Developing nitrogen fertiliser management strategies for wheat (*Triticum aestivum*) under conservation agriculture practices within the Western Cape

by

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DECLARATION

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Abstract

Nitrogen (N) is one of the most limiting plant nutrients. Supplying enough N to growing crops is one of the most critical factors influencing wheat production. There has been a strong drive towards conservation agriculture in South Africa, especially within the Western Cape Province. Conservation agriculture brings forth changes in soil physical, chemical and biological properties that influence the plant-available soil mineral N content, specifically an increased potentially mineralisable N content. The aim of this study was to do a complete analysis of the effect that different preceding crops, N rates, forms of N, and timing of N application would have on the yield, yield components and protein content of wheat, whilst monitoring the effect of different N rates on the soil mineral N concentration throughout the growing season. The first objective of the study was to determine the effect of different fertiliser rates on the grain yield, selected yield components, quality parameters and N use efficiency. The second objective was to determine the effect of a late-season foliar N application on the yield and grain protein content of the wheat crop. The third objective was to test the effect of different N sources on crop growth, yield and quality of wheat. This study was conducted during 2016 and 2017 on nine sites within the dryland grain producing areas of the Western Cape. The trial was subdivided into two separate studies: i) topdressed N rates with or without foliar applications of N and ii) N sources at topdress. Increasing topdress N rates had a less profound effect on crop yields than expected, where most of the sites in both years showed no increase ($P > 0.05$) in yield with increasing topdress N rate. Five of the research sites in Year 1 and all the research sites in Year 2 showed no response ($P > 0.05$) in the number of ear-bearing tillers, as influenced by increasing topdress N rates. An increase ($P < 0.05$) in grain protein content with the increasing topdress N rates was recorded at all the research sites in Year 1. The N use efficiency of wheat decreased ($P < 0.05$) with increasing topdress N rates in both years. Foliar N application at post-anthesis had limited success in increasing yield and grain protein content of wheat. No profound effect of fertiliser N source on the yield, yield components or quality of wheat was recorded. After doing a complete analysis of the N requirement of wheat produced under conservation agriculture practices and dryland conditions in the Western Cape Province, it was apparent that fertiliser N recommendations will possibly have to be adjusted. The N guidelines to produce wheat lead to over-fertilisation in some areas, which may, in turn, lead to environmental pollution and economic losses. Determining the optimal N source might entail choosing the most cost-effective and accessible source.

Uitreksel

Stikstof (N) is een van die mees beperkende plant voedingstowwe. Die voorsiening van genoeg N aan groeiende gewasse is een van die mees kritiese faktore wat koringproduksie beïnvloed. Daar is ‘n sterk drywing na bewaringslandbou in Suid-Afrika, veral in die Wes-Kaap. Bewaringslandbou lei tot veranderinge in die fisiese-, chemise- en biologiese eienskappe van die grond wat die plant-beskikbare grond N beïnvloed, veral ‘n verhoging in potensieël mineraliseerbare N. Die mikpunt van hierdie studie was om ‘n volledige analise te doen oor die effek wat verskillende rotasiestelsels, N peile, N bronne en tydsberekening van N toediening sal hê op die opbrengs, opbrengskomponente en proteininhoud van koring, terwyl die effek van verskillende N peile op grond minerale N-inhoud regdeur die groeiseisoen gemonitor was. Die eerste doelwit van die studie was om die effek van verskillende kunsmis peile op die graanopbrengs, geselekteerde opbrengskomponente, gehalteparameters en N-verbruiksdoeltreffendheid te bepaal. Die tweede doelwit was om die effek van 'n laatseisoen blaar N toediening op die opbrengs en graan proteïen inhoud van die koring gewas te bepaal. Die derde doelwit was om die effek van verskillende N bronne op die groei-, opbrengs- en kwaliteit van koring te bepaal. Hierdie studie is gedurende 2016 en 2017 op nege lokaliteite in die droëland graanproduserende gebiede van die Wes-Kaap uitgevoer. Die proef is onderverdeel in twee afsonderlike studies: i) topbemestings N peile met of sonder blaaraanvullings van N en ii) verskillende N bronne as topbemesting. Die verhoging van topbemestingspeile het 'n kleiner uitwerking op gewasopbrengste gehad as wat verwag is, waar die meeste van die lokaliteite in beide jare geen toename ($P > 0,05$) in opbrengs, met toenemende topbemestingspeile getoon het nie. Vyf van die lokaliteite in jaar 1 en al die lokaliteite in jaar 2 het geen reaksie ($P > 0.05$) in die aantal aardraende halms, soos beïnvloed deur vehogende N topbemestingspeile, getoon nie. 'n Toename ($P < 0,05$) in graan proteïeninhoud met toenemende N topbemestingspeile is by al die lokaliteite in jaar 1 aangeteken. Die N-verbruiksdoeltreffendheid van die koring het afgeneem ($P < 0.05$) met toenemende N topbemestingspeile in albei jare. Die toediening van laat-seisoen vloeibare N het beperkte sukses gehad om die opbrengs en graan proteïeninhoud van koring te verhoog. Geen diepgaande effek van kunsmis N-bron op die opbrengs, opbrengskomponente of koringkwaliteit is aangeteken nie. Nadat 'n volledige analise van die N-vereiste van koring wat onder bewaringslandboupraktyke en droëlandtoestande in die Wes-Kaap geproduseer word gedoen is, was dit duidelik dat die aanbevelings van kunsmis N moontlik aangepas moet word. Die N-riglyne vir koringproduksie kan lei tot moontlike oorbemesting in sommige gebiede, wat op sy beurt kan lei tot omgewingsbesoedeling en ekonomiese verliese. Om die optimale N-bron te bepaal kan neerkom op die kies van die mees koste-effektiewe en toeganklike bron.

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1 Introduction

1.1 Background

Nitrogen (N) is one of the most limiting plant nutrients (Provin and Hossner, 2001; Zhu et al., 2013). Supplying adequate N to growing crops is one of the most critical factors influencing crop production (Jansson and Persson, 1982; Shober, 2015; Sinclair et al., 1989). The link between N and optimal crop growth has led to the green revolution, which averted a global food crisis when synthetically produced fertilisers became commercially available (Stein and Klotz, 2016). Before the use of the Haber-Bosch process (industrial fixation of N_2 into NH_3) was implemented in 1909, mostly all the reactive N in the biosphere was controlled by microorganisms (Stein and Klotz, 2016). Currently, the Haber-Bosch process is responsible for feeding approximately 48% of the global population (Stein and Klotz, 2016). Although the green revolution has been essential for global food security, it has, in some cases, come at a high environmental cost, such as pollution and degradation of soils, pollution of groundwater and increased greenhouse gas emissions which contribute to climate change – currently one of the world´s biggest problems (Cameron et al., 2013; Shober, 2015; Stein and Klotz, 2016).

The global amount of N fertilisers used annually is showing an increasing trend. The world uses approximately 80 million tons of N annually (Gibbon, 2012). That equates to a 100-fold increase over the past 100 years (Ladha et al., 2005). The projected annual application of N for the Year 2030 is 180 million tons (Grahmann et al., 2014). That means that the N fertiliser usage, worldwide, will have increased with 125% over a 40-year period. In South Africa alone, the amount of fertiliser used annually has increased from 1.2 million tons in 1960 to 2.2 million tons in 2017 (FERTASA, 2016a). That amounts to an approximate N fertiliser use increase of 55% in roughly 50 years.

Apart from driving increased crop production, another reason for N fertiliser applications being so high is N losses from cultivated fields (Cheng et al., 2008; Dang et al., 2009; Miransari and Mackenzie, 2011; Wang et al., 2007). The worldwide N use efficiency averages at 33% for cereal crops, which means there is potential for improvement (Grahmann et al., 2014). The loss of N from cultivated fields not only leads to pollution of air and water bodies, but is also a significant economic loss for producers. Therefore, it is important to establish optimal and effective N management programmes that will increase food production, lower environmental impact and be economically attractive to farmers (Jansson and Persson, 1982; Shober, 2015; Sinclair et al., 1989).

For the past few decades, it was considered more profitable to produce wheat from monoculture cropping systems. However, in the 1990s agriculture in South Africa was deregulated and marketing boards abolished, preventing producers to produce wheat at internationally competitive prices (Hoffmann, 2001). Furthermore, wheat yields declined through time and it became well-known that producing wheat in monoculture is not sustainable due to increased pest and disease pressure. In order to protect themselves from the dangers of monocropping, producers adopted crop rotation systems, thereby diversifying their crop production and minimising their exposure risks (Basson et al., 2017). Ryegrass started to build up herbicide resistance, pushing producers towards the adoption of minimum-tillage and the application of pre-emergent herbicides (Basson et al., 2017).

Therefore, the need for Conservation Agriculture (CA) and drive toward better soil health and consequently healthier microbial communities arises. There has been a strong drive towards CA in South Africa, especially within the Western Cape Province (Basson et al., 2017). The Western Cape has a Mediterranean-type climate, which means that most of the annual precipitation occurs during the cool months. Since wheat (*Triticum aestivum*) is a cool-season crop which can be produced under dryland conditions, the Swartland, Overberg and southern Cape regions within the Western Cape are amongst the most important wheat producing areas in the country (Basson et al., 2017). Wheat is produced in rotation with other crops adapted to the climate, such as lucerne (*Medicago sativa*), annual medics (*M. trancatula* and *M. polymorpha*), canola (*Brassica napus*), barley (*Hordeum vulgare*) and oats (*Avena sativa*).

1.2 Nitrogen fertilisation programme

Projections estimate that the global population will increase to 9.3 billion people by the Year 2050. In order to feed the global population an estimated increase of 50 to 70% in cereal production will be necessary (Ladha et al., 2005). If the efficiency of crops to utilise applied N is not improved, it will lead to a major increase in globally applied N. When it comes to improving N use efficiency, improving the synchronisation between N supply and crop demand is an important step in the right direction.

To develop an effective N fertilisation programme, it is necessary to understand the N requirement of a wheat plant. When N is applied in excessive amounts, the wheat plant is susceptible to lodging, disease and a consequent decrease in yield (Brown et al., 2005). Insufficient N application to wheat plants, on the other hand, results in decreased yield and profit compared to adequately fertilised wheat. Once an effective programme is established it will be possible to supply the wheat plant with adequate amounts of N during the most critical growth stages of the plant (Labuschagne and Langenhoven, 2012). Understanding the effect of N availability during the critical growth stages of the wheat plant is important when creating an optimal N application programme. Maximum N uptake by the wheat plant starts with tillering and ends when heading starts (stem elongation) (Abbate et al., 1995; Demotes-Mainard et al., 1999).

The application of N until the booting phase (Feekes' growth stage 10) leads to an increase in grain yield (Labuschagne and Langenhoven, 2012). There is also minimal risk of N leaching when applying fertiliser after Feekes' growth stage 5, due to the extensive root systems of the plants at this stage. Earlier applications of N may lead to increased tiller production, a larger leaf area, and therefore a higher production potential (Labuschagne and Langenhoven, 2012).

Any applications after Feekes' growth stage 10, at or after flowering, will not result in yield increases. Foliar applications of N after the flowering stage, can however lead to an increase in grain protein content (Bly and Woodard, 2003; Brown and Petrie, 2006; Rawluk et al., 2000). The producer's aim should be to ensure that the plant has enough N available during the early growth stages (Feekes' stages 5 till 10) in order to ensure a higher yield potential, as well as enough N during later growth stages (Feekes' stages 10 and later) to keep grain protein intact.

Before a fertilisation programme can be developed, certain information should be collected, i.e. N required for a certain yield potential, efficiency of the fertilisation, amount of residual soil nitrate (carried over from the previous season) and the amount of potentially mineralisable N (PMN) (USDA Natural Resources Conservation Service, 2014).

Firstly, the rate of N to satisfy crop demand should be determined. The next step is to determine the N contribution from the soil in the form of residual nitrate and/or PMN from soil organic matter (SOM). The term PMN is defined as the total fraction of residual N that can be converted to plant available (or mineral) forms (USDA Natural Resources Conservation Service, 2014). PMN is usually a function of SOM. Thus, it can be anticipated that the higher the SOM content of a soil, the higher the PMN of that soil will be. In conventional tillage systems, where plant residues are incorporated back into the soil, a typical acceleration of SOM and N mineralisation is common (Grahmann et al., 2014). When residues are left on the soil surface, which would be the case of CA systems in the Western Cape, they are less susceptible to microbial breakdown, and thus in CA it is common to find soils with a higher SOM and N fraction (Grahmann et al., 2014).

The determination of PMN content in soil gives a rather accurate estimate of the potential plant available N in the soil (USDA Natural Resources Conservation Service, 2014). It has been found that different cropping systems leads to varying amounts of residual N in the soil and consequently to varying mineralisation potentials (Labuschagne and Langenhoven, 2012). For example, when rotating wheat with annual medics, a farmer can save up to 50% on fertiliser costs when compared to the standard application in conventional systems (Labuschagne and Langenhoven, 2012). When wheat is cultivated in monoculture systems it is dependent on applied fertiliser and the soil shows little signs of residual N.

The third step in setting up the optimal N fertilisation programme is to subtract the soil mineral N from the N requirement of the crop. In the final step the efficiency of the fertiliser is accounted for. After all the N contributions (mainly from the soil) are subtracted from the required amount of N, the N requirement is divided by the fertiliser effectiveness and this will result in the amount of fertiliser necessary to achieve the desired yield.

Equation 1 shows how to calculate the amount of N fertiliser needed to achieve a specific yield goal:

$$\boldsymbol{N\ Rate} = \frac{\boldsymbol{N\ requirement\ (kg\ ha^{-1}) - N\ contributions\ (kg\ ha^{-1})}}{\boldsymbol{N\ fertiliser\ efficiency}\ (\%)}\ \boldsymbol{x\ 100}$$

(Equation 1)

Once the required amount of N has been determined, the best timing of application should be considered. The general consensus suggests that the best way to apply N fertiliser is by using split applications where some N (20 to 30%) is applied during planting and most of the N (60 to 80%) is applied between Feekes' growth stages 5 to 10. An additional foliar application of soluble urea to the wheat plant after Feekes' growth stage 10 can be used to increase the protein content of the grain. The desired protein content of 12%, to qualify for grade B1 in terms of grain protein content in South Africa, can only be achieved when sufficient N is available to the wheat plant late in the growing season.

When a N fertilisation programme is in place, a decision should be made on which source of fertiliser N to use. Various sources of N are commercially available and these sources differ in various properties (Grahmann et al., 2014). The form of N and N concentration are important factors to consider when the choice of topdressed fertiliser source is made. The chemical composition of fertilisers, in terms of additional elements is also an important factor to consider. Crop yields normally increases with the addition of N fertilisers, but may level off when other elements, like sulphur (S) are deficient in the soil profile (Salvagiotti et al., 2009). This may be remedied by making sure an adequate amount of the limiting nutrient is available (Aulakh and

Malhi, 2004) through addition of the deficient nutrient to the existing fertiliser programme. Certain sources, such as ammonium sulphate (AMS) and limestone ammonium nitrate with added sulphur (LAN + S), contain both N and S in their composition. It is believed that S addition to S deficient environments will lead to higher N uptake (Salvagiotti et al., 2009) which in turn might lead to an increase in yield and grain protein (Jones and Olson-Rutz, 2012).

1.3 Problem statement

The prevailing climate and soil characteristics are contributors toward problems associated with N deficiencies in wheat cultivation. In areas with high annual rainfall one would commonly find that nitrate (mobile form of N) is leached out of the soil profile during the wet winter months. In the shallow soils of the Swartland and southern Cape the winter rains can cause N losses of 50 to 60% of the applied fertiliser (Labuschagne and Langenhoven, 2012). Therefore, it is important to do soil nitrate analysis to determine the amount of leachable nitrate in the soil as well as carried over N from the previous season and make effective N fertiliser recommendations accordingly.

