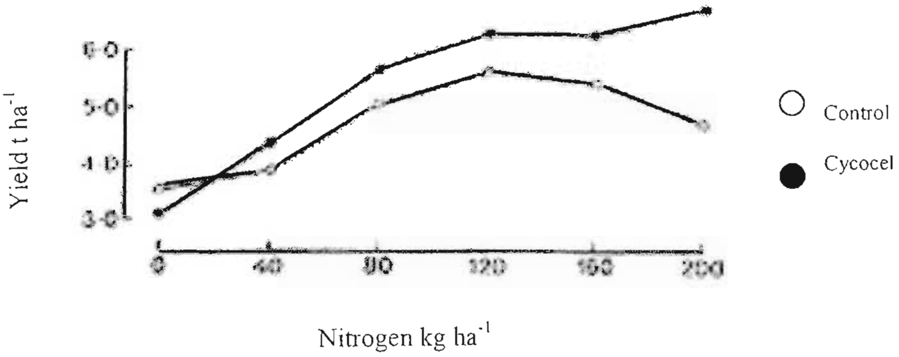

Fig. 3. Yield response of winter wheat to chlormequat (Cycocel®) at different nitrogen levels (after Herbert, 1983).

Studies involving ethephon and N applications have been inconsistent. Van Sanford (1989), in the same experiment, reported that total plant N at anthesis was significantly increased by 15% in plots of winter wheat treated with ethephon and that remobilization of vegetative nitrogen was increased 13% in ethephon treated plots. Webster & Jackson (1993), in an investigation of management practices to reduce lodging in wheat, suggested that ethephon application and a N top-dressing should be considered in wheat production environments to improve grain yield and protein. In contrast to these reports Mohamed *et al.* (1990) reported no significant increases in grain yield or protein content of wheat after application of ethephon even at higher N rates. These results were supported by Foster & Taylor (1993), who suggested that ethephon was unlikely to increase grain yield under conditions of intense irrigation and higher N fertility.

The effect of PGR's on N fertilization and N usage is dependant on cultivars (Van Sanford *et al.*, 1989), as well as the time of application of the PGR. The possibilities of PGR's being used to permit greater levels of N fertilization under South African conditions have yet to be investigated. The wide range of cereal cultivars and fertilization practices employed locally are likely to produce some favorable results.

1.5 Effects of PGR's on small grain cereal quality

It is clear from sections 1.2 and 1.3 that PGR's affect various aspects of small grain growth and development, which ultimately influences grain yield potential. In order to ensure economic profit this yield potential has to be accompanied by satisfactory quality standards, as low quality grain can lead to severe losses to the producer. Any treatment that affects grain quality must therefore be considered in detail before application. Plant growth regulators exert many effects on grain quality by altering internal concentrations of hormones as well as modifying source-sink relations in the plant.

1.5.1 Protein content

Protein content of cereal grains such as wheat is an essential component of the overall grading process. With regards to wheat, protein content is associated with adequate rising of dough, which is essential in the baking process. The protein or nitrogen content of barley is also a key factor with regards to grading and it has to be at an optimal level to ensure successful malting. Given the effects of PGR's on growth, development and alterations of souce-sink relations (Bruinsma, 1982), possible beneficial or negative effects on the protein content of the grain would be expected. However, reports have varied, with occasional increases and some decreases in protein content.

Foster & Taylor (1993), in a three-year study on the responses of barley to ethephon, found a significant improvement (25%), a significant reduction (3%) and no response in grain protein content in the first, second and third years of investigation, respectively. In this study it was concluded that ethephon does not affect the protein content in the whole plant, but it may effect the redistribution of protein between grain and straw. In another experiment Knapp & Harms (1988) found that ethephon increased grain protein content by 0.5-1.5% in two wheat cultivars in both years in which the study was conducted. In the same study, it was found that chlormequat had very little effect on the protein content. Khan & Spilde (1992) found no differences in grain protein content between control and ethephon treated plants.

Similar results were obtained by Mohamed *et al.* (1990), who concluded that the use of ethephon in an ICM system does not affect protein content of the grain.

The protein content of the grain is related to N fertilization, with higher rates of N leading to increased protein content (Knapp & Harms, 1988). With this in mind, together with the possibility of PGR's allowing greater responses to N fertilization, one would expect improvements in grain protein content. The improvement could be attributed to increased N fertilization or a reduction in vegetative growth, thereby allowing greater N distribution to the grain. However, there has been no convincing data that indicates definitive improvements in grain protein content after PGR application. One of the reasons for this could be the differences and interactions between environments, cultivars and times of application as demonstrated by Knapp & Harms (1988) who found differential responses of cultivars to ethephon application. In keeping with this, Foster & Taylor (1993) mentioned small but significant increases in grain protein in ethephon treated maize, however, the effect was dependent on the rate and timing of application of the ethephon. Effects of chlormequat on grain protein concentration have not been well documented.

1.5.2 Hectolitre mass

Hectolitre mass or test weight is a quality parameter used in wheat, which gives an indication of the density of the grain, and it is closely linked to the process of grain filling. Any treatment that affects grain filling will therefore have an effect on the test weight. Given the effects that PGR's have on grain weight (Stahli *et al.*, 1995; Green, 1986), applications of these compounds are likely to have effects on test weight.

Khan & Spilde (1992) found a significant increase in test weight of 7kg m^{-3} averaged over four spring wheat cultivars following ethephon application. This agrees with the results of Wiersma *et al.* (1986) who found significant 1.3% improvement in test weight of ethephon treated winter wheat compared to controls. These results are in contrast to Rowland (1973) who reported characteristic reductions in test weight ranging from 0.8-1.3% after ethephon application to spring wheat cultivars. In the same experiment it was shown that chlormequat did not have an effect on test weight. Stahli *et al.* (1995) found that chlormequat-induced yield increases could be attributed to increases in grain weight and this could be related to possible improvements in test weight.

One of the possible reasons for improvements in test weight following ethephon application could be the redirection of assimilate to the grain following the reduced growth of the stem. Any reductions in test weight after ethephon treatment may be attributed to the release of ethylene (Lurssen, 1982) which may speed up senescence and hence the grain filling process. According to Green (1986), chlormequat has a similar effect to imposing short days i.e. a reduction in growth rate. One possibility is that the reduced growth rate following chlormequat application may allow greater time for grain filling to occur thereby improving test weight. Reductions in test weight following chlormequat application may be attributed to the stimulating effects of the product on tillering, when applied early. The improved tillering may lead to compensation by the plant, thereby reducing grain filling. Any of the abovementioned scenarios are possible, however, extensive testing on a range of local cutivars is necessary in order to ascertain the correct mechanisms.

1.5.3 Preharvest sprouting

Very little information is available on the effects of PGR's on preharvest sprouting in cereals. This may be due to the fact that most of the research on PGR's was conducted many years before research on preharvest sprouting began. Preharvest sprouting is detrimental to wheat production and marketing in South Africa (Barnard, 1997) and any factor that could possibly alleviate the situation should be investigated.

Paleg *et al.* (1965), reported that chlormequat inhibited GA_3 synthesis in barley endosperm. Given the role of GA_3 in initiating hydrolysis of starch in the endosperm during germination one would expect inhibition of germination in the presence of chlormequat. This has possible implications in terms of preharvest sprouting, provided the effect of applied chlormequat persists in the seed until harvest. The effect of a recovery response by the plant could possibly be eliminated through later applications. In this way, one could ensure the presence of chlormequat in the grain in order to inhibit preharvest sprouting. No previous work has been done to establish the effect of PGR's on preharvest sprouting under South African conditions.

1.6 Summary

The current lodging losses experienced by small grain cereals such as wheat, barley and oats in South Africa has necessitated the search for methods other than those currently used in order to eliminate the problem of lodging. The use of plant growth regulators such as chlormequat and ethephon as tools against lodging has been extensively investigated, however, little to no research has been conducted on newer South African cultivars. Previous research indicated the potential of these products as effective anti-lodging agents that reduce stem elongation in cereals. By affecting the endogenous levels of the hormones gibberellin and ethylene, these products alter plant growth and development.

In most instances the compounds have been shown to enhance cereal tillering and root growth, reduce plant biomass and plant height, and have variable effects on lodging. Aside from plant height, plant growth regulators have inconsistently affected all other vegetative and agronomic aspects of growth. Most improvements in yield and yield components occur when lodging is successfully controlled by these plant growth regulators, however, many reports indicate an improvement in yield even in the absence of lodging. The ultimate inhibition of lodging is dependant on the type of product, the time of application, environmental conditions, the type of crop, and the cultivar.

The relationship between yield and lodging control may suggest the use of plant growth regulators when environmental conditions are conducive to lodging or in intensive management systems where higher seeding rates and N inputs may increase the probability of lodging. However, the uncertainty associated with lodging prediction indicates the need for the use of plant growth regulators as an insurance against lodging. Intensive management practices together with plant growth regulators may improve yields and quality without the associated lodging losses. The inconsistencies associated with these products suggest the need to further investigate their potential under South African production conditions.

CHAPTER 2

GENERAL MATERIALS AND METHODS

In order to assess the effects of plant growth regulators on small grain cereal growth and productivity, field trials were conducted on wheat, barley and oats. These are the major small grain crops that are currently affected by lodging losses in intensive management systems in South Africa, and were therefore chosen for this study. For all three crops field trials were conducted at two locations, namely the Small Grain Institute research station in Bethlehem (28°30' S, 28°30' E, 1855m) in the Free State province and the Vaalharts Agricultural Experimental Station in Vaalharts (28°00' S, 25°00' E, 1224m), Northern Cape province.

Vaalharts forms part of the cooler central irrigation zone of South Africa, which produces approximately 50% of the total wheat production, while Bethlehem forms part of the Eastern Highveld production region, which accounts for a small percentage of total South African production. At Bethlehem, trials were planted on an Avalon Mafikeng loam soil type, while the soil type at Vaalharts was a fine, sandy Hutton type with a deep red colour (Soil Classification Workgroup, 1991) Long-term and seasonal temperatures for both localities and seasons are presented in Appendix 1.

2.1 Wheat trials

Trials were conducted over the 2003 and 2004 seasons at the above-mentioned localities. The seasons generally proceeded from the middle of June until the middle of December at both localities and years.

2.1.1 Experimental layout

Trials were planted using a $4x3^2$ factorial arranged in randomized complete block designs (RCBD) with four replications and a total of 36 treatment combinations. A control (water) treatment was split over three times of application and three cultivars, resulting in the production of dummy treatments. A trial plan is presented in Appendix 2. The 36 treatments were made up of all possible combinations of the following factors (treatment names are in bold):

- Cultivar (3)

The cultivars investigated were:

- **Kariega** (lodging susceptible),
- **Olifants** (lodging tolerant), and
- **SST 876** (lodging tolerant).

- Plant growth regulator (4)

The plant growth regulator active ingredients were:

- **control**	(water)
- **chlormequat chloride**	(applied as CeCeCe®)
- **ethephon**	(applied as Ethapon®)
- **PGR combination** of both active ingredients	(applied as Uprite®)

All PGR spray treatments were performed using a portable CO_2 knapsack sprayer consisting of a hand-held boom with three nozzles. The spray volume of the sprayer was 197 L ha^{-1} with a tank volume of 2 L. The plant growth regulators were applied at the following dosages with water:

-chlormequat chloride (1575 g a.i ha^{-1}) applied as CeCeCe® at 2.1 L ha^{-1}
-ethephon (600 g a.i ha^{-1}) applied as Ethapon® at 1.25 L ha^{-1}
-chlormequat and ethephon (750 g a.i ha^{-1} and 375 g a.i ha^{-1} respectively) applied as Uprite® at 2.5 L ha^{-1}.

These dosages were chosen according to current recommendations for use of the products in South Africa according to Vermeulen *et al.* (2000).

- Time of application (3)

The above treatments were applied at either the:

- **tillering** stage of growth (Zadoks growth stage 20-29), the
- **stem elongation** stage of growth (Zadoks growth stage 30-39), or the
- **flag leaf** stage of growth (Zadoks growth stage 40-49) (Zadoks *et al.*, 1974).

In order to get an estimate of plant biomass accumulation during the season without destructively sampling from the experimental units, six extra plots were planted alongside each trial and selected treatments were applied to these plots. These six treatments were; three plots of Kariega and three plots of SST 876, which were each sprayed with either chlormequat, ethephon, or left unsprayed. The chlormequat treatment was applied at the tillering stage, while ethephon was applied at the flag leaf stage of development, for both cultivars. These are the recommended application times of these growth regulants on wheat in South Africa according to Vermeulen *et al.* (2000). As resources did not allow a complete sampling for growth analysis on all treatments, only selected treatments were sampled. Kariega and SST 876 were chosen to investigate the effect of the PGR's on a lodging tolerant vs lodging susceptible cultivar. Only chlormequat and ethephon were chosen for this part of the study to observe the effects of the active ingredients alone, and not when combined. The data were used to produce growth curves of biomass accumulation during the season for each of the selected treatments.

2.1.2 Trial details

Trials were planted using a Wintersteiger plot planter comprising eight rows that were 0.17m apart and 5m long (6.8m^2). All three cultivars were planted at an elevated (above recommended, according to Barnard & Burger, 2003) planting density of 400 plants m^{-2} and seeding rates (approximately 150-

175kg seed ha $^{-1}$) were calculated from the respective seed mass of the cultivars. Planting densities were increased to simulate intensive management practices (Mohamed *et al.*, 1990). An overhead floppy irrigation system was employed in Vaalharts while a sprinkler irrigation system was implemented in Bethlehem. A typical water budget system was employed for irrigation scheduling resulting in applications of 20–35mm with irrigation cycles of 7–12 days depending on the growth stage of the crop. All evaporation measurements were obtained from automatic weather stations on site. Pest and disease control were not required, while mechanical weed control was employed when necessary in all trials. The planting dates for the trials at Vaalharts were 24 June 2003 and 25 June 2004 while the planting dates at Bethlehem were 27 June 2003 and 22June 2004.

Both trials at Vaalharts received 90 kg N ha^{-1}, 26 kg P ha^{-1} and 37 kg K ha^{-1} in the form of a compound mixture of 7:2:3 (31), applied to individual plots by means of a mechanical applicator prior to planting. Two additional applications of 90 kg N ha^{-1} each in the form of limestone ammonium nitrate [LAN (28)] were top dressed towards the end of the tillering and stem elongation phases to produce a total N fertilization of 270 kg N ha^{-1}. The top dressing applications were made by hand. Both the trials at Bethlehem received 180 kg N ha^{-1}, 26 kg P ha^{-1} and 13 kg K ha^{-1} in the form of 3:2:1 (25) and LAN (28) applied onto the individual plots by hand prior to planting. This was then followed by a N topdressing at the end of stem elongation of 40 kg N ha^{-1} in the form of LAN (28) to produce a total N fertilization of 220 kg N ha^{-1}. Above optimal N rates (220 – 270 kg N ha^{-1}) were used in all trials to simulate intensive management practices and in doing so increase the incidences of lodging. The levels of N fertilization were decided upon based on the recommendations for highest target yields (>8 t ha^{-1}) in the specific localities from Barnard & Burger, (2003).

2.1.3 Variables investigated

- Biomass accumulation

Sampling was done irregularly (approximately twice a month) during the season from the six extra plots beginning from the tillering stage of growth until harvest maturity. Four sampling units were allocated to each plot at any given sampling date and each sampling unit was a 0.3 m length of a row. Sampling was done randomly by pulling out whole plants, however only aboveground plant material was sampled as roots were cut off before drying. Dry mass was determined by oven-drying the samples for a minimum of 48h at 65°C. The dry mass for a given sampling date was calculated as an average of the four sampling units and expressed as g m^{-2}. These data were used to produce growth curves comparing cultivar responses to chlormequat and ethephon in terms of biomass accumulation during the season.

- Plant height

Plant height was determined from the mean height of five plants in each trial plot. The five plants were randomly tagged or marked out prior to maturity (beginning of stem elongation) in order to eliminate bias when determining plant height at a later stage. Plant height was measured in mm from the ground to the tips of the tallest spike per plant, excluding the awns. All measurements were done once, prior to harvesting.

- Lodging score

Visual ratings for lodging were done on each trial plot just prior to harvest and the following formula was employed:

Lodging index = S X I X 0.2 (1)

where

S = area of plot lodged (1= none to 9 = total plot) which was estimated visually,

I = intensity of lodging (1= upright or 90° to 5= flat or 0°, relative to ground) which was also estimated visually,

and 0.2 is a correction factor. (Wiersma *et al.*, 1986).

The lodging ratings therefore ranged from 0.2, for no lodging, to 9, for completely lodged plots.

- Yield and yield components

Yield components were determined by sampling a 0.5m length of a row (0.085 m^2), which was marked out after planting, from each trial plot and counting the number of spikes sampled. The sample was then used to calculate the number of spikes m^{-2}. The spikes from each plot sample (0.085m^2) were mechanically threshed using an appropriate threshing machine and the mass of all the seed was recorded. A sub-sample of seed was also counted and weighed to determine mass $seed^{-1}$. The seeds $spike^{-1}$ were calculated using the following formulas:

$$\text{Seed mass spike}^{-1} = \frac{\text{Mass of seed (g) from all spikes sampled (0.085 m}^2\text{)}}{\text{Number of spikes sampled (0.085 m}^2\text{)}} \qquad (2)$$

$$\text{Seeds spike}^{-1} = \frac{\text{Seed mass spike}^{-1}\text{ (g)}}{\text{Mass seed}^{-1}\text{(g)}} \qquad (3)$$

Harvesting was done by means of a Winersteiger plot harvester and all eight rows of each plot were harvested. The harvested grain was then cleaned mechanically and weighed. No artificial drying of the seed was necessary, as the moisture was sufficiently low in all trials (<13%). The seed masses of the sampling units were also included in the calculation of overall yield, in t ha^{-1}.

- Hectolitre mass

This was determined using the Dickey-John® grain analysis meter which determines the mass of grain in a given volume (500 ml). After determining the weight of seed $plot^{-1}$ for yield, a sub-sample of seed from each plot was passed through the machine to determine the hectolitre mass, in kg hL^{-1} according to the specifications of the manufacturer.

- Protein content

After determining the hectolitre mass, a sample of grain from each trial plot was milled using an electric mill, which allows wheat flour to move through a screen of 0.8 to 1.0mm. A 500g sample of milled, sifted wheat from each trial plot was then tested using the InfraAlyzer 260® whole grain analyser, which makes use of near infrared reflectance (NIR) methodology. The protein content was then determined on a 12% moisture basis according to the specifications of the manufacturer using the pre-calibrated instrument. All determinations were performed twice and the average of the two readings were used as the protein content, which is expressed as a percentage of the grain. Where the difference between two readings of the same sample differed by more than 0.2%, another determination was done on a separate, original sample taken from the plot.

- Falling number

Falling number is a factor that is associated with sprouting damage in wheat and it is influenced by the amount of α-amylase in the grain. A low falling number indicates high α-amylase activity and therefore, sprouting damage. This negatively influences the texture and colour of bread and causes severe problems for the baking and milling industry (Barnard & Burger, 2003).

This quality parameter was determined according to The American Association of Cereal Chemists (2000), using the Hagberg Falling Number Apparatus®, which measures the time in seconds for a stirrer to fall through a suspension of flour and water. A thicker suspension indicates greater amounts of starch (lower α-amalyse activity) and hence a higher falling number. After determining the hectolitre mass a sample of grain from each trial plot was milled twice using an electric mill, which allows wheat flour to move through a screen of 0.8 to 1.0 mm. A sample of clean sifted wheat was then thoroughly mixed using a spatula and the final sample size was determined according to the moisture readings obtained from a suitable moisture meter. The final sample (approximately 300g) was placed into a clean, dry viscometer tube with 25 ml of distilled water. The viscometer tube was then shaken vigorously with a rubber stopper and thereafter, within 40 sec, placed into a boiling distilled water bath, which is part of the apparatus. A mechanical stirrer was then placed into the viscometer tube and allowed to sink to the bottom, during which time the apparatus measured the time taken (in sec) for the stirrer to fall through the suspension. A correction table for height above sea level was employed thereafter to calculate the actual time.

- Preharvest sprouting tolerance

This was only determined in the 2004 season by sampling ten spikes from each plot. The individual spikes were tagged at anthesis and at harvest maturity these spikes were hand-harvested (final yield corrected using grains spike^{-1} and mass grain^{-1} of corresponding plots). The peduncles were cut 10 cm below the base of the spikes and placed in a chest freezer (-20°C) in order to maintain seed dormancy. The intact spikes were thereafter subjected to a rain simulator treatment in which a misty spray was applied overhead while the spikes rotated at a uniform speed attached to a perforated tray. After 72 hrs the spikes were evaluated for sprouting damage on a scale from 1 (no visible sprouting) to 8 (fully sprouted) according to Barnard *et al.* (1997). The preharvest sprouting scores expressed are therefore the mean scores of ten spikes per plot.

2.1.4 Statistical analyses

A combined analysis of variance for years was conducted at each locality using the Genstat statistical package (Genstat 5, 1993) and all main and interaction effects were tested. The distinct differences in observations between the two localities suggested a clear environmental effect, and this prompted a separate analysis of variance at each locality. Treatment mean comparisons were made using least significant differences (LSD) when $P=0.05$. Significant ($P<0.05$) and highly significant ($P<0.001$) interactions are indicated by "*" and "**" respectively.

An analysis of variance was also conducted for each biomass sampling date at each locality and season to detect for differences between the six treatment means. Additionally, curvilinear regression techniques were utilised to fit significant sigmoid curves per year, locality and cultivar in order to establish general responses to the PGR's. The type of curve fitted was a Gompertz curve, which is similar to the logistic curve, but is asymmetric about its point of inflection (van Ark, 1995). The growth model fitted was:

$Y = A + C\,(e^{-e(B(X-M))})$, where:

Y = the dependent variable
A + C = the saturation value for Y (asymptote)
e = the base of the natural log (ln) (2.718)
M = the inflection point (point of maximum growth)
B = the maximum growth rate at time M
X = the independent variable

A separate ANOVA was conducted for each year, locality and cultivar to test for differences between the regression coefficients of each PGR curve.

2.2 Barley trials

Field trials were conducted at the same localities of the wheat trials in the 2004 season only. Barley is a major commodity produced in the Vaalharts region, however, lodging is a severe restriction especially when high yield potential conditions are exceeded. The Vaalharts region was therefore chosen for the study as lodging is a common occurrence in barley production systems. Barley production in Bethlehem is less common and this site was chosen primarily for practical reasons. Many of the experimental and practical methods applied for the barley trials were similar to those employed for the wheat. Therefore, details of methods will be mentioned only where they differed.

2.2.1 Experimental layout

Both trials were planted in $4x3^2$ factorials using a RCBD with 36 treatment combinations and 4 replications. Trials were conducted using the barley cultivar Puma, which was introduced in 2004 as the predominant irrigated barley cultivar under intensive management systems and it was therefore chosen as an ideal cultivar for this study. The 36 treatment combinations were made up from the following factors and levels thereof (treatment names are in bold):

- Plant growth regulator (4)
  The plant growth regulators and active ingredients applied were similar to those used for the wheat trials (Chapter 2.1.1).

- Time of application (3)
  Applications were made either at the:
  - **stem elongation** stage of growth(Zadoks growth stage 25-35),
  - **flag leaf** stage of growth (Zadoks growth stage 40-49), or as a
  - **split** (two full dose applications) application at stem elongation and the flag leaf stage of growth (Zadoks *et al.*, 1974).

- Level of nitrogen fertilization (3)

  The three levels of N investigated were:

  - **120 N** (120 kg N ha^{-1}),
  - **150 N** (150 kg N ha^{-1}) and
  - **180 N** (180 kg N ha^{-1}).

The three different levels of N were chosen based on the recommendations for conventional (120 N) and above recommended (150 and 180N) practices for barley according to Barnard & Burger, (2003). In the context of this study, the 120 N application rate could be considered as a control treatment.

Biomass sampling was done by planting ten extra plots alongside each trial and applying selected treatments to each plot. Once again, resources did not allow a complete sampling of all treatments for growth analysis and only selected treatments were sampled. The ten selected treatments were sprayed with the PGR's chlormequat, ethephon and the PGR combination, combined with the three times of application at the stem elongation stage, the flag leaf stage or both, and an unsprayed control. The PGR treatments were chosen to evaluate the effects of the active ingredients on biomass accumulation alone, and in combination with each other. The application times were chosen as they are in keeping with the application times used in the main trials. The ten extra plots were treated with 120 N, as this is the recommended level of N for barley production in these localities. The data were used to produce growth curves of biomass accumulation during the season in a similar way to the wheat.

2.2.2 Trial details

Plot dimensions and planting methods were similar to the wheat trials (Chapter 2.1.2, Appendix 2). Standard planting densities of 227 plants m^{-2} (100 kg seed ha^{-1}) of Puma were used in both trials. A center pivot irrigation system was employed in Vaalharts while a sprinkler irrigation system was used in Bethlehem. All scheduling details employed were similar to those used with the wheat. Pest and disease control were not required, while mechanical weed control was employed where necessary. The planting date for the trial at Vaalharts was 8 June 2004 while the planting date at Bethlehem was 22June 2004.

Split applications of fertilizer were made, with two thirds of the respective levels of N applied at planting, while the remainder was applied approximately six weeks after emergence. Plant applications of nutrients were made in the form of 7:2:3 (31) mixed with LAN (28) in order to reach the levels of N desired. Topdressings were made in the form of LAN (28) alone. All fertilizer applications were done by hand at Bethlehem, while a mechanical applicator was employed at Vaalharts.

The spray equipment, products and dosages used were the same as those employed for the wheat trials (Chapter 2.1.2).

2.2.3 Variables investigated

- Biomass accumulation
- Plant height
- Lodging, and
- Yield

These variables were determined using the same methods utilized in the wheat trials (Chapter 2.1.3).

2.2.4 Statistical analyses

A separate analysis of variance was conducted at each locality for all variables investigated. The statistical package used and methods employed were similar to the wheat trials (Chapter 2.1.4).

2.3 Oat trials

Field trials were conducted at the two localities mentioned in the wheat studies in the 2003 and 2004 seasons (Chapter 2.1). However, the experimental layouts differed between these two seasons. Once again, the experimental and practical methods applied were similar to those employed for the wheat and differences are mentioned.

2.3.1 Experimental layout

2003

Trials were planted using a 3^3 factorial arranged in RCBD's with 27 treatment combinations and three replicates. The 27 treatments were made from all possible combinations of the following factors and levels thereof (treatment names are in bold):

- Cultivar (3)

The three cultivars investigated were:

- **Kompasberg** (lodging tolerant),
- **Overberg** (lodging susceptible), and
- **Sederberg** (lodging susceptible).

- Plant Growth Regulator (3)

The plant growth regulators and active ingredients applied were:

- **Control** (water)
- **ethephon** (applied as Cerone®)
- **PGR combination** of ethephon and chlormequat (applied as Uprite®),

- Time of application (3)

The times of application tested were similar to those tested in the wheat trials (Chapter 2.1.1).

2004

Trials were planted using a 4 X 3^2 factorial in a RCBD with 36 treatment combinations and four replicates. The 36 treatments were made up from the following factors:

- Cultivar (3)

Above (Chapter 2.3.1, 2003).

- Plant growth regulator (4)

Same as wheat trials (Chapter 2.1.1).

- Time of application (3)

Same as wheat trials (Chapter 2.1.1).

2.3.2 Trial details

Plot dimensions, planting methods, irrigation techniques and pest and disease control were similar to those employed for the wheat and barley trials. Standard planting densities of 250 plants m^{-2} were applied for all trials and seeding rates were calculated from the thousand kernel masses of the respective cultivars. The planting dates for the trials at Vaalharts were 23 June 2003 and 27 June 2004 while the trials at Bethlehem were planted on 20 June 2003 and 24 June 2004. Sprinkler irrigation systems were employed at both localities and seasons, and scheduling details are similar to those of the wheat and barley.

All trials received 90 kg N ha^{-1}, 26 kg P ha^{-1} and 37 kg K ha^{-1} in the form of a mixture of 7:2:3 (31), applied to individual plots by means of a mechanical distributor prior to planting. This was then followed by a topdressing of 30 kg N ha^{-1} in the form of LAN (28) to bring the total N fertilization to 120 kg N ha^{-1}. Soil samples were done previously in the two localities and the appropriate recommendations for N fertilization were followed according to those of

Barnard & Burger, (2003). The procedures and equipment utilized for spraying were the same as those employed for the wheat and barley trials (Chapter 2.1.2). The product Cerone®, which was used in 2003, was applied at the same dosage as Ethapon® (1.25 L ha^{-1}) at 600 g a.i. ha^{-1}.

2.3.3 Variables investigated

- Plant height (2004 only)
- Lodging ratings (2004 only)
- Yield , and
- Hectoliter mass

These measurements were done in a similar way to the wheat trials (Chapter 2.1.3).

2.3.4 Statistical analyses

All statistical procedures were similar to those employed with the wheat trials (Chapter 2.1.4).

CHAPTER 3

THE EFFECTS OF CHLORMEQUAT AND ETHEPHON ON AGRONOMIC AND QUALITY CHARACTERISTICS OF WHEAT

ABSTRACT

Lodging in wheat (*Triticum aestivum*) under irrigation in South Africa leads to severe yield and quality losses. Plant growth regulators (PGR's) that reduce plant height and lodging have not been evaluated on commercial wheat cultivars under local conditions. The objective of this study was to assess the effects of plant growth regulators on plant height, lodging, yield and yield components and quality parameters of three wheat cultivars under irrigation in the field. A water control and two PGR's, chlormequat chloride and ethephon, were applied individually (1.575 kg chlormequat ha^{-1} and 0.6 kg ethephon ha^{-1}) and in combination with each other (1.75 and 0.375 kg ai ha^{-1} of chlormequat and ethephon respectively) at either the tillering, stem elongation or the flag leaf stage of growth to the cultivars Kariega (lodging susceptible), Olifants (lodging tolerant) and SST 876 (lodging tolerant) at Vaalharts and Bethlehem. The 4 X 3^2 factorial treatment combinations were tested in a RCBD with four replications in the 2003 and 2004 seasons at both sites.

Chlormequat reduced plant height by approximately 4.5% when applied at the flag leaf stage and had no effect on lodging with any cultivar. Yield and yield components, protein content, hectolitre mass, and falling number were generally not affected by chlormequat. Ethephon and the PGR combination significantly reduced plant height (8.6 and 17%, respectively) and lodging (84 and 94%, respectively) of Kariega when applied at the flag leaf stage, while lodging was not reduced with the lodging tolerant cultivars. Yields were either improved or reduced by ethephon and the PGR combination, depending on the cultivar, time of application (TOA), and locality. The yield reductions were primarily attributed to reductions in mass grain^{-1} and grains spike^{-1}. Differential hectolitre mass, protein content, falling number and preharvest sprouting were observed, depending on the environment, cultivar and TOA of ethephon and the PGR combination. Generally, the results of the study suggest that chlormequat is not suitable as an anti-lodging tool in wheat production, while ethephon and the PGR combination may successfully control lodging and occasionally improve grain yield and quality.

INTRODUCTION

As the dominant small grain crop produced around the world, wheat has proven to be an invaluable commodity that sustains life on earth. Approximately 85% of the winter small grain production in South Africa is dominated by wheat (Anon, 2004), emphasising its importance in relation to other small grain crops. The optimisation of production practices in wheat has been taking place for decades with considerable success. However, there are certain limitations, such as lodging that have consistently restricted yield potentials.

With the advent of semi-dwarf wheat culitvars, lodging has been successfully limited under moderate levels of inputs. However, under intensive agronomic conditions even some semi-dwarf wheat cultivars have been known to lodge (Tripathi *et al.*, 2004). To avoid lodging, producers may withhold the last irrigation, which may be crucial for grain filling and can ultimately limit grain yield (Fischer & Stapper, 1987). Other producers may opt to reduce nitrogen inputs or seeding rates, which can also limit yield potential. One way of reducing lodging in wheat without limiting yield potential is through the use of stem shortening plant growth regulators (PGR's) such as chlormequat chloride and ethephon. Most of the research conducted involving PGR's has been done on wheat and the effects of these compounds on the crop are well documented (Rajala & Peltonen-Sainio, 2000).