Soil characteristics may influence the behaviour of both applied and residual N by the end of the season. In lighter textured soils (high sand fraction) the potential leaching is higher than in soils with high clay content. Therefore, soil particle size distribution should be determined, and N recommendations be made accordingly. Producers will have to use the best N source for their specific environmental and soil conditions, in order to reduce volatilisation and leaching losses to a minimum (Grahmann et al., 2014). In sandy soils the use of N fertilisers containing different sources of N i.e. ammonium (low leaching potential) in combination with nitrate (immediately available but high leaching potential) may be a remedy to try and mitigate the high leaching potential, whilst offering the crop enough available N.

Conservation agriculture changes soil physical, chemical and biological properties as a result of amongst others minimum-tillage (Grahmann et al., 2014). Soil organic matter is particularly affected and may build up, but distribution is highly limited to the soil surface (Swanepoel et al., 2017). The SOM influences the plant-available soil mineral N content, specifically leading to an increase in potentially mineralisable N (described in section 2.2.2).

The problem with the increase in CA adoption is that most N application programmes are still using guidelines which were developed under and adopted from conventional production systems. This does not account for the potential increase in PMN in the soil; therefore, the guidelines may have to be revised and amended. Each individual system where N application takes place should be managed differently, because of all the role-playing factors contributing to the differences in N use efficiency of the wheat plants (Labuschagne and Langenhoven, 2012). Nitrogen fertilisation programmes under CA needs to be adjusted, as N fertilisation has different effects on crops in CA systems (Grahmann et al., 2014).

The effect of late-season N applications on grain yield and protein content is relatively untested under dryland conditions in the Western Cape and the results of this study could be indicative as to whether late season N applications are feasible.

1.4 Aim and objectives

The aim of this study was to do a complete analysis of the effect that different preceding crops, N rates, forms of N, and timing of N application would have on the yield, yield components and protein content of wheat, whilst monitoring the effect of different N rates on the soil mineral N concentration throughout the growing season.

1. The first objective of the study was to determine the effect of different fertiliser rates on the grain yield, selected yield components, quality parameters and N use efficiency of the wheat crop.
2. The second objective was to determine the effect of a late-season foliar N application, in the form of urea ammonium nitrate (UAN), on the yield and grain protein content of the wheat crop.
3. The third objective was to test the effect of different N sources on crop growth, yield and quality of wheat.

2 Literature review

2.1 Characteristics of conservation agriculture (CA)

2.1.1 Overview of conservation agriculture

Historically, conventional tillage practices formed part of most crop farming systems. However, through time, soils became significantly degraded under these practices (Hobbs, 2007). Conventional tillage practices can be defined as the inversion of the soil layers by means of ploughing followed by other implements, used to flatten the soil surface. This leaves the soil bare and exposed to the environment, leading to potential soil erosion and the drying out of the soil profile. The continuous intensification of tillage practices during the last few decades has led to an estimated global loss of 60 to 90 pentagram (10^{15} g) of soil organic matter (Prasad et al., 2015). Conservation tillage practices were consequently included in the management of farms in an attempt to combat soil degradation (Hobbs, 2007). No-tillage is a method of directly planting crops with minimum soil disturbance (Pittelkow et al., 2014) and forms part of the three crop management principles of conservation agriculture (CA) (Gibbon, 2012; Hobbs et al., 2008; Pittelkow et al., 2014). No-tillage is considered as a transitional step towards CA (Gibbon, 2012).

For decades, wheat was grown in monoculture systems, since it is such a profitable cash crop. This lack of rotation with other crops led to the development of a ryegrass problem in wheat cropping systems. The burning of stubble and the removal thereof by grazing or baling, as was the case in most wheat monoculture systems, also left the soil bare and exposed to erosion. One of the biggest global challenges of our time is ensuring a sustainable future for the growing world population with minimal environmental impacts, under very variable climatic conditions (Foley et al., 2011; Godfray and Garnett, 2014; Lobell et al., 2008; Pittelkow et al., 2014; Tilman et al., 2011). The three crop management principles of CA are minimal soil disturbance, insuring permanent or semi-permanent (at least 30% after planting) soil cover and using crop rotations in a sustainable, yet productive way (Gibbon, 2012; Hobbs et al., 2008; Pittelkow et al., 2014).

Conservation agriculture is still, like any new method of change, a debated subject with some debating its effect on crop yields (Brouder and Gomez-Macpherson, 2014; Giller et al., 2009; Rusinamhodzi et al., 2011) and others debating the applicability thereof in different environments (Giller et al., 2011; Kassam et al., 2012; Stevenson et al., 2014; Sumberg et al., 2012). In a meta-analyses done by Pittelkow et al., (2014) it was found that no-tillage reduces yield globally. However, when no-tillage practices are used in conjunction with the other two principles of CA it may significantly increase the productivity of dryland crops in dryer climates (Pittelkow et al., 2014). Globally, the adoption of no-tillage has occurred over 125 million hectares with varying degrees of application for the other two CA principles (Friedrich et al., 2015; Gibbon, 2012). Over the last two decades there has been an increase in the adoption of CA practices in South Africa, with the Western Cape Province having the highest adoption rate (Basson et al., 2017).

Mostly, the economic benefits of CA is driven by cost reductions, rather than increased yields (Erenstein et al., 2012), and that may be the biggest limitation surrounding the adoption of CA, especially for poorer farmers (Corbeels et al., 2014; Stevenson et al., 2014). Pittelkow et al. (2014) concluded their meta-analyses by highlighting the importance of implementing at least one, if not both principles of CA in addition to no-tillage, to ensure optimal economic benefits within dryland cropping systems in dry climates.

The adoption of no-tillage, by means of seed-drilling, ensures better placement of fertiliser relative to seed, and higher N use efficiency is to be expected. With a better N use efficiency, less N is lost during the growing season and consequently less N must be applied, making CA and the usage of a seed drill a beneficial practice. By using leguminous crops in rotation with cash crops, the fertiliser rate required for optimal yields may be reduced (Corsi et al., 2010). An immediate effect that may occur under CA is the improved capture of rainfall through better infiltration and less evaporation from the soil surface (Corsi et al., 2010; Pittelkow et al., 2014). This is especially important in drier regions, like sub-Saharan African, where proper water management may result in bigger economic benefits (Pittelkow et al., 2014). Corsi et al. (2010) found that an increase in soil carbon © is possible under CA practices. This increase of soil C, the retaining of stubble and consequent increase in microbial activity, associated with CA, may lead to a reduction in N application demands in dryland cropping systems.

Due to all the advantageous physical, chemical and biological changes in soils under CA crop yields could be increased, whilst soil and water resources are conserved and energy usage is potentially reduced (Gotosa et al., 2011). CA can also reduce the cost of production, save time, increase yield through planting on time, reduce diseases and pests through stimulation of biological diversity, and reduce greenhouse gas emissions (Gotosa et al., 2011).

The successfully implementation of CA can be difficult, due to suitable equipment not being readily available, but local manufacturers are making advances in the design and production of seed drills and enabling farmers to implement the technology worldwide. To meet growing population demands in the next decade, agriculture needs to produce more food on less arable land in such a way as not to have a negative impact on the environment. This will be a challenge for the whole agricultural community, from scientists, to producers. The promotion and adoption of CA may help to contribute toward this goal (Gotosa et al., 2011).

2.1.1.1 Physical effects on the soil

In successfully implemented CA systems an increase in water-use efficiency is commonly achieved, which leads to reduced runoff, better infiltration and evidently more plant available water in the soil profile throughout the growing period (Hobbs et al., 2008). Conservation agriculture improves productivity through improved water infiltration and reduced erosion, improved soil aggregates and reduced compaction, temperature moderation and weed suppression (Hobbs, 2007). During fallow periods the slower nitrification rate under no-tillage could reduce the nitrate leaching potential of a soil (Grahmann et al., 2014).

2.1.1.2 Chemical effects on the soil

The potential mineralisable N of soils under CA, that experienced an increase in soil organic matter, tends to be higher than those of soils under conventional farming practices. This might lead to a decrease in N fertiliser rate requirements. Nitrogen loss through volatilisation are commonly higher in soils that retain stubble or crop residue (Jones et al., 2013). Losses may be higher under these conditions since crop residues promote higher enzyme activity, create a barrier that prevents urea from reaching the soil and keeps the soil surface moist for longer. Therefore, it may be considered that CA increases the risk of ammonia volatilisation, especially under warm conditions.

2.1.1.3 Biological effects on the soil

In CA the mulch on the soil surface promotes higher stability of soil aggregates and this leads to increased microbial activity (Hobbs, 2007). The higher concentration of soil microorganisms promotes a higher population of beneficial biological agents and consequently leads to a higher degree of antagonistic effects on soil pathogens (Hobbs, 2007). The soil organic C content can be used as a measure of soil health and potential, seeing as it is linked to better cation exchange capacities and thus nutrient retention of soils. The soil organic C can be modified through agricultural land use (like tillage) and may be negatively influenced by continuous conventional tillage (Corsi et al., 2010). When compared with soils that have been continuously tilled, it was found that no-tillage may lead to a higher production of surface soil organic C (Hobbs, 2007).

A clear trend can be seen when comparing the soil organic C content of soils cultivated under conventional tillage practices and no-tillage (Table 2.1). The results from trials done in Brazil, during 1997 and 1998, showed that the soil organic C content of soils under no-tillage was higher than soils cultivated conventionally, irrespective of the crop rotations used (Hobbs, 2007).

Table 2.1 Total soil C under different crop rotations, using conventional tillage and no-tillage practices on an oxisol in Brazil. Table adopted from Hobbs (2007).

Crop Rotations	Total soil organic C (mg g^{-1})	
	Conventional tillage	No-tillage
Depth: 0-50 mm		
Wheat after soybean	15.3	20.6
Wheat after maize	14.7	22.4
Wheat after cotton	13.9	20.6
Depth: 50-100 mm		
Wheat after soybean	13.4	17.3
Wheat after maize	15.3	19.0
Wheat after cotton	13.2	19.7
Depth: 100-200 mm		
Wheat after soybean	14.4	16.3
Wheat after maize	15.6	17.2
Wheat after cotton	13.8	16.2

In studies, conducted in Zimbabwe, it was found that the prolonged use of CA led to improved crop yields and this improvement was attributed to the rise of soil organic C in those soils (Gotosa et al., 2011). These increases in soil organic C can be attributed to higher residue retention and reduced soil disturbance (Gotosa et al., 2011). Under high residue retention, where residues accumulate in the soil, the C fixed in crop by photosynthesis is potentially available as net gain of C in the soil (Corsi et al., 2010).

The lower soil organic C under conventional tillage is believed to be a result of high soil organic matter decomposition by the disruption of aggregates (Gotosa et al., 2011). Some authors report significant increases in advantageous microbes and soil organic C soon after switching from conventional tillage to CA, but full advantages are usually seen only when CA is well established within a system (Corsi et al., 2010). The increase in soil organic C under CA when compared to conventional tillage is usually more pronounced in fields that have been cultivated under CA for more than 8 years (Gotosa et al., 2011). Soils that have been degraded and are low in soil organic C content can still be restored to a healthier, more sustainable environment by applying the three principles of CA (Corsi et al., 2010). Rotation cycles with different crops which make use of crops with varying root depths insure that soil organic C gets distributed throughout the whole soil profile (Corsi et al., 2010).

There are other ways to quantify soil health and potential, other than using soil organic C. One such way is by measuring the particulate organic matter of a soil. Particulate organic matter can also be described as the macro-organic fraction of the soil, and range in size from 0.053 mm to 2 mm. This fraction commonly includes decomposed plant material other forms of organic matter and residue. Systems under CA commonly experience a rise in the particulate organic matter of soils, especially in the topsoil layers of a profile (Figure 2.1).

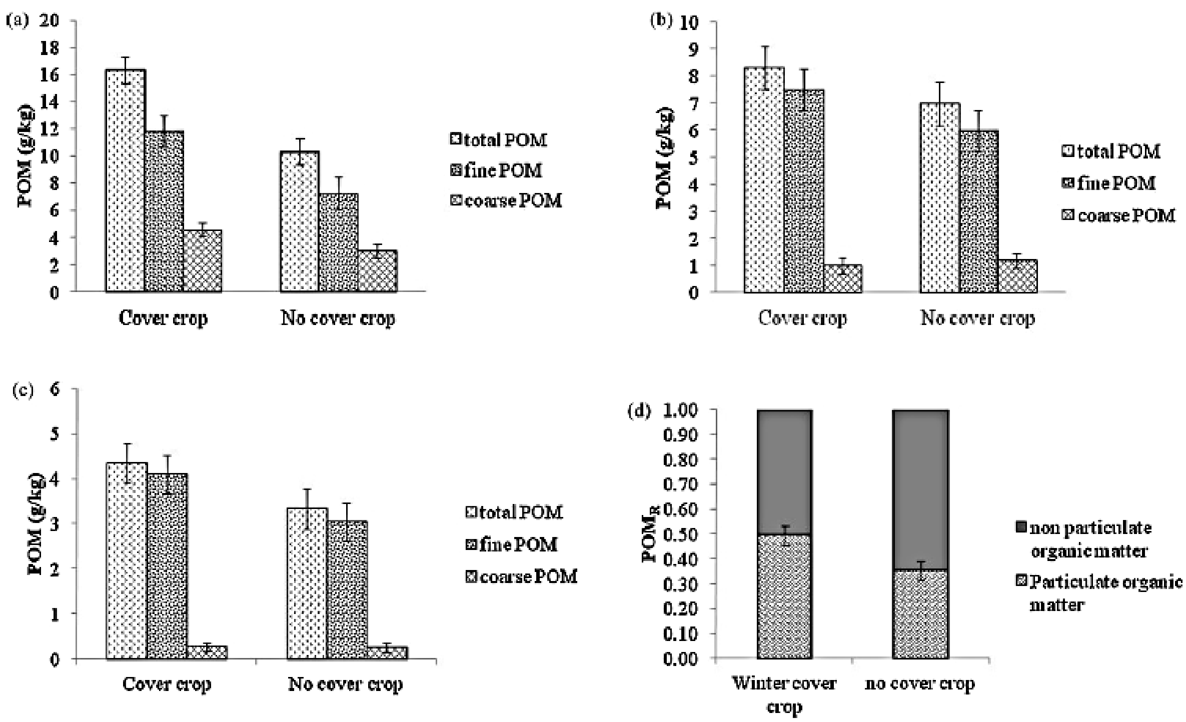


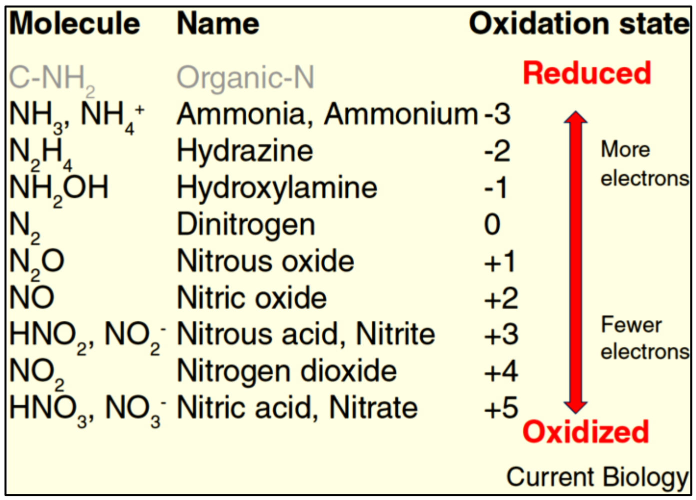
Figure 2.1 Winter cover cropping effects on particulate organic matter. Soil depths as follows: a) 0-5 cm; b) 5-20 cm; c) 20-50 cm. d) Winter cover crop effect on relative portions of particulate organic matter at 0-5 cm depth. Data was collected on a Haplic Cambisol after four years of maize–oat and maize–grazing vetch rotations in South Africa (Dube et al., 2012).

Soil microbes also play a vital role in organic matter mineralisation, mobilisation and immobilisation, i.e. soil nutrient availability (Grahmann et al., 2014). In addition to the enhanced microbial activity, another advantage of CA is increased earthworm activity. The increased earthworm population may lead to a natural tillage effect of soils (Hobbs, 2007).

2.2 The nitrogen (N) cycle

2.2.1 Major processes involved in the N cycle

Traditionally the N cycle is divided into three processes: N_2 fixation/ammonification, nitrification and denitrification (Stein and Klotz, 2016). Although N comes in many forms (Figure 2.2), only nitrate and ammonium are 'plant-available' (Jones et al., 2013; Provin and Hossner, 2001).



Molecule	Name	Oxidation state
$C\text{-}NH_2$	Organic-N	Reduced
NH_3, NH_4^+	Ammonia, Ammonium	-3
N_2H_4	Hydrazine	-2
NH_2OH	Hydroxylamine	-1
N_2	Dinitrogen	0
N_2O	Nitrous oxide	+1
NO	Nitric oxide	+2
HNO_2, NO_2^-	Nitrous acid, Nitrite	+3
NO_2	Nitrogen dioxide	+4
HNO_3, NO_3^-	Nitric acid, Nitrate	+5
		Oxidized

Figure 2.2 The N cycle intermediates, representing nine oxidisation states (Stein and Klotz, 2016).

The N cycle, including most of the major processes involved, is depicted in Figure 2.3. Soil microorganisms are responsible for changing the unavailable forms of N to nitrate and ammonium, which can then be taken up by plant roots (Shober, 2015).

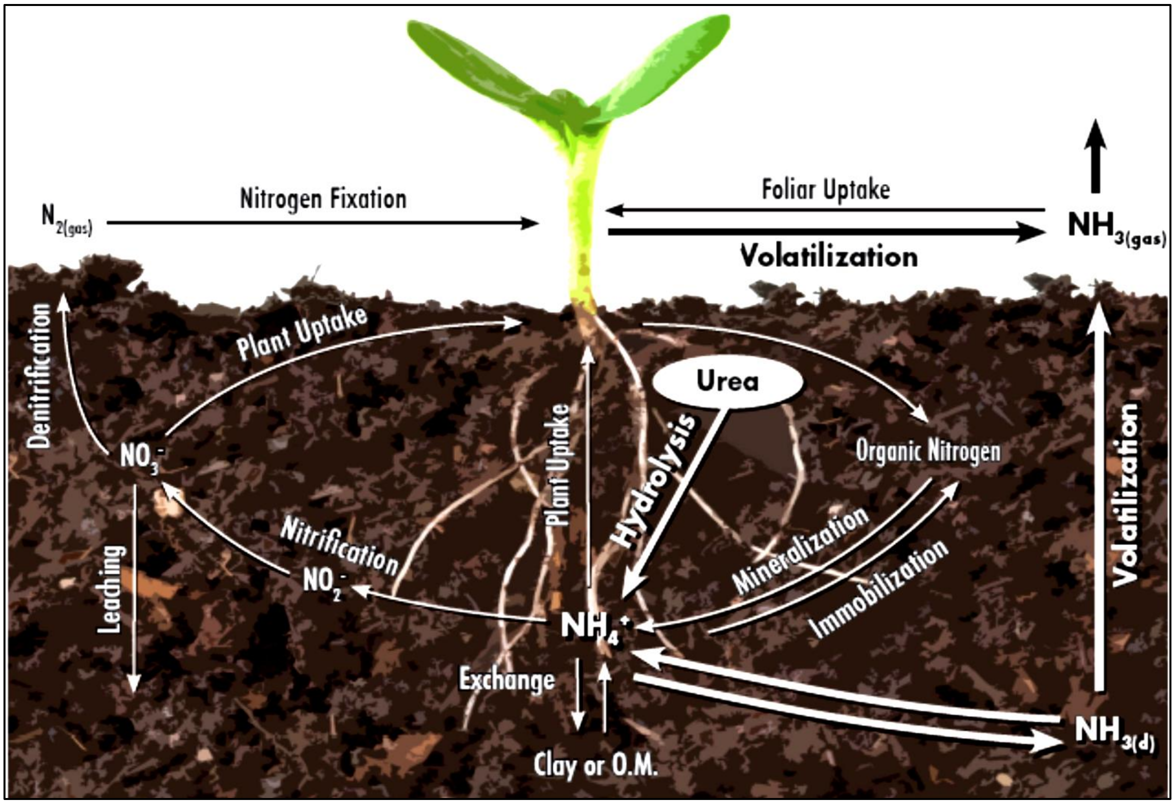


Figure 2.3 The N cycle and most of the major processes involved (Jones et al., 2013).

2.2.1.1 Nitrogen fixation/ammonification

The biological fixation of N_2-gas can only be performed by microbes (Stein and Klotz, 2016). There are two types of microbes that can convert N_2 gas to ammonium, namely free-living N_2-fixing bacteria (Cyanobacteria, Azotobacter, Clostridium, etc.) and symbiotic bacteria, such as *Rhizobium*, that can be found in the nodules on the roots of leguminous plants, such as medics and lupins (Provin and Hossner, 2001). The fixated ammonium is then assimilated into biomass or may be further respired by aerobic and anaerobic microbes (Stein and Klotz, 2016).

2.2.1.2 Nitrification

The nitrification process can be driven by three different groups of microorganisms: i) ammonia oxidisers that oxidise ammonia to nitrite (nitritation), ii) nitrite oxidisers that that oxidise nitrite to nitrate (nitratation) and iii) complete ammonia oxidisers that oxidise ammonia all the way to nitrate (comammox) (Figure 2.4) (Stein and Klotz, 2016).

Nitrification can also lead to N losses when the oxidation of ammonium leads to the production of nitrous oxide gas (Figure 2.4) (Cameron et al., 2013; Kool et al., 2009). This reaction happens under low O_2 concentrations when NO_2^- replaces O_2 as the terminal electron carrier during metabolic processes (Cameron et al., 2013).

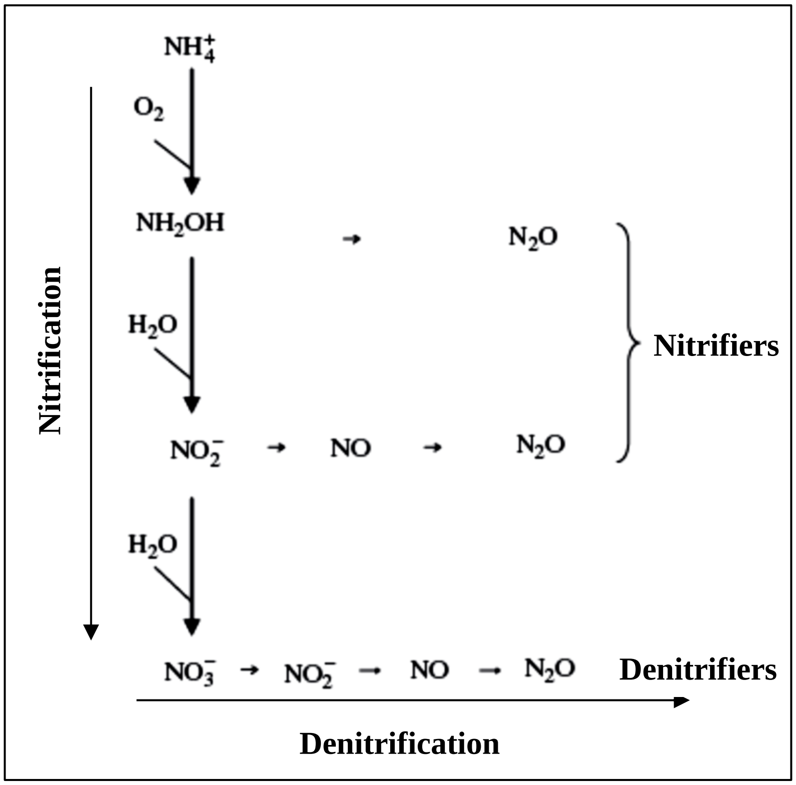


Figure 2.4 The nitrification and denitrification processes. Figure adapted from Kool et al. (2009).

2.2.1.3 Denitrification

Denitrification is the anaerobic respiration of nitrate to N_2O - or N_2 gas (Figure 2.4) (Cameron et al., 2013; Jones et al., 2013; Stein and Klotz, 2016). This process usually occurs in poorly drained, waterlogged soils with low oxygen availability and low redox conditions (Bateman and Baggs, 2005; Cameron et al., 2013; Dobbie and Smith, 2001). Under these waterlogged conditions facultative anaerobic bacteria can use nitrate, instead of oxygen, as the terminal electron acceptor during respiration (Cameron et al., 2013). This leads to the reduction of nitrate to nitrite (NO_2^-), nitric oxide (NO), nitrous oxide (N_2O) and finally dinitrogen (N_2 gas) (Figure 2.4). Mitigating the loss of N through denitrification may be accomplished by lowering the nitrification rate in the soil and lowering the denitrification potential (Cameron et al., 2013; Cameron and Di, 2002; de Klein et al., 2001; De Klein and Eckard, 2008; Di and Cameron, 2003; Thomson et al., 2012; Vergé et al., 2007).

Reducing the N fertiliser application rate may be an effective way of reducing the N_2O emission rate of the soil, but may lead to decreased yields (Millar et al., 2010). Halvorson et al. (2010) considered that the optimisation of N fertiliser sources, specifically the use of controlled-release fertilisers, may lead to a reduction of N_2O emissions without the negative impact on yields. Planting N fixating crops, and thus reducing the N fertiliser application needs of the soil, may also play a big role in the reduction of N losses (Beatty and Good, 2011). It has been found that increasing the pH of agricultural soils by liming may lead to a reduction in N_2O emissions (Bakken et al., 2012; Thomson et al., 2012).

Omonode et al. (2011) suggested that the modification of tillage regimes may also have a positive effect on reducing the N_2O emissions from the soil. However, the effectiveness of these strategies may vary depending on site specific soil and other conditions (Akiyama et al., 2010). In a study done by Venterea et al. (2011), it was found that producing an equivalent amount of grain under no-tillage would generate substantially more N_2O compared to conventional tillage. They also found that the use of controlled-release fertilisers led to the reduction of soil nitrate intensity, but not in N_2O emissions, compared to normal urea.

2.2.1.4 Leaching

The downward movement of nitrate with water lower into the soil profile, beneath the root zone, is called leaching (Jones et al., 2013). The leaching of N into water sources may lead to eutrophication and a consequent excessive growth of weeds and algae. Eutrophication diminishes water sources of oxygen and consequently has a negative impact on fish communities and can lower the recreational value of the water (Cameron et al., 2013).

Rainfall soon after N application, especially at high fertiliser rates in sandy soils, can leach N below the root zone. Optimising the N application rate, hence reducing the amount of excess N in soils, may be one of the most important management factors that lowers leaching risks (Cameron et al., 2013). In areas with high rainfall and risk of leaching, it is wise to control erosion and consequently minimise the potential loss of plant available N (USDA Natural Resources Conservation Service, 2014).

2.2.1.5 Ammonia volatilisation

The loss of gaseous ammonia from the soil surface is called ammonia volatilisation (Cameron et al., 2013). Volatilisation of ammonia from fertilisers is a pathway that leads to substantial losses of nutrients. This may lead to substantial economic losses and potential pollution of the air by releasing abnormally large amounts of ammonia-gas into the atmosphere (Upadhyay, 2012). Surface applied ammonia- and ammonium-based N fertilisers are susceptible to ammonia volatilisation (Jones et al., 2013).

The rate of urea hydrolysis and the rate of the conversion from ammonium to ammonia-gas determines the amount of volatilisation that occurs (Figure 2.5). The soil pH also strongly determines the risk of soils to lose N through volatilisation. The more acidic a soil, the less prone it is to volatilisation and vice versa (Cameron et al., 2013; Jones et al., 2013) (Figure 2.5).

CHEMICAL REACTIONS

Urea + water	$\xrightarrow{\textbf{\textit{urease}}}$	ammonium	Equation 1: *Hydrolysis* (increases pH)
Ammonium	$\rightarrow$	ammonia gas	Equation 2: *Volatilisation* (faster at higher pH)

Figure 2.5 The chemical reactions involved in ammonia volatilisation losses (Jones et al., 2013).

Ammonia losses from fertilised soils may range from 0 to 65% of applied N, depending on soil and environmental conditions (Cameron et al., 2013). Proper placement (3-5 cm below the soil surface) and timing of fertiliser application can limit these losses (Cameron et al., 2013; Prasertsak et al., 2001; Sommer et al., 2004). Three other management practices that may reduce ammonia volatilisation losses from dryland cropping systems are: i) urease inhibitor coating, ii) applying fertiliser during or immediately prior to rainfall and iii) incorporating the fertiliser into the soil (Cameron et al., 2013).

2.2.2 Potentially mineralisable nitrogen (PMN)

PMN is the fraction of residual N in the soil that may potentially be converted to plant available forms of N (USDA Natural Resources Conservation Service, 2014). The microbial biomass and decomposing plant and animal residues in the soil serves as the main source of the organic N pool (USDA Natural Resources Conservation Service, 2014). When simplified, the term PMN can be described as the fraction of soil N that is easily decomposed by soil microbes and is commonly used as a measure of N available in the soil. According to the USDA Natural Resources Conservation Service (2014) the ratio of total mineralised N to total organic N in the soil serves as an indicator of the total soil organic matter.

Since the processes are invariably linked, soil properties and management practices that affect soil organic matter and soil organic C will also affect soil N and PMN levels. No-tillage practices significantly increased PMN levels compared to conventional tillage practices in different states of the USA (Figure 2.6).