Both chlormequat and ethephon act by inhibiting stem elongation in the plant, thereby reducing biomass production. Lowe & Carter (1972) reported significant reductions in plant dry matter at harvest in chlormequat-treated wheat plants as compared to controls. Cox & Otis (1989) applied ethephon to wheat plants at the flag leaf stage and found 7 and 13% reductions in dry matter in the two years in which the study was conducted. According to Rajala & Peltonen-Sainio (2001), an application of ethephon to wheat plants at tillering led to significant reductions in dry matter of 39 mg plant^{-1}.

The effects of PGR's on biomass production are dependent on the type of compound applied. Ethephon consistently reduces biomass (Cox & Otis, 1989), while chlormequat has variable effects (Green, 1986). Chlormequat has been shown to stimulate tillering in wheat (Tolbert, 1960), and this may be the primary reason for any improvements in biomass production. Alternatively, the consistent reduction in biomass following ethephon application may be due to the compound normally being applied at the flag leaf stage, thereby having minimal effects on tillering.

The most consistent effect of chlormequat and ethephon is the reduction in plant height (Tripathi *et al.*, 2004). When environmental conditions are conducive to lodging, these reductions in plant height are often accompanied by reductions in lodging (Tripathi *et al.*, 2004). Tolbert (1960) reported significant height reductions in wheat ranging from 60 to 180 mm after soil applications of chlormequat at different concentrations. Woolley *et al.* (1991) reported that a 5.8% reduction in height of wheat plants was accompanied by a 30% reduction in lodging after chlormequat application. Wiersma *et al.* (1986) found that a 50 mm reduction in plant height after ethephon treatment led to a subsequent 31% reduction in the lodging score of winter wheat.

The effects on plant height and lodging are dependent on the time of application of the PGR's. The compound chlormequat is normally applied at earlier growth stages (late tillering or stem elongation stages) and therefore affects the lower internodes (Humphries *et al.*, 1965). Reports of recovery responses by the plants (Bruinsma, 1982) have suggested the need to investigate later application times of the compound. The effects on plant height and lodging may be greater if the inhibition of elongation shifts to the upper internodes which are the longest. Ethephon, which releases ethylene in a slow release mechanism (Lurssen, 1982), is normally applied at the flag leaf stage. However, if applied earlier, it could be possible that the elongation-inhibiting effects could be spread out in both lower and upper internodes thereby reducing plant height and lodging to a greater degree. The above theories suggest a need to re-investigate the proper times of application of PGR's on wheat.

The effects of PGR's on wheat yield and yield components have been variable. Rowland (1973) reported significant yield increases ranging from 3% to 7% after early chlormequat application. These improvements in yield were attributed to a greater number of spikes m^{-2}. In a study involving chlormequat, Tolbert (1960) attributed yield increases in treated wheat plants to improvements in mass $grain^{-1}$ rather than grains $spike^{-1}$ or spikes m^{-2}. Stahli *et al.* (1995) also attributed chlormequat-induced yield increases of 16-20% to improvements in mass $grain^{-1}$. Alternatively, other reports have indicated no effects of chlormequat on yield or yield components (Kettlewell *et al.*, 1983), and in some instances yields were actually decreased (Green, 1986).

Most reports on the effects of ethephon on wheat have suggested that the compound may be detrimental to yield unless lodging is prevented (Cox & Otis, 1989; Simmons *et al.,* 1988). Wiersma *et al.* (1986) reported a yield increase of up to 6.4% in ethephon-treated wheat plants and the primary reason for the increase was that the treated plots did not lodge. In the absence of lodging, ethephon has been shown to reduce the number of grains $spike^{-1}$. Foster *et al.* (1991) reported that the number of grains $spike^{-1}$ decreased significantly by 26-36% in wheat when treated with two different rates of ethephon. Rowland (1973) also found that the number of grains $spike^{-1}$ was reduced by 11 in wheat plants treated with ethephon. Ethephon is known to be an effective gametocide that induces male sterility in wheat (Rowell & Miller, 1971), and this may be the primary reason for the reduction in grains $spike^{-1}$ that is often experienced. It is clear that the effects of chlormequat and ethephon on yield and yield components are variable and may be dependent on the type of compound used, environmental conditions, cultivar characteristics, time of application, and either the presence or absence of lodging.

Limited research has been conducted on the effects of PGR's on wheat grain quality characteristics. The hectolitre mass (test weight) and protein content of wheat grain are important grading parameters utilized in the South African grain industry (Barnard & Burger, 2003). PGR's have been shown to enhance

(Knapp & Harms, 1988; Khan & Spilde, 1992), and in some instances, to reduce (Rowland, 1973) both hectoliter mass and protein content. Non-optimal hectolitre masses or protein contents can lead to downgrading of wheat, which will limit producer income. Any possible effects of PGR's on these parameters should therefore be investigated.

In South Africa, many commercial wheat cultivars are susceptible to lodging under irrigated conditions (Otto, 2005 pers. comm.*). Consequently, this has limited the implementation of intensive management systems as producers are forced to reduce nitrogen inputs and seeding rates. The objective of this study was to assess the effectiveness of PGR's (chlormequat and ethephon) on wheat lodging in South Africa. Investigations into the effects of the PGR's on vegetative growth, yield, yield components and grain quality were undertaken. The findings of the study will be used in wheat management programmes to possibly assist in lodging control.

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RESULTS AND DISCUSSION

Plant height and lodging

In general, plant height and lodging were influenced by the PGR's, times of application, and cultivars at both localities (Table 1, Appendix 3a). At Vaalharts, lodging only occurred occasionally in a few plots in both seasons, as reflected by the low lodging scores observed. Lodging did not occur in Bethlehem in 2004, while there were low lodging scores obtained in 2003 (Table 1).

The lodging susceptible cultivar Kariega produced plants that were 1.8 and 7.6% taller and significantly different from those of the lodging tolerant cultivar Olifants at Vaalharts and Bethlehem respectively (Table 1). No differences in plant height were observed between Kariega and SST 876 at Vaalharts, while Kariega produced plants that were 2.7% taller and significantly different from those of SST 876 at Bethlehem. Plants of Olifants were significantly shorter than those of SST 876 at both localities.

The significant 15.7 mm reduction in plant height of Olifants compared to Kariega was comparatively accompanied by an 82% reduction in lodging score at Vaalharts. The reduction in lodging is, however, unlikely to be attributed to such a minor change in plant height and could possibly be due to weaker stem characteristics of Kariega relative to Olifants. Additionally, no differences in plant height were observed between Kariega and SST 876 at Vaalharts, with Kariega exhibiting a greater lodging score. This further demonstrates the possible weaker stem characteristics of Kariega relative to the other two cultivars. At Bethlehem the reductions in plant height with Olifants and SST 876 were not accompanied by lodging reductions. This may be due to lodging not being severe at Bethlehem in 2003 and no differences between the cultivars were detected.

Table 1. Plant height and lodging responses of three wheat cultivars to plant growth regulators (PGR) and their times of application (TOA) in the 2003 and 2004 seasons at two sites (Vaalharts and Bethlehem).

TREATMENTS		PLANT HEIGHT	LODGING SCORE[†]
		--------------mm------------------	----------------0.2 - 9----------------
		Vaalharts	
		2003-2004	**2003-2004**
PGR			
	Control	$891.4^{a\S}$	1.1^{a}
	Chlormequat	864.8^{b}	1.1^{a}
	Ethephon	854.8^{b}	0.8^{ab}
	PGR comb.	836^{c}	0.7^{b}
	LSD $_{(0.05)}$	15.8	0.4
Cultivar (C)			
	Kariega	863.3^{a}	2.2^{a}
	Olifants	847.6^{b}	0.4^{b}
	SST 876	874.3^{a}	0.2^{b}
	LSD $_{(0.05)}$	13.7	0.3
TOA			
	Tillering	891.7^{a}	1.0^{a}
	Elongation	853.6^{b}	1.0^{a}
	Flag leaf	840^{b}	0.8^{a}
	LSD $_{(0.05)}$	13.7	NS
C X PGR		NS	NS
C X TOA		NS	NS
PGR X TOA		**	**
PGR X C X TOA		NS	**
		Bethlehem	
		2003-2004	**2003**
PGR			
	Control	749.9^{a}	0.6^{a}
	Chlormequat	718.2^{b}	0.4^{ab}
	Ethephon	683.4^{c}	0.3^{b}
	PGR comb.	664.3^{d}	0.3^{b}
	LSD $_{(0.05)}$	14.9	0.3
Cultivar			
	Kariega	727.6^{a}	0.3^{a}
	Olifants	675.9^{c}	0.5^{a}
	SST 876	708.3^{b}	0.5^{a}
	LSD $_{(0.05)}$	12.9	NS
TOA			
	Tillering	744.2^{a}	0.3^{a}
	Elongation	700.1^{b}	0.5^{a}
	Flag leaf	667.6^{c}	0.4^{a}
	LSD $_{(0.05)}$	12.9	NS
C X PGR		NS	NS
C X TOA		NS	NS
PGR X TOA		**	NS
PGR X C X TOA		NS	NS

† Lodging scale where 0.2= no lodging and 9 = completely flat.

§ Values within a particular treatment and column with the same superscript letters are not significantly different from each other

* Significance of difference when $P<0.05$

** Significance of difference when $P<0.01$

NS No significant difference

The PGR X TOA interaction for plant height was highly significant (P<.001) at both localities (Table 1; Appendix 3a). In general, significant reductions in plant height were observed as the application of ethephon and the PGR combination proceeded towards the flag leaf stage at Vaalharts (Fig. 4a) and Bethlehem (Fig. 4b). The PGR combination treatment produced significantly progressive lowering in plant height relative to the control at all three times of application at both localities with the flag leaf application being most effective at reducing height. The height difference with the application of ethephon at the elongation and the flag leaf stage was not significantly different from the control at Vaalharts (Fig. 4a). A significant difference to ethephon application was observed between application at stem elongation and flag leaf at Bethlehem (Fig. 4b). The PGR chlormequat only reduced plant height relative to the control when applied at the flag leaf stage at both localities while the earlier application did not produce a response. The height reduction of chlormequat was not as large as that produced by ethephon or the PGR combination at both localities. The response of plant height to combining chlormequat with ethephon appeared to be additive at both sites and most application times (Fig. 4a,b). However, the addition of chlormequat in the combination did not significantly enhance the height-reducing ability of ethephon applied alone.

The PGR X C X TOA lodging interaction was highly significant (P<.001) at Vaalharts (Table 1; Appendix 3a). The lodging tolerant cultivars SST 876 and Olifants did not respond to the application of any PGR irrespective of the TOA (Fig. 4c). The lodging susceptible cultivar Kariega, however, responded by producing significantly lower lodging scores when ethephon and the PGR combination treatment were applied at the flag leaf stage compared to applications at elongation and tillering. Danhous *et al.* (1982) also reported cultivar specific reactions when PGR's were applied to both wheat and barley in the field. In addition to the height reduction observed at Vaalharts (Fig. 4a) ethephon may have reduced lodging in Kariega by increasing lignin synthesis in the plant stems as it is known to stimulate production of two of the enzymes involved in lignin synthesis: phenylalanine ammonia lyase and peroxidase (Blomquist *et al.*, 1973).

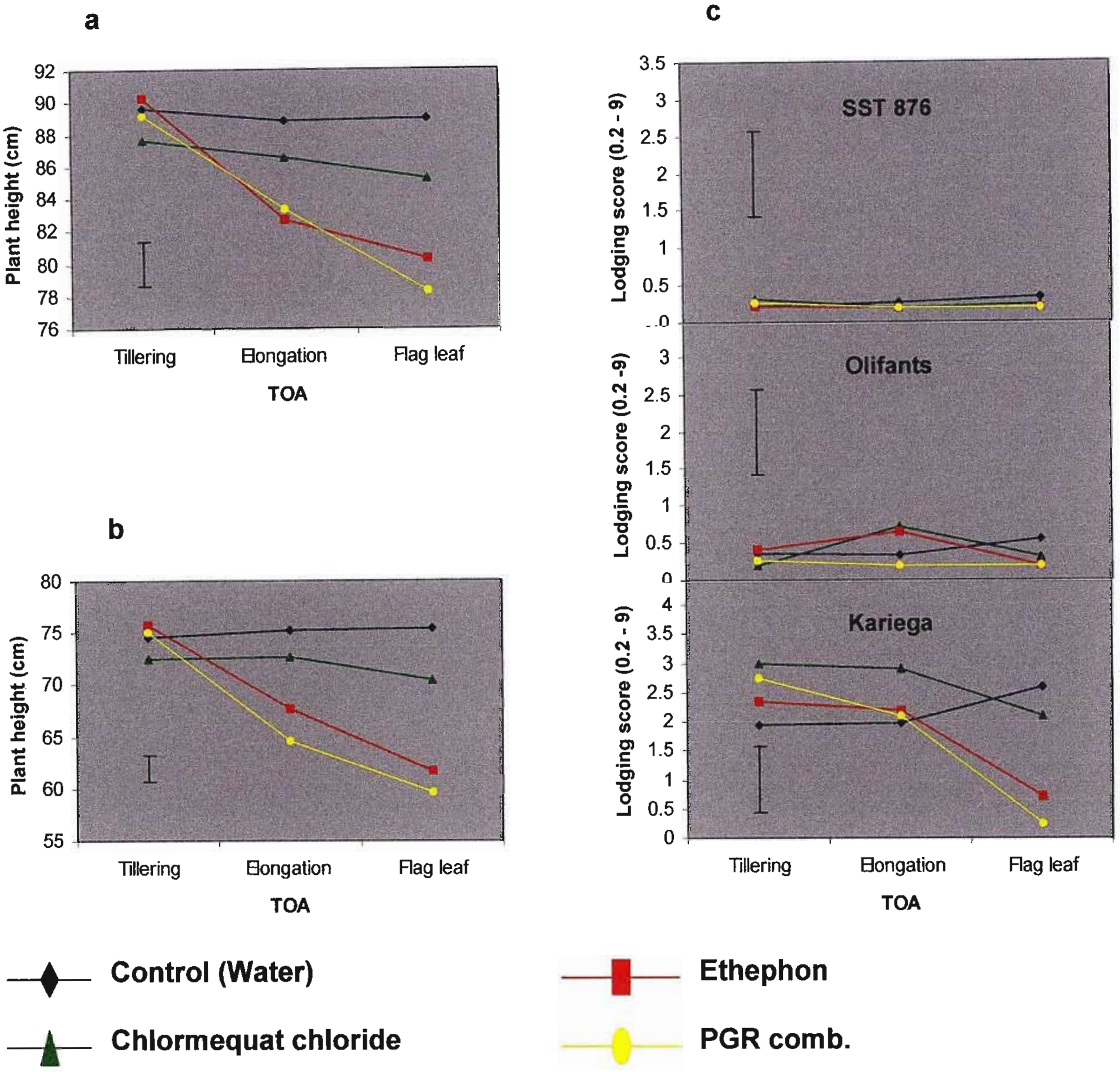


Fig 4. The plant growth regulator (PGR) X time of application (TOA) interactions for plant height at Vaalharts (a) and Bethlehem (b), and the PGR X cultivar (C) X TOA interaction for lodging at Vaalharts (c). Vertical bars represent the LSD$_{(0.05)}$ for the specific interaction.

Chlormequat applications did not produce a reduction in lodging as similar lodging scores were obtained at all three application times (Fig. 4c). A slight decline in lodging was observed at the flag leaf stage. However, the reduction was not significant. At Bethlehem, none of the two or three factor interactions were significant for lodging, however, ethephon and the combination treatment significantly reduced lodging by 50% (Table 1). No differences in lodging were observed between the different cultivars or times of application at Bethlehem in 2003.

Reports of chlormequat and ethephon reducing plant height are many, however, the time of application may influence the overall response. Woolley *et al.* (1991) observed a 5.8% reduction in mean height of wheat cultivars with a single chlormequat application at the beginning of stem elongation at three different sites. Work done by Myhre *et al.* (1973) suggested that the greatest reduction in plant height and lodging occurs when chlormequat is applied at around the fifth leaf stage of development. The results of this study are in contrast to those of Myhre *et al.* (1973) because plant height was only reduced when chlormequat was applied at the flag leaf stage at both localities (Fig. 4a and b). It is possible that the cultivars investigated were most sensitive to height reductions when late applications were employed. The responses produced by ethephon application are in keeping with the literature (Danhous *et al.*, 1982; Foster *et al.*, 1991) as plant height was reduced to a greater extent as later applications of ethephon were employed (Fig. 4a and b). The flag leaf application may be more suited to height reductions as the growth inhibition is more concentrated on the upper, longer internodes.

Yield and yield components

In general, grain yields at Vaalharts were much higher than those at Bethlehem in both seasons. Average yields of 6.5 and 5.8 t ha^{-1} were produced at Vaalharts in the 2003 and 2004 seasons respectively while the average yield at Bethlehem in 2003 was 4.12 t ha^{-1} compared to the average of 4.34 t ha^{-1} produced in 2004. This was in keeping with the long-term average for these localities. Vaalharts is a higher yield potential environment than Bethlehem due to the higher soil fertility and general lack of frost (Barnard & Burger, 2003).

The highly significant PGR X TOA interaction for mass $grain^{-1}$ at Vaalharts (Fig. 5a, Appendix 3b) indicates that the PGR combination significantly reduced the mass $grain^{-1}$ when applied at the elongation stage compared to the tillering and flag leaf applications. The application of ethephon at elongation also reduced mass $grain^{-1}$ compared to the tillering application while chlormequat did not produce a response at the different application times. The PGR X TOA interaction for mass $grain^{-1}$ at Bethlehem was not significant, however, Fig. 5b indicates that a similar response was obtained i.e. ethephon and the PGR combination reduced mass $grain^{-1}$ when applied at the elongation stage compared to the control while chlormequat produced no significant differences.

The reduction in mass $grain^{-1}$ by the ethephon and combination treatments may be attributed to the effects of ethephon on tillering. Moes & Stobbe (1991) reported that the production of late tillers after ethephon application may lead to competition for assimilate, since shoots which appeared after ethephon application would initially be dependent on assimilate partitioning from the main stem. It was concluded that this was the primary reason for the reduction in grain weight that is often observed after early ethephon application. However, applications of ethephon at tillering did not reduce mass $grain^{-1}$ at Vaalharts (Fig. 5a) or Bethlehem (Fig. 5b) while applications at elongation did. This may indicate that ethephon application could stimulate late tiller production to a greater extent than it does normal tillering.

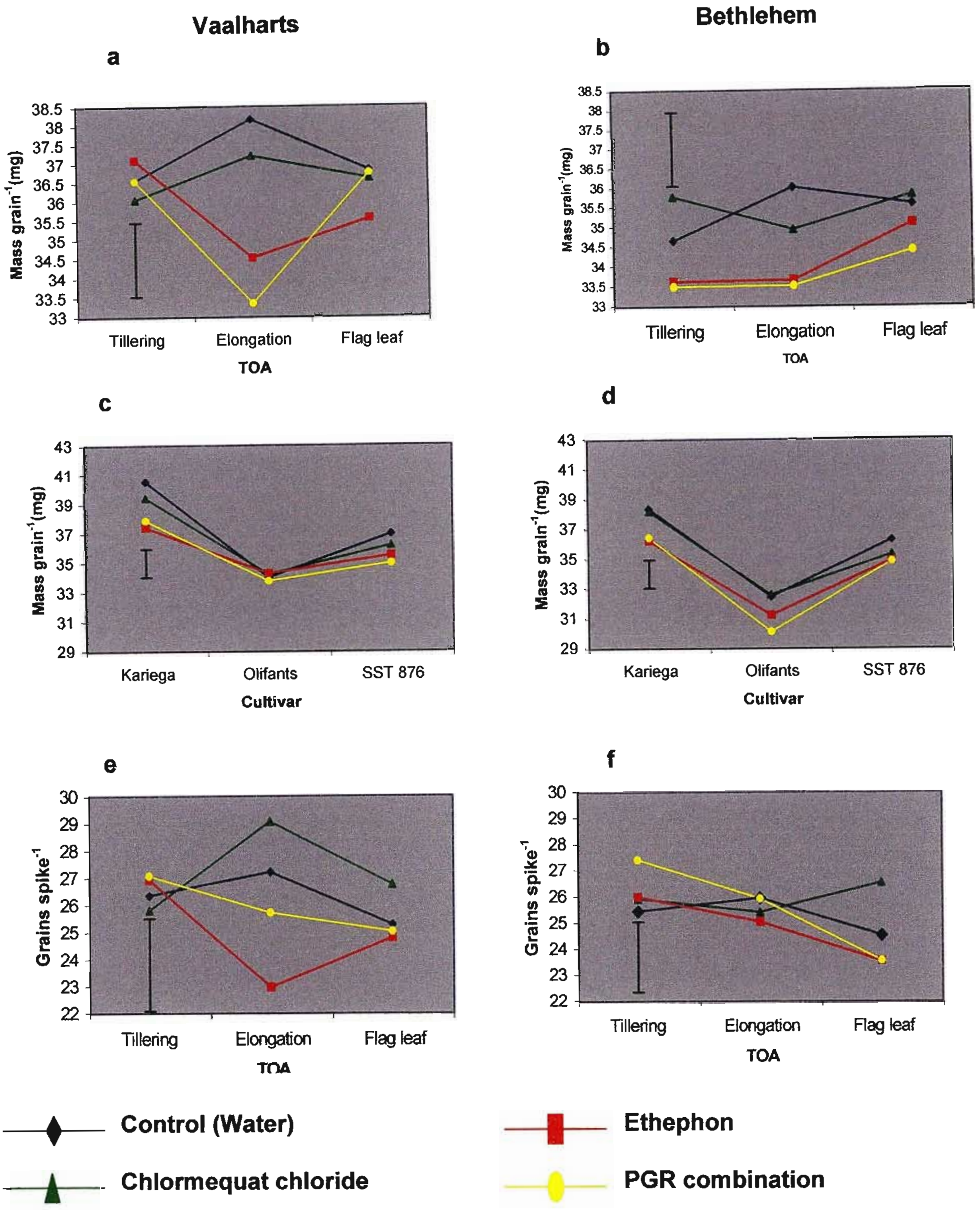


Fig. 5 The plant growth regulator (PGR) X time of application (TOA) interactions (a and b), the cultivar X PGR interactions (c and d) for mass grain^{-1}, and the PGR X TOA interactions for grains spike^{-1} at Vaalharts and Bethlehem. Vertical bars represent the LSD$_{(0.05)}$ for the particular interaction.

The cultivar Kariega produced a significantly higher mass grain^{-1} than the other cultivars at both localities (Table 2). The non-significant C X PGR interaction for mass grain^{-1} indicates that the application of ethephon and the PGR combination significantly reduced mass grain^{-1} in Kariega at Vaalharts (Fig. 5c) and Bethlehem (Fig. 5d). The PGR combination also reduced the mass grain^{-1} of the cultivar Olifants at Bethlehem (Fig. 5d). This may be attributed to significant reduction in plant height after ethephon and the combination treatment (Fig. 4a), which may have in turn reduced the photosynthetic capacity of Kariega thereby reducing mass grain^{-1}. The lodging tolerant cultivars Olifants and SST 876 did not respond to applications of PGR's in general, as mass grain^{-1} was similar to that obtained from the controls.

None of the PGR's had main effects on grains spike^{-1} at either locality compared to the control (Table 2). However, the non-significant (P=0.194) PGR X TOA interaction indicates that ethephon application at the elongation stage reduced the number of grains spike^{-1} compared to the control at Vaalharts (Fig. 5e, Appendix 3b). At Bethlehem, ethephon did not significantly affect grains spike^{-1} at any TOA (Fig. 5f). Instead, the PGR combination treatment significantly reduced grains spike^{-1} at the flag leaf stage compared to the tillering applications. This led to an overall 6.1% reduction in grains spike^{-1} with the flag leaf application compared to applications at the tilering stage (Table 2).

Ethephon is known to be an effective gametocide that induces male sterility in wheat (Rowell & Miller, 1971). This may be the primary reason for the reductions in grains spike^{-1}. Alternatively, the release of ethylene from ethephon (Lurssen, 1982) may enhance the developmental rate and the processes involved in senescence. The improved growth rate may ultimately result in the formation of fewer grain sites as well as shorten the duration of grain filling thereby negatively affecting grains spike^{-1} (Fig. 5e) and grain weight (Fig. 5a,b,c and d).

Table 2. Yield and yield component responses of three wheat cultivars (C) to plant growth regulators (PGR) and their times of application (TOA) at Vaalharts and Bethlehem (2003-2004)

TREATMENTS		YIELD		SPIKES M^{-2}		GRAINS $SPIKE^{-1}$		GRAIN MASS	
		t ha^{-1}		no				mg	
PGR		Vaalharts	Bethlehem	Vaalharts	Bethlehem	Vaalharts	Bethlehem	Vaalharts	Bethlehem
	Control	$6.2^{a\S}$	4.4^{a}	581.9^{b}	559.6^{a}	26.3^{ab}	25.3^{a}	37.2^{a}	35.7^{a}
	Chlormequat	6.2^{a}	4.4^{a}	598.9^{ab}	545.4^{ab}	27.2^{a}	26.0^{a}	36.6^{ab}	35.4^{a}
	Ethapon	6.0^{a}	4.1^{b}	627^{a}	560.6^{a}	25.1^{b}	24.9^{a}	35.7^{b}	34.1^{b}
	PGR comb.	6.1^{a}	4.0^{b}	586.8^{ab}	515.7^{b}	26.0^{ab}	25.7^{a}	35.6^{b}	33.8^{b}
	$LSD_{(0.05)}$	NS	0.3	43.9	40.8	2.0	NS	1.1	1.1
Cultivar (C)									
	Kariega	5.7^{b}	4.6^{a}	662.9^{a}	550.6^{a}	21.9^{c}	22.1^{c}	38.8^{a}	37.3^{a}
	Olifants	6.3^{a}	4.2^{b}	586.6^{b}	546.3^{a}	24.3^{b}	25.5^{b}	34.1^{c}	31.6^{c}
	SST 876	6.4^{a}	4.0^{b}	546.3^{c}	539.2^{a}	32.2^{a}	28.8^{a}	35.9^{b}	35.3^{b}
	$LSD_{(0.05)}$	0.2	0.3	38.0	NS	1.7	1.4	1.0	1.0
TOA									
	Tillering	6.3^{a}	4.4^{a}	589.1^{a}	557.5^{a}	26.6^{a}	26.2^{a}	36.6^{a}	34.4^{a}
	Elongation	6.1^{b}	4.3^{ab}	611.6^{a}	551.9^{a}	26.4^{a}	25.6^{ab}	35.8^{a}	34.6^{a}
	Flag leaf	6.0^{b}	4.1^{b}	595.1^{a}	526.7^{a}	25.5^{a}	24.6^{b}	36.4^{a}	35.2^{a}
	$LSD_{(0.05)}$	0.2	0.3	NS	NS	NS	1.4	NS	NS
C X PGR		NS	*	NS	*	NS	NS	NS	NS
C X TOA		NS	NS	NS	NS	NS	NS	NS	NS
PGR X TOA		*	*	NS	NS	NS	NS	**	NS
PGR X C X TOA		*	NS	NS	NS	NS	NS	NS	NS

§ Values within a treatment and column with the same superscript letters are not significantly different from each other.
* Significance of difference when $P<0.05$.
* * Significance of difference when $P<0.001$.
NS No significant difference.

The cultivar Kariega produced the lowest number of grains spike^{-1} compared to the other cultivars at both localities (Table 2). The highest number of grains spike^{-1} was produced by SST 876, followed by Olifants. The reduction in the number of grains spike^{-1} in Kariega may be related to the greater plant height of the cultivar compared to the lodging tolerant cultivars (Table 1). The process of stem elongation normally coincides with spikelet and floret initiation. This implies that in shorter cultivars such as Olifants and SST 876 less assimilate is required for stem elongation thereby allowing greater assimlate availability for spikelet and floret initiation. In Kariega, however, there may be greater partitioning of assimilate for stem elongation thereby limiting spikelet and floret initiation. The number of grains spike^{-1} may therefore be reduced in Kariega and improved in SST 876 and Olifants due to the differences in height morphology.

The PGR ethephon significantly increased the number of spikes m^{-2} by approximately 45 at Vaalharts (Table 2). The C X PGR interaction was not significant at Vaalharts, however, Fig. 6a indicates that an improvement in spikes m^{-2} occurred when ethephon and the PGR combination were applied to Kariega. This explains the significant 13 and 21% improvement in spikes m^{-2} of Kariega relative to Olifants and SST 876 at Vaalharts respectively (Table 2). The cultivars Olifants and SST 876 did not produce any improvements in spikes m^{-2} with applications of any PGR. At Bethlehem, however, the significant ($P=0.022$; Appendix 3b) C X PGR interaction indicates that applications of all three PGR's caused a significant reduction in spikes m^{-2} of Kariega compared to the control (Fig. 6b). This suggests that the PGR's may have variable effects on the lodging susceptible cultivar Kariega in different environments.

The TOA did not have an effect on spikes m^{-2} at either locality. This is in contrast to the work of Humphries *et al.* (1965) who indicated that an early application of chlormequat may increase tiller production, thereby improving spikes m^{-2}. Additionally, Rajala & Peltonen-Sainio (2001) reported that the application of ethephon just before tillering led to significant improvements in tiller number in wheat, barley and oats.

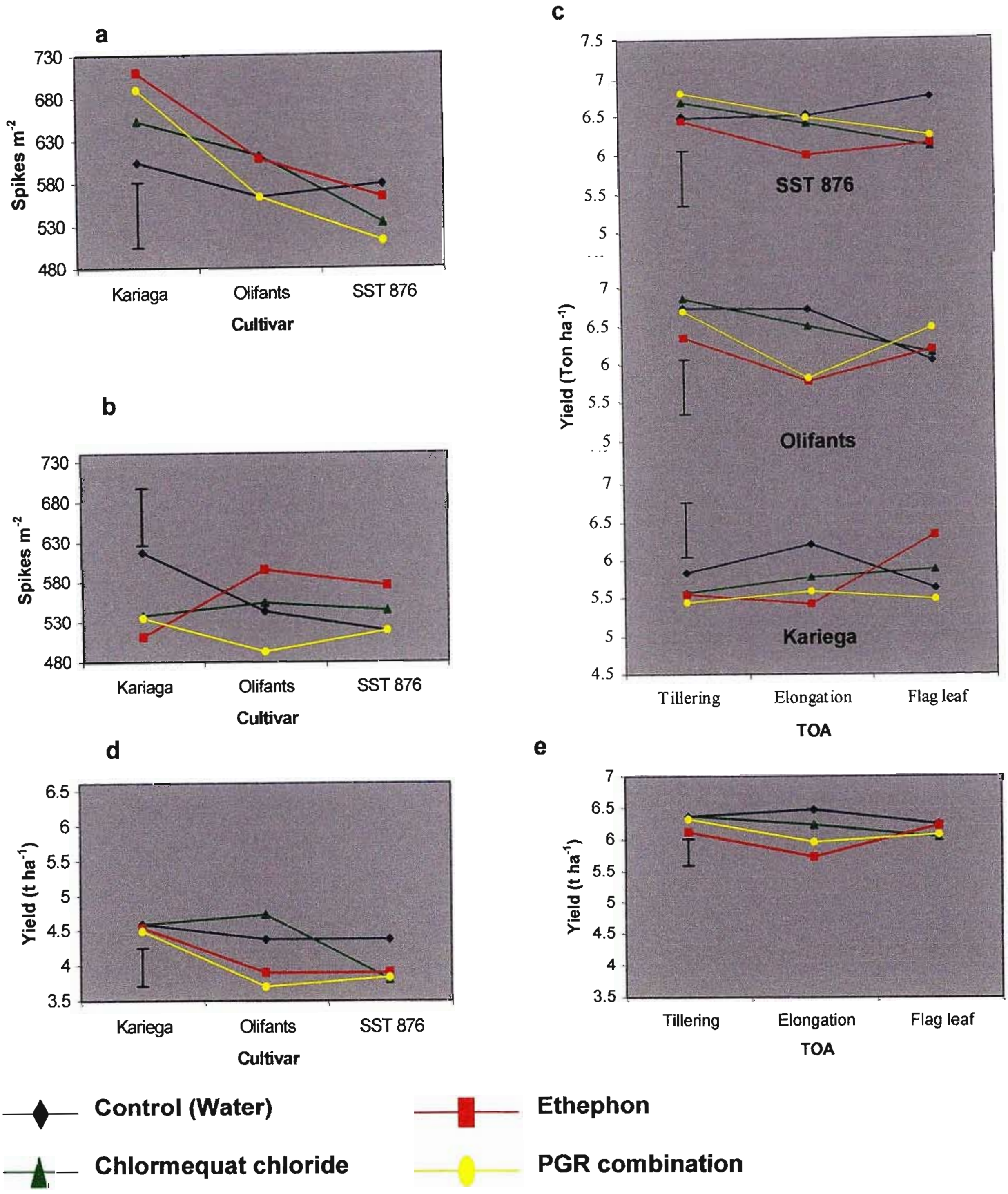


Fig. 6 The cultivar (C) X plant growth regulator (PGR) interaction for spikes m^{-2} at Vaalharts (a) and Bethlehem (b). The C X PGR X time of application (TOA) yield interaction at Vaalharts (c). The C X PGR yield interaction at Bethlehem (d) and the PGR X TOA yield interaction at Vaalharts (e). Vertical bars represent the LSD$_{(0.05)}$ for the particular interaction.