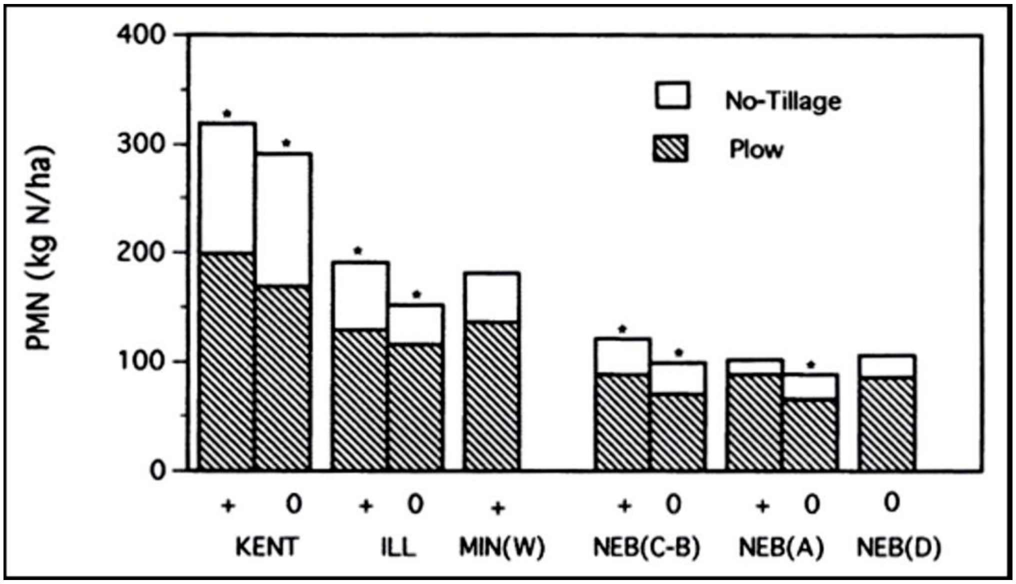


Figure 2.6 PMN levels in the 0-7 cm soil layer (top layer) of long-term tillage trials, done at seven sites in the United States by J.W. Doran in 1987. Figure taken from USDA Natural Resources Conservation Service (2014). + = *fertilised with ammonium nitrate; 0 = no fertiliser*

Because PMN is such a readily available fraction of total N, it is important to understand and fathom the high potential of PMN as a source of crop available N. The N mineralized from the organic N fraction can serve as a source for microbes and enhances microbial growth, including C and N cycling (USDA Natural Resources Conservation Service, 2014). PMN is converted to two main forms of N, namely nitrates and ammonium. In well aerated soils, nitrates are released through aerobic mineralisation and in poorly drained soils anaerobic mineralisation is responsible for releasing ammonium into the soil (USDA Natural Resources Conservation Service, 2014).

The C:N ratio of amendment materials, added to the soil, influence the accumulation and mineralisation of N (USDA Natural Resources Conservation Service, 2014). There is also a strong correlation between soil organic matter and PMN, i.e. when a soil is low in organic matter, it will most likely have a low PMN content. A potential problem may arise under sparse live vegetation, where the N mineralised from the PMN pool can build up and become a potential source of nitrate contamination of groundwater (USDA Natural Resources Conservation Service, 2014).

When producers have problems with the PMN levels of their soils, there are a few practices that may be useful in increasing the available N. The application of organic residues will increase the organic N pool and microbial activity of a soil. When N fertilisers are applied at the correct times and at recommended rates, it can largely increase the N use efficiency of a crop (Ju et al., 2009). Conservation agriculture practices like minimum tillage, crop rotations and implementation of cover crops may not only increase N use efficiency, but also promotes the formation of soil organic C (Hobbs, 2007).

2.2.3 Nitrogen use efficiency (NUE)

Nitrogen use efficiency (NUE) is an indication of how well crops can transform applied N into grain yield (Salvagiotti et al., 2009; Nielsen et al., 2006). Many different definitions are used for NUE, depending on whether it is used in agronomic, genetic or physiological studies (Fageria et al., 2008; Good et al., 2004). The first definition for NUE was made by Moll et al. (1982), who defined it as grain produced per unit of available N in the soil. Semenov et al. (2007) defined NUE as the relationship between yield and N input, regardless of source. Great disagreement exists among authors on which NUE definition is the best and most applicable (Faraj, 2011).

Under field conditions, N fertilisation plays a major role in achieving optimal yields and therefore a high NUE is desired to protect ground and surface water (Cassman et al., 2003). Production factors play a big role in determining the NUE of a certain crop, these production factors include: i) preceding crops, ii) tillage systems and iii) water availability (Campbell et al., 1993; Salvagiotti et al., 2009; Sieling et al., 1998; Timsina et al., 2001). Because N becomes less limiting at higher rates (Salvagiotti et al., 2009), NUE usually declines with increasing N fertiliser rates (Doyle and Holford, 1993; McDonald, 1992; Timsina et al., 2001). Salvagiotti et al. (2009) recorded an increase in NUE when S fertiliser was applied. Ensuring a higher NUE may reduce potential pollution risks by utilising excess residual soil nitrate and preventing the leaching thereof into water sources (Alva et al., 2006; Salvagiotti et al., 2009).

2.3 Nitrogen management in wheat production

The production of a wheat plant with sufficient protein, whilst maintaining a high yield, is one of the biggest challenges in modern day wheat cultivation. To ensure the crop has high grain protein, there must be sufficient nutrient resources to meet the wheat plant's need for optimal vegetative growth, i.e. establish high yield potential (Jones and Olson-Rutz, 2012).

The N uptake of the plant just after emergence is low, followed by a period of increased uptake (during stem extension) (Abbate et al., 1995; Demotes-Mainard et al., 1999; Labuschagne and

Langenhoven, 2012) (Figure 2.7 & Figure 2.8). Maximum N uptake by the wheat plant starts with tillering and ends when heading starts, and proven so previously by Abbate et al. (1995)and Demotes-Mainard et al. (1999). After this stage of high N uptake the plant's demand for N decreases and consequently leads to a lower N uptake (Labuschagne and Langenhoven, 2012; Orloff et al., 2012). This could be mainly due to N redistribution from stems and leaves to the developing grain (Orloff et al., 2012). The management of N applications is very important, because the correct management programmemme will mean that the plant receives optimal amounts of fertiliser during the period of high N uptake.

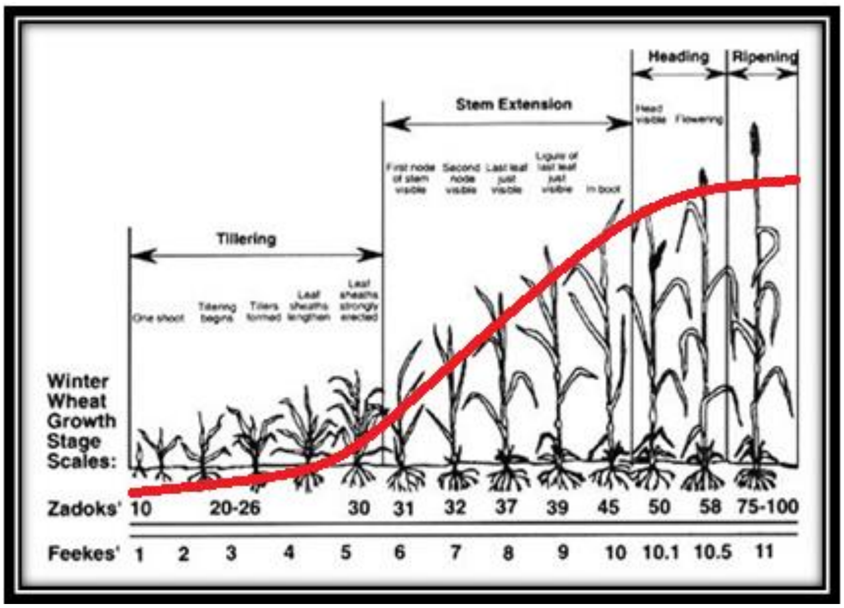


Figure 2.7 The different growth stages of a wheat plant, according to the Zadoks and Feekes scales, are depicted in this diagram. Indicated by the red line is the N uptake curve of the plant (Alley et al., 1994).

Measuring and knowing the residual N of a soil within a production system is another important factor in optimising the yield and grain protein of a wheat crop. Early season N application rates may be determined by making use of soil nitrate tests (Jones and Olson-Rutz, 2012; Ludwick and Westfall, 2015). According to a three-year long study, making use of the previous cropping season's soil data proved to be a very insufficient way of determining N application rates and 35% of the soil samples had lower nitrate levels in April than in the previous November (Jones and Olson-Rutz, 2012). If topdressed N rates were to be based on the soil data from the previous November, the crop may be under- or over fertilised (Jones and Olson-Rutz, 2012).

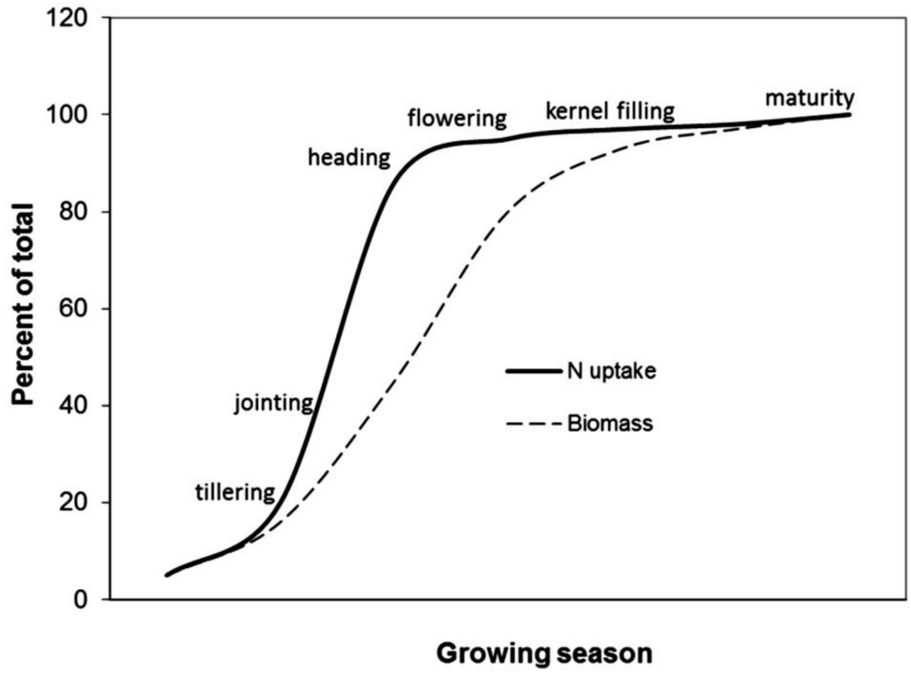


Figure 2.8 Percentage of total N uptake by the wheat plant and biomass accumulation during the season (Orloff et al., 2012).

A common occurrence in wheat production is high grain protein for wheat grown under drought stressed conditions, but certain management practices can increase grain protein without forfeiting yield (Jones and Olson-Rutz, 2012). According to research done by Orloff et al. (2012), wheat producers can achieve high yield and optimal grain protein content simultaneously by applying proper N fertility management.

Early season N applications (prior to boot and heading) will mostly affect yield and determine yield components (Orloff et al., 2012). These early season N applications may also play a vital role in the breakdown of residues from the previous season, while late season applications of N (post boot stage), have a big effect on grain protein and quality (Orloff et al., 2012).

Early season N applications have a profound effect on the crop yield, and a late season application affects the grain protein concentration (Figure 2.9). Nitrogen fertiliser strategies have to be intensively managed in order to ensure yield increases, improve grain quality and minimise any and all negative impacts on the environment (Mohammed et al., 2016). Because of the change in soil characteristics, due to CA implementation, and the effects thereof on N availability, current N fertiliser programmes have to be adjusted (Grahmann et al., 2014).

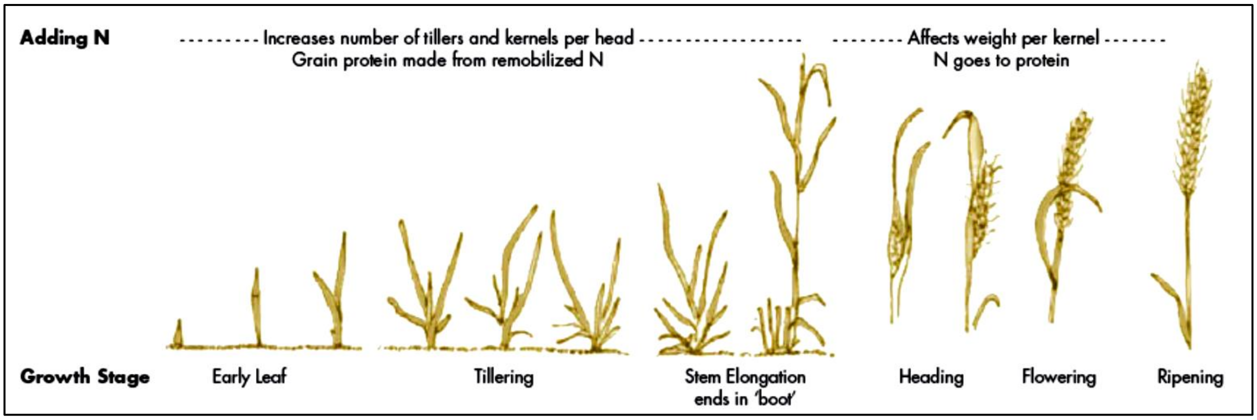


Figure 2.9 Effect of N application timing on yield and protein at different wheat growth stages (Weisz and Heiniger, 2012).

The optimal rate of N fertiliser may be determined by making use of pre-plant soil samples and yield potential of the specific system (Grahmann et al., 2014). In order to determine and apply N at an optimal rate, a few factors have to be taken into account: i) the production potential of a soil, ii) cropping systems (previous crops), iii) the relative N fertiliser costs vs. crop value, and iv) minimising N losses from the soil (Grahmann et al., 2014). Nitrogen application recommendations have to be site-specific and take all abiotic factors (rainfall, soil type and temperature) into account, as well as agronomic practices (crop rotation, tillage type, amount of residue) and the farmer's need for higher crop yields or better grain quality (Grahmann et al., 2014). The effect that different years may have on the soil available N must also be taken into consideration, i.e. in a year with high yield potential, leguminous crops will potentially fixate more N in the soil, leading to a possible decrease in N demand the following year or alternatively crops like canola might utilise more N from the soil and lead to a potentially higher N fertiliser rate the following year (FERTASA, 2016b). The opposite may be true for a year with a low yield potential.

The placing of N relative to seed at planting is an important factor to take into consideration when developing a N fertiliser programme. The use of no-tillage planters allows the producer to place fertiliser relatively close to seeds. This may promote NUE of the wheat crop, but may also lead to better seedling populations when compared to conventional tillage (McKenzie et al., 2001). The authors also found that N fertilser could be applied at rates as high as 90 kg N ha^{-1} with a no-tillage planter, without any negative effects on wheat growth or yield, this means that seed burn risk is low when implementing a no-tillage planter.

2.3.1 Nitrogen management for optimal yield

In wheat production, the yield components and final grain yield are dependent on cultivar type, crop and nutrient management and environmental conditions (Lu et al., 2015). Optimal N management is very important for the improvement of both yield and NUE (Lu et al., 2015). Understanding the effect of N availability, during the critical growth stages, on the wheat plant is important when setting up an optimal N application programme. In-season root zone N tests may be used to determine and prove the correlation between N supply and crop N uptake. When optimal N rate was based on in-season root zone N management, it lead to a reduction in N rate necessary to achieve optimal yield, because of better NUE (Lu et al., 2015).

Lu et al. (2015) did field experiments comparing the response of wheat yield to an optimal N rate vs. a 130% optimal N rate, and found that no significant increase of biomass or yield occurred. When N is applied in excessive amounts a reduction in grain yield may even occur due to lodging and pathogen pressure (Lu et al., 2014; Woodard and Bly, 1998). Insufficient N, on the other hand, limits yield components as well as final grain yield because of low biomass production. Woodard and Bly (1998) found that a split application of N was more effective at ensuring optimal yields compared to a once-off application of all N at planting.

Nitrogen application up to and including Feekes' growth stage 10 (in ''boot'') leads to an increase in grain yield (Labuschagne and Langenhoven, 2012). Any N applications after Feekes' growth stage 10 (at or after flowering) will deliver little to no yield increase for wheat produced under dryland conditions. Earlier applications of N lead to a larger leaf area and consequently a higher production potential (Labuschagne and Langenhoven, 2012). The growth period between Feekes' stage 5 and 10 (stem elongation to anthesis) is known as stem elongation and this is where N uptake is at a maximum (Lu et al., 2015). Proper N management during this crucial period of plant growth ensures high tiller survival and grain yield (Lu et al., 2015). N application prior to and during this period will ensure maximum N availability and lead to higher achievable yields (Lu et al., 2015). There is also minimal risk of N leaching when applying fertiliser after Feekes' growth stage 5, due to the extensive root systems already established by the wheat plant.