At Vaalharts the PGR X C X TOA interaction was significant (P=0.039) for yield (Table 2; Appendix 3b). The interaction indicates that yields of the cultivar SST 876 were not significantly affected by the PGR's at any TOA (Fig. 6c). The cultivar Olifants responded by producing lower yields relative to the control when ethephon and the PGR combination were applied at the elongation stage. Additionally, the yields of Olifants were also reduced when chlormequat was applied at the flag leaf stage compared to the application at tillering. The cultivar Kariega responded in a similar way to Olifants as yields were also reduced by the application of ethephon at the elongation stage as compared to the control treatment (Fig. 6c). The yield reduction may be attributed to the reduction in mass grain^{-1} after ethephon and the combination treatments at Vaalharts (Fig. 5c). This general trend of a reduction in yield following applications of ethephon at elongation is also demonstrated by the PGR X TOA yield interaction at Vaalharts (Fig. 6e).

Furthermore, ethephon applied to Kariega at the flag leaf stage produced a significantly higher yield than applications at the tillering or elongation stages (Fig. 6c). This response may be associated with the reduced plant height observed with ethephon applications at the flag leaf stage compared to earlier applications (Fig. 4a) as greater amounts of assimilate were available for yield rather than elongation growth.

At Bethlehem, the C X PGR yield interaction was significant (P=0.048; Appendix 3b) indicating that Kariega did not respond to applications of any PGR while the yields of Olifants were significantly reduced with applications of the PGR combination (Fig. 6d). Yields of the cultivar SST 876 were also significantly reduced with applications of the PGR combination and chlormequat. The PGR X TOA yield interaction was also significant (P=0.008; Appendix 3b) at Vaalharts (Fig. 6e). No differences in yield were observed between the different times of application with the control and chlormequat treatments, however, yields were decreased as the application of ethephon and the PGR combination proceeded towards the elongation stage. A similar pattern of height reduction was observed at Bethlehem with applications of ethephon and the PGR combination (Fig. 4b) suggesting the positive correlation between plant height and yield. The yield reduction may be attributed to the reduced photosynthetic capacity of the shortened plants.

In general, the application of ethephon and the PGR combination reduced mass grain^{-1} when applied to the cultivar Kariega at both localities. The reduction was greater when these PGR's were applied at the elongation stage. Ethephon and the PGR combination also reduced the number of grains spike^{-1}, however, the responses were dependent on the TOA and the environment. The number of spikes m^{-2} of Kariega were increased by these PGR's at Vaalharts, while at Bethlehem the spikes m^{-2} were reduced. Overall yields at Vaalharts were either reduced or improved depending on the cultivar and the TOA. Later applications of ethephon and the PGR combination reduced yields at Bethlehem, particularly in SST 876 and Olifants. At both localities SST 876 proved to be a low population (spikes m^{-2}), highly fertile (grains spike^{-1}) cultivar, while Olifants and Kariega demonstrated signs of being high population, low fertile cultivars (Table 2).

Hectolitre mass

In general, significant differences in hectolitre mass were observed between the cultivars. At Vaalharts, the highest hectolitre mass was produced by the cultivar SST 876, followed by Olifants and then Kariega (Table 3, Appendix 3a), all of which were significantly different from each other. The greater degree of lodging observed with Kariega compared to the lodging tolerant cultivars (Table 1) may have contributed to the low hectolitre mass observed, as assimilate flow to the grain would be interrupted if plants are not standing upright (Rajala & Peltonen-Sainio, 2000). The lack of lodging at Bethlehem would then explain the similar hectolitre mass of Kariega relative to SST 876 at this locality (Table 3), as assimilate flow to the grain was not interrupted and normal hectolitre mass was observed with Kariega.

The cultivar Kariega produced a significantly lower (3 kg hl^{-1}) hectolitre mass than SST 876 at Vaalharts, however, at Bethlehem, no significant differences were observed between these cultivars (Table 3). The improvement in hectolitre mass of Kariega relative to SST 876 at Bethlehem may be partially attributed to the application of ethephon and the PGR combination (Fig. 7b). The non-significant (P=0.133; Appendix 3a) C X PGR interaction at Bethlehem indicates that the application of ethephon and the PGR combination significantly improved hectolitre mass of Kariega compared to the control. Additionally, the application of chlormequat to SST 876 significantly reduced hectolitre mass relative to the control. The improvement in hectolitre mass of Kariega following ethephon and the PGR combination treatment coupled with the reduction in hectolitre mass of SST 876 following chlormequat application may have contributed to the similar hectolitre masses of SST 876 compared to Kariega at Bethlehem.

Table 3. Quality responses of three wheat cultivars (C) to plant growth regulators (PGR) and their times of application (TOA) at Vaalharts and Bethlehem (2003-2004)

TREATMENTS		HECTOLITRE MASS		PROTEIN CONTENT		FALLING NUMBER		PHS SCORE (2004)	
		------------kg hl^{-1}----------		--------------%----------------		-------------sec--------------		------------(1-8)------------	
PGR		Vaalharts	Bethlehem	Vaalharts	Bethlehem	Vaalhart	Bethlehem	Vaalharts	Bethlehem
	Control	75.2^{ab}	76.6^{b}	12.4^{a}	14.7^{b}	374^{a}	401^{a}	4.1^{a}	4.2^{a}
	Chlormequat	74.6^{b}	76.4^{b}	12.3^{a}	14.7^{b}	355^{b}	398^{a}	4.1^{a}	4.1^{ab}
	Ethephon	75.3^{a}	77.1^{a}	12.4^{a}	14.9^{a}	361^{ab}	394^{a}	3.7^{b}	3.8^{b}
	PGR comb.	75.1^{ab}	76.6^{b}	12.4^{a}	14.9^{a}	369^{ab}	399^{a}	3.7^{b}	4.0^{ab}
	LSD$_{(0.05)}$	0.6	0.3	NS	0.2	16.31	NS	0.3	0.4
Cultivar (C)									
	Kariega	73.8^{c}	76.5^{b}	12.4^{b}	14.5^{b}	380^{a}	390^{b}	2.8^{c}	3.1^{c}
	Olifants	74.6^{b}	77.1^{a}	12.7^{a}	15.4^{a}	372^{a}	402^{a}	3.9^{b}	4.3^{b}
	SST 876	76.8^{a}	76.4^{b}	12.0^{c}	14.6^{b}	342^{b}	402^{a}	5.0^{a}	4.7^{a}
	LSD$_{(0.05)}$	0.5	0.3	0.2	0.2	14.13	6.62	0.3	0.3
TOA									
	Tillering	74.8^{b}	76.5^{b}	12.3^{a}	14.7^{b}	366^{a}	400^{a}	4.0^{a}	4.2^{a}
	Elongation	74.9^{b}	76.8^{a}	12.4^{a}	14.8^{ab}	361^{a}	401^{a}	3.7^{a}	3.9^{b}
	Flag leaf	75.4^{a}	76.7^{ab}	12.4^{a}	14.9^{a}	367^{a}	393^{b}	4.0^{a}	4.1^{ab}
	LSD$_{(0.05)}$	0.5	0.3	NS	0.2	NS	6.62	NS	0.3
C X PGR		NS	NS	NS	NS	NS	NS	NS	NS
C X TOA		NS	NS	NS	NS	NS	NS	NS	*
PGR X TOA		*	NS	NS	NS	NS	*	*	NS
PGR X C X TOA		NS	NS	NS	NS	NS	NS	NS	NS

§ Values within a treatment and column with the same superscript letters are not significantly different from each other.
* Significance of difference when $P<0.05$.
* Significance of difference when $P<0.01$.
NS No significant difference.
PHS Preharvest sprouting

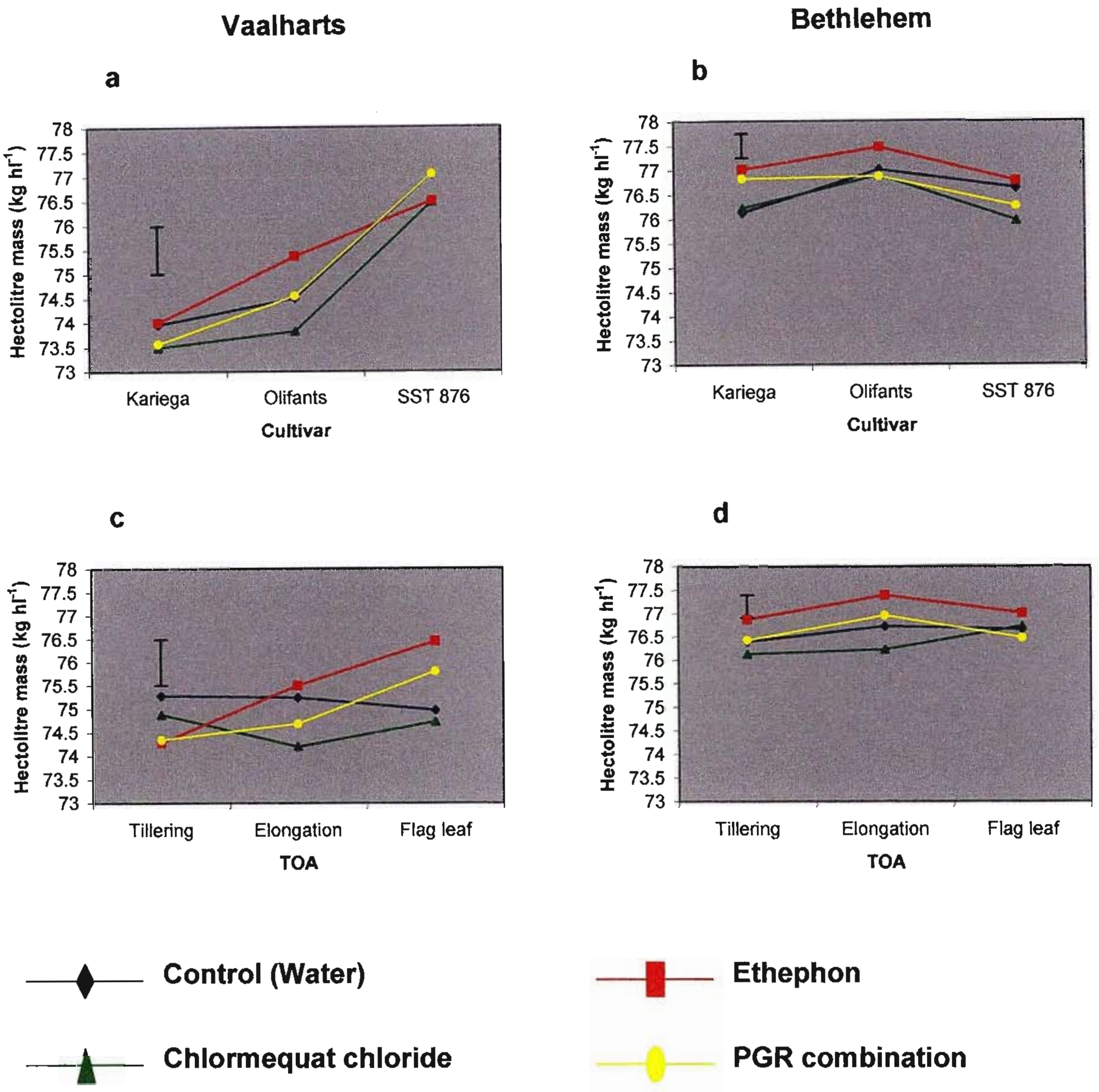


Fig. 7 The cultivar (C) X plant growth regulator (PGR) interactions (a and b) and the PGR X time of application interactions (c and d) for hectolitre mass at Vaalharts and Bethlehem. Vertical bars represent the LSD$_{(0.05)}$ for the specific interaction.

The non-significant C X PGR interactions (P=0.326, Appendix 3a) also indicate that applications of ethephon significantly improved the hectolitre mass of Olifants compared to applications of chlormequat at both localities (Figs. 7a and b). Furthermore, ethephon significantly improved hectolitre mass by 0.5 kg hl^{-1} compared to the control at Bethlehem, while the improvement by 0.1 kg hl^{-1} at Vaalharts was not significant (Table 3). Khan & Spilde (1992) and Wiersma *et al.* (1986) have made similar reports of ethephon improving hectolitre mass after applications to wheat.

In addition to having variable effects on cultivars, the PGR's also responded to different times of application. The significant (P=0.017; Appendix 3a) PGR X TOA interaction at Vaalharts indicates that no differences in hectolitre mass were observed between the three times of application with the chlormequat and control treatments (Fig. 7c). However, the flag leaf applications of ethephon and the PGR combination significantly improved hectolitre mass compared to applications at tillering. The improvement may be linked to the effects of these PGR's on plant height (Fig. 4a) and lodging (Fig. 4c), which were significantly reduced after applications of ethephon and the PGR combination at the flag leaf stage. The flag leaf application lead to a greater reduction in elongation, thereby allowing more assimilate availability for grain filling. Furthermore, the reduction in lodging after flag leaf applications may allow efficient assimilate flow to the developing grain further contributing to improved hectolitre masses.

The response at Bethlehem was slightly different, as ethephon and the PGR combination significantly improved hectolitre mass when applied at elongation compared to the tillering application (Fig. 7d). No signifcant differences were observed between the elongation and flag leaf applications with either PGR. It is possible that in the absence of lodging, the flag leaf application of ethephon and the PGR combination may not have favourable effects on hectolitre mass. The release of ethylene from ethephon (Lurssen, 1982) may speed up senescence and the grain filling process thereby limiting hectolitre mass. Rowland (1973) also reported characteristic reductions in hectolitre mass ranging from 0.8-1.3% after ethephon application to spring wheat cultivars at the flag leaf stage.

Chlormequat responded to application times at Bethlehem by improving hectolitre mass when applied at the flag leaf stage rather than at tillering (Fig. 7d). The improvement may be attributed to the effects of chlormequat on developmental rate. According to Green (1986), chlormequat has a similar effect to short days i.e. a reduction in growth rate. It is possible that the reduced growth rate following chlormequat application may allow greater time for grain filling to occur thereby improving hectolitre mass. The slower growth rate may not persist in the plant following earlier applications due to a possible recovery response (Bruinsma, 1982), hence the suitability of the flag leaf application to hectolitre mass.

Generally, the PGR ethephon may have beneficial effects on hectolitre mass when applied to the cultivars Kariega and Olifants, while chlormequat significantly reduced the hectolitre mass of SST 876. At Vaalharts, ethephon and the PGR combination improved hectolitre mass when applied at the flag leaf stage, while at Bethlehem these PGR's were more suited to the elongation stage of application. Chlormequat may also have beneficial effects on hectolitre mass when applied at the flag leaf stage rather than at tillering at Bethlehem, however, at Vaalharts no differences in hectolitre mass were observed between the different times of chlormequat application.

Grain protein content

The most significant differences in grain protein content were observed between the cultivars, while the PGR's and times of application produced responses at Bethlehem only. The cultivar Olifants produced a significantly higher protein content than the other cultivars at both localities (Table 3, Appendix 3c). Olifants was also significantly shorter than SST 876 and Kariega at both localities (Table 1). It is possible that the reduced N usage for vegetative growth due to the lack of elongation, subsequently led to the redistribution of N to the grain, thereby improving grain protein content.

The higher protein content of Olifants at Bethlehem may also be attributed to the application of ethephon and the PGR combination (Fig. 8b). The non-significant (P=0.224; Appendix 3c) C X PGR interaction indicates that the application of ethephon and the PGR combination significantly improved the protein contents of Olifants and SST 876 compared to the control, while the protein content of Kariega was unaffected by any PGR. At Vaalharts, no significant differences were observed between the PGR's with any cultivar (Fig. 8a). Knapp & Harms (1988) also found differential cultivar responses to ethephon application in terms of grain protein content. When plant height and lodging are not reduced, ethephon may have detrimental effects on yield (Simmons *et al.,* 1988). In this study, yields of Olifants and SST 876 were significantly reduced by ethephon and the PGR combination (Fig. 6d) as these cultivars did not lodge at Bethlehem (Table 1). Given the usual negative relationship between yield and protein content, the improvement in protein content following ethephon application was therefore expected as yields were simultaneously reduced.

In addition to having variable effects on cultivars, the PGR's also produced variable responses at the different times of application. The non-significant (P=0.893; Appendix 3c) PGR X TOA interaction indicates that there was no effect of the time of application of PGR with any of the PGR or control treatments used at Vaalharts (Fig. 8c). At Bethlehem (P=0.051; Appendix 3c), however, the protein content was significantly increased as the application of ethephon and the PGR combination approached the flag leaf stage (Fig. 8d). The chlormequat and control treatments responded similarly as no differences between any application times were observed. Knapp & Harms (1988) also found that ethephon increased grain protein content by 0.5-1.5% in two wheat cultivars in both years in which the study was conducted. In the same study, it was found that chlormequat had very little effect on the protein content, as observed in this study.

Plant height was significantly reduced when applications of ethephon and the PGR combination were made at the flag leaf stage rather than at tillering (Fig. 4b). The greater reduction in plant height after flag leaf applications suggests a possible redirection of assimilate to the grain following reduced growth of the longer internodes, thereby improving protein content. This explanation of response may be further enhanced by the slight improvement in mass grain^{-1} with applications of ethephon and the PGR combination at the flag leaf stage compared to applications at tillering (Fig. 5b). Furthermore, Foster & Taylor (1993), in a three-year study on the responses of barley to ethephon, found a significant improvement, a significant reduction and no response in grain protein content in the first, second and third years of the investigation, respectively. In this study it was concluded that ethephon does not affect the protein content in the whole plant, but it may effect the redistribution of protein to the grain from the straw.

In general, the results suggest that ethephon and the PGR combination may have beneficial effects on protein content. The improvement in protein content only occurred in the lodging tolerant cultivars SST 876 and Olifants, while Kariega did not respond to the applications. Additionally, the protein content may be increased to a greater extent if these PGR's are applied at the flag leaf stage rather than the tillering stage. The responses are also locality dependant as effects were only observed at Bethlehem and not at Vaalharts.

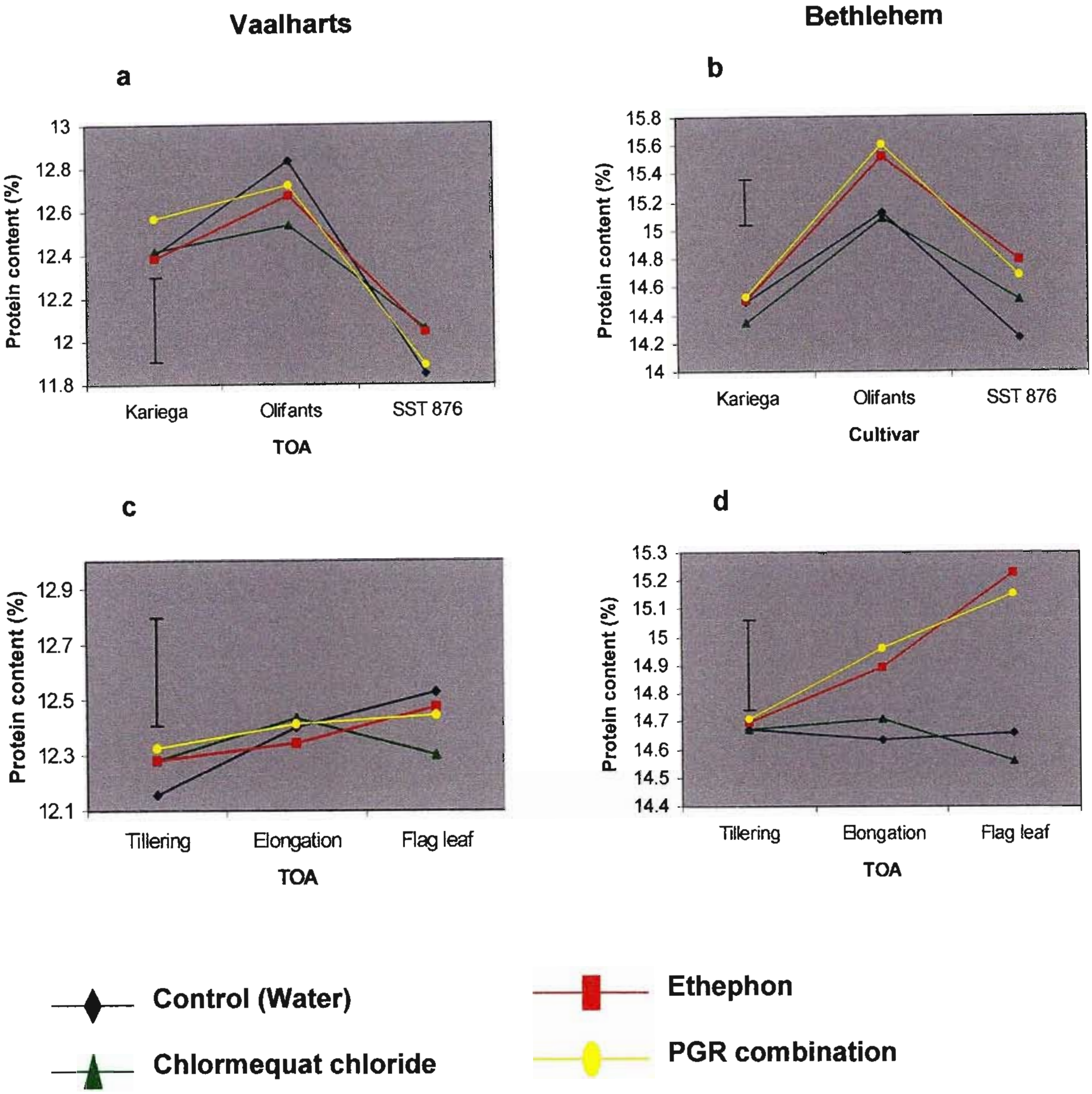


Fig. 8 The cultivar (C) X plant growth regulator (PGR) interaction (a and b) and the PGR X time of application (TOA) interaction (c and d) for grain protein content at Vaalharts and Bethlehem. Vertical bars represent the $LSD_{(0.05)}$ of the specific interaction.

Falling number

In general, the falling number responses varied between the localities. The cultivar Kariega produced a significantly higher falling number than SST 876 at Vaalharts, however, the falling number of SST 876 at Bethlehem was superior to that of Kariega (Table 3, Appendix 3c). Olifants produced high falling numbers at both localities. These responses clearly indicate the differential falling number responses of culitvars in different environments.

The PGR effects on falling number were also dependent on the environment as well as the TOA. At Vaalharts, the non-significant (P=0.198; Appendix 3c) PGR X TOA interaction indicates that ethephon application at the flag leaf stage slightly improved falling number compared to applications at tillering, while no differences in falling number were observed between the times of application with any other PGR treatment (Fig. 9a). The responses at Bethlehem (P=0.019; Appendix 3c) were different to those of Vaalharts as applications of ethephon and the PGR combination significantly reduced falling numbers when applied at the flag leaf stage compared to applications at tillering (Fig. 9b). Additionally, applications of chlormequat at the flag leaf stage significantly improved falling numbers as compared to applications at tillering.

The response produced by ethephon at Vaalharts may be linked to the effects of the compound on lodging. Ethephon application at the flag leaf stage significantly reduced lodging of the cultivar Kariega, while applications at tillering and elongation produced high lodging scores (Fig. 4c). Moisture conditions within a lodged crop canopy are normally much higher than normal (Paulsen, 1987). It is possible that the higher moisture conditions in the lodged crop stimulated the process of germination and starch degradation within the grains, thereby reducing falling number. The successful control of lodging by ethephon application at the flag leaf stage thereby improved falling number as these high moisture conditions were not prevalent.

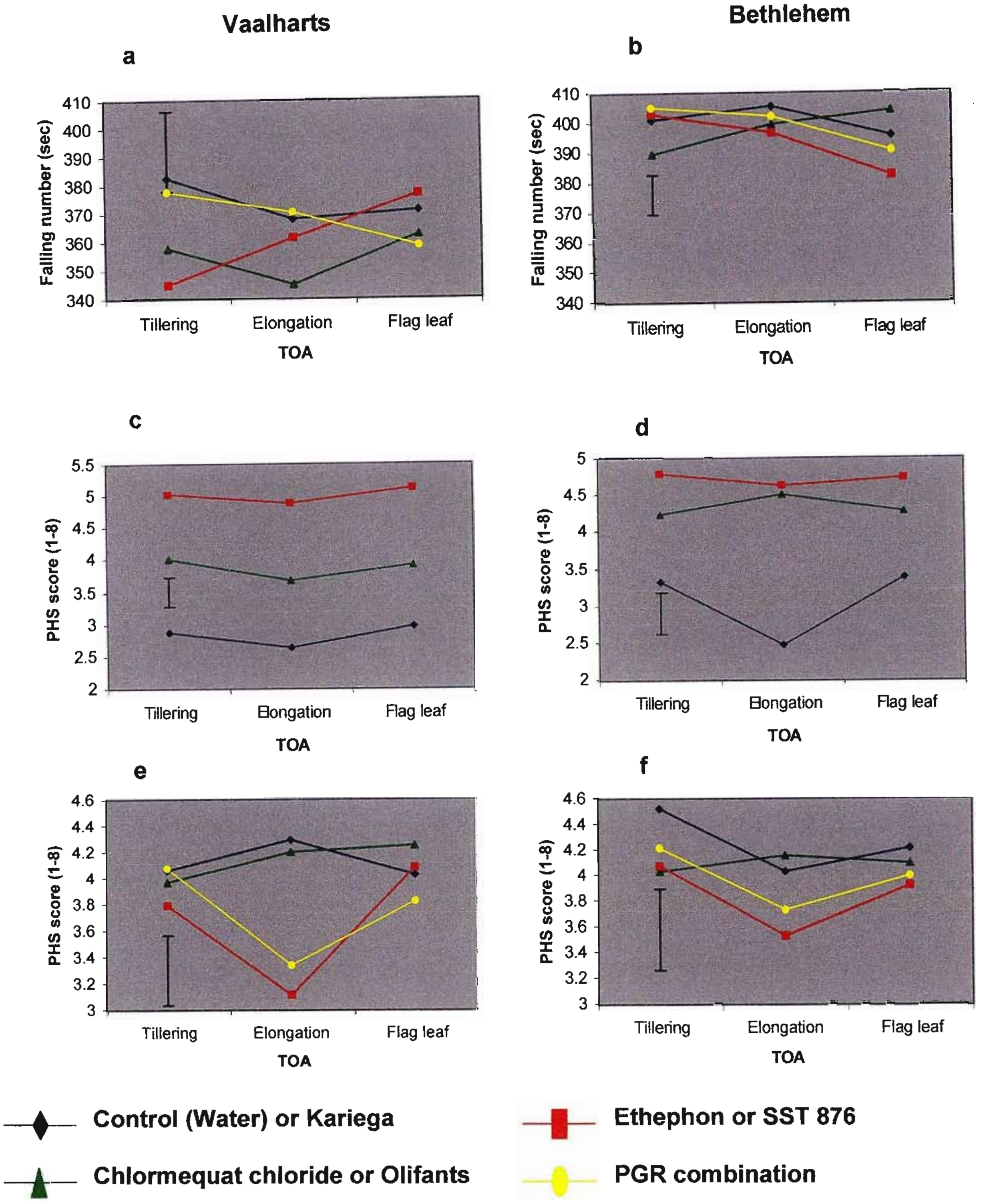


Fig. 9 The plant growth regulator (PGR) X time of application (TOA) interactions for falling number (a and b), the cultivar (C) X TOA interactions (c and d) and the PGR X TOA interactions (e and f) for preharvest sprouting (PHS) scores at Vaalharts and Bethlehem. Vertical bars represent the $LSD_{(0.05)}$ for the specific interaction.

The reduction in falling number with applications of ethephon and the PGR combination at the flag leaf stage may be related to the effects of the compound ethephon on developmental rate. The release of ethylene from ethephon (Lurssen, 1982) may have increased the rate of senescence. Subsequently, the processes involved in seed germination could have occurred at a faster rate thereby reducing the falling number. It is possible that the earlier applications of ethephon resulted in a recovery response by the plants (Bruinsma, 1982) and was therefore not effective at increasing the developmental rate and reducing falling number.

The improvement in falling number following the flag leaf application of chlormequat may be linked to the mode of action of the compound. Paleg *et al.* (1965) indicated that chlormequat acts by blocking one of the pathways of gibberellin synthesis. Gibberellins play a vital role in the initiation of starch hydrolysis in the endosperm thereby reducing falling numbers. The inhibition of gibberellin biosynthesis by chlormequat may prevent starch hydrolysis and improve falling numbers. The later applications of chlormequat, such as the flag leaf application, may ensure the presence of the compound in the seed in order to exert it's effect, while the earlier applications may be ineffective due to a recovery response by the plants.

According to the results, the effects of PGR's on falling number are dependent on the environment as well as the TOA of the compounds. Ethephon application may improve falling numbers when lodging is successfully controlled, however, it may have negative effects on falling number in the absence of lodging. Chlormequat application at the flag leaf stage may be beneficial to falling number at Bethlehem, while the compound caused an overall reduction in falling number at Vaalharts.

Preharvest sprouting tolerance

Generally, the most significant differences were observed between the cultivars, while the effects of the PGR's were dependent on TOA thereof. According to Barnard& Burger, (2003), the cultivar Kariega is known for its excellent preharvest sprouting tolerance, while the cultivars Olifants and SST 876 have poor sprouting tolerance. This was confirmed by the results of this trial as Kariega produced significantly lower sprouting scores than the other cultivars at both localities (Table 3, Appendix 3d). Additionally, the sprouting scores of Olifants were significantly lower than those of SST 876 at both localities indicating the greater tolerance to preharvest sprouting of the former.

The responses of the cultivars were also affected by the times of application of the PGR's. At Vaalharts, no significant differences were observed between the times of application with any cultivar (Fig. 9c). However, at Bethlehem, the significant (P=0.007; Appendix 3d) C X TOA interaction suggests that applications of PGR's at the elongation stage significantly reduced the sprouting scores of Kariega compared to applications at tillering or the flag leaf stages (Fig. 9d). The cultivars Olifants and SST 876 did not respond to the different application times. It is possible that the application of chlormequat to Kariega at the elongation stage caused an inhibition of gibberellin synthesis (Paleg *et al.*, 1965), which persisted in the grain after harvest, thereby improving the sprouting tolerance.

In addition to having an effect on cultivars, the TOA also produced variable responses with the PGR's. The significant (P=0.007; Appendix 3d) PGR X TOA interaction at Vaalharts indicates that the applications of ethephon and the PGR combination at the elongation stage significantly reduced sprouting scores compared to applications at tillering or the flag leaf stage (Fig. 9e). The control and chlormequat treatments produced no significant differences in sprouting scores between the times of application at both localities. The responses to ethephon and the PGR treatments at Bethlehem were similar to those at Vaalharts, however, the responses were not significant (Fig. 9f).

Applications of ethephon at elongation also significantly reduced mass grain^{-1} (Fig. 5a) and grains spike^{-1} (Fig. 5e) at Vaalharts, thereby indicating a possible relationship between these two yield components and preharvest sprouting.

Generally, preharvest sprouting was only affected by ethephon and the PGR combination treatments at both localities. Sprouting may be reduced when these PGR's are applied at the elongation stage rather than at tillering or the flag leaf stage. Additionally, sprouting tolerance of the cultivar Kariega may be improved with applications of these PGR's at the elongation stage, while SST 876 and Olifants did not respond to the PGR's or the times of application.

Biomass accumulation

Generally, biomass accumulation followed typical sigmoid patterns of growth in both seasons and localities (Fig. 10 and 11). The maximum dry weights achieved at Vaalharts were approximately 3500 and 2500 g m^{-2} in the 2003 and 2004 seasons, respectively (Fig. 10 and 11). In both seasons, these maximum dry weights were achieved by the control treatment of the lodging susceptible cultivar Kariega. The maximum dry weights produced at Bethlehem were much lower with approximately 2500 and 1700 g m^{-2} produced in 2003 and 2004, respectively. These maximum dry weights were not necessarily produced by the control treatments.

The lodging tolerant cultivar SST 876 did not respond to the applications of chlormequat or ethephon in the 2003 season at either locality (Fig. 10). This is reflected in the similar shapes of the control and PGR curves (Fig. 10a and b) as well as the similar maximum growth rates (B) and asymptotes (A + C) of the fitted curves (Table 4, Appendix 4a,b). Although a significant difference in the inflection points (M) was observed between the control (95.9 DAP) and ethephon (84.2 DAP) treatments at Vaalharts (Table 4), the difference is unlikely to be attributed to the application of ethephon, which was only applied approximately 100 DAP. A similar response was obtained in the 2004 season at Vaalharts (Fig. 10c) where no significant differences were observed between the treatments throughout the season and no significant differences were detected between any of the regression coefficients (Table 4). At Bethlehem, however, the application of chlormequat at 70 DAP reduced the growth rate of the crop as significant differences were observed between the control and chlormequat treatments at 79, 85 and 99 DAP (Fig. 10d). The crop subsequently recovered as the normal growth rate resumed thereafter and the maximum dry weight was similar to the control (Table 4). The final dry weight produced at harvest was lower, but not significantly different from the control treatment (Fig. 10d).

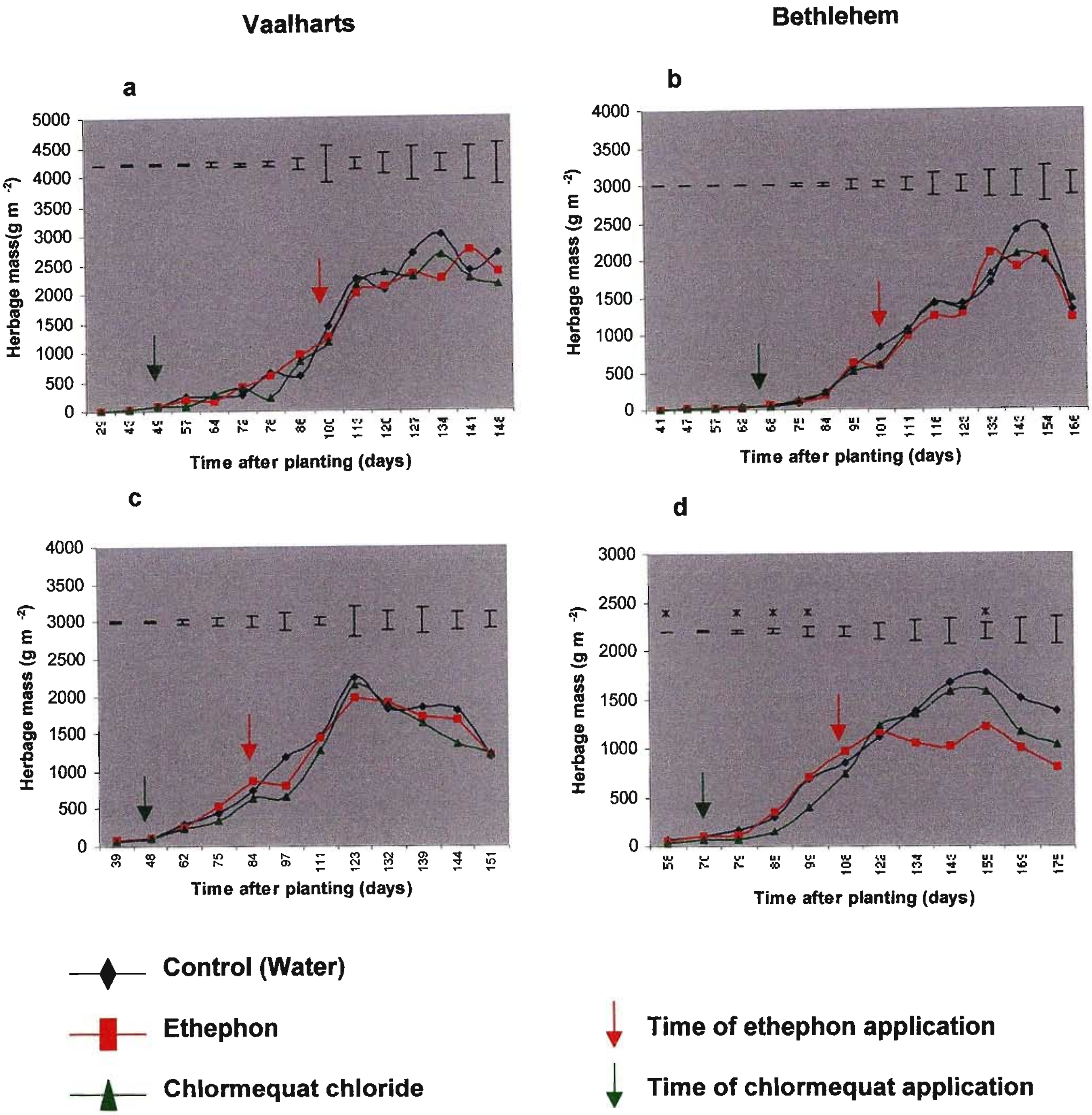


Fig. 10 Biomass accumulation of SST 876 wheat in the 2003 (a and b) and 2004 (c and d) seasons at Vaalharts and Bethlehem. Standard errors for specific sampling dates are indicated by vertical bars. The "*" indicates significance of difference ($P<0.05$) between the treatments at specific sampling dates.

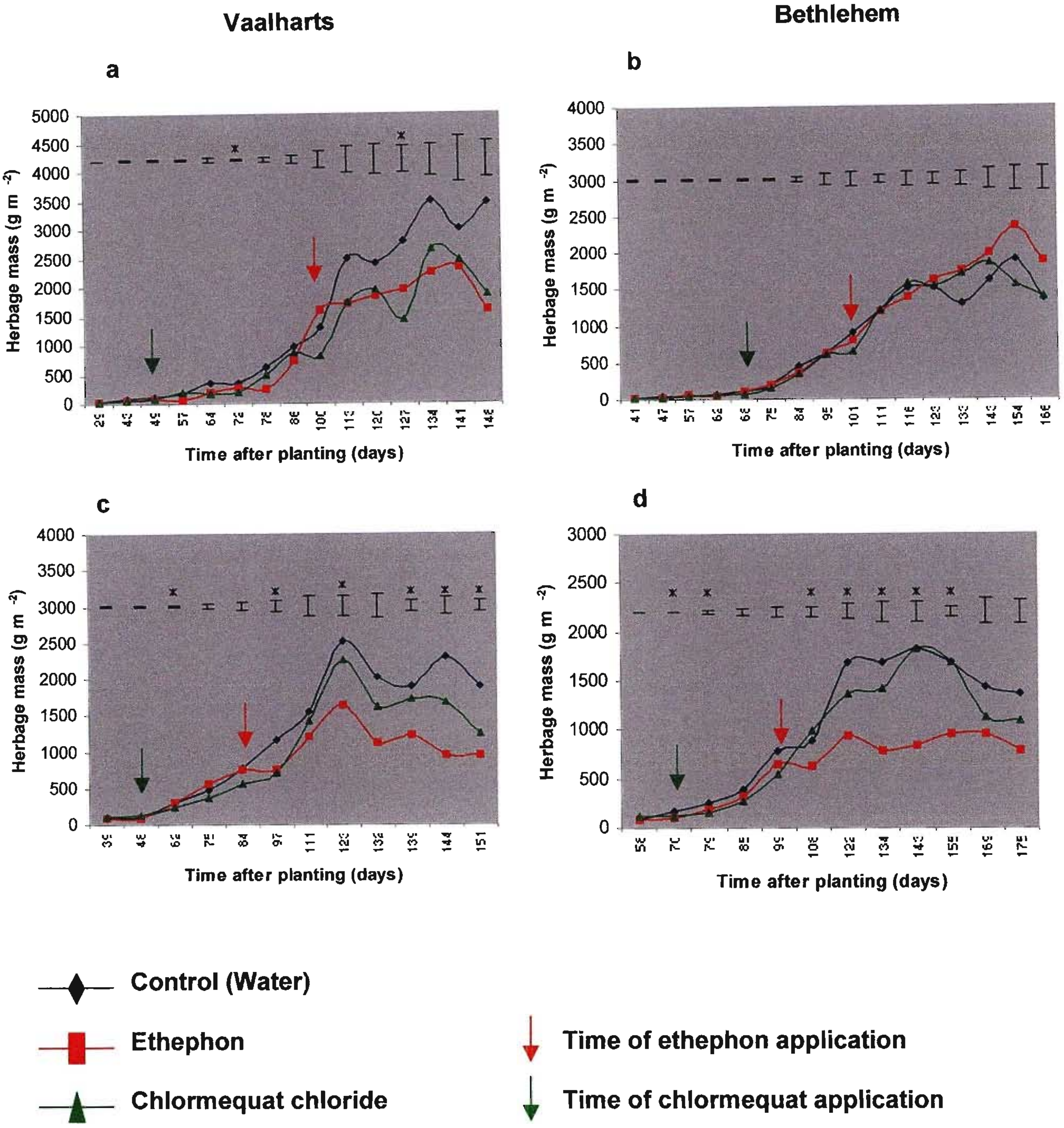


Fig. 11 Biomass accumulation of Kariega wheat in the 2003 (a and b) and 2004 (c and d) seasons at Vaalharts and Bethlehem. Standard errors for specific sampling dates are indicated by vertical bars. The "*" indicates significance of difference (P<0.05) between the treatments at specific sampling dates.

Table 4. **Maximum growth rates (B), inflection points (M) and asymptotes (A+C) of fitted curves for the different treatments and cultivars at Vaalharts and Bethlehem in the 2003 and 2004 seasons**

Locality	**Treatment**						
				SST 876			
		Max growth rate (g day^{-1}) B		**Inflection point (days) M**		**Asymptote (g) A+C**	
		2003	**2004**	**2003**	**2004**	**2003**	**2004**
Vaalharts	**Control**	0.18^{a*}	0.09^{a}	95.9^{a}	85.1^{a}	2565^{a}	1781^{a}
	Chlormequat	0.07^{a}	0.12^{a}	91.5^{ab}	93.3^{a}	2248^{a}	1634^{a}
	Ethephon	0.08^{a}	0.10^{a}	84.2^{b}	86.8^{a}	2679^{a}	1745^{a}
	LSD	NS	NS	8.08	NS	NS	NS
Bethlehem	**Control**	0.06^{a}	0.05^{a}	100.9^{a}	100.6^{a}	2060^{a}	1727^{a}
	Chlormequat	0.10^{a}	0.12^{a}	103.0^{a}	102.9^{a}	1934^{a}	1350^{ab}
	Ethephon	0.09^{a}	0.10^{a}	103.8^{a}	88.9^{b}	1862^{a}	1093^{b}
	LSD	NS	NS	NS	7.27	NS	415.2
				KARIEGA			
		Max growth rate (g day^{-1}) B		**Inflection point (days) M**		**Asymptote (g) A+C**	
		2003	**2004**	**2003**	**2004**	**2003**	**2004**
Vaalharts	**Control**	0.11^{a}	0.06^{a}	98.9^{a}	87.8^{a}	3723^{a}	2215^{a}
	Chlormequat	0.06^{a}	0.15^{a}	95.4^{a}	95.2^{a}	2696^{b}	1709^{b}
	Ethephon	0.13^{a}	0.08^{a}	87.9^{a}	74.4^{b}	2089^{b}	1187^{c}
	LSD	NS	NS	NS	8.9	568.2	338.3
Bethlehem	**Control**	0.07^{a}	0.09^{a}	93.0^{a}	98.3^{a}	1695^{a}	1647^{a}
	Chlormequat	0.09^{a}	0.14^{a}	96.4^{a}	100.7^{a}	1672^{a}	1437^{a}
	Ethephon	0.05^{a}	0.10^{a}	102.1^{a}	79.3^{a}	2328^{b}	841^{b}
	LSD	NS	NS	NS	NS	429.2	371.5

*** Values within the same column and locality with the same superscript letters are not significantly different from each other**

The reduction in the growth rate after chlormequat application is in keeping with the work done by Craufurd & Cartwright (1989) who reported similar growth rate reductions with chlormequat application. The recovery response of the plants thereafter was also demonstrated by Bruinsma (1982), who stated that very early spraying gives a strong stem base, but a subsequent recovery response by the plant can reduce the overall shortening effect of the treatment.

The application of ethephon to SST 876 at Bethlehem in 2004 caused an almost immediate response as the growth rate of the crop changed after application at 108 DAP (Fig. 10d). The effect persisted thereafter resulting in an earlier attainment of maximum growth by the ethephon treatment (88.9 DAP) compared to the control (100.6 DAP) treatment (Table 4, Appendix 4d). Additionally, the maximum dry weight achieved (A + C) was significantly lower than the control treatment (Table 4). The reduction in dry weight may be primarily attributed to the reduced elongation growth of the upper internodes following ethephon application, which ultimately reduced plant height (Fig. 4b). Danhous *et al.* (1982) also reported significant reductions in plant height of lodging tolerant cultivars, however, the magnitude of the height reduction was lower than that of the taller, lodging susceptible cultivars.

The lodging susceptible cultivar Kariega responded to the applications of the PGR's at Vaalharts in 2003 (Fig. 11a) as the asymptote (A + C) for the control (3723) was significantly higher than that of the chlormequat (2696) and ethephon (2089) treatments (Table 4, Appendix 5a). No significant differences were observed between the coefficients B and M. No significant differences in dry matter were detected at any sampling dates between the treatments at Bethlehem in 2003 (Fig. 11b), however, ethephon produced a significantly higher asymptote (A + C) than the control and chlormequat treatments when the curves were fitted (Table 4, Appendix 5b). At Vaalharts, the application of chlormequat at 49 DAP did not produce an immediate response, however, the growth rate of the crop was gradually reduced during the season and maximum dry weight was significantly lower than the control (Table 4, Appendix 5a). The application of ethephon at 100 DAP caused an immediate drop in the growth rate, which persisted until harvest, where final dry weight was lower than the control (Fig. 11a).

In the 2004 season similar responses were observed at Vaalharts (Fig. 11c) and Bethlehem (Fig. 11d) as chlormequat produced a gradual decline in the growth rate relative to the controls. Ethephon application at the flag leaf stage produced a change in the growth rate at both localities (Fig. 11c,d) resulting in the production of significantly lower inflection points (M) and asymptotes (A + C) compared to the control (Table 4, Appendix 5c,d). At Vaalharts, chlormequat produced a significantly lower asymptote compared to the control, while at Bethlehem, no significant differences were detected (Table 4). At Bethlehem, significant differences in dry weight were observed between the control and ethephon treatments between 108 and 155 DAP as a result of the PGR application (Fig. 11d) and this is reflected in the extremely low asymptote (841) obtained for that treatment (Table 4).

The biomass results obtained in this study with respect to chlormequat is in contrast to the work of Lowe & Carter (1972) and Humphries *et al.* (1965), who reported significant reductions in plant biomass after chlormequat applications. In this study, applications of chlormequat were made at the tillering stage and the growth rate was temporarily reduced by the treatment. However, the subsequent recovery response often resulted in no differences in maximum and final dry weights (Figs. 10d, 11c and d). It is possible that a later application may be more effective as the plants may not have time to recover. This may indeed be the case, as observed by the reductions in plant height when chlormequat was applied at the flag leaf stage at both localities (Figs. 4a and b). However, in general, the lack of a biomass response to chlormequat was reflected in the minimal effects of the compound on lodging (Fig. 4c), yield and yield components (Figs. 5 and 6), as well as the various quality characteristics (Figs. 7, 8 and 9). With most of the variables investigated, chlormequat responded similarly to the control treatments.

The PGR ethephon, however, produced significant reductions in biomass in both seasons and localities. Additionally, most of the responses were observed with Kariega, while SST 876 only responded to the ethephon application once (Fig. 10d). The reductions in the dry weight of Kariega following ethephon applications may be attributed to the reduced plant height (Fig. 4a and b). This may in turn have led to the reduction in lodging (Fig. 4c). Unfortunately, ethephon applications also led to reductions in yield when averaged over cultivars and times of application (Table 2). This may be attributed to the normal positive association between biomass production and yield. Also, the greater reductions in plant height after ethephon applications at the flag leaf stage (Fig. 4a and b) may alter assimilate distribution to produce beneficial effects on protein content (Fig. 8d), hectolitre mass (Fig. 7c), and falling number (Fig. 9a). In general, ethephon significantly reduced biomass production thereby producing subsequent positive and negative effects on other aspects of growth and development.

CONCLUSIONS

The minor changes in biomass production after chlormequat application (Figs. 10 and 11) were reflected in the slight changes in plant height, which was only reduced when chlormequat was applied at the flag leaf stage (Fig. 4a and b). The changes in plant height did not reduce lodging with any cultivar (Fig. 4c) suggesting the ineffectiveness of chlormequat as a lodging prevention tool on these cultivars in these environments. The effects of chlormequat on yield were also negligible as the PGR produced responses that were similar to the control with respect to yield and it's components. Chlormequat did, however, improve hectolitre mass (Fig. 7d) and falling number (Fig. 9b) when applied at the flag leaf stage compared to the earlier applications at Vaalharts. Protein content and preharvest sprouting scores were not affected by chlormequat. Generally, the overall lack of responses to chlormequat application does not justify the use of the PGR as a lodging prevention tool in commercial wheat production in South Africa.

Ethephon alone produced similar responses to that of the PGR combination with respect to all variables investigated. The general reductions in biomass production after ethephon applications (Figs. 10 and 11) are reflected in the reduced plant heights (Fig. 4a and b) with applications at the flag leaf stage. Lodging was only reduced when ethephon and the PGR combination were applied to Kariega at the flag leaf stage (Fig. 4c) suggesting that the PGR's are suitable to control lodging in susceptible cultivars. Ethephon and the PGR combination had no effect on the yield of Kariega at Bethlehem (Fig. 6d) and improved the yield of Kariega at Vaalharts when applied at the flag leaf stage (Fig. 6c). This yield improvement may be attributed to the reduction in lodging. With respect to the lodging tolerant cultivars, yields are normally reduced by the PGR's, particularly with the later applications indicating that when lodging is not a factor, ethephon and the PGR combination may have negative effects on yield.

The effects of ethephon and the PGR combination on grain quality are dependant on the cultivar and the TOA. Hectolitre mass was improved with applications to Kariega, while Olifants and SST 876 did not respond (Fig. 7b). Additionally, the later applications of these PGR's either improved or reduced hectolitre mass depending on the environment (Fig. 7c and d). The protein contents were generally improved by ethephon and the PGR combination, especially when applied to Olifants and SST 876 (Fig. 8b), and when applied at the flag leaf stage (Fig. 8d). Preharvest sprouting scores were normally reduced with applications of these PGR's at the elongation stage (Fig. 9e), while the effects on falling number were dependent on the environment (Fig. 9a and b).

Generally, the most consistent effect of ethephon and the PGR combination was the reduction in plant height and lodging. Effects on grain yield and quality parameters were inconsistent and are dependent on the cultivar, TOA and environment. The reductions in plant height and lodging coupled with the occasional improvements in yield and quality justifies the use of ethephon or the PGR combination as tools against lodging in commercial wheat production. The general lack of significant differences between ethephon and the PGR combination suggest that the addition of chlormequat in the combination does not necessarily enhance performance compared with ethephon alone. With regard to the active ingredients alone, chlormequat was less effective than ethephon in reducing height and lodging. Further research on the interactions between the PGR's, cultivars and the environment may be required to accurately determine whether these PGR's have overall beneficial or detrimental effects on yield and quality.

CHAPTER 4

EFFECTS OF CHLORMEQUAT, ETHEPHON AND NITROGEN FERTILIZATION ON AGRONOMIC CHARACTERISTICS OF BARLEY

ABSTRACT

Lodging is a limiting factor for the production of barley (*Hordeum vulgare* L.) under irrigation in South Africa and can lead to severe yield losses. Plant growth regulators (PGR's) such as chlormequat chloride and ethephon are often used to inhibit elongation growth and control lodging. The objective of this study was to evaluate the effects of chlormequat, ethephon and their combination on biomass production, plant height, lodging and grain yield of the barley cultivar Puma with differing amounts of N (120, 150 & 180 kg N ha^{-1}). Three PGR treatments, chlormequat (1.575 kg ai ha^{-1}), ethephon (0.6 kg ai ha^{-1}), and their combination (0.75 and 0.375 kg ai ha^{-1} of chlormequat and ethephon respectively) were applied at three times of application (TOA): the beginning of stem elongation, at the flag leaf stage, or as a split (double) application at elongation and the flag leaf stage at two localities (Bethlehem and Vaalharts). Both field trials were planted as a 4 X 3^2 factorial in a RCBD with 4 replications.

Chlormequat had no effect on biomass accumulation at any TOA leading to no effects on plant height, lodging or grain yield. The application of ethephon and the PGR combination at the flag leaf stage and as a split application significantly reduced plant height (100-260 mm), lodging (85 to 95%) and biomass accumulation at both localities while yields were only significantly reduced (48 to 56%) when split applications of these two PGR treatments were employed. Plant height and lodging increased by 31 mm and 55%, respectively as the level of N fertilization increased at Vaalharts, however, ethephon was able to significantly reduce lodging at higher N levels. Lodging of Puma was reduced as a result of ethephon or the PGR combination application at the flag leaf stage. Height of Puma was most often reduced and yield was not detrimentally affected with the flag leaf applications. Ethephon also provided protection against lodging when higher levels of N fertilization were employed.

INTRODUCTION

Barley production in South Africa contributes significantly to both the commercial and developing agricultural sector with approximately 0.23 million tons produced in the 2003/04 season (Anon, 2004). The crop is produced in both the summer and winter rainfall regions of South Africa primarily for malting purposes. Lodging is a limiting factor for the production of barley under irrigation and can lead to severe yield losses. Current methods of reducing lodging in South Africa include limiting N fertilization and seeding rates (Barnard & Burger, 2003). Limiting irrigation at critical growth stages is also employed as a strategy to reduce lodging. Such practices may reduce lodging losses, however, they may simultaneously limit yield potential and quality.

Plant growth regulators (PGR's) such as chlormequat chloride (chlormequat) and ethephon are commonly used in small grain management systems around the world to restrict shoot height and control lodging (Rajala *et al.*, 2002). The compounds are primarily used in intensive management systems in conjunction with higher nitrogen and seeding rates, extensive pest and disease control and irrigation (Foster & Taylor, 1993). The effects of PGR's on barley growth and development are highly variable and effects on yield and yield components, plant height and lodging, and nitrogen interactions have been well documented (Rajala & Peltonen-Sainio, 2002).

Clark & Fedak (1977) applied chlormequat to three barley cultivars in the field and reported an average height reduction of 11.5% one month after treatment. Ethephon applied at 0.28 and 0.56 kg ha^{-1} significantly reduced peduncle length of spring barley at harvest by 99 to 121 mm, and this was accompanied by a simultaneous reduction in lodging of 85 to 92%, respectively (Schwartz *et al.*, 1983). Similar reports were made by Simmons *et al.* (1988) who found height reductions of 140 to 200 mm after ethephon was applied to a spring barley cultivar at 0.28 and 0.42 kg ha^{-1}, respectively. ratings. Danhous *et al.* (1982) and Foster *et al.* (1991) also reported consistent reductions in barley height and lodging following treatments with PGR's.

The effects of chlormequat and ethephon on barley yield and yield components are not as consistent as are the effects on plant height and lodging. Simmons *et al.* (1988) reported a 10.5% increase in grain yield averaged over three barley cultivars after treatment with ethephon at the flag leaf stage. In a three year study of the effects of ethephon on spring barley, Moes & Stobbe (1991) found significant improvements in spikes m^{-2}, grains $spike^{-1}$ and mass $grain^{-1}$ after ethephon treatment in the first year of the study. In the second and third years of the study ethephon only improved the number of grains $spike^{-1}$ while grain yield and the other components of yield were unaffected. Schwartz *et al.* (1983) found that ethephon significantly increased grain yield by 1.8 t ha^{-1} in spring barley and this was attributed to an improvement in the number of spikes m^{-2}. A possible reason for this improvement in spikes m^{-2} may be the stimulatory effects that ethephon has on tillering as explained by Woodward & Marshall (1988). In contrast to these reports other researchers have indicated no effects of PGR's on yield and yield components of barley (Caldwell *et al.*, 1988; Foster & Taylor, 1993).

PGR's have also been reported to affect the response of barley to N fertilization. Herbert (1983) clearly showed that the use of chlormequat on wheat allowed higher levels of nitrogen fertilizer to be used and this resulted in higher yield. In that study, it was shown that lodging may limit yield at high nitrogen levels, however, chlormequat may be used to successfully control lodging thereby preserving potential yield. Foster & Taylor (1993), in a study of barley responses to ethephon and nitrogen levels also reported significant nitrogen X PGR interactions with respect to yield in two years. In that study, ethephon prevented an increase in lodging as the level of N increased. Such interactions may suggest a possible translocation of assimilate to grain rather than vegetative growth. Rajala & Peltonen-Sainio (2001) reported an 8.4 and 17% reduction in shoot weight of barley plants treated with chlormequat chloride and ethephon, respectively. Similar reports were made by Simmons *et al.* (1988) who found that vegetative mass of three barley cultivars was significantly reduced as higher levels of ethephon were applied.

The objectives of the present study were to evaluate the effects of different PGR's on agronomic and vegetative aspects of barley at two sites in South Africa. Biomass production, plant height, lodging and grain yield were assessed. It is expected that the study will contribute to the long term aim of reducing lodging in barley production in South Africa.

RESULTS AND DISCUSSION

Plant height and lodging

In general, significant differences in plant height and lodging were observed between PGR's, times of application and nitrogen levels at Vaalharts (Table 5, Appendix 6a). Lodging was a common occurrence at Vaalharts with most plots lodging to some extent. Plants grown at Bethlehem were significantly shorter than those grown at Vaalharts. As a result of the shorter, upright plants no lodging was experienced in Bethlehem throughout the season, therefore no lodging data for this site is presented.

The PGR chlormequat did not have an effect on plant height or lodging as values were not significantly different from the control at either locality, while ethephon and the PGR combination reduced height and lodging only at specific application times (Table 5). This is indicated by the highly significant (P<.001) PGR X TOA interaction for plant height and lodging at Vaalharts and the significant (P=0.007) PGR X TOA interaction for plant height at Bethlehem (Appendix 6a). Figure 12 (a and b), clearly depicts the nature of these interactions, and indicates that no differences in height were observed between the different times of application with the control or chlormequat treatments at either locality. The application of ethephon and the PGR combination at the flag leaf stage or as a split application reduced plant height by approximately 200-250 mm at Vaalharts and by 120-150 mm at Bethlehem in comparison to the control. A similar response was obtained for lodging at Vaalharts (Fig. 12c) i.e. ethephon and the PGR combination only reduced lodging (by approximately 83 – 95%) when applied at the flag leaf stage or as a split application while chlormequat did not produce a response to application times, as observed in Figs. 12a, b and c.

Table 5. Plant height and lodging scores of barley in response to plant growth regulators (PGR) applied at different times (TOA), and levels of N at Vaalharts and Bethlehem in the 2004 season.

TREATMENTS		PLANT HEIGHT	LODGING SCORE†
		------------mm----------	------------------0.2 - 9-------
		Vaalharts	
		2004	2004
PGR			
	Control	$910^{a\Psi}$	3.4^{a}
	Chlormequat	897^{a}	3.4^{a}
	Ethephon	770^{b}	1.7^{b}
	PGR comb.	778^{b}	1.6^{b}
	LSD $_{(0.05)}$	22	0.7
TOA			
	Elongation	901^{a}	3.8^{a}
	Flag leaf	812^{b}	2.0^{b}
	Split	802^{b}	1.8^{b}
	LSD $_{(0.05)}$	19	0.6
Nitrogen (N)			
	120N	822^{b}	1.5^{c}
	150N	840^{ab}	2.7^{b}
	180N	853^{a}	3.4^{a}
	LSD $_{(0.05)}$	19	0.6
PGR X TOA		**	**
PGR X N		NS	NS
TOA X N		NS	NS
PGR X TOA X N		NS	NS
		Bethlehem	
PGR			
	Control	650^{a}	
	Chlormequat	639^{a}	NIL
	Ethephon	555^{b}	
	PGR comb.	567^{b}	
	LSD $_{(0.05)}$	21	
TOA			
	Elongation	622^{a}	
	Flag leaf	615^{a}	NIL
	Split	570^{b}	
	LSD $_{(0.05)}$	19	
Nitrogen (N)			
	120N	600^{a}	
	150N	607^{a}	NIL
	180N	601^{a}	
	LSD $_{(0.05)}$	NS	
PGR X TOA		*	
PGR X N		NS	NIL
TOA X N		NS	
PGR X TOA X N		NS	

† Lodging index ranging from 0.2 (no lodging) to 9 (completely lodged).

Ψ Means within a column and treatment with similar superscript letters are not significantly different from each other.

* Significance of difference at $P<0.05$.

** Significance of difference at $P<0.001$.

NS No significant difference.

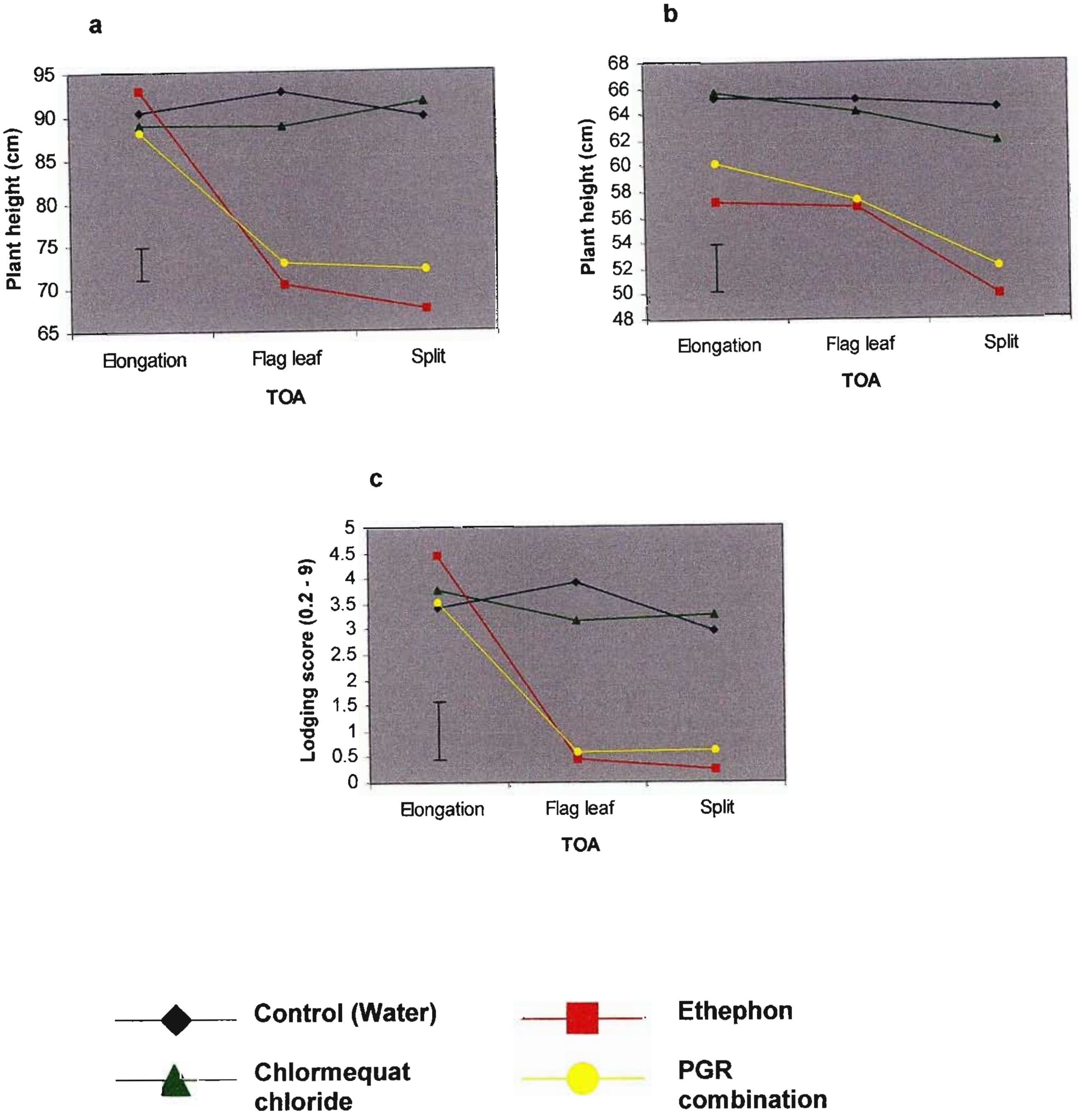


Fig. 12 Plant growth regulator (PGR) X time of application (TOA) interactions for plant height at Vaalharts (a) and Bethlehem (b) and the PGR X TOA interaction for lodging at Vaalharts (c). Vertical bars represent the LSD's $_{(0.05)}$ for the specific interactions.