Salvagiotti and Miralles (2008) found that increasing the N fertiliser rate above 80 kg ha^{-1} led to no further increases in yield which agrees with the results of Salvagiotti et al. (2009), who found no further grain yield increases above 90 kg N ha^{-1}. However, a rise in grain N content and possibly grain protein content is possible when crops are grown above these non-limiting N fertiliser rates (Gooding et al., 2007a, 2007b; Lázzari et al., 2007; Uhart and Andrade, 1995), although Salvagiotti et al. (2009) found this to be untrue. Cassman et al. (1992), Ehdaie and Waines (2001) and Salvagiotti et al. (2009) also found that higher N concentration in the biomass are apparent when increasing the N rate above 80 kg ha^{-1}, suggesting high absorption of N, but showing the crop's inability to distribute the N to sinks during grain filling.

2.3.2 Nitrogen management for high grain protein

Most of the plant N, used for protein synthesis, is only taken up right before heading and flowering (Jones and Olson-Rutz, 2012). Additional N will only increase grain protein to optimal levels when the yield potential has reached its maximum and the plant's N need for vegetative growth has been satisfied (Jones and Olson-Rutz, 2012; Woodard and Bly, 1998). When N supply is sufficient for maximum wheat yield, any additional N leads to a consequent potential increase in grain protein (Figure 2.10).

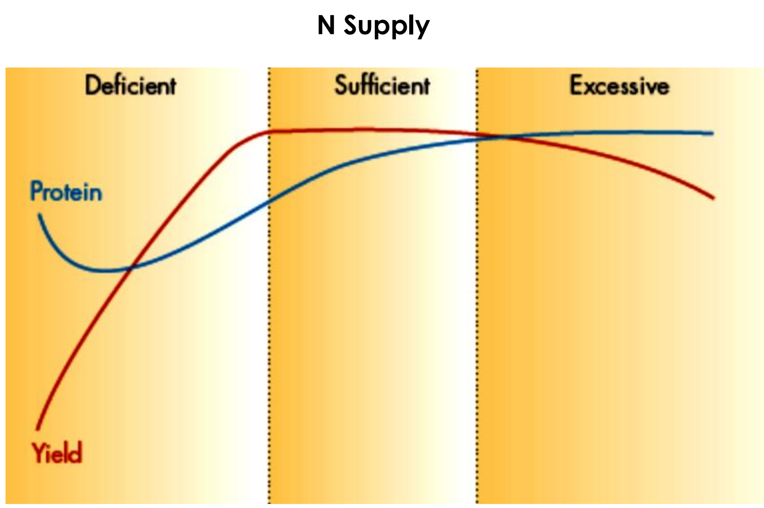


Figure 2.10 Grain protein and yield response to increasing N (McKenzie et al., 2006).

Wheat, grown under dryland conditions, typically produces grain with higher protein content when grown after legume crops than after fallow or grassy crops (Jones and Olson-Rutz, 2012). This effect of legumes on grain protein may be accredited to the *Rhizobium* driven fixation of N that takes place and the higher availability of soil N to drive vegetative growth and protein synthesis.

Nitrogen rates at seeding should be based on a realistic yield goal. When N rates before or at seeding is too high it may lead to excessive leaching of nitrates under high rainfall conditions.

High rates of N early in the season may also lead to exuberant vegetative growth and depletion of soil moisture before grain fill (Jones and Olson-Rutz, 2012). When all the N necessary for the production of high yielding wheat crops is applied early in the season the plant may produce too many tillers and it may not be able to supply them all with the needed nutrients (Jones and Olson-Rutz, 2012). When winter wheat with a protein content lower than 12.5% is produced, the plant's growth cycle was most likely N limited (Jones and Olson-Rutz, 2012). Table 2.2 shows guidelines of how to interpret the protein content of the wheat grain with regards to the yield vs. protein ratio.

Table 2.2 Rough guidelines for estimating wheat yield vs. protein relations (Ludwick and Westfall, 2015).

Protein level	Interpretation
< 11.1%	Yields may be significantly limited by N deficiency. More N fertiliser would probably increase yields and protein content.
11.1 - 12.0%	Yields may have been limited by N deficiency. Applying more N fertiliser *may* increase yield, but *will* increase protein content.
>12%	Yields were probably not limited by N deficiency. Applying more N probably will not increase yield, but *will* increase protein content.

Higher yields will however, demand a higher rate of in-season N application in order to keep grain protein intact (Jones and Olson-Rutz, 2012). In other words, protein increases for a certain N rate will be higher for low yields and vice versa (Jones and Olson-Rutz, 2012). In a trial done under dryland conditions, when wheat was produced with 67 kg ha^{-1} N pre-plant and 34 kg ha^{-1} N topdressed at tillering, the grain protein increased by 1.4%, 0.5% and 0.1% at yields of 3.56, 5.11 and 5.99 ton ha^{-1}, respectively (Jones and Olson-Rutz, 2012).

The final grain protein is mostly determined by the availability of N in the plant that can be translocated to the developing grain (Brown et al., 2005). Sometimes it can prove profitable to test the N status of the crop before determining whether it is necessary to apply any N post-anthesis. Determining flag-leaf N concentration or taking chlorophyll readings (SPAD) are two of the most common ways to determine the late-season N requirement of the wheat plant (Jones and Olson-Rutz, 2012).

The best time to take flag leaf samples is at 50% heading (Feekes' 10.3) (Flowers et al., 2007). Flag leaf measurements containing 4.2% N are associated with optimal grain protein (12-14%), and any concentration lower than 4.2% would mean that the plant is in need of late-season N applications to ensure optimal protein synthesis in the developing grain (Brown et al., 2005; Flowers et al., 2007; Jones and Olson-Rutz, 2012; Orloff et al., 2012). Protein responses to late-season N applications are more likely to be successful when low flag leaf N concentrations are recorded (Flowers et al., 2007). However, the lower the flag leaf N concentration, the more N will be required to reach the desired grain protein levels (Jones and Olson-Rutz, 2012).

When the measured flag leaf N % was as low as 3%, late season N rates as high as 44,8 kg ha^{-1} were not adequate for raising grain protein to optimal levels (Brown et al., 2005). There may however be a limit to the amount of N that can be applied to the wheat crop during the late-season period. A study, done in Idaho, found that late-season N applications exceeding 84.06 kg ha^{-1} increased the occurrence of lodging and consequently reduced yield (Brown et al., 2005).

Late-season applications of N may be done using two different methods, namely foliar or granular applications. When making use of late-season topdressing in granular form, there is a risk of volatilisation and losing a large amount of N to the atmosphere in the form of N_2 gas (Jones and Olson-Rutz, 2012). Foliar applications, however, are less susceptible to volatilisation and are more rapidly taken up by the wheat plant. High concentrations of foliar applied N can lead to leaf burn; therefore care must be taken to select N rates that are low enough not to cause leaf burn or with the addition of an additive like humic acid. Grain protein content has been found to increase with as much as 1.6% when using foliar sprays, despite some leaf burn (Woodard and Bly, 1998). When urea ammonium nitrate (UAN) is used, N rates should be no higher than 34 kg ha^{-1} and when liquid urea is used rates should not exceed 50 kg ha^{-1}, in order to prevent leaf burn and the yield losses associated with it (Jones and Olson-Rutz, 2012).

Bly and Woodard (2003), Brown and Petrie (2006) and Rawluk et al. (2000) found that when comparing late season N applications during or before flowering with applications post-flowering, the pre-flowering applications had a higher success with raising grain protein. The lower success rate of the post-flowering application may be due to the fact that there is less time for the N to be converted to grain protein (Jones and Olson-Rutz, 2012).

2.4 Different fertiliser sources

Different N fertilisers differ largely in N concentration, as well as the form in which N is added to soils, and are important factors in determining the optimal source of N for a specific production system (Grahmann et al., 2014). Fuertes-Mendizábal et al. (2013) suggested that choosing the correct N source may play a larger role in achieving higher yields than splitting the N applications.

A producer's decision on which N source to use is also largely influenced by: i) soil pH, ii) soil moisture, iii) availability of equipment and iv) cost of kg ha^{-1} N (Grahmann et al., 2014).

2.4.1 Nitrogen-containing fertilisers

2.4.1.1 Limestone ammonium nitrate (LAN)

In limestone ammonium nitrate (LAN) half of the N is in the form of nitrate and the other half in the form of ammonium. When applying a fertiliser that contains both ammonium and nitrate, the nitrate becomes plant-available quickly, but has a high leaching potential, whilst the ammonium does not leach as readily and is transformed into nitrate over time. The combination of ammonium and nitrate also means a lower risk of losing N due to volatilisation (Weiss et al., 2009). It is very effective, but economically less unattractive than cheaper N sources, because of its high price per kg of N. It consists of 28% N, which is relatively high when compared to some N sources. Ammonium nitrate, when applied on its own is illegal in South Africa due to its explosive properties and leads to acidification of the soil, therefore limestone is added to make the fertiliser less volatile and it gives the secondary advantage of less acidification of the soil.

2.4.1.2 Urea

One of the most common N sources used in commercial production systems is urea, because of its relatively low price and high availability. The N from urea becomes crop-available when it is converted to ammonium and the nitrate (Weiss et al., 2009). Urea may be effectively used as a starter, broadcast, top dress or foliar application (Weiss et al., 2009). About 46% of the total global consumption of fertilisers are in the form of urea (Upadhyay, 2012). Urea also has a very high proportion of N in its formulation (46%), which makes it a very economically attractive and effective fertiliser to consider.

The use of urea have many advantages, like its high N content, relatively low cost per kg, as well as its fast conversion to crop-available forms of N (Weiss et al., 2009). Urea is popular because of its good storage and handling characteristics and it is readily available worldwide. Urea is also widely used as a foliar application of N, due to its high solubility (Grahmann et al., 2014). When urea is applied too close to seeds, the rapid hidrolisation process may lead to a sharp pH increase and consequent damage to seedlings (Weiss et al., 2009). Urea, when used, may also lead to great N losses from soils under CA, because of increased urease activity and high leachability (Grahmann et al., 2014). The enzyme urease is responsible for hydrolysing urea-N to ammonia-N, which, especially in the presence of low moisture conditions, is highly volatile and can easily be lost from the soil system (Upadhyay, 2012). Volatilisation of urea is considered a severe problem, and leads to great N losses from commercial systems within a warmer, dryer climate. When ammonium is converted to nitrate, H^+ ions are formed and, like for most N fertilisers, leads to a gradual acidification of the soil (Weiss et al., 2009).

2.4.1.3 Urea + urease inhibitor

High urease activity in the soil during the application of urea fertilisers may cause severe environmental and economic problems, due to the release of extremely high amounts of ammonia into the atmosphere and ground water (Upadhyay, 2012). To make the use of urea fertilisers more efficient, urease inhibitors are commonly used with the fertiliser to ensure a more controlled release of ammonia into the soil (Upadhyay, 2012). By controlling/delaying the hydrolysis of urea in the soil, the N losses due to volatilisation and leaching may be limited (Mohammed et al., 2016; Upadhyay, 2012).

The use of urease inhibitors are growing in popularity, due to the efficient use of urea fertiliser, reduced nitrate runoff and the release of ammonia associated with it (Upadhyay, 2012). A study done in Montana, USA found that the incorporation of urease inhibitors into urea-based fertilisers may reduce ammonia losses by up to 66% (Mohammed et al., 2016). In fields cultivated under CA practices, where a layer of mulch or crop residues are present, the urease activity in the soil may be extremely high (Mohammed et al., 2016). Broadcast urea on these fields is highly susceptible to ammonia volatilsation; hence the need for urease inhibitors becomes quite apparent. The economic and environmental advantages of using urea-based fertilisers with urease inhibitors are especially observable in years yielding high rainfall (Mohammed et al., 2016).

2.4.2 Sulphur- and nitrogen-containing sources

Sulphur (S) is considered to be another essential nutrient in plant nutrition (Salvagiotti et al., 2009), and is readily available in the form of sulphate. Low organic matter content, soil erosion and high leaching capacities of soils may lead to S deficiencies in crops (Scherer, 2001). A positive interaction between S and N have previously been reported by Salvagiotti and Miralles (2008) and Reussi et al. (2011), where S addition led to an increase in biomass and grain yield of wheat.

The addition of S-containing fertilisers may also lead to larger volumes of the soil being explored by plant roots (Kätterer et al., 1993; Mandal et al., 2003), thus increasing the N uptake of the crop. However, S fertilisation does not always modify the harvest index of a plant (Giller et al., 2004; Ladha et al., 2005; Salvagiotti and Miralles, 2008).

2.4.2.1 Limestone ammonium nitrate + sulphate

Limestone ammonium nitrate + sulphate is a product that combines the N fertiliser LAN with sulphate to reap the benefits from the addition of both N and S to the soil profile. Limestone ammonium nitrate + sulphate contains 24% N and 3% S.

2.4.2.2 Ammonium sulphate (AMS)

Nitrogen in ammonium sulphate (AMS) is in the form of ammonium, which means it is readily available for plant uptake and commonly used as a start-off fertiliser during planting. It is also well-suited as a topdressing application, because of its relatively low volatilisation rate when compared to surface applied urea (Weiss et al., 2009). Because the N released from AMS is in the form of ammonium and not nitrate, which is highly mobile, it has a low leaching capacity. AMS contains 21% N and 24% S, which makes it perfect for use on soils with a S deficiency.

A few drawbacks to consider, when making use of AMS, include its higher cost per kg of N, when compared to urea-based fertilisers, and its relatively low N content (Weiss et al., 2009). Ammonium sulphate also has a relatively high salt index and has a larger potential for acidifying the soil profile per unit N applied, when compared to other ammonium-based N sources (Weiss et al., 2009).

2.5 Summary

The effects that CA practices have on soil physical-, chemical- and biological composition will influence the fertiliser management programme of wheat under dryland cropping systems. It is thus necessary to improve N fertilisation studies and to understand the processes involved therein. Understanding the relationship between N fertilisation, the timing thereof and the consequent effect on crop development is a step in the right direction when developing a N fertilisation program.

3 Materials and methods

3.1 Description of research sites

This study was conducted during 2016 (Year 1) and 2017 (Year 2) on six sites within the dryland grain producing areas of the Western Cape, South Africa (Figure 3.1). Due to the conditions (i.e. climate and soil) that differ significantly from each other in these wheat-producing areas, six individual sites were identified within the larger Western Cape area.

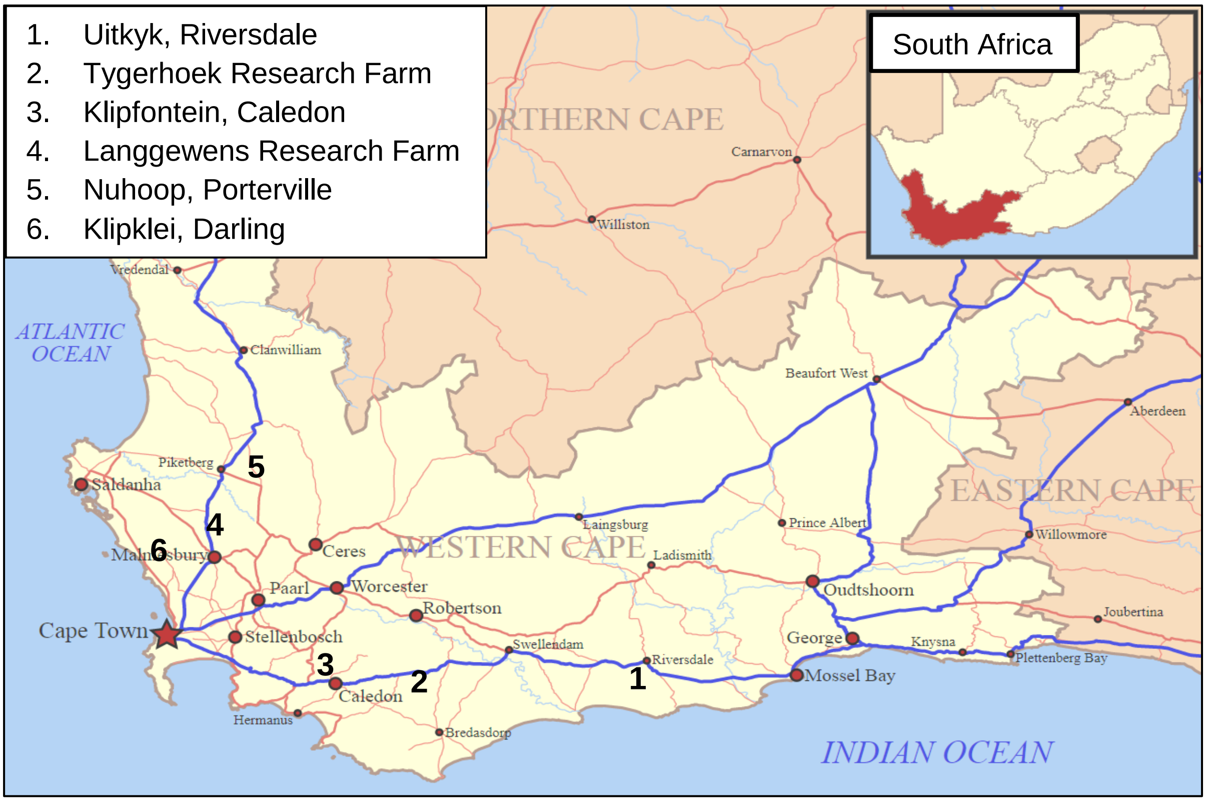


Figure 3.1 Map of the Western Cape and annotated locations of the six research sites used in the study (https://commons.wikimedia.org/wiki, 2008).

Data loggers were installed at each site to monitor rainfall, soil moisture and soil temperature. Excluding the Caledon data logger (both years) and Tygerhoek data logger (Year 1), data loggers were equipped with automatic rainfall gauges and 5TM soil probes, measuring volumetric soil water content (VWC) and soil temperature. The type of data logger used at the Caledon (both years) and Tygerhoek (Year 1) sites, differed from the loggers at the other sites as it could not measure rainfall. In Year 1, only one 5TM soil probe was installed per data logger at a depth of 10 cm. In Year 2, two 5TM soil probes were installed per data logger; one at a depth of 7 cm and the other at a depth of 15 cm.

3.1.1 Uitkyk, Riversdale

The Uitkyk farm is situated approximately 12 km southwest of Riversdale (34°9'38" S, 21°9'6" E altitude 145 m) and is roughly 25 km from the Indian Ocean. The area is predominately used to produce dryland winter cereals and canola. This area is also known as the Riversdale "*vlakte*" that has shallow to medium-deep red and grey sandy loam soils, derived from marine sediments, with shale in some locations (A. Ellis, personal communication, October 14, 2017).

The long-term average rainfall for this area is 430 mm (per annum) of which approximately 70% occurs between the months of April and October. The rainfall, VWC and minimum soil temperatures for Year 1 and Year 2 can be seen in Figure 3.2 and Figure 3.3, respectively.

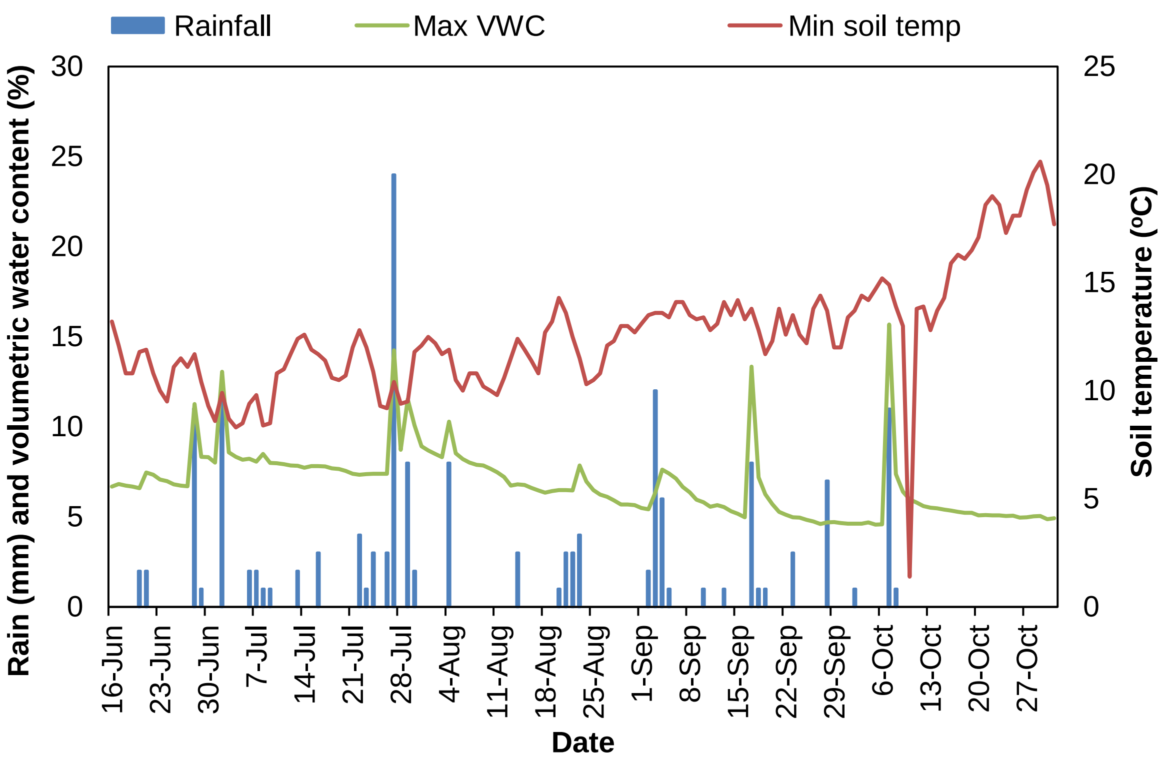


Figure 3.2 Rainfall (mm), maximum volumetric soil water content (VWC, %) and minimum soil temperature (ºC) at a 10 cm depth during Year 1 at Riversdale.

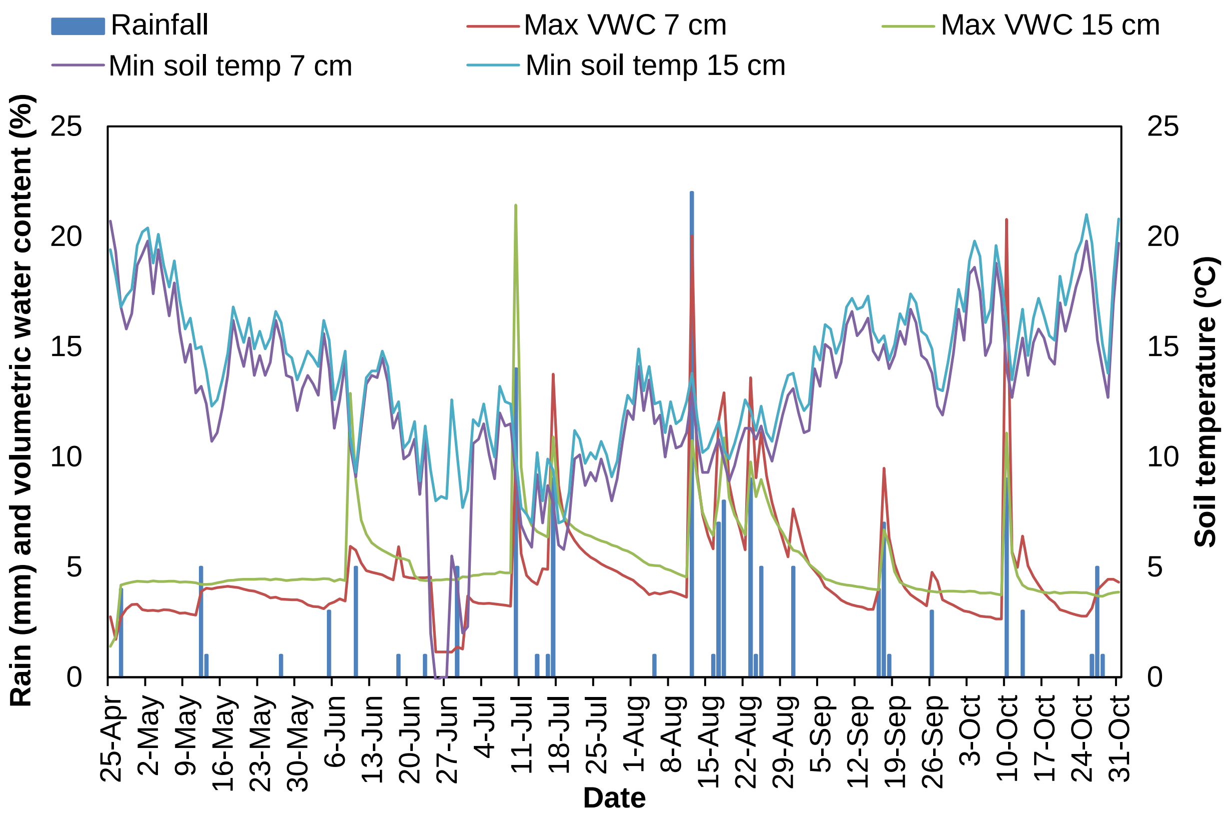


Figure 3.3 Rainfall (mm), maximum volumetric soil water content (VWC, %) and minimum soil temperature (ºC) at 7 and 15 cm depths during Year 2 at Riversdale.

3.1.2 Tygerhoek Research Farm

The Tygerhoek Research Farm is situated near Riviersonderend (34°09'32" S, 19°54'30" E, altitude 190 m). This area, also referred to as the Rûens, produces dryland winter cereals and canola. The research site is approximately 60 km from the Indian Ocean. Along the Sonderend River, soils are predominately grey, shallow and sandy loam, shale-derived, with some medium-deep to deep sandy loam alluvial soils (A. Ellis, personal communication, October 14, 2017).

The long-term average annual rainfall is 450 mm with 70% of the total rain occurring between the months of April and October. The average long-term maximum and minimum temperatures are 24 and 11 °C respectively. Figure 3.4 depicts the soil water content (m^3 m^{-3}) and soil temperature at a 10 cm depth for Year 1 at the Tygerhoek Research Farm. Daily rainfall data, maximum VWC and minimum soil temperature, at depths of 7 and 15 cm, for Year 2 can be seen in Figure 3.5.

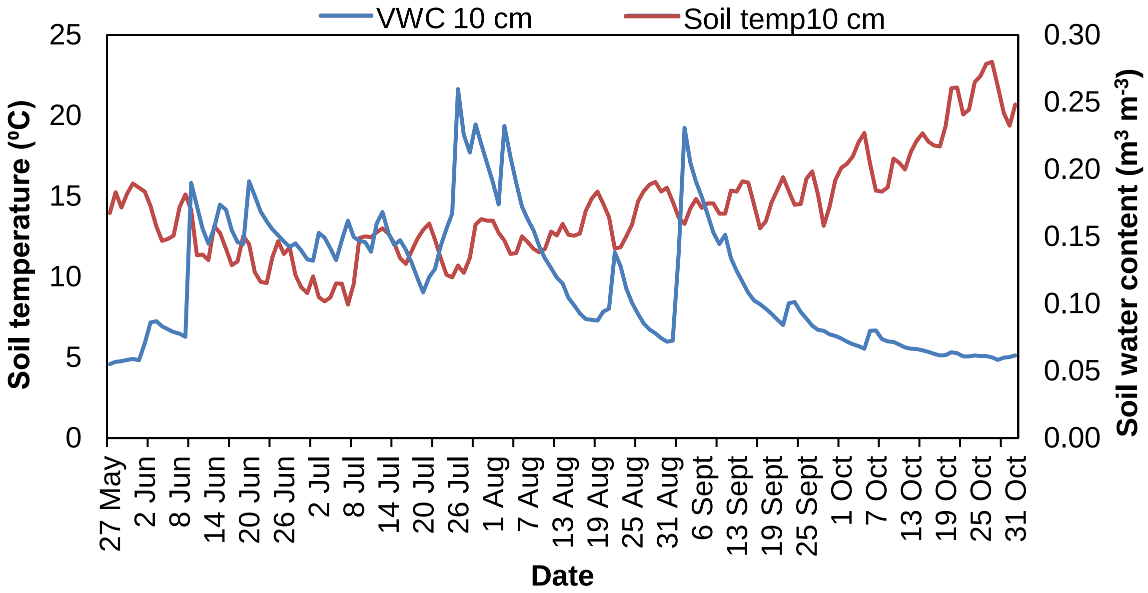


Figure 3.4 Volumetric soil water content (VWC, m^3 m^{-3}) and soil temperature (ºC) at a 10 cm depth during Year 1 at Tygerhoek Research Farm.

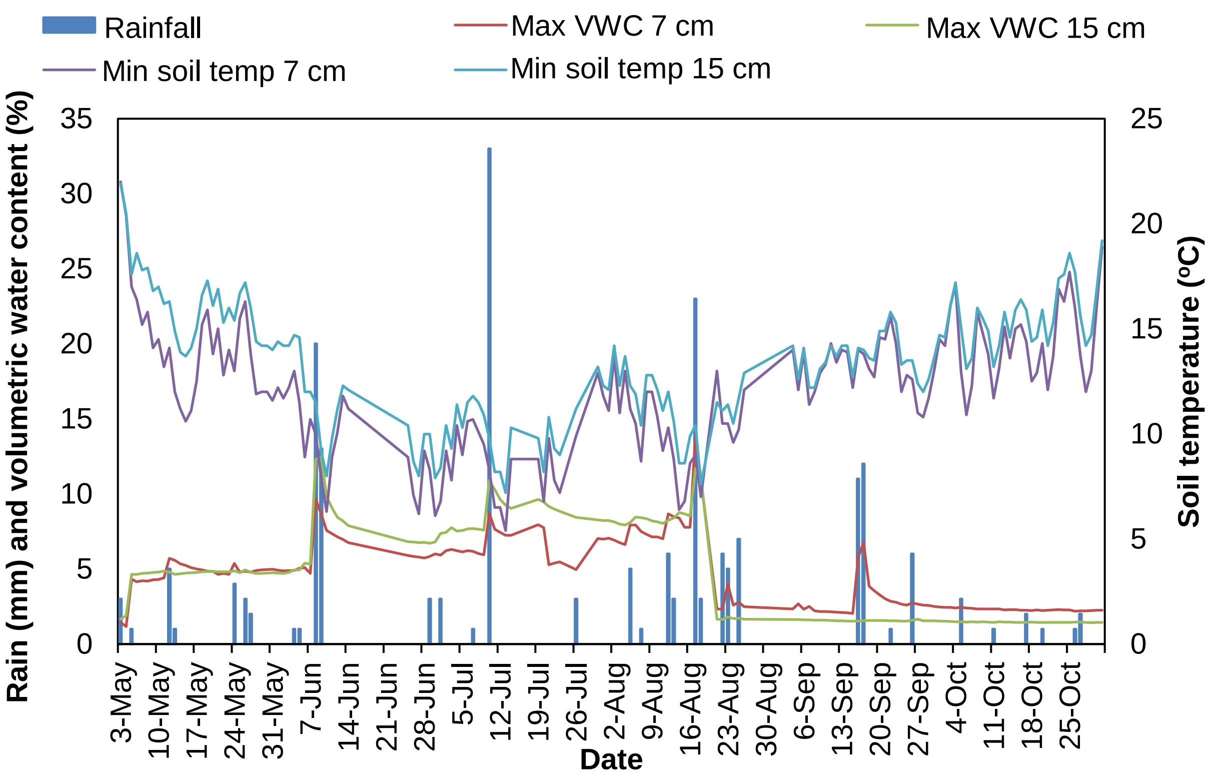


Figure 3.5 Rainfall (mm), maximum volumetric soil water content (VWC, %) and minimum soil temperature (ºC) at 7 and 15 cm depths during Year 2 at Tygerhoek Research Farms.