The lack of a height or lodging response to chlormequat was in contrast to the findings of Clark & Fedak (1977) who indicated that applications of chlormequat to barley may reduce plant height and lodging. However, in the same study it was shown that any height or lodging response may be cultivar dependant. It is therefore possible that the mode of action of chlormequat is not effective in the barley cultivar Puma, and height and lodging were therefore, unaffected.

Applications of ethephon and the PGR combination at elongation did not reduce plant height and lodging as much as the flag leaf or split applications at Vaalharts (Figs. 12a and c). This may be due to the reduction in plant height being greater as the inhibition of elongation shifts to the upper, longer internodes, hence the effectiveness of the flag leaf or split applications. This theory agrees with the work of Brown & Earley (1973), who suggested that a later application of the active ingredient ethephon was most effective at reducing height and lodging. At Bethlehem, ethephon and the combination treatment reduced plant height at all three applications, however, the magnitude of the reduction was greatest when the split application was employed (Fig. 12b). The split application may have inhibited elongation growth in the lower and upper internodes thereby having a greater total effect on plant height.

The overall height reduction by applications of ethephon and the PGR combination at Bethlehem was less than that at Vaalharts. This may be due to plants being generally shorter at Bethlehem, and further height reductions may not be attained as easily as it would if plants were taller in general (as observed at Vaalharts). Additionally, applications of ethephon and the PGR combination at elongation significantly reduced plant height at Bethlehem (Fig. 12b), however no reduction in height was experienced at Vaalharts (Fig. 12a). Such a response suggests a possible environment X PGR interaction.

A response to the different levels of N was observed as plant height increased steadily as the level of N was increased from 120 to 180 kg N ha^{-1} at Vaalharts (Table 5). The height response may be attributed to an increase in vegetative growth normally associated with higher N levels (Foster & Taylor, 1993). This was also accompanied by a simultaneous increase in lodging scores (Table 5). The non-significant increase in plant height between the 120 and 150 kg N ha^{-1} levels produced a significant 80% increase in lodging score. Similarly, the non-significant increase in plant height between the 150 and 180 kg N ha^{-1} levels produced a significant 26% increase in lodging score. These responses demonstrate the sensitivity of lodging to changes in plant height. No significant differences in plant height were detected between the different N levels at Bethlehem, as plants were much shorter than at Vaalharts.

The overall PGR X N interaction was not significant for plant height and lodging at Vaalharts and Bethlehem (Appendix 6a). However, Figure 13a indicates that lodging increased as the level of N increased with the control, chlormequat and combination treatments while no significant increase in lodging score was observed as the level of N was increased with the ethephon treatment at Vaalharts. This finding is in keeping with the work of Herbert (1982), who concluded that application of PGR's should allow higher levels of N to be applied without an increase in lodging. The lodging reduction may be due to ethephon reducing plant height at all three levels of N (Fig. 13b) compared to the control and chlormequat treatment. Although the PGR combination reduced plant height at the 120 and 150 kg N ha^{-1} levels compared to the control (Fig. 13b), plant height did increase at the 180 kg N ha^{-1} level and this led to an increase in lodging (Fig. 13a). It is possible that the presence of the active ingredient chlormequat in the combination may cause it to produce a similar response to the chlormequat treatment itself.

It would be expected for the PGR X N interaction to be highly significant for lodging as PGR's may prevent higher levels of N from stimulating further elongation growth. The excess N may be redirected to grain yield or other vegetative organs such as leaves. In this study, only ethephon controlled lodging at all three N levels indicating its effectiveness in controlling lodging of the cultivar Puma.

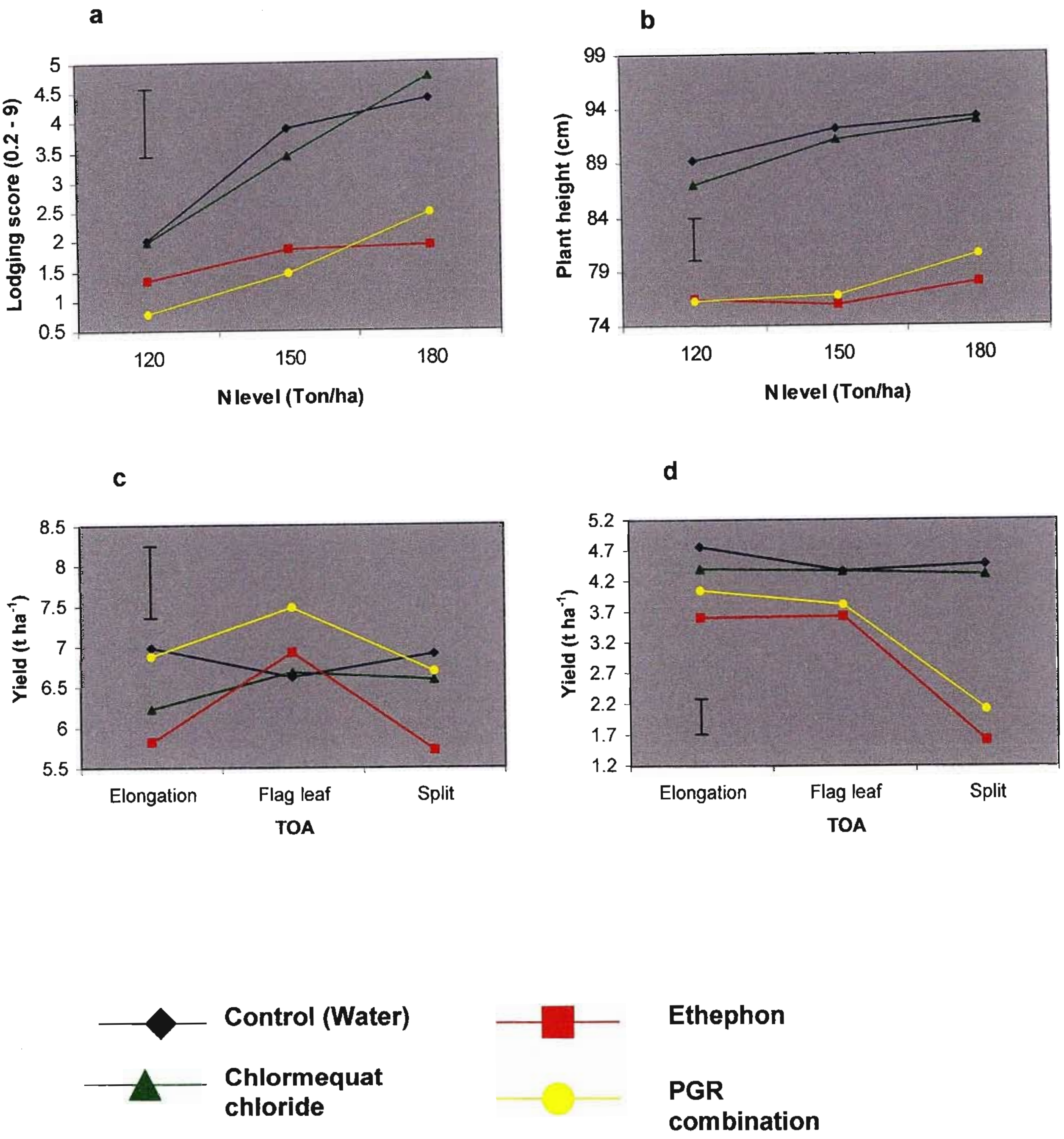


Fig. 13 Plant growth regulator (PGR) X nitrogen (N) interactions for lodging (a) and plant height (b) at Vaalharts, and the PGR X time of application (TOA) interactions for yield at Vaalharts (c) and Bethlehem (d). Vertical bars respresent the LSD's $_{(0.05)}$ for the specific interactions.

Grain yield

The high incidences of lodging at Vaalharts were indications of a good yield (there is often a positive correlation between lodging and grain yield) with most plots exceeding 5 t ha^{-1} (Table 6) while the yields at Bethlehem were lower in comparison.

On average, the PGR ethephon significantly reduced grain yield by 10 and 12%, respectively, in comparison with the control and combination treatments at Vaalharts. Additionally, applications of PGR's at the flag leaf stage significantly improved yields by 6.9% compared to applications at elongation or the split application at Vaalharts. It may be possible that the applications at elongation were not effective enough to improve yields due to possible recovery responses by the plants. The overall PGR X TOA interaction was not significant at Vaalharts, however, Fig. 13c shows that split applications of ethephon significantly reduced yield compared to the flag leaf application. Additionally, the split application of ethephon significantly reduced yield compared to the split application of the PGR combination. At Bethlehem, however, the highly significant PGR X TOA interaction (Fig. 13d; Appendix 6a) shows that the PGR combination produced a similar response to ethephon as yield was reduced with a split application compared to the flag leaf or elongation applications.

The yield reductions with ethephon applications are in keeping with the results of Simmons *et al.* (1988), Moes & Stobbe (1991) and Rowland (1973), who reported yield reductions after ethephon application. However, in this study it was found that the yield reduction was only evident when a split application was employed. Ethephon is known to be an effective male gametocide that induces male sterility in wheat (Rowell & Miller, 1971). Additionally, the release of ethylene from ethephon (Lurssen, 1982) may enhance the developmental rate thereby leading to the formation of fewer grain sites as well as shorten the duration of grain filling, ultimately reducing yields. When applied as a split application (double dose) rather than a single application at the flag leaf stage, these effects may be enhanced leading to a greater reduction in yield.

Generally, significant reductions in yield were observed as the level of N increased at Vaalharts (Table 6) while no significant differences in yield were observed between the three N levels at Bethlehem. These results are in contrast with those of Herbert (1983) who found that yield increases as the level of N is increased. One of the major reasons for the different results is that Herbert (1983) also tested N levels below 120 kg N ha^{-1} and found that yield increased until this level, after which yield decreased. In this study, N levels above the optimal of 120 kg N ha^{-1} (Barnard & Burger, 2003) were tested, thereby causing a reduction in yield as the level of N increased further. It is possible that the reduction in yield with increasing levels of N may also be attributed to the effect that the higher N levels had on increasing lodging at Vaalharts (Table 5). This may also explain the lack of a yield response at Bethlehem i.e. no lodging was experienced at Bethlehem (Table 5), hence no effect of N levels on yield.

Table 6. Grain yield responses of barley to plant growth regulators (PGR) and their times of application (TOA) with different levels of N at Vaalharts and Bethlehem in the 2004 season.

TREATMENTS		YIELD	YIELD
		----------t ha^{-1}-----------	------------t ha^{-1}------------
		Vaalharts	Bethlehem
PGR			
	Control	$6.83^{ab\Psi}$	4.53^{a}
	Chlormequat	6.49^{bc}	4.36^{a}
	Ethephon	6.15^{c}	2.95^{c}
	PGR comb.	7.01^{a}	3.54^{b}
	LSD $_{(0.05)}$	0.51	0.33
TOA			
	Elongation	6.47^{b}	4.20^{a}
	Flag leaf	6.92^{a}	4.04^{a}
	Split	6.47^{b}	3.29^{b}
	LSD $_{(0.05)}$	0.44	0.29
Nitrogen (N)			
	120N	7.45^{a}	3.89^{a}
	150N	6.49^{b}	3.97^{a}
	180N	5.94^{c}	3.68^{a}
	LSD $_{(0.05)}$	0.44	NS
PGR X TOA		NS	**
PGR X N		NS	NS
TOA X N		NS	NS
PGR X TOA X N		NS	NS

Ψ Means within a column and treatment with similar superscript letters are not significantly different from each other.

* Significance of difference at P<0.005.

** Significance of difference at P<0.001.

NS No significant difference.

Biomass accumulation

Biomass accumulation followed typical sigmoid patterns of growth with most treatments at both localities (Fig. 14). The maximum dry weight achieved at Vaalharts was approximately 1700 g m^{-2} produced by the control treatment at 140 DAP. Similarly, the control treatment also produced the highest dry weight of 1500 g m^{-2} at Bethlehem at 150 DAP.

Generally, similar patterns of dry matter accumulation were observed between the control and PGR treatments when applications were made at the stem elongation stage at Vaalharts (Fig. 14a). This is indicated by the similar growth rates (B), inflection points (M) and asymptotes (A + C) obtained for the fitted curves (Table 7, Appendix 7a). The temporary drop in the growth rate of the chlormequat treatment at 101 DAP may be attributed to the greater initial partitioning of assimilate to root growth as a result of the reduced above ground growth (Fig. 14a). The rise in the growth rate thereafter may be due to the re-mobilization of the stored assimilate for vegetative growth. A similar pattern of growth was observed at Bethlehem (Fig. 14b), where the rate of growth of the chlormequat treatment was lower after application, however, the recovery response led to no differences in maximum and final dry weights. This apparent recovery response by the plants after chlormequat is applied earlier is in keeping with the work of Bruinsma (1982), and may be the reason for the lack of the height, yield or lodging response to chlormequat observed in this study. It is possible that the effects of chlormequat do not persist in the plant and normal growth and development continues after application.

Additionally, the general lack of a biomass response after chlormequat application may be explained by the work of Craufurd & Cartwright (1972), who reported that chlormequat produced a similar response to that of short days i.e. a reduction in the rate of development. They suggested that the application of chlormeuat slows down the developmental rate thereby allowing more time for tiller primordia to be initiated hence compensating for the reduction in elongation growth by producing more tillers. This may ultimately lead to an improvement or no difference in biomass production as observed in this study.

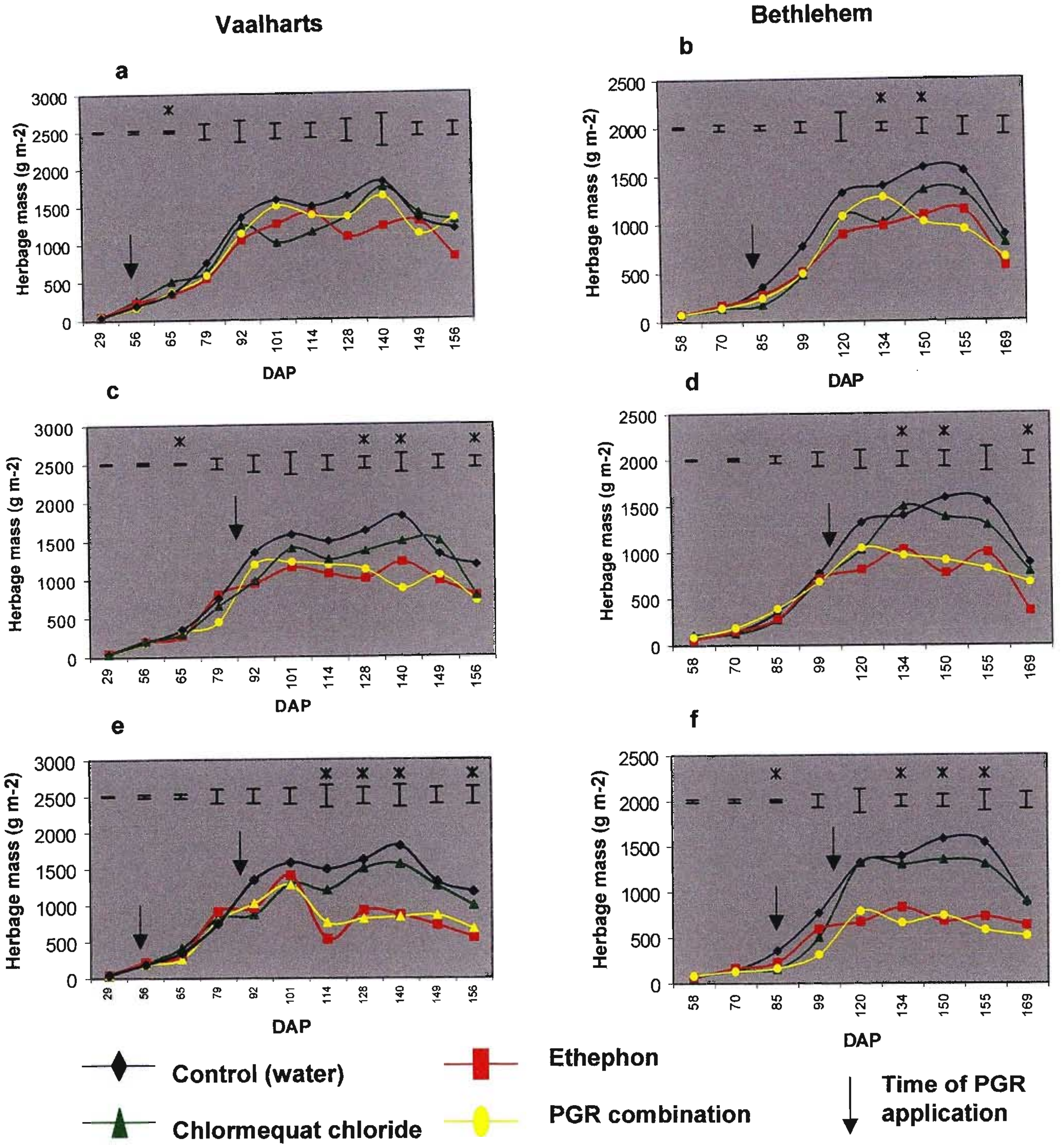


Fig 14. Biomass accummulation of Puma barley at Vaalharts and Bethlehem when PGR's were applied at elongation (a and b), the flag leaf stage (c and d) and a split application at elongation and the flag leaf stage (e and f). Standard errors for specific sampling dates are represented by vertical bars. The "*" indicates signficance of difference (P<0.05) between treatments at specific sampling dates.

Table 7. Maximum growth rates (B), inflection points (M) and asymptotes (A+C) of fitted curves for each application time of the plant growth regulator treatments at Vaalharts and Bethlehem

LOCALITY	TREATMENT			
			ELONGATION	
		B **(g m^{-2})**	**M** **(days)**	**A+C** **(g)**
Vaalharts	**Control**	0.13^{a*}	76.4^{a}	1512^{a}
	Chlormequat	0.05^{a}	72.0^{a}	1484^{a}
	Ethephon	0.22^{a}	75.6^{a}	1216^{a}
	PGR comb.	0.22^{a}	74.5^{a}	1387^{a}
	LSD	NS	NS	NS
Bethlehem	**Control**	0.10^{a}	93.2^{a}	1365^{a}
	Chlormequat	0.19^{a}	101.0^{a}	1198^{ab}
	Ethephon	0.20^{a}	93.7^{a}	955^{c}
	PGR comb.	0.25^{a}	96.9^{a}	993^{bc}
	LSD	NS	NS	229.2
			FLAG LEAF	
		B **(g m^{-2})**	**M** **(days)**	**A+C** **(g)**
Vaalharts	**Control**	0.13^{a}	76.4^{a}	1512^{a}
	Chlormequat	0.10^{a}	71.9^{a}	1130^{b}
	Ethephon	0.25^{a}	71.0^{a}	1027^{b}
	PGR comb.	0.35^{a}	75.4^{a}	1060^{b}
	LSD	NS	NS	270.1
Bethlehem	**Control**	0.10^{a}	93.2^{a}	1365^{a}
	Chlormequat	0.21^{a}	94.4^{a}	1231^{ab}
	Ethephon	0.19^{a}	87.1^{a}	803^{c}
	PGR comb	0.13^{a}	74.7^{a}	942^{bc}
	LSD	NS	NS	372.7
			SPLIT APPLICATION	
		B **(g m^{-2})**	**M** **(days)**	**A+C** **(g)**
Vaalharts	**Control**	0.13^{a}	76.4^{a}	1512^{a}
	Chlormequat	0.32^{b}	77.9^{a}	1293^{a}
	Ethephon	0.25^{b}	67.4^{a}	947^{b}
	PGR comb.	0.27^{b}	70.8^{a}	910^{b}
	LSD	0.11	NS	314.4
Bethlehem	**Control**	0.10^{a}	93.2^{bc}	1365^{a}
	Chlormequat	0.34^{bc}	99.8^{ab}	1153^{a}
	Ethephon	0.17^{ab}	86.7^{c}	730^{b}
	PGR comb.	0.45^{c}	100.9^{a}	664^{b}
	LSD	0.23	7.61	216.6

* Values within the same column and locality with similar superscript letters are not significantly different from each other

Ethephon and the PGR combination did not have an effect on dry matter accumulation when applied at elongation at Vaalharts as the growth curves were not significantly different from the control treatment (Fig. 14a, Table 7, Appendix 7a). This may explain the similar plant height and lodging values obtained between the ethephon, PGR combination and control treatments in Figs. 1a and c when these PGR's were applied at elongation. At Bethlehem, however, the clear reduction in the maximum dry weight (Table 7, Appendix 7b) may explain the significantly lower plant heights obtained by the ethephon treatments when applied at elongation in Fig. 12b. The PGR combination produced a similar response as the asymptote (A + C) was significantly different from the control (Table 7). This implies that the biomass reduction may be attributed to the reduction in height. Additionally, the lower biomass produced by the ethephon treatment may have limited source potential in the form of shorter leaves. The reduction in height could also have promoted leaf shading as the vertical distance between two leaves could be reduced. These factors may have contributed to reducing photosynthetic capacity, hence reducing yields (Fig. 13d).

Applications of PGR's at the flag leaf stage (Fig. 14c and d) and as a split application (Fig. 14e and f) produced similar responses at both localities. Chlormequat only reduced the maximum dry weight when applied at the flag leaf stage at Vaalharts (Fig. 14c, Table 7). This led to a minor reduction in plant height (Fig. 12a) and lodging (Fig. 12c), however yield was unaffected (Fig. 13c). The application of ethephon and the PGR combination at the flag leaf stage caused an almost immediate response as no apparent increase in dry matter followed after applications of these PGR's (Fig. 14c and d). The fitted curves, however, indicate no significant differences in growth rate or inflection points (Table 7). Only the maximum dry weight achieved (A + C) was significantly different from the control at both localities (Appendix 7c,d).

The split applications produced a similar response to the flag leaf application, however, the rate changing response was only observed after the second application at the flag leaf stage (Fig. 14e and f), indicating that the elongation application was ineffective when used in conjunction with the flag leaf application. The split application produced clear significant differences in growth rates (B), inflection points (M) and asymptotes (A+C) at both localities, with ethephon and the PGR combination being most effective (Table 7, Appendix 7e,f). Generally, the most significant differences were observed between the asymptotes (A + C) with all application times, while very few differences were observed between the growth rates and inflection points (Table 7). This implies that PGR's may have little effect on growth rates, however, the maximum dry weight achieved may be reduced.

The reduction in dry weight after applications of ethephon and the PGR combination at the flag leaf stage may be attributed to most of the elongation growth occurring in the higher internodes (peduncle). As these are longer and hence heavier, the reduction in dry weight was greater when applications were made later as opposed to earlier, where only shorter internodes are targeted. This may explain the reduction in height and lodging with applications of ethephon and the combination at the flag leaf and split applications at Vaalharts (Fig. 12a and c) and Bethlehem (Fig. 12b). Although height and lodging were reduced by the split application of ethephon, yield was also significantly reduced at Vaalharts (Fig. 13c) and Bethlehem (Fig. 13d). The yield reduction may be due to the effect that ethephon has as a male gametocide (Rowell & Miller, 1971) or the effect it has on enhancing developmental rate (Lurssen, 1982). The split application may have enhanced senescence and the growth rate from an early stage, preventing the formation of adequate source (leaf material) and sink potential (grain sites) resulting in lower yields.

CONCLUSIONS

In general, the barley cultivar Puma did not respond significantly to the PGR chlormequat chloride at any TOA. This was evident from the similar patterns of biomass accumulation between the control and chlormequat treatments at both localities. Additionally, plant height, lodging and yield were not affected by chlormequat indicating that it may not be suitable as an anti-lodging tool against the barley cultivar Puma. The distinct changes in the growth rate after applications of ethephon and the PGR combination at the flag leaf stage may be attributed to the effective reduction of elongation growth. This was evident by the significant reductions in plant height, which in turn reduced lodging. Although ethephon and the combination treatment successfully controlled lodging, yield was reduced when a split (double dose) application was employed. This either implies that very high concentrations of ethephon or the combination treatment may be detrimental to yield, or that excessive height reductions may be the cause of the yield loss through reduced photosynthetic capacity. The most effective TOA for ethephon and the PGR combination seems to be at the flag leaf stage as plant height and lodging were successfully controlled with no detrimental effects on yield.

Increasing the N above optimal (120 kg N ha^{-1}) levels is not recommended with Puma as plant height and hence lodging were increased while yields were subsequently decreased. The use of ethephon may allow higher levels of N to be used without increases in lodging (Fig. 13a) indicating ethephon's suitability as an anti-lodging tool with Puma. Nitrogen levels below 120 kg N ha^{-1} should also be tested to determine the cultivar response to ethephon at normal N levels. In conclusion, the barley cultivar Puma responds favourably with respect to a reduction in height and lodging to an application of either ethephon or the PGR combination at the flag leaf stage at optimal N application levels. It is under these conditions that height and lodging are reduced and yield is not detrimentally affected. Additionally, lodging may be controlled with ethephon when higher N levels are employed.

CHAPTER 5

EFFECTS OF CHLORMEQUAT AND ETHEPHON ON AGRONOMIC AND QUALITY CHARACTERISTICS OF OATS

ABSTRACT

Lodging in irrigated oats (*Avena sativa* L.) in South Africa may lead to severe yield and quality losses. Plant growth regulators (PGR's) that reduce plant height and lodging have not been evaluated on commercial oat cultivars under local conditions. The objective of this study was to assess the effects of two plant growth regulators and their combination on plant height, lodging, yield and hectolitre mass of three oat cultivars under irrigation in the field. The PGR treatments, chlormequat chloride (1.575 kg ai ha^{-1}), ethpehon (0.6 kg ai ha^{-1}), and their combination (0.75 and 0.375 kg ai ha^{-1} of chlormequat and ethephon respectively) were applied to the cultivars Kompasberg (lodging tolerant), Overberg (lodging susceptible) and Sederberg (lodging susceptible) at either the tillering, stem elongation or the flag leaf stage of growth at Vaalharts and Bethlehem. A 4x3^2 factorial in a RCBD with 3 and 4 replications in the 2003 and 2004 seasons, respectively was used.

Kompasberg produced significantly lower plant height, lodging scores and hectolitre mass, compared with the other cultivars at both localities, however, yields were significantly higher. Overberg was more lodging tolerant than Sederberg, and the relative yield potential of these two cultivars depended on the locality and the presence of PGR's. Overberg responded to an application of ethephon and to the PGR combination with a reduction in plant height and an enhancement in yield. Ethephon generally reduced plant height and lodging, improved hectolitre mass, and had no effect on yields when applied at the flag leaf stage averaged over all three cultivars. Chlormequat had no effect on plant height and hectolitre mass, reduced lodging, and improved yields at Vaalharts. The PGR combination reduced lodging while hectolitre mass was only increased when applied to the cultivar Sederberg at tillering and yields of this cultivar were unaffected. Results of the study indicate that the PGR's investigated had moderate effects as tools to inhibit or reduce lodging in oats, and further testing may allow reliable recommendations to be made.

INTRODUCTION

Cultivation of oats in South Africa has previously been limited to hay production and grazing. This may be due to the crops high biomass production and the regrowth characteristics thereof (Barnard & Burger, 2003). Additionally, the quality of oat grain produced locally (particularly low hectolitre mass) is not suitable for processing, resulting in the majority of the grain market requirement being filled through imports. Lodging is one of the principal causes of low hectolitre mass among local oat cultivars as a disturbed canopy associated with lodging interferes with normal photosynthetic processes during grain filling. Current recommendations indicate that lodging may be managed by cultivar choice, seeding density and nutrient management (Barnard & Burger, 2003). Currently, no research has been conducted on plant growth regulator (PGR) effects on lodging of commercial oat cultivars in South Africa.

The majority of research involving PGR effects on small grain stem elongation has been limited to wheat and barley production while research on responses in oat is somewhat lacking. Much of the research suggests that PGR's may have variable effects on oat growth and development. Brown & Earley (1973) reported significant reductions in grain yield when the PGR ethephon was applied to two field grown spring oat cultivars at the tillering and boot stages. When applied at heading, however, ethephon produced a 7.8% improvement in yield. In the same experiment it was found that treatments of ethephon that were most effective in reducing height and lodging also caused yield reductions, and it was concluded that ethephon has little to no potential for use on spring oats. In contrast to these reports Browne *et al.* (2003) found that a 70% reduction in lodging of chlormequat-treated oats was accompanied by a 2% improvement in yield averaged over four cultivars. A similar report was made by Clark & Fedak (1977) who indicated that lodging reductions in three oat cultivars were attributed to an average 8.7% reduction in plant height after chlormequat application.

The variable effects of PGR's on oat grain yields may be related to their contributions to vegetative aspects of growth such as tillering. Harrison & Kaufman (1982) indicated that ethylene, which is released from ethephon, directly plays a role in promoting tiller swelling and elongation in oats. These results were verified by Rajala & Peltonen-Sainio (2001) who reported a 38% improvement in tiller number per main shoot following ethephon application to greenhouse grown oats. Growth and elongation of the additional tillers were also retarded in a similar way to that of the main stem as shown by Peltonen-Sainio *et al.* (2003). This suggested that a change in partitioning of assimilate in favour of reproductive growth in both the main stem and tillers is the reason for the improved grain yields.

Limited research has been conducted on the effects of PGR's on quality characteristics of oats such as hectolitre mass. Browne *et al.* (2003) reported non-significant reductions in hectolitre mass after chlormequat applications to four oat cultivars in both years that these trials were conducted. In keeping with these reports Brown & Earley (1973) indicated no significant improvements in hectoliter mass following ethephon applications to field grown spring oats. In the same experiment it was found that several applications of ethephon actually reduced hectolitre masses. It was also found that the % N in the grain was increased by some ethephon treatments, however, these increases were accompanied by lower yields. No research has been conducted testing the effects, either positive or negative, of PGR's on quality characteristics of commercial cultivars of oats in South Africa.

The objectives of the experiments that follow were to evaluate the effects of the PGR's chlormequat and ethephon on yield, quality and lodging characteristics of South African commercial oat cultivars. Cultivar responses and times of application were also investigated in an attempt to optimize the effectiveness of the PGR's as tools against lodging.

RESULTS AND DISCUSSION

Grain yield

The average yield at Vaalharts in 2003 was 4.28 t ha^{-1} compared to the average of 6.9 t ha^{-1} produced in 2004. At Bethlehem, average yields did not differ much between seasons with an average of 4.72 and 4.58 t ha^{-1} produced in 2003 and 2004, respectively.

Generally, yields were not significantly affected by PGR's at Vaalharts in either season (Table 8, Appendix 8a,b). In Bethlehem, however, yields were significantly increased by 10.7% with an application of ethephon in 2003, while chlormequat significantly improved yields by 9.5% in 2004 compared to the control. The yield improvement following chlormequat application may be linked to the effect that it has on reducing the rate of growth. Green (1986) has suggested that the reduction in growth rate after chlormequat application may increase the duration of pre-anthesis growth, thereby allowing more time for spikelet and floret initiation, hence improving grain number. Alternatively, Tolbert (1960) has suggested that the slower growth rate may allow more time for grain filling, thereby improving mass $grain^{-1}$.

Table 8. Average grain yields and hectolitre mass responses of three cultivars of oats to plant growth regulators (PGR) and their times of application (TOA) at Vaalharts and Bethlehem in the 2003 and 2004 season.

TREATMENTS		YIELD		HECTOLITRE MASS	
		------------t ha^{-1}------------		----------------kg hl^{-1}----------------	
		Vaalharts			
		2003	**2004**	**2003**	**2004**
PGR					
	Control	$4.28^{a\Psi}$	6.68^{a}	40.07^{a}	45.88^{b}
	Chlormequat		6.89^{a}		46.41^{b}
	Ethephon	4.25^{a}	7.02^{a}	40.57^{a}	46.29^{b}
	PGR comb.	4.31^{a}	7.03^{a}	40.41^{a}	47.74^{a}
	LSD $_{(0.05)}$	NS	NS	NS	1.12
Cultivar (C)					
	Kompasberg	5.26^{a}	8.19^{a}	38.19^{b}	44.93^{b}
	Overberg	3.13^{c}	5.75^{c}	41.51^{a}	45.21^{b}
	Sederberg	4.44^{b}	6.77^{b}	41.35^{a}	49.6^{a}
	LSD $_{(0.05)}$	0.19	0.57	0.61	0.97
TOA					
	Tillering	4.24^{a}	6.57^{b}	40.63^{a}	46.92^{a}
	Elongation	4.27^{a}	6.88^{ab}	40.41^{ab}	46.11^{a}
	Flag leaf	4.34^{a}	7.27^{a}	40.01^{b}	46.71^{a}
	LSD $_{(0.05)}$	NS	0.57	0.61	NS
C X PGR		NS	NS	NS	NS
C X TOA		NS	NS	NS	NS
PGR X TOA		NS	NS	NS	*
C X PGR X TOA		NS	NS	NS	*
		Bethlehem			
		2003	**2004**	**2003**	**2004**
PGR					
	Control	4.47^{b}	4.43^{b}	49.03^{b}	52.39^{a}
	Chlormequat		4.85^{a}		52.21^{a}
	Ethephon	4.95^{a}	4.41^{b}	49.23^{ab}	52.61^{a}
	PGR comb.	4.75^{ab}	4.64^{ab}	49.88^{a}	52.33^{a}
	LSD $_{(0.05)}$	0.32	0.34	0.71	NS
Cultivar (C)					
	Kompasberg	6.36^{a}	5.43^{a}	48.8^{b}	50.46^{c}
	Overberg	4.22^{b}	4.06^{b}	50.92^{a}	52.70^{b}
	Sederberg	3.58^{c}	4.25^{b}	48.43^{b}	53.99^{a}
	LSD $_{(0.05)}$	0.32	0.29	0.71	0.42
TOA					
	Tillering	4.69^{a}	4.57^{a}	49.44^{a}	52.27^{a}
	Elongation	4.70^{a}	4.56^{a}	49.46^{a}	52.47^{a}
	Flag leaf	4.77^{a}	4.61^{a}	49.25^{a}	52.41^{a}
	LSD $_{(0.05)}$	NS	NS	NS	NS
C X PGR		*	NS	NS	NS
C X TOA		NS	*	NS	NS
PGR X TOA		NS	NS	NS	*
C X PGR X TOA		NS	NS	NS	NS

Ψ Means within a column and treatment with similar superscript letters are not significantly different from each other

* Significance of difference at $P<0.05$

** Significance of difference at $P<0.001$

NS No significant difference.

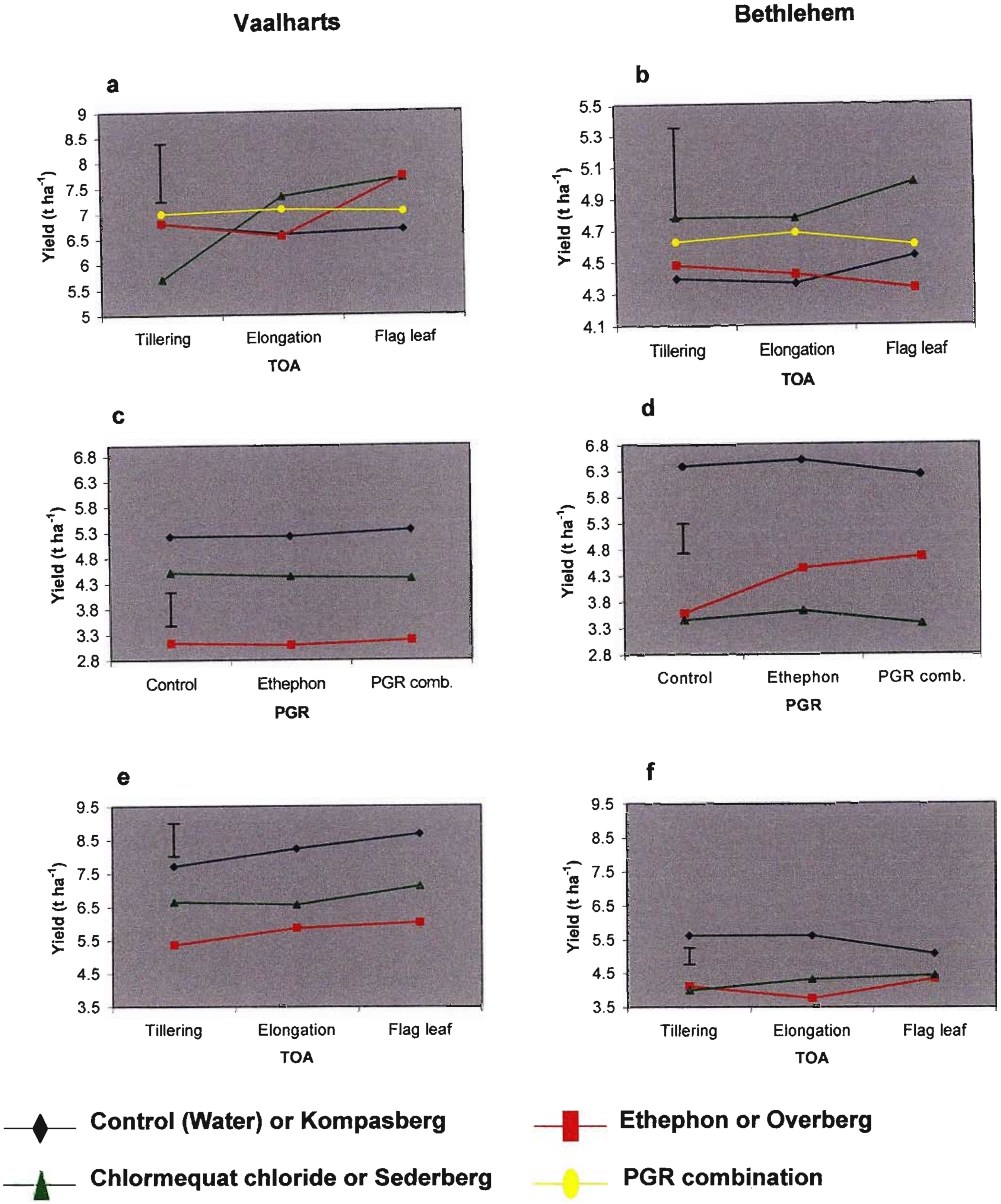


Fig. 15 The plant growth regulator (PGR) X time of application (TOA) interactions in 2004 (a and b), the cultivar (C) X PGR interactions in 2003 (c and d) and the C X TOA interactions in 2004 (e and f) for yield at Vaalharts and Bethlehem. Vertical bars represent the $LSD_{(0.05)}$ for the specific interaction.

No significant differences in yield were observed between the different times of application at either locality in 2003, while in 2004 applications at the flag leaf stage significantly improved yields by 10.7% relative to applications at tillering in Vaalharts. The PGR X TOA interaction in 2004 was not significant at Bethlehem or Vaalharts (P=0.064; Appendix 8a). However, the responses at Vaalharts (Fig. 15a) do indicate that an application of chlormequat at elongation and the flag leaf stage produce a significantly higher yield compared to application at tillering. Additionally, the application of ethephon at the flag leaf stage significantly improved yield in comparison to the elongation application time. This may be attributed to later applications shifting inhibition of elongation to the upper internodes, and because these internodes are longer, the greater the relative reduction in plant height. The yield improvement may therefore be attributed to a reduction in lodging through effective plant height reduction. The TOA did not affect yield with any PGR at Bethlehem in 2004 (Fig. 15b) as differences were not significant within a PGR. However, chlormeqat produced a significantly higher yield than ethephon when applications were made at the flag leaf stage.

The cultivar (C) X PGR interaction was not significant at Vaalharts in 2003 (Fig. 15c) or 2004 as Kompasberg consistently produced the highest yields, followed by Sederberg, and then Overberg. At Bethlehem, however, the C X PGR interaction was significant (P=0.018; Appendix 8b) in 2003 (Fig. 15d). The cultivar Overberg, which yielded significantly lower than Sederberg at Vaalharts with any PGR (Fig. 15c), produced a higher yield than Sederberg with applications of ethephon and the PGR combination at Bethlehem (Fig. 15d). The yield improvement of Overberg at Bethlehem in 2003 may therefore be attributed to the application of ethephon and the PGR combination. Kompasberg and Sederberg did not produce a yield response to any of the PGR's at either locality in 2003. The lack of a response by Kompasberg suggests that the cultivar is insensitive to applications of PGR's, while the lodging susceptible cultivar Overberg may produce higher yields with an application of the PGR combination. The lack of a response by Kompasberg may be due to the cultivar already being dwarfed to some extent, implying that further dwarfing is not advantageous with respect to yield improvement.

The C X TOA interaction was not significant at Vaalharts in 2004 (P=0.888; Appendix 8a) as no differences in yield were observed between the different times of application with any cultivar (Fig. 15e). The C X TOA interaction was, however, significant (P=0.009, Appendix 8a) at Bethlehem in 2004 (Fig. 15f). Yield was significantly reduced in Kompasberg by applications of PGR's at the flag leaf stage compared to the earlier applications. It is possible that the elongation-inhibiting effects of PGR's are not operational in a dwarfed cultivar and when applied at the flag leaf stage other processes such as grain set and grain filling were negatively affected. This may occur through the effect that ethephon has as a male gametocide (Rowell & Miller, 1971). No differences in yield were observed between the different times of application with Sederberg, while applications of PGR's significantly improved yields of Overberg when applied at the flag leaf stage rather than at elongation. The yield improvement may be related to a reduction in lodging by the PGR's.

Hectolitre mass

In the 2003 season neither of the PGR's had a significant effect on hectolitre mass at Vaalharts, while the PGR combination significantly improved hectolitre mass by 1.7% at Bethlehem (Table 8). The PGR combination also significantly improved hectolitre mass by 4% compared to the control at Vaalharts in 2004. Such responses indicate the possible suitability of using the combination to enhance grain quality. As discussed earlier, the PGR ethephon significantly improved yield by 10.7% compared to the control at Bethlehem in 2003 (Table 8). A similar report was made by Khan & Spilde (1992), who reported a 5.4% increase in wheat grain yield after treatment with ethephon in the field. In the same study, ethephon application tended to increase spikes m^{-2}, but had no effect on mass grain^{-1} or grains spike^{-1}. The lack of a hectolitre mass response to ethaphon at both sites and seasons may be partially explained by the ineffectiveness of ethephon on grain weight observed by Khan & Spilde (1992), as both grain weight and hectolitre mass are dependant on the process of grain filling.

Applications of PGR's at the flag leaf stage significantly reduced hectolitre mass by 1.5% as opposed to applications at tillering at Vaalharts in 2003. This reduction may be attributed to the effects of ethylene (released by ethephon) on stimulating the process of senescence thereby limiting the grain filling period. Chlormequat has also been shown to reduce grain filling when applied at the flag leaf stage (Kettlewell *et al.*, 1983). By reducing developmental rate, chlormequat may allow the formation of more grain sites. The larger number of grain sites competing for the same supply of assimilate could limit the amount of assimilate partitioned to each grain, thereby reducing grain weight and hectolitre mass. In the 2003 season no differences in hectolitre mass were observed between the different times of application at Bethlehem.

In 2004 the C X PGR X TOA interaction was significant (P=0.01) at Vaalharts (Fig. 16a; Appendix 8a). The interaction demonstrates that the cultivars Kompasberg and Overberg did not respond to any of the PGR's at any TOA. Sederberg, however, produced a significantly higher hectolitre mass when the PGR combination was applied at tillering compared to applications at elongation or the flag leaf stage. Additionally, the application of ethephon to Sederberg at the flag leaf stage significantly improved hectolitre mass compared to applications at tillering.

The PGR X TOA interaction was significant (P=0.022) in Bethlehem in the 2004 season (Fig. 16b; Appendix 8a). The interaction indicates that the application of ethephon at the flag leaf stage significantly improved the hectolitre mass compared to applications at tillering or elongation. The increase in hectolitre mass may be due to the redirection of assimilate partitioned to the grain associated with reduced growth of the stem. This may improve grain filling, hence improving hectolitre mass. Khan & Spilde (1992) and Wiersma *et al.* (1986) have reported similar improvements in hectolitre mass following applications of ethephon at the flag leaf stage. No differences in hectolitre mass were observed between the times of application with any other PGR.

A clear cultivar main effect was obtained over seasons and localities, with Kompasberg consistently producing lower hectolitre mass values than the other two cultivars (Table 8). The morphological characteristics associated with lower lodging in Kompasberg may have contributed to the higher yields and lower hectolitre masses observed at the two localities in both seasons with this cultivar. Bruinsma (1982) has suggested that a shorter plant with more upright leaves allows more light penetration into the canopy thereby encouraging late developing tillers to survive. The improvement in tillering may lead to an increase in the number of spikes m^{-2}. Additionally, the lower partitioning of assimilate into vegetative growth may allow more assimilate availability for grain yield thereby contributing to the improved yield of Kompasberg compared to the other cultivars at both localities in 2003 and 2004 (Table 8). However, subsequent compensation growth by the plants may have led to poor grain filling, hence the reduction in hectolitre mass which was accompanied by higher yields. A similar response was obtained by De Rocquigny *et al.* (2004), who indicated that yield improvements in semi-dwarf oat cultivars may be associated with improved spike density, however, the characteristic lower kernel weights of semi-dwarf oats may lead to a reduction in oat quality characteristics.

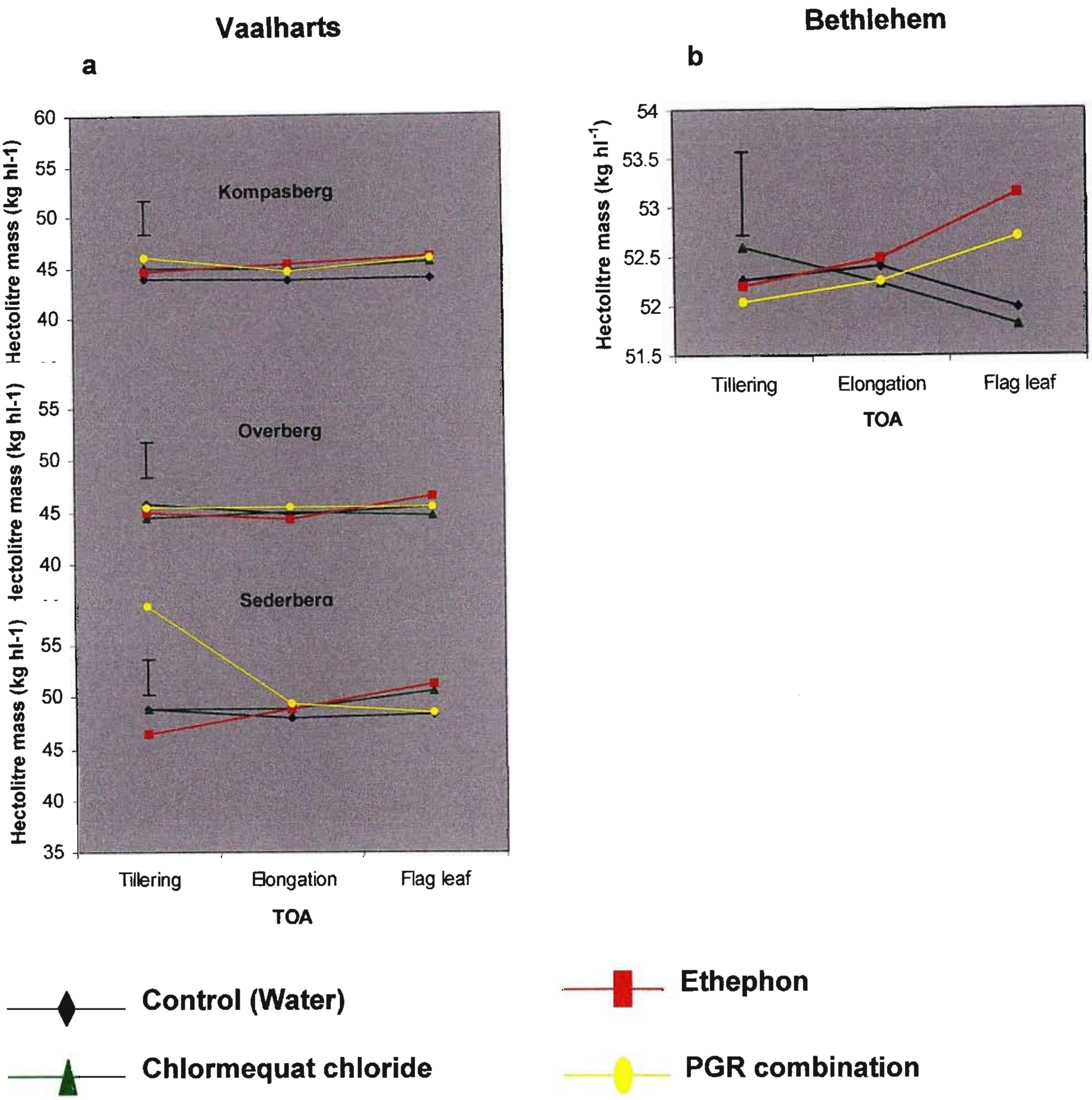


Fig. 16 The cultivar (C) X plant growth regulator (PGR) X time of application (TOA) interaction at Vaalharts in 2004 (a) and the PGR X TOA interaction at Bethlehem in 2004 (b) for hectolitre mass. Vertical bars represent the LSD (0.05) for the specific interactions.

Plant height and lodging

Generally, the crop at Vaalharts grew extremely tall, and lodging was a severe problem in the 2004 season. Plants at Bethlehem were generally much shorter and lodging was not as severe as it was at Vaalharts.

In general there were no significant differences in plant height between the PGR treatments at Vaalharts and this led to a lack of a lodging response (Table 9). The lack of a plant height or lodging response may have contributed to the lack of the yield or hectolitre mass response at Vaalharts (Table 8) in 2004 as the mechanisms described by Bruinsma (1982) and De Rocquigny *et al.* (2004) were not operatianal i.e. no dwarfing response, hence no effect on yield or hectolitre mass. It is also possible that lodging was not controlled at Vaalharts due to its severity, with lodging scores above five being obtained. Even the lodging tolerant cultivar Kompasberg experienced lodging to some degree (Table 9).

The PGR X TOA interaction for plant height was not significant (Table 9) indicating that plant height was not affected by any of the PGR's irrespective of the TOA (Fig. 17a). The PGR X TOA lodging interaction was not significant at Vaalharts (P=0.238; Appendix 8a), however, the overall significant reduction in lodging from applications of PGR's at the flag leaf stage (Table 9) may be attributed primarily to the application of ethephon and chlormequat (Fig. 17c). The interaction indicates that ethephon significantly reduced lodging when applied at the flag leaf stage as compared to applications at tillering or elongation, while chlormequat significantly reduced lodging when applied at the flag leaf stage compared to applications at tillering.

Table 9. Average plant height and lodging responses of three oat cultivars to plant growth regulators (PGR) and their times of application (TOA) at Vaalharts and Bethlehem in the 2004 season

TREATMENTS		PLANT HEIGHT	LODGING SCORE[†]
		----------mm--------------	---------------0.2 - 9---------------
		Vaalharts	
		2004	2004
PGR			
	Control	1228$^{a\Psi}$	5.42^{a}
	Chlormequat	1218^{a}	5.59^{a}
	Ethephon	1238^{a}	5.20^{a}
	PGR comb.	1221^{a}	5.26^{a}
	LSD $_{(0.05)}$	NS	NS
Cultivar (C)			
	Kompasberg	1080^{c}	3.28^{c}
	Overberg	1392^{a}	5.52^{b}
	Sederberg	1207^{b}	7.31^{a}
	LSD $_{(0.05)}$	33	0.81
TOA			
	Tillering	1242^{a}	5.85^{a}
	Elongation	1222^{a}	5.63^{a}
	Flag leaf	1215^{a}	4.63^{b}
	LSD $_{(0.05)}$	NS	0.81
C X PGR		NS	NS
C X TOA		NS	NS
PGR X TOA		NS	NS
C X PGR X TOA		NS	NS
		Bethlehem	
		2004	2004
PGR			
	Control	881^{a}	0.79^{a}
	Chlormequat	862^{ab}	0.71^{a}
	Ethephon	802^{c}	0.48^{a}
	PGR comb.	824^{bc}	0.58^{a}
	LSD $_{(0.05)}$	46	NS
Cultivar (C)			
	Kompasberg	727^{c}	0.59^{ab}
	Overberg	924^{a}	0.44^{b}
	Sederberg	874^{b}	0.89^{a}
	LSD $_{(0.05)}$	40	0.31
TOA			
	Tillering	869^{a}	0.71^{ab}
	Elongation	854^{a}	0.80^{a}
	Flag leaf	803^{b}	0.41^{b}
	LSD $_{(0.05)}$	40	0.31
C X PGR		NS	NS
C X TOA		NS	NS
PGR X TOA		NS	NS
C X PGR X TOA		NS	NS

[†] Lodging index ranging from 0.2 (no lodging) to 9 (completely lodged).

[Ψ] Means within a column and treatment with similar superscript letters are not significantly different from each other.

* Significance of difference at $P<0.05$.

** Significance of difference at $P<0.001$.

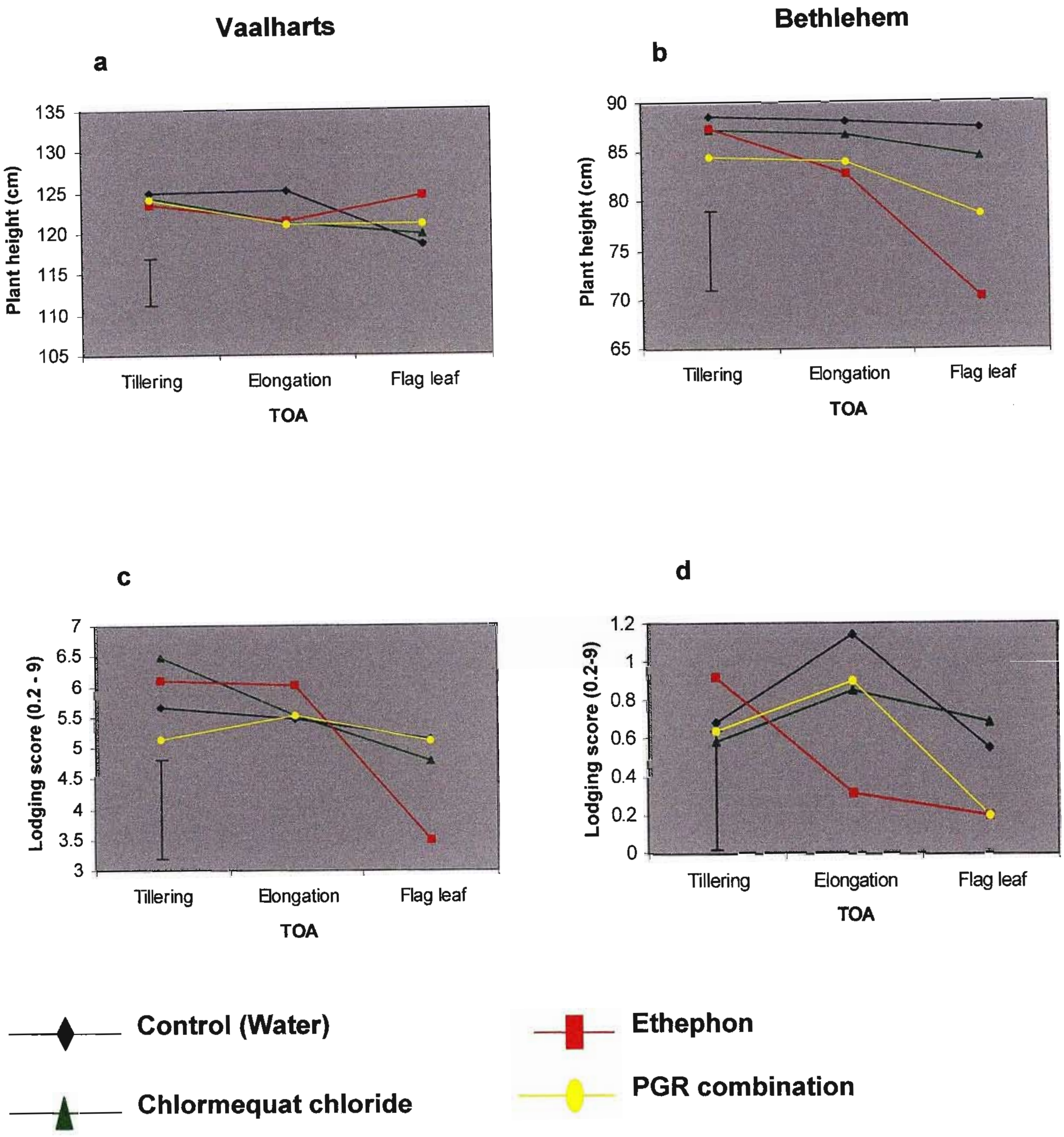


Fig. 17 The plant growth regulator (PGR) X time of application (TOA) interaction for plant height (a and b) and lodging (c and d) in Vaalharts and Bethlehem. Vertical bars respresent the LSD (0.05) for the specific interaction.

The height reduction with applications of ethephon and chlormequat may be attributed to the inhibition of elongation shifting to the upper, longer internodes when applications are made at the flag leaf stage subsequently leading to a greater reduction in lodging. This reduction in lodging was simultaneously acompanied by a significant 10.6% and a non-significant 5.6% improvement in grain yield relative to applications of PGR's at the tillering and elongation stages at Vaalharts in 2004, respectively (Table 8). However, applications at the flag leaf stage also produced a significant reduction in hectolitre mass relative to the tillering application in 2003 at Vaalharts (Table 8). This may be due to the release of ethylene from ethephon (Lurssen, 1982), which may have stimulated the processes of senescence, thereby shortening the duration of grain filling and reducing hectolitre mass.

At Bethlehem, ethephon and the PGR combination significantly reduced plant height by 8.9 and 6.5% respectively compared to the control (Table 9). The height reduction did not produce a main effect on lodging, as lodging was not severe at Bethlehem with plants being relatively short. The absence of lodging may be the primary reason for the similar yields obtained between the ethephon, PGR combination and control treatments in Bethlehem in 2004 (Table 8). This response is similar to the work done by Cox & Otis (1989), who found that the active ingredient ethephon was only effective at improving yields when this PGR successfully controlled lodging. The significant reduction in plant height with applications of PGR's at the flag leaf stage (Table 9) may be primarily attributed to the application of ethephon at the flag leaf stage as opposed to applications at tillering or elongation (Fig. 17b). The height reduction was simultaneously accompanied by a reduction in lodging when ethephon was applied at the flag leaf stage (Fig. 17d). Additionally, the non-significant reduction in plant height when the PGR combination was applied at the flag leaf stage (Fig. 17b) lead to a significant reduction in lodging compared to the application at elongation (Fig. 17d) further demonstrating the suitability of the flag leaf application to reductions in plant height and lodging.

As expected, the lodging tolerant cultivar Kompasberg produced significantly shorter plants than the other cultivars at both localities (Table 9). In most instances this was accompanied by simultaneous reductions in lodging. Kompasberg has a short, upright stature while Overberg and Sederberg are characterized by thinner, longer stems which tend to lodge under stress. These characteristics are clearly reflected in the lower plant height and lodging scores of Kompasberg compared to the other two cultivars (Table 9). At Bethlehem, however, the application of ethephon to Kompasberg significantly reduced plant height compared to applications of chlormequat (Fig. 18b). This produced a significant lodging response as ethephon reduced lodging in Kompasberg compared to applications of chlormequat (Fig. 18d). Such a response may indicate that ethephon could have beneficial effects on reducing plant height and lodging even when lodging tolerant cultivars are used.

The cultivar Overberg produced plants that were significantly taller than those of Sederberg at both localities (Table 9). However, Sederberg produced significantly higher lodging scores compared to Overberg thereby indicating the weaker stem characteristics of the cultivar Sederberg. Sederberg therefore seems to be the more lodging susceptible cultivar of the two. The cultivar Overberg produced plants that were significantly taller than those of Kompasberg at Vaalharts (Fig. 18a). However, lodging of Overberg was not significantly different from that of Kompasberg when no PGR's were applied (Fig. 18c). It was only when PGR's were applied that the lodging score of Overberg was significantly different from the lodging scores of Kompasberg. This may imply that Overberg may be fairly lodging tolerant and that applications of PGR's could possibly affects it's tolerance. The application of ethephon and the PGR combination significantly reduced the plant height of Overberg compared to the control at Bethlehem (Fig. 18b). Lodging was not significantly affected (Fig. 18d), however, yields were significantly increased (Fig. 15d), probably due to the redirection of assimilate partitioning to grain yield rather than stem elongation.

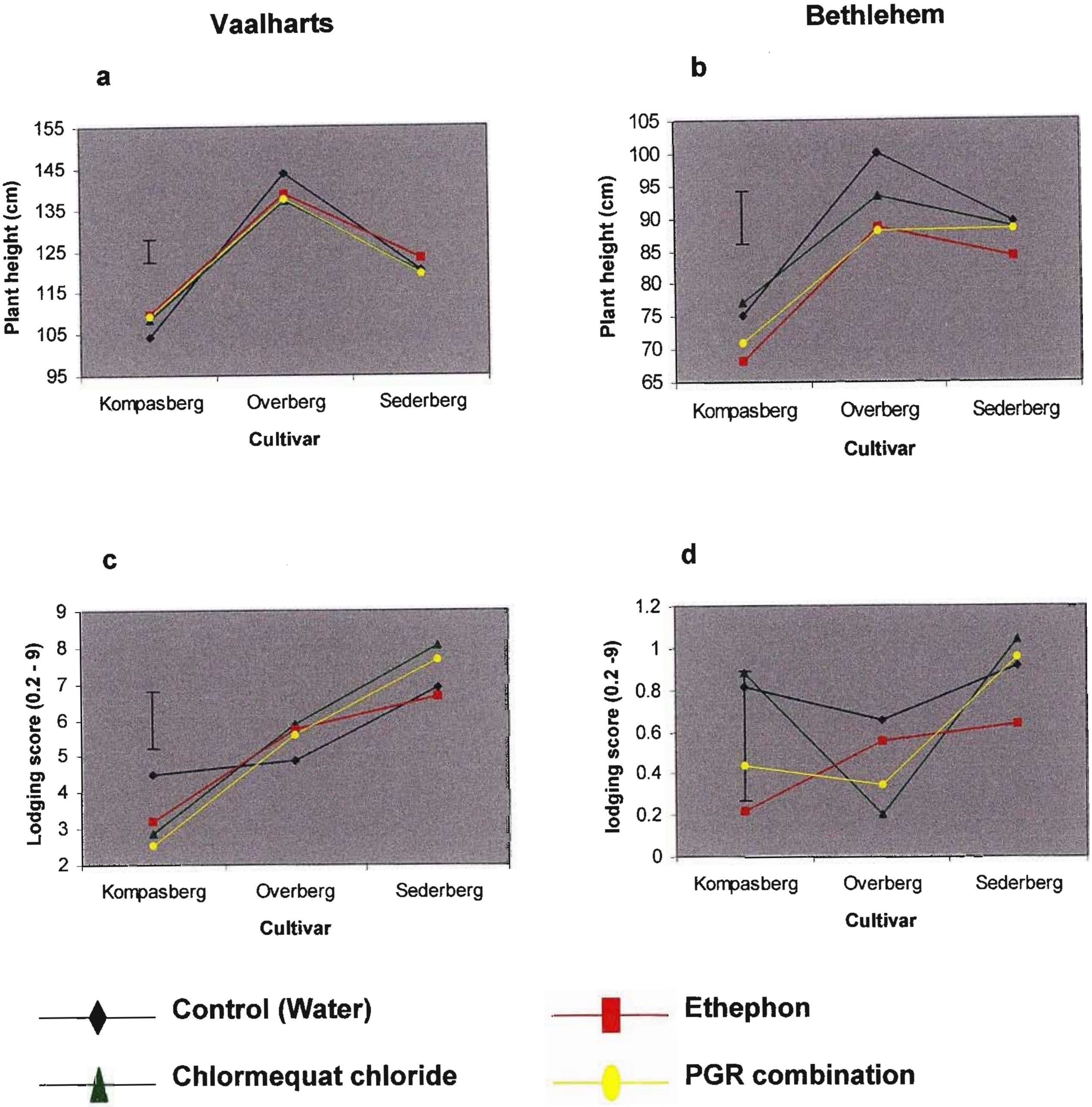


Fig. 18 The cultivar (C) X plant growth regulator (PGR) interactions for plant height (a and b) and lodging (c and d) at Vaalharts and Bethelehem. Vertical bars represent the LSD (0.05) for the specific interaction.