3.1.3 Klipfontein, Caledon

The Klipfontein farm is in the Overberg region approximately 17 km northwest of Caledon (34°12'03" S, 19°16'12" E, altitude 275 m). This area, also referred to as the Overberg, has a high winter cereal and canola producing potential. Wheat and canola are grown in rotation with annual or perennial pastures such as medics or lucerne. The soil profile is mostly comprised of grey shallow sandy loam shale-derived soils. It is a stable region in terms of annual grain production and climate.

The Overberg region is situated between the Swartland and Southern Cape grain production areas. It has the most temperate climate of all the sites included in the study, with the smallest fluctuations in annual rainfall. The average annual rainfall for this area is 384 mm in lower lying areas and 534 mm in higher lying areas (Arcus GIBB (PTY) LTD, 2009). The average daily minimum and maximum temperatures in Caledon ranges from 15.5 to 28.6 °C in January and 5.6 to 17.7 °C in July, respectively (Arcus GIBB (PTY) LTD, 2009).

The VWC and soil temperatures at a 10 cm depth for Year 1 and 2 are shown in Figure 3.6 and 3.7, respectively.

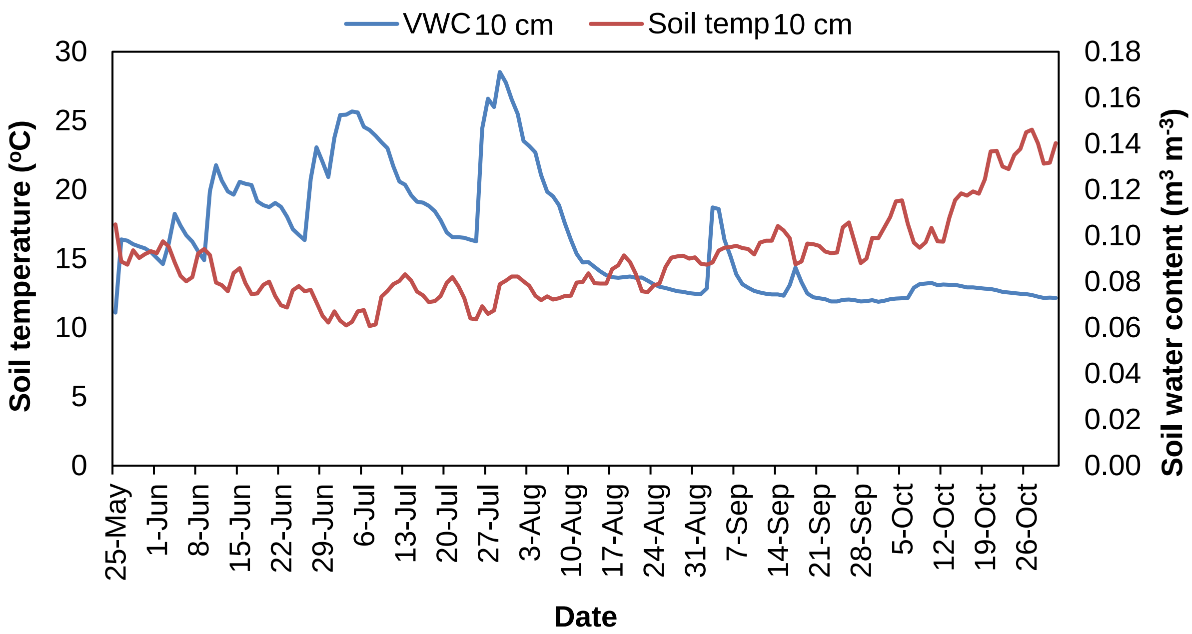


Figure 3.6 Volumetric soil water content (VWC, m^3 m^{-3}) and soil temperature (ºC) at a 10 cm depth during Year 1 at Caledon.

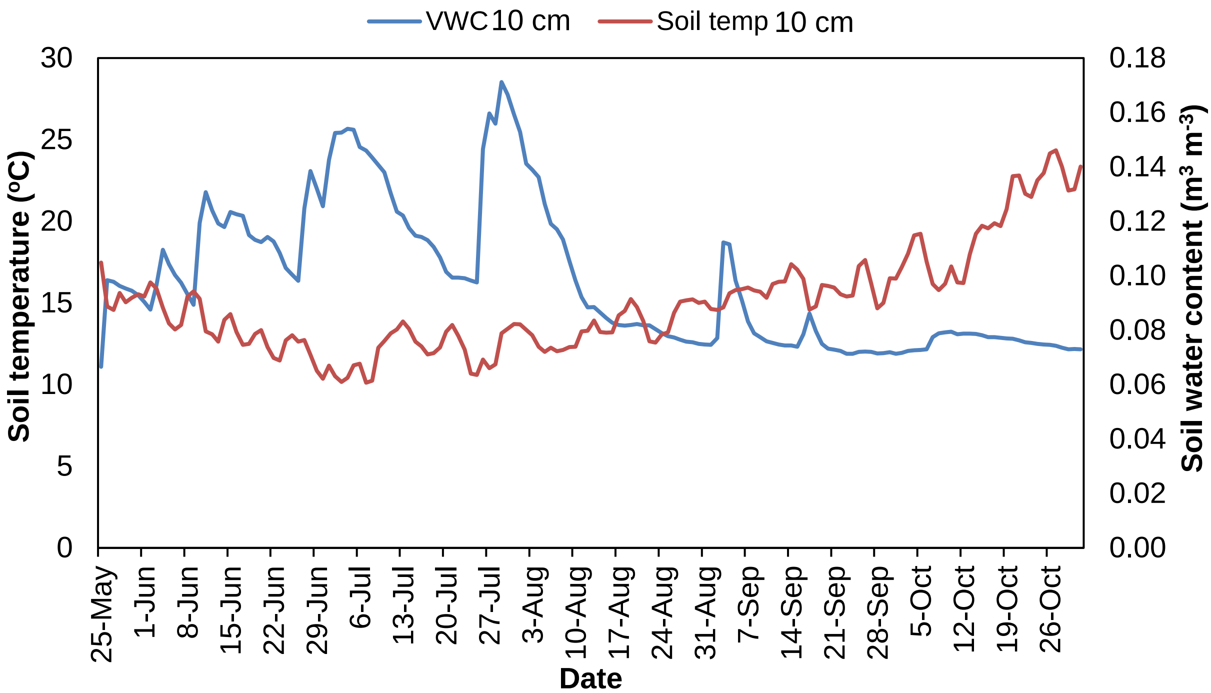


Figure 3.7 Volumetric soil water content (VWC, $m^3\ m^{-3}$) and soil temperature (ºC) at a 10 cm depth during Year 2 at Caledon.

3.1.4 Langgewens Research Farm

The Langgewens Research Farm is situated approximately 18 km north of Malmesbury (33°16'34" S, 18°45'51" E, altitude 179 m). Langgewens Research Farm is situated in the Swartland region, where wheat is produced in rotation with canola and medics. The dominant soils in the area are Glenrosa and Mispah forms with a high stone content (>40%). The parent material is mainly greywacke and phyllite of the Moorreesburg Formation, Malmesbury Group. Soils have limited pedological development and are therefore usually shallow with a sandy loam texture (A. Ellis, personal communication, October 14, 2017).

The long-term average rainfall is 400 mm rain per annum. More than 80% of the rainfall is recorded between the months of April and October. The average long-term minimum and maximum temperatures are 12 and 24 °C, respectively. Due to a faulty data logger, only rainfall and ambient temperature data were recorded for both years at the Langgewens Research Farm (Figure 3.8 and Figure 3.9).

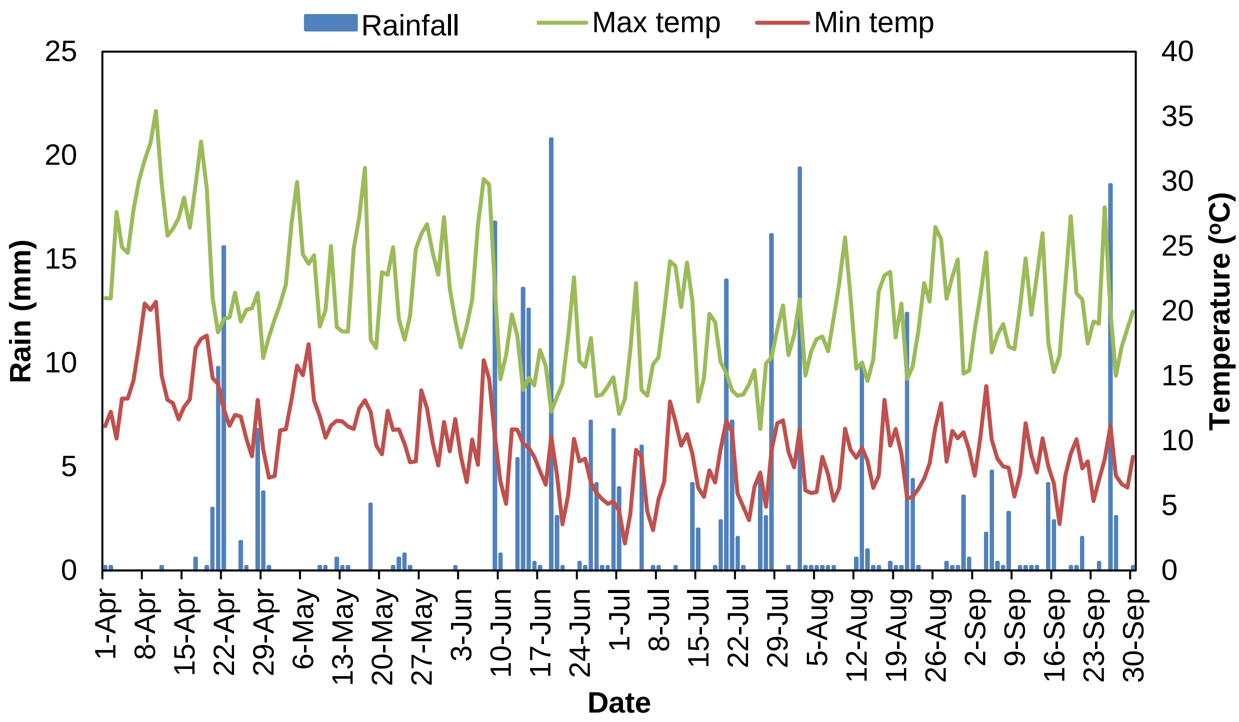


Figure 3.8 Rainfall (mm), maximum and minimum air temperatures (ºC) during Year 1 at Langgewens Research Farm.

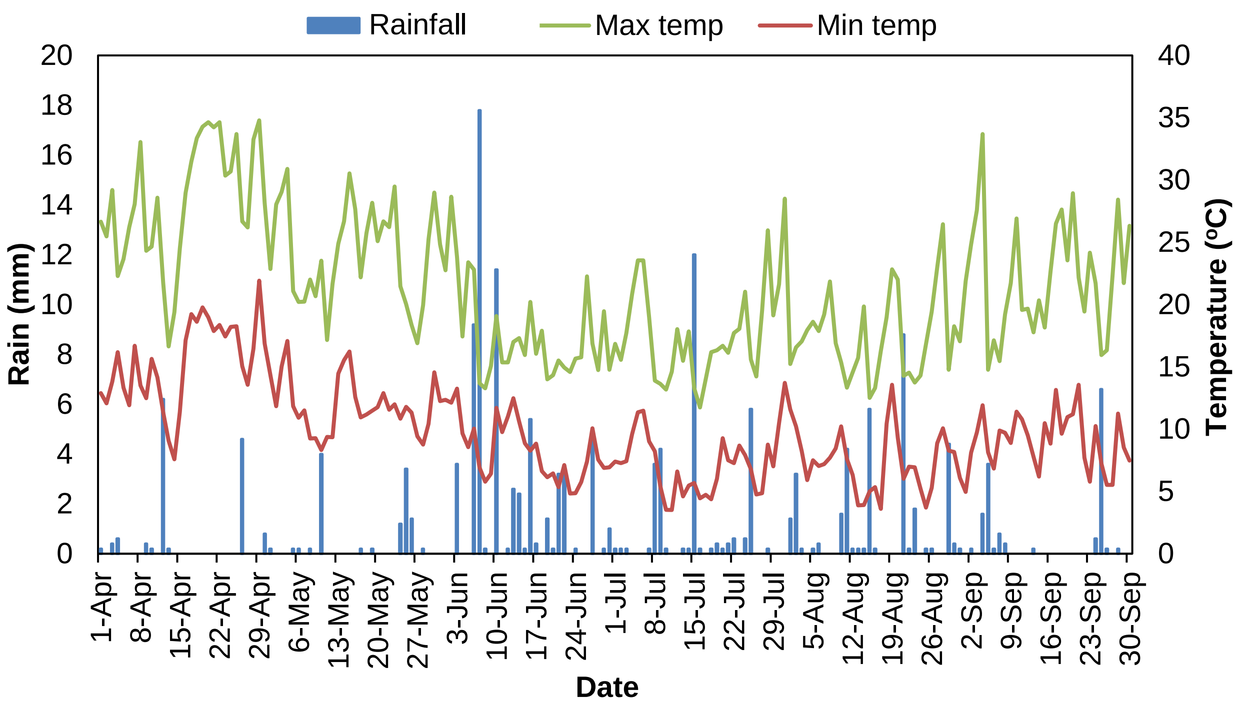


Figure 3.9 Rainfall (mm), maximum and minimum air temperatures (ºC) during Year 2 at Langgewens Research Farm.

3.1.5 Nuhoop, Porterville

The Nuhoop farm is located approximately 15 km north of Porterville (32°54’30” S, 18°55’57” E, altitude 153 m). Porterville also forms part of the Swartland region and was included in this study due to its position in the middle Swartland/Rooi-karoo sub-regions. Most of the soil profile is deep reddish-coloured clay loam to clay, developed on old (African surface) pre-weathered acidic materials. About 25% of the area consists of termite mounds called “*heuweltjies*” with medium-deep to shallow neutral soils (A. Ellis, personal communication, October 14, 2017).

The long-term average annual rainfall is 455 mm and approximately 80% falls between the months of April and October. The rainfall, VWC and soil temperature data for Year 1 and 2 can be seen in Figure 3.10 and Figure 3.11, respectively.