CONCLUSIONS

Generally, the most consistent responses were those produced by the different cultivars while the PGR's and times of application produced inconsistent responses to all variables measured. The lodging tolerant cultivar Kompasberg was significantly shorter than the other cultivars leading to a reduction in lodging (Table 9). Kompasberg also produced higher yields than the lodging susceptible cultivars. However, hectolitre mass was significantly lower on most occasions (Table 8). The cultivar Sederberg had weaker stem characteristics than Overberg as lodging in Sederberg was significantly greater even though its plant height was lower (Table 9). The use of PGR's may possibly have enhanced lodging in Overberg (Fig. 18c), however, yields were significantly increased when ethephon or the PGR combination was applied to the cultivar (Fig. 15d).

The PGR ethephon generally reduced plant height when applied at the flag leaf stage (Fig. 17b) and this lead to a significant reduction in lodging (Fig. 17d) as well as an improvement in hectolitre mass (Fig. 16b). Chlormequat had no effect on plant height at either site. However, lodging was significantly reduced when applications were made at the flag leaf stage compared to the tillering stage application at Vaalharts (Fig. 17c). This subsequently led to an improvement in grain yield (Fig. 15a), however, hectolitre mass was unaffected (Fig. 16a). A slight reduction in plant height with the PGR combination at Bethlehem (Fig. 17b) led to a significant reduction in lodging (Fig. 17d), however, yield and hectolitre mass were unaffected. The most effective TOA was at the flag leaf stage as yields were improved at both localities (Table 8), while plant height and lodging were reduced (Table 9). Hectolitre mass was significantly improved when the PGR combination was applied to the cultivar Sederberg at the tillering stage (Fig. 16a).

The results of this study indicate that PGR's have moderate effects as tools against lodging in oats, however, when lodging is severe, the type of PGR and the time of application may have effects on yield and hectolitre mass. Another season of testing may possibly eliminate some of the inconsistencies and allow reliable recommendations to be made. The use of a lodging tolerant cultivar such as Kompasberg is a more reliable method of reducing lodging and maintaining high yields. Selecting short cultivars with strong stem characteristics and high yield potentials may be a more dependable longer-term solution to eliminating lodging susceptibility.

CHAPTER 6

GENERAL DISCUSSION

Current recommendations and guidelines for small grain cereal production in South Africa acknowledge lodging as a serious constraint in cereal production (Barnard & Burger, 2003). Suggested remedies to alleviate lodging in South Africa include the use of lodging-resistant cultivars, reducing seeding densities, nutrient management and irrigation management. The option of implementing PGR's to reduce lodging in South Africa is not widely reported due to the lack of scientific data regarding the issue. The results of the present study suggest that PGR's may be utilized as effective lodging control treatments for wheat, barley and oats under South African conditions. However, the subsequent effects on grain yield and quality parameters differ according to the type of PGR, the cultivar utilised, and the TOA.

Generally, the PGR chlormequat chloride produced moderate effects on all three crops. Plant height was occasionally reduced in wheat and barley when chlormequat was applied at the flag leaf stage, however, lodging was not affected. Lodging was only reduced when chlormequat was applied to oats at the flag leaf stage compared with the tillering stage at Vaalharts. Visual observation revealed that lodging of oats at Vaalharts in both seasons was severe in comparison to lodging of the barley and wheat. It is possible that chlormequat may significantly reduce lodging when it is severe and have no effect when lodging is negligible. At Bethlehem, lodging was not reduced by the chlormequat treatment at any TOA possibly due to the fact that lodging was not severe.

Grain yield of oats at Vaalharts was improved when chlormequat was applied at the flag leaf stage compared to the earlier applications, however, at Bethlehem no effects of chlormequat were observed on yield. The yield improvement at Vaalharts may be attributed to the successful control of lodging. Hectolitre masses and falling numbers were also improved in wheat with applications of chlormequat at the flag leaf stage. It seems that the flag leaf application of chlormequat does produce responses, however, the inconsistency and variability of these responses over crops and localities prevents any general conclusions from being made. There is simply not enough evidence to conclude that chlormequat consistently reduces lodging in all three crops. One could conclude that chlormequat application at the flag leaf stage does reduce lodging when it is severe and that yield increases thereafter may be due to the reduction in lodging. Effects on quality parameters were negligible with occasional improvements and reductions depending on the crop, cultivar and TOA.

Ethephon and the PGR combination produced much more consistent plant height and lodging reducing responses with the three crops investigated. Plant biomass production was immediately reduced after the flag leaf applications to barley and wheat. The biomass response was cultivar dependent as only the lodging suscptible wheat cultivar Kariega responded to the application while SST 876 was unaffected. Similarly, with the oats, the lodging tolerant cultivar Kompasberg was not reduced in height by the ethephon or the PGR combination treatment, while plant height was reduced with the lodging susceptible cultivars. The differential plant height and lodging responses between the tolerant and susceptible cultivars were also observed with respect to yield and hectolitre mass. This suggests that PGR's may primarily exert their lodging and height reducing effects on lodging susceptible cultivars, while they may be ineffective against lodging tolerant cultivars.

The reductions in biomass after ethephon and the PGR combination application may be attributed to the reduced plant height, which was observed with all three crops. The height reduction significantly reduced lodging when prevalent, such as with the oats and barley at Vaalharts. In such instances, plant height and lodging were reduced to a greater degree with applications of ethephon and the PGR comb. at the flag leaf stage compared with the earlier applications. The height reduction may be due to the inhibition of elongation shifting to the upper, longer internodes thereby having a greater effect on plant height. These height and lodging reductions produced subsequent positive and negative effects on yield and quality parameters suggesting the effectiveness of the flag leaf application compared with the earlier applications which generally did not produce responses. The split (double) application of ethephon and the PGR combination to barley reduced plant height and lodging, however, yields were simultaneously reduced. This implies that higher concentrations of ethephon within the plant may have negative effects on yield, or the split application may reduce plant height to such a degree that the photosynthetic capacity of the plant is reduced, hence reducing yield.

Generally, the only consistent response reported on the small grain cereals was the reduction in plant height, lodging and biomass production following ethephon and the PGR combination treatments at the flag leaf stage. Other factors such as yield and yield components and crop quality varied from significant improvements to significant reductions. These variations could be attributed to different crop responses between barley, wheat and oats as demonstrated by Clark & Fedak (1977). In addition to this, variations between cultivars of crops are sure to produce varying results, with cultivars differing in growth rate, lodging tolerance, yield potentials, and quality characteristics (Danhous *et al.*, 1982). Additional factors such as type of PGR and time of application further complicate and diversify the interactions.

The large variation in responses may also be attributable to inappropriate experimental techniques. An increase in the accuracy of the yield component results could be improved upon by employing hand-threshing techniques as opposed to mechanical threshing, which led to large amounts of seed loss and breakage. Additionally, one would be able to obtain a more accurate idea of lodging effects on yield and quality by comparing lodged plants to plants of the same cultivar supported mechanically. Precision of biomass measurements could be improved upon by ensuring proper plant spacing and emergence within a row in order to obtain a similar number of plants in each sampling unit.

The results of the study suggest that ethephon and the PGR combination have potential as tools against small grain cereal lodging under South African conditions. The reductions in lodging must be weighed against occasional yield and quality reductions as well as possible improvements. To prevent these yield and quality losses some producers may opt to plant shorter cultivars that do not lodge. Selecting shorter cultivars for lodging prevention has been practiced for some time, however, there may be some distinct disadvantages of this practice in comparison to PGR usage.

It should be noted that most of the characteristics acquired with plant breeding are long-term, and since desirable and undesirable characteristics may be linked in some cases, the long-term nature of plant breeding may not always provide short-term agronomic solutions. On the other hand the use of PGR's are optional and therefore offer a more flexible approach to reducing lodging and increasing yield (Green, 1986). Also, the positive association between total biomass production and yield (Bruinsma, 1982) suggests that the producer might be better off growing a taller cultivar and intervening with a PGR only if necessary. Another advantage of PGR's over plant breeding is the considerably less time required to develop use of the registered compounds as compared to the development of a new cultivar. One of the negative aspects of PGR's, however, is that plant hormones are extremely complex, exerting multiple effects on plant growth and development. This makes the use of PGR's for a specific function very difficult, as other aspects of growth and development are sure to be affected. This is clearly evident by the variation in yield and quality responses obtained with the three crops investigated. Furthermore, PGR's offer a short-term solution to intensive management lodging losses, whereas plant breeding of short, stiff-strawed cultivars may provide a longer term solution.

The introduction of semi-dwarf cultivars with higher harvest indexes has revolutionized the wheat industry by limiting lodging and increasing harvestable grain (Fischer, 1993). However, PGR's may provide an alternative method of manipulating harvest index in a more flexible manner. Nevertheless, the arguments and comparisons of plant breeding techniques against PGR's were beyond the scope of this study, which was undertaken to find an alternative method of reducing lodging, and not to find a replacement for breeding techniques.

Reports of PGR's only being effective when lodging occurs (Simmons *et al.*, 1988) implies that these products will be most valuable in intensive management systems or when environmental conditions are conducive to lodging. The results from the barley trials indicate that ethephon and the PGR combination may be suited to intensive management as application of these PGR's allowed higher levels of N to be used with only minor increases in lodging. Meanwhile, lodging was significantly increased when higher levels of N were applied to the control and chlormequat treatments.

With intensive management systems the producer must consider the economic impact of increasing seeding rates, nitrogen fertilization, use of fungicides and pesticides, and the use of PGR's. However, this must be weighed against a possible higher economic return in the form of improved yields and quality. Baylis (1990) in a study of economic aspects of plant growth regulators showed that the use of PGR's in intensive regimes was justified in terms of yield and profitability. In the same study it was found that fields treated with PGR's consistently yielded around 0.5 t ha^{-1} more than untreated fields. With the difficulties involved in predicting lodging the most viable option would be the use of ethephon or the PGR combination on wheat and barley as an effective insurance measure in an intensive management system.

Further research on the effects of PGR's on South African wheat, barley and oats should involve testing of ethephon and the PGR combination, while the effects of chlormequat are modest and further testing is not recommended. Aspects that need attention include the effects of later applications on grain yield and quality parameters of all three crops. Additionally, these effects should be investigated in conjunction with intensive management practices such as higher N and seeding rates combined with an extensive economic analysis to determine the possible profitability of PGR's. Another observation that could be made is to determine the actual gametocidic effects of ethephon by measuring floret fertility. Furthermore, photosynthetic measurements may also provide an indication of the effects of PGR's on the rates as well as the capacity of photosynthesis of shortened plants. Other observations such as leaf area index, the rate and duration of grain filling, N distribution and movement, and hormonal changes within the plant, may further assist in the understanding of the physiology of PGR applications.

REFERENCES

AMERICAN ASSOCIATION OF CEREAL CHEMISTS, 2000. Approved Methods of the AACC, 10th ed. Volume 2. Falling Number Determination. Method 56-81B. The Association: St. Paul, Minnesota.

ANON., 2004. South African Grain Information Services. On wheat, barley, oats and conola. IN: Wheat Focus (November/December). 22.6, 4-5.

BARNARD, A., PURCHASE, J.L., SMITH, M.F., van LILL, D., 1997. Determination of the preharvest sprouting resistance of South African winter wheat (*Triticum aestivum* L.) cultivars. *South African Journal of Plant and Soil.* 14, 4-8.

BARNARD, A. & BURGER, E., 2003. Guidelines for the production of small grains in the summer rainfall region 2003. ARC-Small Grain Institute. Hooglandpers. Bethlehem.

BAYLIS, A.D., 1990. Economic aspects of plant growth regulators. Plant Growth Substances 1988. Springer-Verlag GmbH & Co. KG; Berlin; Germany. 576-584.

BERRY, P.M., GRIFFIN, J.M., SYLVESTER-BRADLEY, R., SCOTT, R.K., SPINK, J.H., BAKER, C.J., CLARE, R.W., 2000. Controlling plant form through husbandry to minimise lodging in wheat. *Field Crops Research*. 67, 59-81.

BLOMQUIST, R.V., KUST, C.A. & SCHRADER, L.E., 1973. Effect of Ethrel on seasonal activity of three enzymes and lodging resistance in soybeans. *Crop Science*. 13, 4-7.

BROWN, C.M. & EARLEY, E.B., 1973. Response of one winter wheat and two spring oat varieties to foliar application of 2-Chloroethyl phosphonic acid (Ethrel). *Agronomy Journal*. 65, 829-832.

BROWNE, R.A., WHITE, E.M. & BURKE, J.I., 2003. Effect of nitrogen, seed rate and plant growth regulator (chlormequat chloride) on the grain quality of oats (*Avena sativa*). *Journal of Agricultural Science*. 141, 249-258.

BRUINSMA, J., 1982. Plant growth regulators in field crops. In: McLAREN, J.S. (ed). Chemical manipulation of crop growth and development. Butterworth Scientific. London, 3-10.

CALDWELL, C.D., MELLISH, D.R. & NORRIE, J., 1988. A comparison of ethephon alone and in combination with CCC or DPC applied to spring barley. *Canadian Journal of Plant Science*. 68, 941-946.

CLARK, R.V. & FEDAK, G., 1977. Effects of Chlormequat on plant height, disease development and chemical constituents of cultivars of barley, oats and wheat. *Canadian Journal of Plant Science*. 57, 31-36.

COX, W.J. & OTIS, D.J., 1989. Growth and yield of winter wheat as influenced by Chlormequat Chloride and Ethephon. *Agronomy Journal*. 81, 264-270.

CRAUFURD, P.Q. & CARTWRIGHT, P.M., 1989. Effect of photoperiod and Chlormequat on apical development and growth in a spring wheat (*Triticum aestivum*) cultivar. *Annals of Botany*. 63, 515-525.

CROOK, M.J. & ENNOS, A.R., 1995. The effect of nitrogen and growth regulators on stem and root characteristics associated with lodging in two cultivars of winter wheat. *Journal of Experimental Botany*. 46, 931-938.

DAHNOUS, K., VIGUE, G.T., LAW, A.G., KONZAK, C.F. & MILLER, D.G., 1982. Height and yield response of selected wheat, barley, and triticale cultivars to Ethephon. *Agronomy Journal.* 74, 580 -582.

De ROCQUIGNY, P.J., ENTZ, M.H., GENTILE, M.R. & DUGUID, D., 2004. Yield physiology of a semidwarf and tall oat cultivar. *Crop Science.* 44, 2116-2122.

FISCHER, R.A. & STAPPER, M., 1987. Lodging effects on high yielding crops of irrigated semidwarf wheat. *Field Crops Research.* 17, 245-258.

FISCHER, R.A., 1993. Cereal breeding in developing countries: Progress and prospects. IN: International Crop Science I. Buxton, D.R., Shibles, R., Forsberg, R.A., Blad, B.L., Asay, K.H., Paulsen, G.M. & Wilson, R.F. Crop Science Society of America. Inc. Madison, Wisconsin, USA. 201-209.

FOSTER, K.R., REID, D.M. & TAYLOR, J.S., 1991. Tillering and yield responses to Ethephon in three barley cultivars. *Crop Science.* 31, 130-134.

FOSTER, K.R. & TAYLOR, J.S., 1993. Response of barley to Ethephon: Effects of rate, nitrogen, and irrigation. *Crop Science.* 33, 123-131.

GOODING, M.J. & DAVIES, W.P., 1997. Wheat production and utilization: Systems, quality and the environment. CAB International. New York, 231-233.

GREEN, C.F., 1986. Modifications to the growth and development of cereals using chlorcholine chloride in the absence of lodging: A synopsis. *Field Crops Research.* 14, 117-133.

HARMS, C.L., BEUERLEIN, J.E. & OPLINGER, E.S., 1989. Effects of intensive and current recommended management systems on soft winter wheat in the U.S. corn belt. *Journal of Production Agriculture.* 2, 325-332.

HARRISON, M.A. & KAUFMAN, P.B., 1982. Does Ethylene play a role in the release of lateral buds (tillers) from apical dominance in oats. *Plant Physiology.* 70, 811-814.

HERBERT, C.D., 1982. Growth regulation in cereals – Chance or design? In: McLAREN, J.S. (ed). Chemical manipulation of crop growth and development. Butterworth Scientific. London, 315-325.

HERBERT, C.D., 1983. Interactions between nitrogen fertilizers and growth retardants in practical cereal production. Monograph, British Plant Growth Regulator Group. 9, 87-95.

HOFNER, W. & KUHN, H., 1982. Effect of growth regulator combinations on ear development, assimilate translocation and yield in cereal crops. In: McLAREN, J.S. (ed). Chemical manipulation of crop growth and development. Butterworth Scientific. London, 375-397.

HUMPHRIES, E.C., WELBANK, P.J. & WITTS, K.J., 1965. Effect of CCC on growth and yield of spring wheat in the field. *Annals of Applied Biology.* 56, 351-361.

HUTLEY-BULL, P.D. & SCHWABE, W.W., 1982. Some effects of low-concentration gibberellic acid and retardant application during early growth on morphogenesis in wheat. In: McLAREN, J.S. (ed). Chemical manipulation of crop growth and development. Butterworth Scientific. London, 329-342.

KETTLEWELL, P.S., WHITLEY, E.A. & MEREDITH, W.S., 1983. Effects of early application of Chlormequat on tillering and yield of winter wheat. *Journal of Agricultural Science, Cambridge.* 100, 735-738.

KHAN, A. & SPILDE, L., 1992. Agronomic and economic response of spring wheat cultivars to Ethephon. *Agronomy Journal*. 84, 399-402.

KNAPP, J.S. & HARMS, C.L., 1988. Nitrogen fertilization and plant growth regulator effects on yield and quality of four wheat cultivars. *Journal of Production Agriculture*. 1, 94-98.

KORANTENG, G.O. & MATTHEWS, S., 1982. Modifications of the development of spring barley by early application of CCC and GA_3 and the subsequent effects on yield components and yield. In: McLAREN, J.S. (ed). Chemical manipulation of crop growth and development. Butterworth Scientific. London, 343-357.

LOWE, L.B. & CARTER, O.G., 1972. The influence of CCC (2-Chloroethyltrimethylammonium chloride) and temperature on dry matter and assimilate accumulation in wheat. *Australian Journal of Agricultural Research*. 23, 573-583.

LURSSEN, K., 1982. Manipulation of crop growth by ethylene and some implications of the mode of generation. In: McLAREN, J.S. (ed). Chemical manipulation of crop growth and development. Butterworth Scientific. London, 67-78.

MOES, J. & STOBBE, E.H., 1991. Barley treated with Ethephon: I. Yield components and net grain yield. *Agronomy Journal*. 83, 86-90.

MOHAMED, M.A., STEINER, J.J., WRIGHT, S.D., BHANGOO, M.S. & MILLHOUSE, D.E., 1990. Intensive crop management practices on wheat yield and quality. *Agronomy Journal*. 82, 701-707.

MYHRE, D.L., SANFORD, J.O., BIEBER, G.L., PLUENNEKE, R.H. & JOHNSON, C., 1973. Response of wheat to foliar applications of 2-Chloroethyltrimethylammonium chloride. *Crop Science*. 13, 95-98.

NAFZIGER, E.D., WAX, L.M. & BROWN, C.M., 1986. Response of five winter wheat cultivars to growth regulators and increased nitrogen. *Crop Science*. 26, 767-770.

PALEG, L., KENDE, H., NINNEMANN, H., LANG, A. 1965. Physiological effects of gibberellic acid. VIII. Growth retardants on barley endosperm. *Plant Physiology*. 40, 165-169.

PAULSEN, G.M., 1987. Wheat stand establishment. In: Heyne, E.G. (ed). Wheat and wheat improvement. Second edition. Agronomy Monograph no.13. American Society of Agronomy. Wisconsin, 384-390.

PELTONEN-SAINIO, P., RAJALA, A., SIMMONS, S., CASPERS, R. & STUTHMAN, D.D., 2003. Plant growth regulator and daylength effects on preanthesis main shoot and tiller in conventional and dwarf oat. *Crop Science*. 43, 227-233.

RAJALA, A. & PELTONEN-SAINIO, P., 2000. Manipulating yield potential in cereals using plant growth regulators. IN: Basra, A.S. (ed). Plant Growth Regulators in Agriculture and Horticulture: Their role and commercial uses. Haworth Press, Inc. New York, 27-58.

RAJALA, A. & PELTONEN-SAINIO, P., 2001. Plant growth regulator effects on spring cereal root and shoot growth. *Agronomy Journal*. 93, 936-943.

RAJALA, A.; PELTONEN-SAINIO, P.; ONNELA, M. & JACKSON, M., 2002. Effects of applying stem-shortening plant growth regulators to leaves on root elongation by seedlings of wheat, oat and barley: mediation by ethylene. *Plant Growth Regulation*. 38, 51-59.

ROWELL , P.L. & MILLER, D.G., 1971. Induction of male sterility in wheat with 2-Chloroethylphosphonic acid (Ethrel). *Crop Science.* 11, 629-631.

ROWLAND, P.E.M. 1973., Further studies of the effects of growth regulants on spring wheat. *Rhodesia Agricultural Journal.* 70 (4): 87-89.

SCHWARTZ, T.K., COFFIN, R.H., EVANS, W.F., NASH, R.L. & RAO, K.P., 1983. The effect of ethephon (2-chloroethyl) phosphonic acid on lodging and yield of small grain cereal crops. Monograph, British Plant Growth Regulator Group. 9, 89-95.

SIMMONS, S.R., OELKE, E.A., WIERSMA, J.V., LEESCHEN, W.E. & WARNES, D.D., 1988. Spring Wheat and barley responses to ethephon. *Agronomy Journal.* 80, 829-834.

SOIL CLASSIFICATION WORK GROUP, 1991. A taxonomic system for South Africa. Memoirs on the Natural Agricultural resources of South Africa, no 15. Institute for Soil Climate and Water, Dept. of Agricultural Development, Pretoria.

STAHLI, D., PERRISSIN-FABERT, D., BLOUET, A. & GUCKERT, A., 1995. Contribution of the wheat (*Triticum aestivum* L.) flag leaf to grain yield in response to plant growth regulators. *Plant Growth Regulation.* 16, 293-297.

TOLBERT, N.E., 1960. (2-chloroethyl) – trimethylammonium chloride and related compounds as plant growth substances. II.Effect on growth of wheat. *Plant Physilogy.* 35, 380-385.

TRIPATHI, S.C., SAYRE, K.D., KAUL, J.N. & NARANG, R.S., 2004. Lodging behavior and yield potential of spring wheat (Triticum aestivum L.):

effects of ethephon and genotypes. *Field Crops Research*. 87, 207-220.

VAN ARK, H., 1995. Introduction to curvilinear regression. Agrimetrics Institute, Agricultural Research Council, Pretoria.

VAN SANFORD, D.A., GROVE, J.H., GRABAU, L.J. & MACKOWN, C.T., 1989. Ethephon and nitrogen use in winter wheat. *Agronomy Journal*. 81, 951-954.

VERMEULEN, J.B., GROBLER, H. & VAN ZYL, K., 2000. A guide to the use of plant growth regulants, defoliants and desiccants. Ninth edition. National Department of Agriculture. South Africa. 21.

WARNER, H.C., 1969. Ethylene evolution from 2-Chloroethylphosphonic acid. *Plant Physiology*. 44, 156-158.

WEBSTER, J.R. & JACKSON, L.F., 1993. Management practices to reduce lodging and maximize grain yield and protein content of fall-sown irrigated hard red spring wheat. *Field Crops Research*. 33, 249-259.

WIERSMA, D.W., OPLINGER, E.S. & GUY, S.O. 1986. Environment and cultivar effects on winter wheat response to Ethephon plant growth regulator. *Agronomy Journal*. 78, 761-764.

WOODWARD, E.J. & MARSHALL, C., 1988. Effects of plant growth regulators and nutrient supply on tiller bud outgrowth in barley. *Annals of Botany*. 61, 347-354.

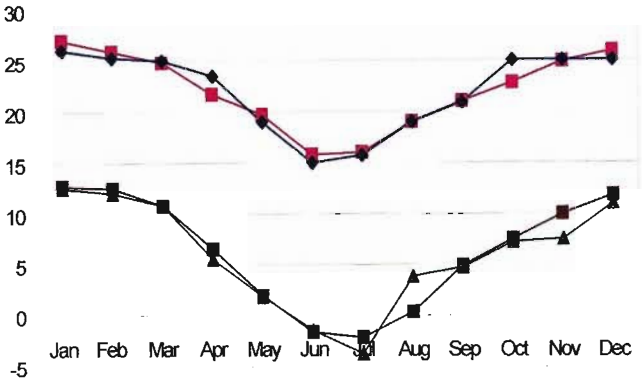
WOOLLEY, E.W.; FIELDER, A.G. & BRYAN, R., 1991. Recent experience of timing of growth regulators on winter wheat. Proceedings Brighton Crop Protection Conference – weeds. 3, 981-986.

ZADOKS, J.C., CHANG, T.T. & KONZAK, C.F., 1974. A decimal code for the growth stages of cereals. *Weeds Research*. 14, 415-421.

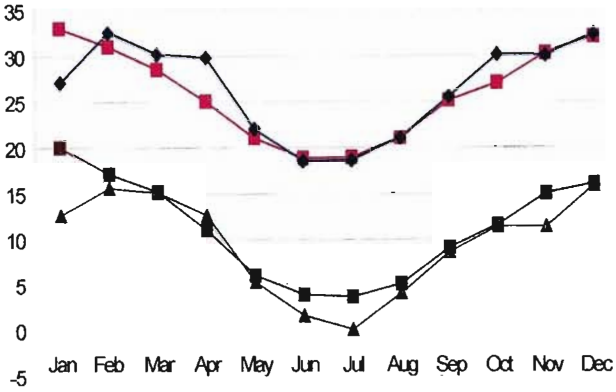
Appendix 1

Seasonal and long term temperatures for Vaalharts and Bethlehem from respective weather stations at sites.

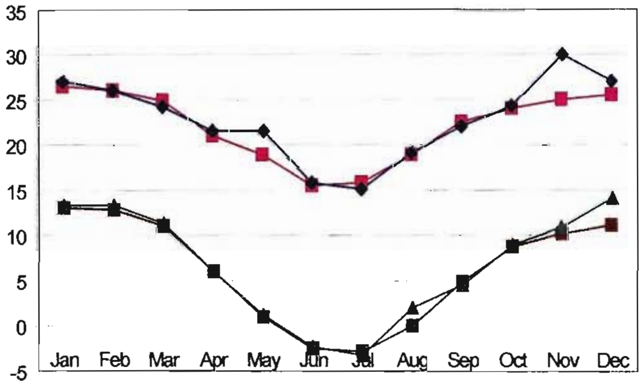
Bethlehem 2003



Vaalharts 2003



Bethlehem 2004



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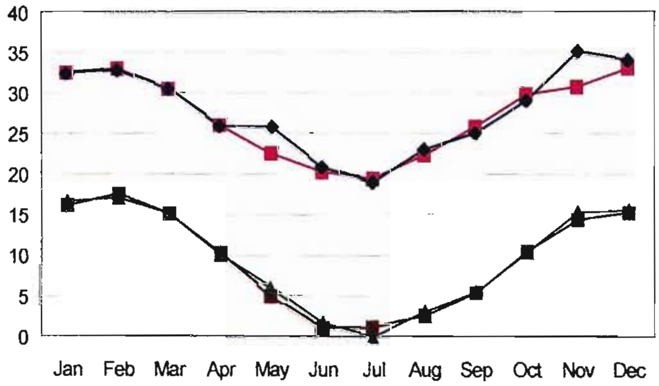


■ **Long term maximum**

◆ **Seasonal maximum**

■ **Long term minimum**

▲ **Seasonal minimum**

APPENDIX 2

An example of a field trial plan which was employed throughout the study.
Field Trial : Vaalharts wheat 2004
Name: Plant Growth Regulator trial (02/09 Task no. 20)
Treatments: 36 **Replications**: 4
Cultivars: **K** – Karieaga **O**- Olifants **S** – SST 876
PGR: **W** – Water **C**- CeCeCe **E** – Ethapon **U** – Uprite
Time of application: **T** – Tillering **E**- Elongation **F**- Flag leaf
Treatments are listed in the order: Cultivar PGR TOA

Plant in this direction →

REP 1

KEE 1	**OUE** 2	**SWF** 3	**KUF** 4
OCF 8	**SCF** 7	**SET** 6	**SUF** 5
SWE 9	**OEE** 10	**OUT** 11	**KET** 12
SCE 16	**KWF** 15	**KCF** 14	**OCT** 13
SUE 17	**OWF** 18	**KCE** 19	**OEF** 20
SCT 24	**OWT** 23	**SEF** 22	**KEF** 21
KWT 25	**KUT** 26	**KUE** 27	**OUF** 28
KCT 32	**OET** 31	**SEE** 30	**SUT** 29
SWT 33	**OWE** 34	**OCE** 35	**KWE** 36

REP 2

KWF 1	**OET** 2	**OCE** 3	**SCT** 4
OUT 8	**OWF** 7	**OEE** 6	**SWF** 5
KCF 9	**KEE** 10	**KCT** 11	**OEF** 12
SWT 16	**KUT** 15	**OUE** 14	**KWE** 13
SUT 17	**SWE** 18	**SET** 19	**SEE** 20
KEF 24	**SCF** 23	**KET** 22	**SUE** 21
KUF 25	**SUF** 26	**SEF** 27	**KCE** 28
OUF 32	**KUE** 31	**OWT** 30	**OCF** 29
KWT 33	**SCE** 34	**OWE** 35	**OCT** 36

REP 3

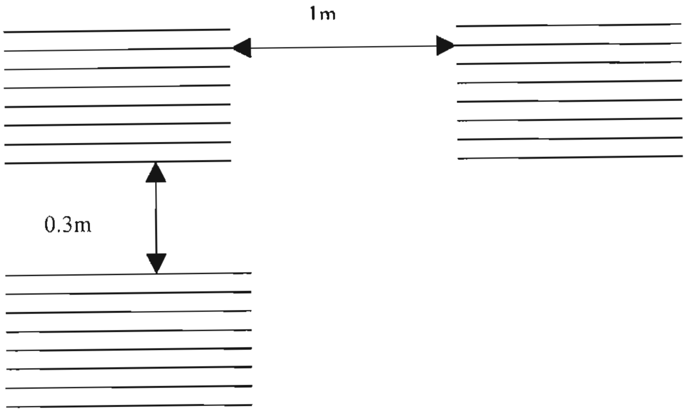
OCF 1	**KET** 2	**SEE** 3	**KEF** 4
SUF 8	**SWT** 7	**KCT** 6	**KEE** 5
KUF 9	**SWE** 10	**OCT** 11	**OUE** 12
SCT 16	**SEF** 15	**SET** 14	**OWE** 13
KCE 17	**KWE** 18	**OCE** 19	**OWF** 20
OET 24	**SUT** 23	**KUT** 22	**KWT** 21
SUE 25	**OUF** 26	**SCF** 27	**OUT** 28
OWT 32	**OEE** 31	**OEF** 30	**SCE** 29
SWF 33	**KCF** 34	**KWF** 35	**KUE** 36

REP 4

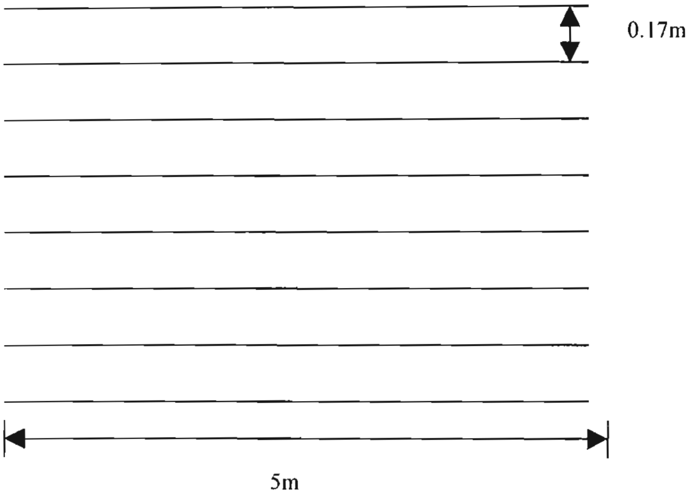
SEE 1	**OUF** 2	**SUT** 3	**KUT** 4
OUE 8	**SCT** 7	**OCE** 6	**SUF** 5
SCE 9	**SWE** 10	**KUE** 11	**SWF** 12
KCE 16	**KET** 15	**KCT** 14	**SCF** 13
OET 17	**KEF** 18	**SEF** 19	**OWE** 20
OCF 24	**KWE** 23	**KCF** 22	**OWF** 21
KEE 25	**OWT** 26	**SUE** 27	**OCT** 28
SWT 32	**KUF** 31	**OEE** 30	**KWT** 29
SET 33	**KWF** 34	**OUT** 35	**OEF** 36

Plot dimensions

Between plots



Within plots



APPENDIX 3

Abbreviated ANOVA tables for wheat trials at Vaalharts and Behtlehem in 2003 and 2004.

(a) Plant height, lodging ratings and hectolitre mass

Vaalharts

SOV		PLANT HEIGHT			LODGING SCORE			HECTOLITRE MASS		
	d.f.	m.s.	v.r.	F pr.	m.s.	v.r.	F pr.	m.s.	v.r.	F pr.
REP stratum	3	112.75	4.81		1.763	1.27		5.640	1.88	
Year	1	13413	572.24	<.001	8.413	6.08	0.014	341.47	113.72	<.001
PGR	2	385.28	16.44	<.001	3.014	2.18	0.092	231.49	77.10	0.095
Cultivar	3	173.27	7.39	<.001	113.40	81.90	<.001	6.449	2.15	<.001
TOA	2	688.40	29.37	<.001	1.022	0.74	0.479	10.033	3.34	0.037
Year.PGR	2	155.69	6.64	<.001	0.620	0.45	0.719	120.844	40.25	0.751
Year.Cult	3	110.62	4.72	0.010	7.115	5.14	0.007	1.209	0.40	<.001
Cult.PGR	6	22.05	0.94	0.467	1.967	1.42	0.208	3.499	1.17	0.326
Year.TOA	2	185.19	7.90	<.001	0.468	0.34	0.714	6.107	2.03	0.133
PGR.TOA	4	158.60	6.77	<.001	5.435	3.93	<.001	5.970	1.99	0.017
Cult.TOA	6	23.56	1.00	0.406	0.896	0.65	0.630	7.925	2.64	0.097
Year.cult.PGR	6	66.21	2.82	0.011	0.752	0.54	0.775	1.737	0.58	0.747
Year.PGR.TOA	4	88.18	3.76	0.001	3.946	2.85	0.011	2.990	1.00	0.010
Year.Cult.TOA	6	61.30	2.62	0.036	0.323	0.23	0.919	8.618	2.87	0.411
Cult.PGR.TOA	12	17.87	0.76	0.689	4.060	2.93	<.001	2.405	0.80	0.649
Residual	225	23.44			1.385			3.003		
Total	287									

Bethlehem

SOV		PLANT HEIGHT			HECTOLITRE MASS			LODGING SCORE (2003)		
	d.f.	m.s.	v.r.	F pr.	m.s.	v.r.	F pr.	Df	v.r.	F pr.
REP stratum	3	900.48	42.86		11.496	15.25		3	7.69	
Year	1	2420.4	115.19	<.001	377.89	501.22	<.001			
Cultivar	2	654.44	31.15	<.001	11.792	15.64	<.001	2	1.76	0.178
PGR	3	1035.2	49.27	<.001	6.6543	8.83	<.001	3	2.52	0.062
TOA	2	1419	67.53	<.001	3.4545	4.58	0.011	2	0.62	0.537
Year.Cult	2	24.07	1.15	0.320	4.1409	5.49	0.005			
Year.PGR	3	26.23	1.25	0.293	0.5811	0.77	0.511			
Cult.PGR	6	6.96	0.33	0.920	1.2480	1.66	0.133	6	1.26	0.285
Year.TOA	2	2.86	0.14	0.873	2.9500	3.91	0.021			
Cult.TOA	4	8.68	0.41	0.799	1.4583	1.93	0.106	4	0.97	0.430
PGR.TOA	6	432.04	20.56	<.001	1.1847	1.57	0.156	6	1.94	0.081
Year.cult.PGR	6	53.08	2.53	0.022	0.3448	0.46	0.839			
Year.cult.TOA	4	19.36	0.92	0.452	0.4085	0.54	0.705			
Year.PGR.TOA	6	11.84	0.56	0.759	1.5638	2.07	0.057			
Cult.PGR.TOA	12	29.39	1.40	0.168	0.2920	0.39	0.967	12	0.64	0.801
Residual	225	21.01			0.7540			105		
Total	287							143		

(b) Yield and yield components

Vaalharts

SOV		YIELD			SPIKES M^{-2}			GRAINS $SPIKE^{-1}$			GRAIN WEIGHT		
	d.f.	m.s.	v.r.	F pr.	m.s.	v.r.	F pr.	m.s.	v.r.	F pr.	m.s.	v.r.	F pr.
REP stratum	3	1.2246	2.34		78888	4.37		16.05	0.43		12.91	1.10	
Year	1	28.329	54.18	<.001	89937	49.77	<.001	90.70	2.46	0.118	1777.92	152.11	<.001
Cultivar	2	16.622	31.79	<.001	336299	18.61	<.001	2807.4	76.06	<.001	546.65	46.77	<.001
PGR	3	0.5613	1.07	0.361	29390	1.63	0.184	57.8	1.57	0.198	41.98	3.59	0.014
TOA	2	1.8098	3.46	0.033	13092	0.72	0.486	31.22	0.85	0.431	15.41	1.32	0.270
Year.Cult	2	1.3492	2.58	0.078	47970	2.65	0.073	201.67	5.46	0.005	262.15	22.43	<.001
Year.PGR	3	0.1755	0.34	0.800	2104	0.12	0.950	4.64	0.13	0.945	4.50	0.38	0.764
Cult.PGR	6	0.5691	1.09	0.370	29645	1.64	0.137	53.07	1.44	0.201	13.24	1.13	0.344
Year.TOA	2	1.4782	2.83	0.061	3300	0.18	0.833	42.78	1.16	0.316	21.24	1.82	0.165
Cult.TOA	4	0.9680	1.85	0.120	23237	1.29	0.276	37.71	1.02	0.397	22.97	1.97	0.101
PGR.TOA	6	1.5685	3	0.008	19801	1.10	0.366	53.77	1.46	0.194	45.68	3.91	<.001
Year.cult.PGR	6	0.7793	1.49	0.182	20853	1.15	0.332	47.74	1.26	0.261	19.64	1.68	0.127
Year.cult.TOA	4	0.3508	0.67	0.613	9567	0.53	0.714	60.26	1.63	0.167	39.43	3.37	0.011
Year.PGR.TOA	6	0.4942	0.95	0.464	19899	1.10	0.362	30.87	0.84	0.543	19.98	1.71	0.120
Cult.PGR.TOA	12	0.9765	1.87	0.039	17195	0.95	0.496	12.29	0.33	0.983	11.38	0.97	0.475
Residual	225	0.5229			18070			36.91			11.39		
Total	287												

Bethlehem

SOV		YIELD			SPIKES M^{-2}			GRAINS $SPIKE^{-1}$			GRAIN WEIGHT		
	d.f.	m.s.	v.r.	F pr.	m.s.	v.r.	F pr.	m.s.	v.r.	F pr.	m.s.	v.r.	F pr.
REP stratum	3	32.148	35.80		106637	6.83		164.94	7.26		29.71	2.64	
Year	1	3.5748	3.98	0.047	168377	10.78	0.001	239.46	10.54	0.001	1112.50	98.85	<.001
Cultivar	2	8.1789	9.11	<.001	3208	0.21	0.815	1066.64	46.96	<.001	799.54	71.04	<.001
PGR	3	3.1369	3.49	0.016	31619	2.02	0.111	15.70	0.69	0.558	61.24	5.44	0.001
TOA	2	2.2632	2.52	0.083	25881	1.66	0.193	65.94	2.90	0.057	17.73	1.58	0.209
Year.Cult	2	3.3475	3.73	0.026	12028	0.77	0.464	34.77	1.53	0.219	55.10	4.90	0.008
Year.PGR	3	0.6290	0.70	0.553	18792	1.20	0.310	7.03	0.31	0.819	3.29	0.29	0.831
Cult.PGR	6	1.9178	2.19	0.048	39271	2.51	0.022	11.65	0.51	0.798	5.67	0.50	0.805
Year.TOA	2	0.7198	0.80	0.450	4320	0.28	0.759	21.76	0.96	0.385	19.19	1.71	0.184
Cult.TOA	4	0.5522	0.61	0.652	10779	0.69	0.600	25.47	1.12	0.347	10.03	0.89	0.470
PGR.TOA	6	3.1406	3.50	0.003	4837	0.31	0.932	26.78	1.18	0.318	16.32	1.45	0.197
Year.cult.PGR	6	0.5847	0.65	0.689	9338	0.60	0.732	24.95	1.10	0.364	13.90	1.24	0.289
Year.cult.TOA	4	0.5089	0.57	0.687	4665	0.30	0.879	6.93	0.31	0.874	0.29	0.03	0.999
Year.PGR.TOA	6	0.1381	0.15	0.988	10948	0.70	0.649	24.61	1.08	0.373	34.74	3.09	0.006
Cult.PGR.TOA	12	1.0310	1.15	0.323	17513	1.12	0.344	15.46	0.68	0.769	15.36	1.36	0.184
Residual	225	0.8980			15622			22.71			11.25		
Total	287												

(c) Protein content, falling number

Vaalharts

SOV	d.f.	PROTEIN CONTENT m.s.	v.r.	F pr.	FALLING NUMBER m.s.	v.r.	F pr.
REP stratum	3	8.0064	17.26		6886	2.76	
Year	1	95.358	205.62	<.001	1172	0.47	0.49
Cultivar	2	13.346	28.78	<.001	37511	15.04	<.001
PGR	3	0.0369	0.08	0.971	4982	2.00	0.115
TOA	2	0.8287	1.79	0.170	910	0.37	0.695
Year.Cult	2	1.9655	4.24	0.016	24844	9.96	<.001
Year.PGR	3	0.1919	0.41	0.743	740	0.30	0.828
Cult.PGR	6	0.3854	0.83	0.547	2013	0.81	0.565
Year.TOA	2	0.7658	1.65	0.194	1086	0.44	0.648
Cult.TOA	4	0.2340	0.50	0.732	2818	1.13	0.343
PGR.TOA	6	0.1751	0.38	0.893	3608	1.45	0.198
Year.cult.PGR	6	0.4620	1.00	0.429	5869	2.35	0.032
Year.cult.TOA	4	0.5537	1.19	0.314	2675	1.07	0.371
Year.PGR.TOA	6	0.4664	1.01	0.422	1522	0.61	0.722
Cult.PGR.TOA	12	0.2087	0.45	0.941	2131	0.85	0.594
Residual	225	0.4638			2493		
Total	287						

Bethlehem

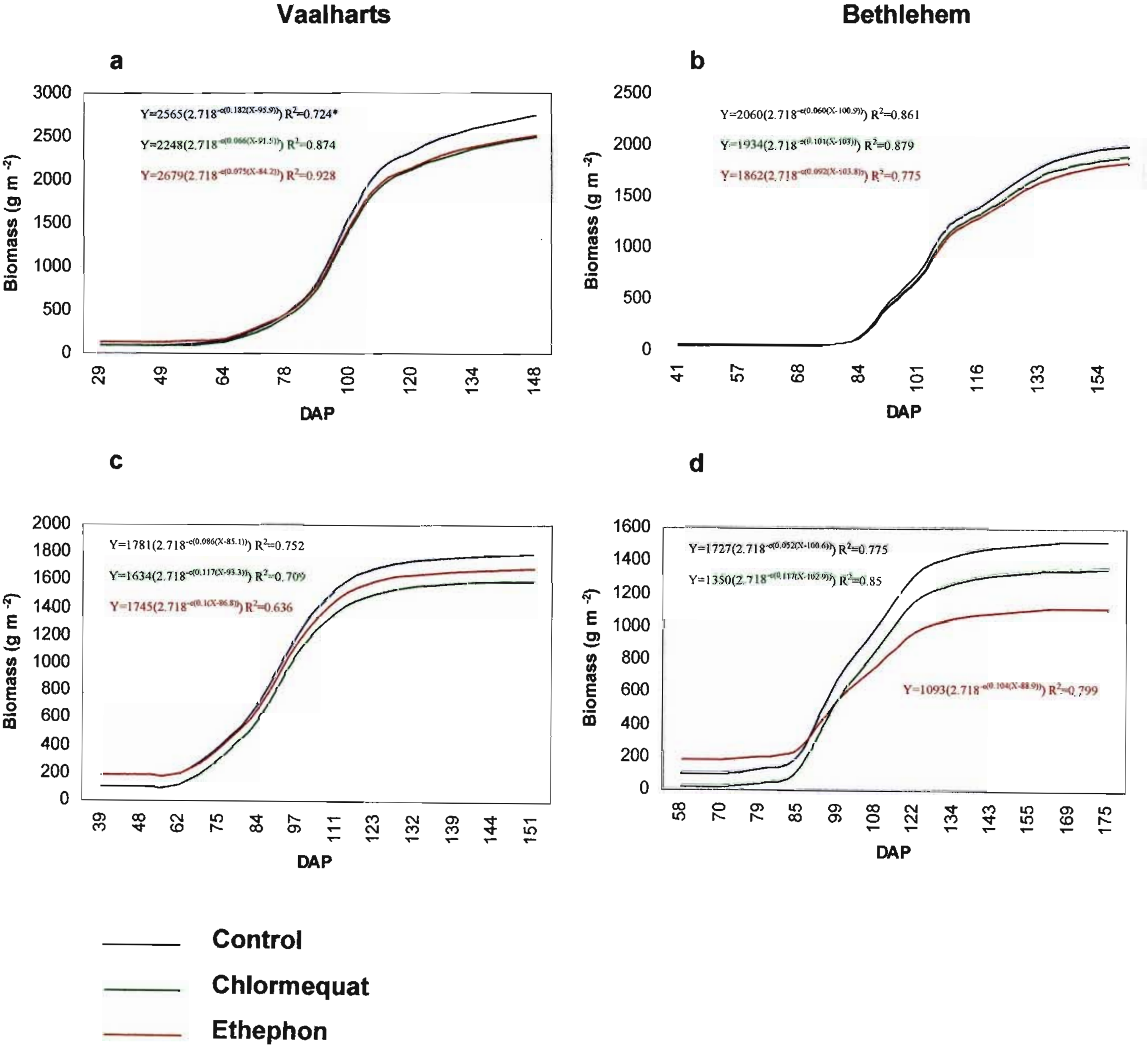
SOV	d.f.	PROTEIN CONTENT m.s.	v.r.	F pr.	FALLING NUMBER m.s.	v.r.	F pr.
REP stratum	3	9.9612	31.87		4106.4	7.48	
Year	1	59.878	191.56	<.001	12482	22.74	<.001
Cultivar	2	22.334	71.45	<.001	4751.6	8.66	<.001
PGR	3	1.9921	6.37	<.001	607.3	1.11	0.347
TOA	2	1.0641	3.40	0.035	1687.6	3.07	0.048
Year.Cult	2	8.5461	27.34	<.001	8629.8	15.72	<.001
Year.PGR	3	0.5101	1.63	0.183	541.8	0.99	0.400
Cult.PGR	6	0.4311	1.38	0.224	287.4	0.52	0.790
Year.TOA	2	0.6162	1.97	0.142	920.5	1.68	0.189
Cult.TOA	4	0.1922	0.61	0.652	664.3	1.21	0.307
PGR.TOA	6	0.6646	2.13	0.051	1422.4	2.59	0.019
Year.cult.PGR	6	0.6739	2.16	0.048	623.4	1.14	0.342
Year.cult.TOA	4	0.3093	0.99	0.414	773.9	1.41	0.232
Year.PGR.TOA	6	0.1677	0.54	0.780	984.2	1.79	0.101
Cult.PGR.TOA	12	0.4475	1.43	0.153	368.7	0.67	0.778
Residual	225	0.3126			548.9		
Total	287						

(d) Preharvest sprouting tolerance (2004)

SOV		Vaalharts			Bethlehem		
	d.f	m.s	v.r	F.pr	m.s	v.r	F.pr
REP stratum	3	1.0160	2.34		0.1519	0.25	
Cultivar	2	57.0286	131.26	<.001	33.8465	55.77	<.001
PGR	3	2.5097	5.78	0.001	1.2871	2.12	0.102
TOA	2	1.0005	2.30	0.105	1.6702	2.75	0.068
Cultivar.PGR	6	0.3416	0.79	0.583	1.1525	1.90	0.088
Cultivar.TOA	4	0.0561	0.13	0.972	2.2935	3.78	0.007
PGR.TOA	6	1.3696	3.15	0.007	0.3732	0.61	0.718
Cultivar.PGR.TOA	12	0.7852	1.81	0.056	0.6162	1.02	0.440
Residual	105	0.4345			0.6069		
Total	143						

APPENDIX 4

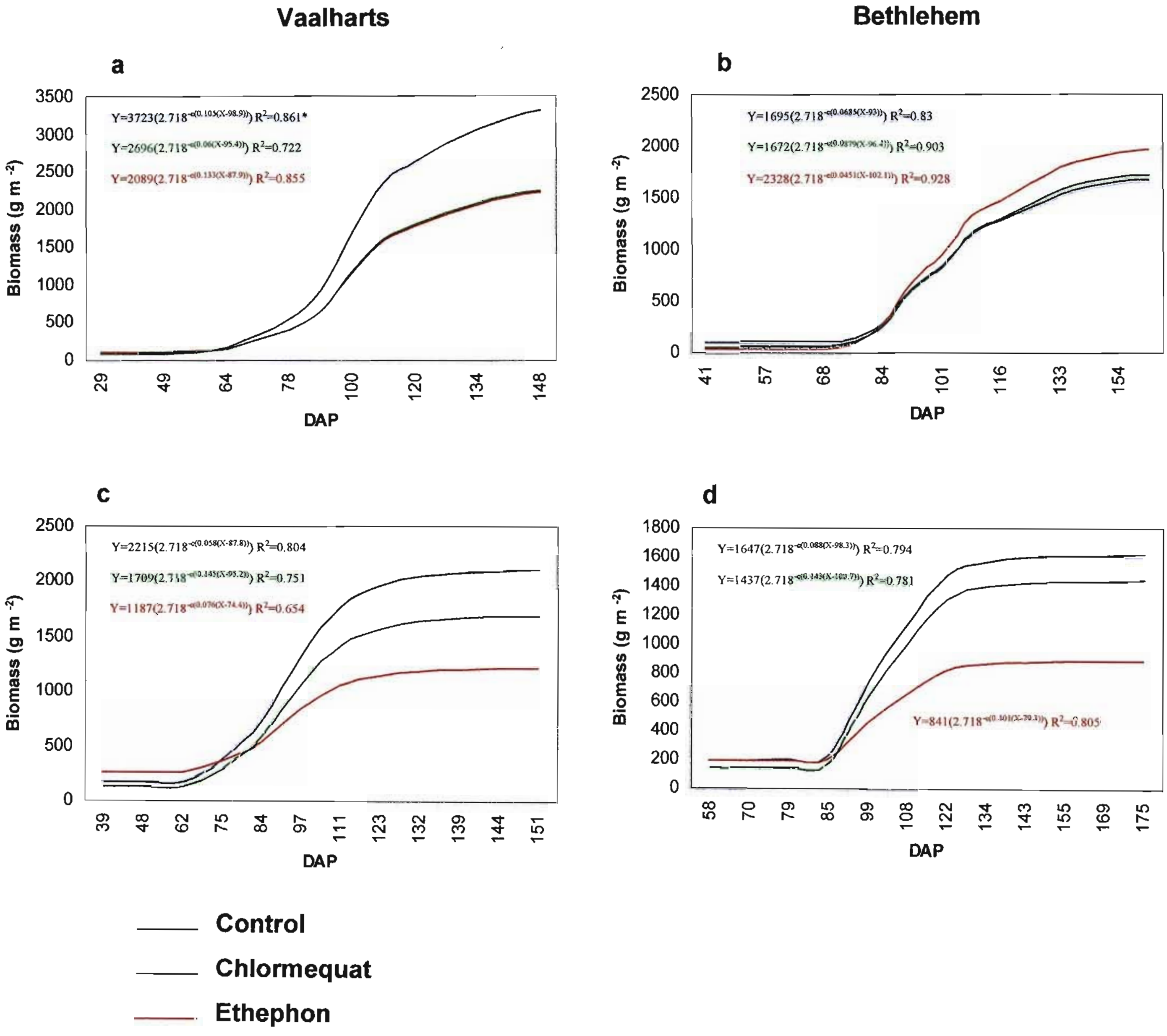
Fitted regression curves for SST 876 in 2003 (a and b) and 2004 (c and d).



* Regression equations correspond to curves of the same colour

Appendix 5

Fitted regression curves for Kariega in 2003 (a and b) and 2004 (c and d).



* Regression equations correspond to curves of the same colour

APPENDIX 6

Abbreviated ANOVA tables for Barley trials at Vaalharts and Bethlehem in 2004.

(a) Yield, plant height and lodging

Vaalharts

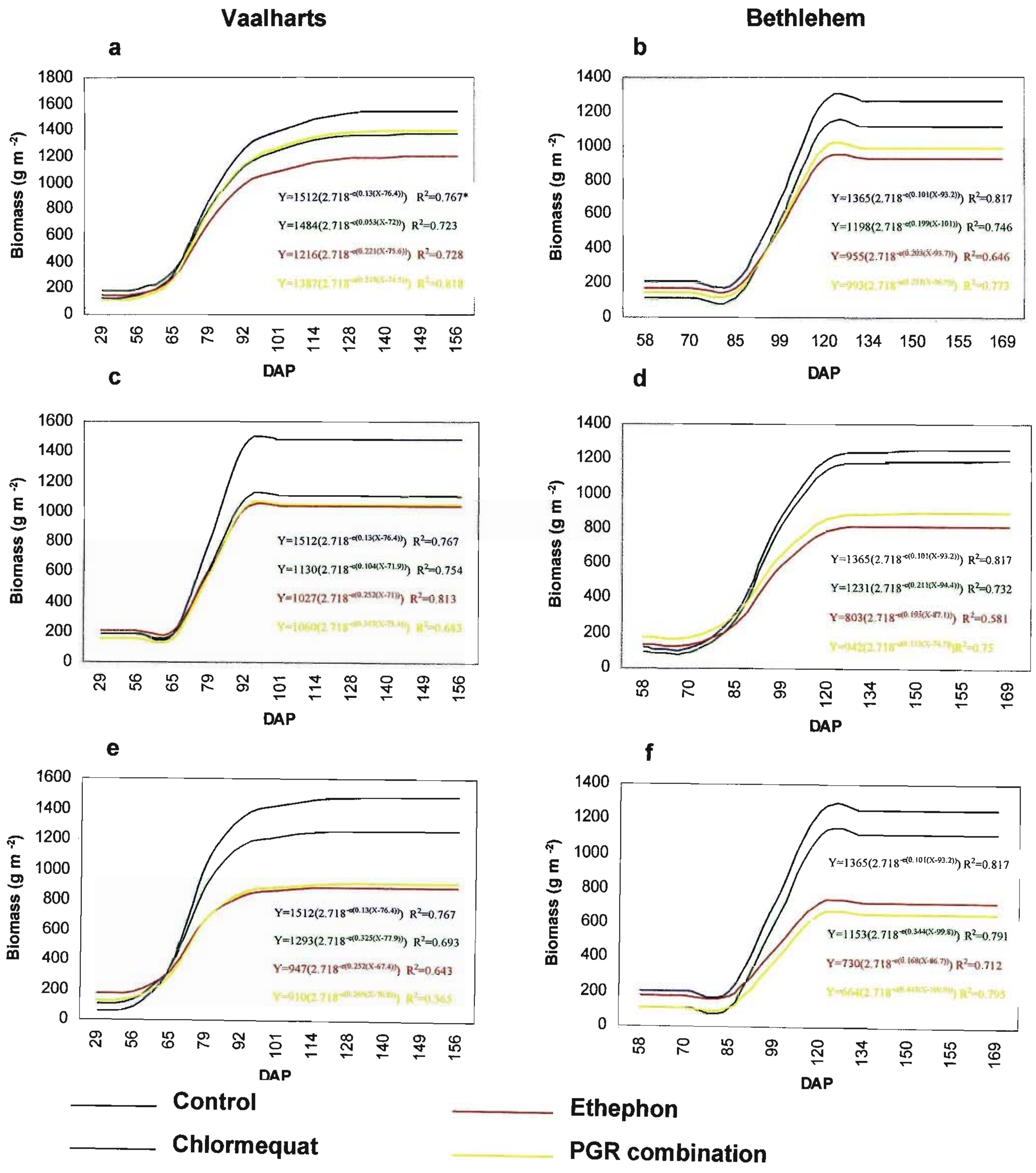
SOV		YIELD			PLANT HEIGHT			LODGING SCORE		
	d.f	m.s.	v.r.	F pr.	m.s.	v.r.	F pr.	m.s.	v.r.	F pr.
Rep stratum	3	11.206	9.34		139.49	6.09		18.661	9.84	
PGR	3	5.193	4.33	0.006	2026.1	88.53	<.001	37.312	19.67	<.001
TOA	2	3.219	2.68	0.073	1436.81	62.78	<.001	59.010	31.10	<.001
Nitrogen	2	28.044	23.37	<.001	115.03	5.03	0.008	41.770	22.02	<.001
PGR.TOA	6	1.758	1.47	0.197	642.25	28.06	<.001	15.733	8.29	<.001
PGR.nigrogen	6	0.436	0.36	0.900	20.23	0.88	0.510	3.274	1.73	0.122
TOA.Nitrogen	4	1.839	1.53	0.198	20.58	0.90	0.467	3.756	1.98	0.103
PGR.TOA.Nitrogen	12	1.972	1.64	0.091	10.36	0.45	0.937	2.926	1.54	0.121
Residual	105	1.200			22.89			1.897		
Total	143									

Bethlehem

SOV		YIELD			PLANT HEIGHT			LODGING SCORE		
	d.f	m.s.	v.r.	F pr.	m.s.	v.r.	F pr.	Df	v.r.	F pr.
Rep stratum	3	29.522	59.28		364.69	17.43				
PGR	3	19.486	39.12	<.001	844.90	40.37	<.001			
TOA	2	11.473	23.04	<.001	377.97	18.06	<.001			
Nitrogen	2	1.0744	2.16	0.121	6.90	0.33	0.720			
PGR.TOA	6	3.5837	7.20	<.001	66.18	3.16	0.007			
PGR.nigrogen	6	0.5279	1.06	0.391	23.90	1.14	0.343			
TOA.Nitrogen	4	0.7786	1.56	0.190	40.09	1.92	0.113			
PGR.TOA.Nitrogen	12	0.4166	0.84	0.613	17.04	0.81	0.635			
Residual	105	0.4981			20.93					
Total	143									

Appendix 7

Fitted regression curves for barley when PGR's were applied at elongation (a and b), flag leaf (c and d) and a split application (e and f).



* Regression equations correspond to curves of the same colour

APPENDIX 8

Abbreviated ANOVA tables for oat trials at Vaalharts and Bethlehem in 2003 and 2004

(a) Yield, hectolitre mass, plant height and lodging (2004)

Vaalharts

SOV		YIELD			HECTOLITRE MASS			PLANT HEIGHT			LODGING SCORE		
	d.f.	m.s.	v.r.	F pr.	m.s.	v.r.	F pr.	m.s.	v.r.	F pr.	m.s.	v.r.	F pr.
Rep stratum	3	0.388	0.20		33.464	5.88		497.76	10.10		23.468	5.84	
Cultivar	2	72.458	36.53	<.001	328.24	57.69	<.001	11798	239.38	<.001	196.24	48.83	<.001
PGR	3	0.941	0.47	0.701	23.354	4.10	0.008	29.76	0.60	0.614	1.124	0.28	0.840
TOA	2	5.934	2.99	0.055	8.429	1.48	0.232	96.38	1.96	0.147	20.145	5.01	0.008
Cultivar.PGR	6	2.781	1.40	0.221	12.270	2.16	0.053	95.51	1.94	0.081	7.491	1.86	0.094
Cultivar.TOA	4	0.562	0.28	0.888	5.658	0.99	0.414	77.81	1.58	0.185	3.584	0.89	0.472
PGR.TOA	6	4.084	2.06	0.064	19.514	3.43	0.004	86.14	1.75	0.117	5.465	1.36	0.238
Cult.PGR.TOA	12	3.251	1.64	0.092	13.445	2.36	0.010	79.14	1.61	0.101	2.249	0.56	0.870
Residual	105	1.984			5.690			49.29			4.019		
Total	143												

Bethlehem

SOV		YIELD			HECTOLITRE MASS			PLANT HEIGHT			LODGING SCORE		
	d.f.	m.s.	v.r.	F pr.	m.s.	v.r.	F pr.	m.s.	v.r.	F pr.	m.s.	v.r.	F pr.
Rep stratum	3	6.3710	12.33		18.885	17.27		352.69	3.33		2.9104	5.04	
Cultivar	2	26.568	51.42	<.001	153.80	140.68	<.001	5061.0	51.71	<.001	2.4708	4.28	0.016
PGR	3	1.5503	3.00	0.034	0.994	0.91	0.439	459.57	4.70	0.004	0.6830	1.18	0.320
TOA	2	0.0412	0.08	0.923	0.498	0.46	0.636	586.55	5.99	0.003	2.00224	3.50	0.034
Cultivar.PGR	6	0.4482	0.87	0.521	1.769	1.62	0.149	85.29	0.87	0.519	0.6382	1.11	0.364
Cultivar.TOA	4	1.8589	3.60	0.009	0.934	0.85	0.494	44.39	0.45	0.770	0.2609	0.45	0.771
PGR.TOA	6	0.1128	0.22	0.970	2.827	2.59	0.022	166.11	1.70	0.129	0.8848	1.53	0.175
Cult.PGR.TOA	12	0.5236	1.01	0.442	1.275	1.17	0.317	154.42	1.58	0.109	0.9912	1.72	0.073
Residual	105	0.5167			1.093			97.86			0.5773		
Total	143												

(b) Yield and hectolitre mass (2003)

Vaalharts

SOV (VH 2003)		YIELD			HECTOLITRE MASS		
	d.f.	m.s.	v.r.	F pr.	m.s.	v.r.	F pr.
Rep stratum	2	0.2205	1.80		0.401	0.32	
Cultivar	2	31.083	253.40	<.001	94.901	76.54	<.001
PGR	2	0.0258	0.21	0.811	1.784	1.44	0.247
TOA	2	0.0692	0.56	0.572	2.663	2.15	0.127
Cultivar.PGR	4	0.0367	0.30	0.877	0.533	0.43	0.787
Cultivar.TOA	4	0.1333	1.09	0.373	0.319	0.26	0.904
PGR.TOA	4	0.1464	1.19	0.325	0.226	0.18	0.946
Cultivar.PGR.TOA	8	0.2125	1.73	0.113	0.748	0.60	0.771
Residual	52	0.1227			1.240		
Total	80						

Bethlehem

SOV (VH 2004)		YIELD			HECTOLITRE MASS		
	d.f.	m.s.	v.r.	F pr.	m.s.	v.r.	F pr.
Rep stratum	2	0.5072	1.44		5.809	3.50	
Cultivar	2	57.125	162.30	<.001	48.997	29.54	<.001
PGR	2	1.5949	4.53	0.015	5.343	3.22	0.048
TOA	2	0.0445	0.13	0.882	0.365	0.22	0.803
Cultivar.PGR	4	1.1520	3.27	0.018	1.546	0.93	0.453
Cultivar.TOA	4	0.6055	1.72	0.160	0.841	0.51	0.731
PGR.TOA	4	0.1940	0.55	0.699	2.112	1.27	0.292
Cultivar.PGR.TOA	8	0.4643	1.32	0.255	2.961	1.79	0.101
Residual	52	0.3520			1.659		
Total	80						