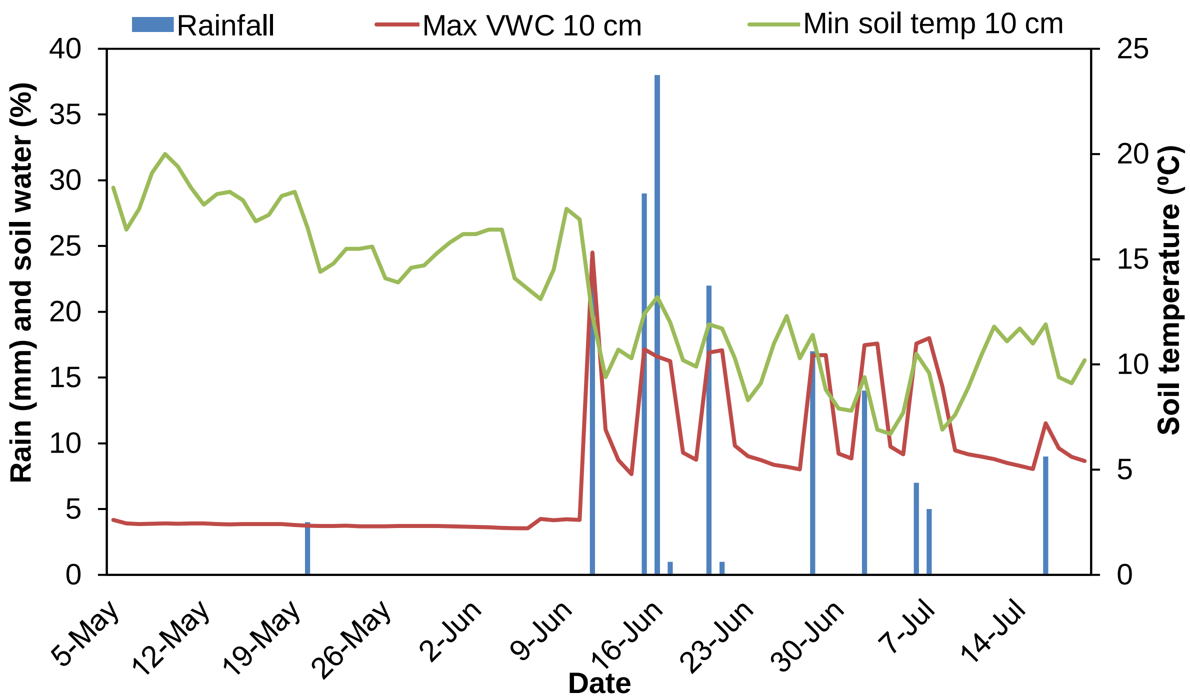


Figure 3.10 Rainfall (mm), volumetric soil water content (VWC, %) and soil minimum temperature (ºC) at a 10 cm depth during Year 1 at Porterville.

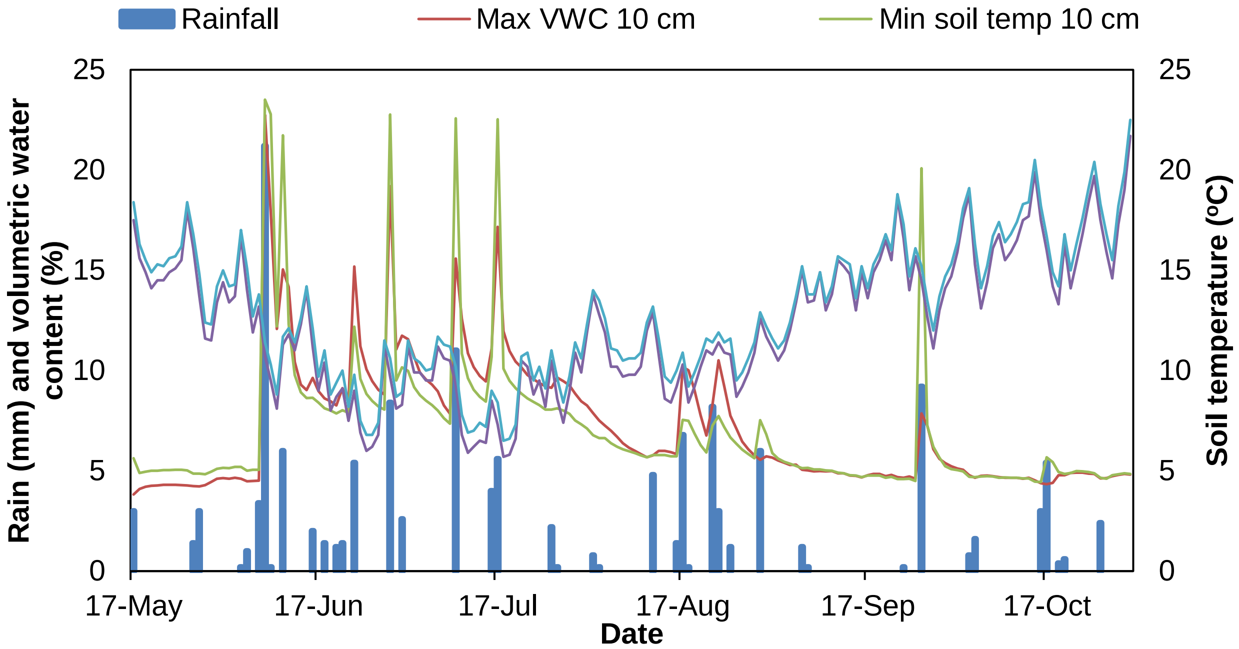


Figure 3.11 Rainfall (mm), volumetric soil water content (VWC, %) and soil minimum temperature (ºC) at 7 and 15 cm depths during Year 2 at Porterville.

3.1.6 Klipklei, Darling

The Klipklei farm is situated approximately 13 km north of Darling (32°54'30" S, 18°55'57" E) and at an altitude of 63 m above sea level. This area is known as the Sandveld, predominately consisting of red and grey medium-deep sandy clay loam soils developed from granite (A. Ellis, personal communication, October 14, 2017). The Sandveld area has a lower potential for wheat production and differs substantially from the other sites in terms of annual rainfall and soil composition.

The long-term average annual rainfall is 418 mm in Darling. The rainfall, VWC and soil temperature data for Year 1 and 2 can be seen in Figure 3.12 and Figure 3.13, respectively.

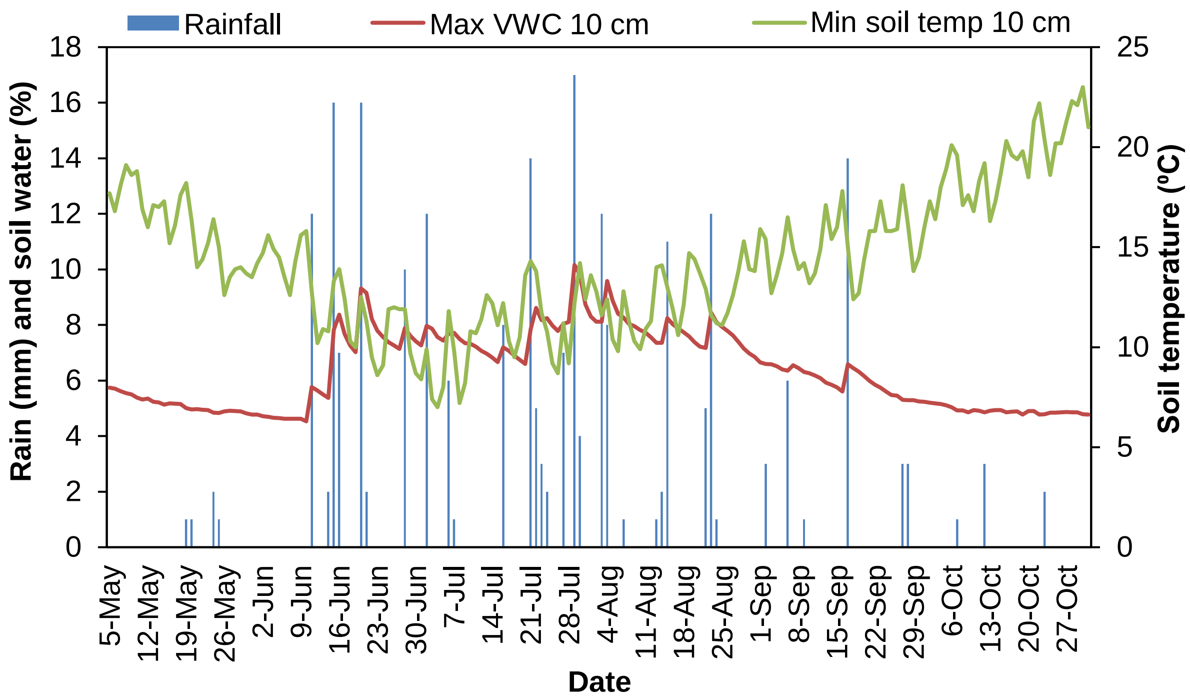


Figure 3.12 Rainfall (mm), volumetric soil water content (VWC, %) and soil minimum temperature (ºC) at a 10 cm depth during Year 1 at Darling.

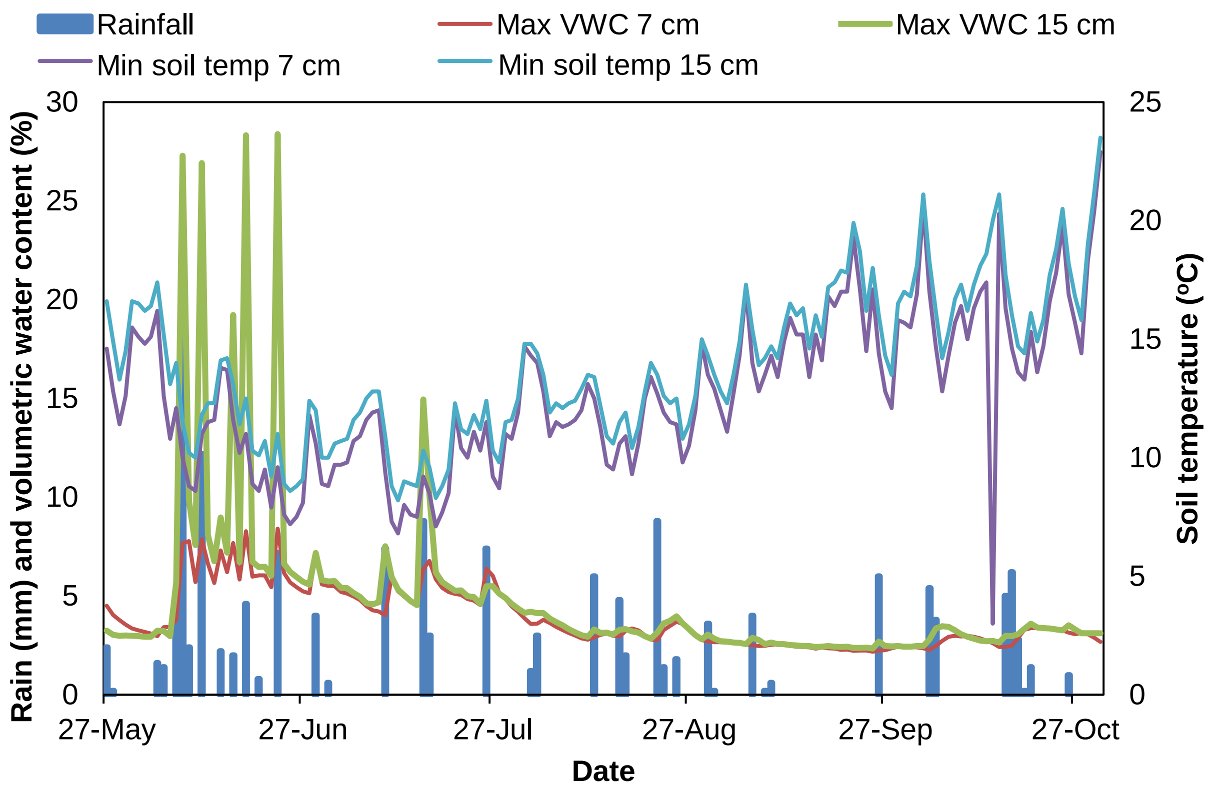


Figure 3.13 Rainfall (mm), maximum volumetric soil water content (VWC, %) and soil minimum temperature (ºC) at 7 and 15 cm depths during Year 2 at Darling.

The total rainfall and average maximum VWC as recorded at a 15 cm depth, between the pre- and post-topdress soil sampling events, are shown in Table 3.1. Due to faulty loggers, especially in Year 1, all the data was not available for publishing.

Table 3.1 The total rainfall (mm) and average maximum volumetric water capacity (% or m m^{-3}) of the soil, at a depth of 15cm, between pre- and post-topdress soil sampling stages at the different research sites.

Site	Year 1		Year 2	
	Rain (mm)	VWC Max	Rain (mm)	VWC Max
Riversdale	*	*	23.0	5.98%
Tygerhoek	*	0.15 m^3 m^{-3}	15.0	8.28%
Caledon	*	*	*	0.14 m^3 m^{-3}
Langgewens	29.4	*	11.4	*
Porterville	43.0	12.20%	5.8	6.26%
Darilng	55.0	7.30%	4.2	3.77%

* No data collected

3.2 Experimental design and treatments

The trial was subdivided into two separate studies namely: i) topdressed Nitrogen (N) rates with or without foliar applications and ii) N sources at topdress. Both studies were repeated over 2 years

Wheat sequences included in the study were site specific:

- Wheat after canola (C/W) (Riversdale, Tygerhoek, Langgewens, Porterville, Darling)
- Wheat after medics (M/W) (Darling, Porterville and Langgewens)
- Wheat after lucerne (L/W) (Caledon)

The first study was laid out in a split-plot design. The whole plot factor was seven N topdressing treatments plus a control. The one half of each whole plot received no foliar application whilst the other half received 10 kg N ha^{-1}, in the form of urea ammonium nitrate (UAN) in Year 1 and 20 kg N ha^{-1} in Year 2. Therefore, the sub-plot factor was foliar N application (Table 3.2). Whole plot sizes were 12.6 x 2.1 m and sub-plot sizes 6.3 x 2.1 m. Each whole plot was replicated in four blocks; except for Riversdale, where only 3 blocks were possible.

Nitrogen, in the form of LAN + S, was applied at topdress stage for the different treatments as stipulated in Table 3.2. Topdress N was applied approximately a week before the period of maximum N uptake (stem elongation); ± 40 days after planting. The N rate for each plot was weighed beforehand and broadcasted by hand to ensure accurate application. Foliar applications of urea ammonium nitrate (UAN) were applied when the flag leaf of the wheat plants became clearly visible. Knapsack sprayers were calibrated and used to apply foliar treatments.

Table 3.2 Treatments and their description pertaining to the N input at topdressing and foliar application at two different crop growth stages that was used in the first study.
Notes: Treatments labelled -Foliar received no foliar UAN application. Those labelled +Foliar received 10 kg N ha^{-1} UAN in Year 1 and 20 kg N ha^{-1} in Year 2.

N input at plant (kg N ha^{-1})	N topdress treatment (Whole plot)	Topdress N rate (kg N ha^{-1})	Foliar N application (split plot)	Total N input (kg N ha^{-1})
0	C (control)	0	-Foliar	0
			+Foliar	10 (Year 1) & 20 (Year 2)
25	T0	0	-Foliar	25
			+Foliar	35 (Year 1) & 45 (Year 2)
25	T1	25	-Foliar	50
			+Foliar	60 (Year 1) & 70 (Year 2)
25	T2	50	-Foliar	75
			+Foliar	85 (Year 1) & 95 (Year 2)
25	T3	75	-Foliar	100
			+Foliar	110 (Year 1) & 120 (Year 2)
25	T4	105	-Foliar	130
			+Foliar	140 (Year 1) & 150 (Year 2)
25	T5	135	-Foliar	160
			+Foliar	170 (Year 1) & 180 (Year 2)
25	T6	165	-Foliar	190
			+Foliar	200 (Year 1) & 210 (Year 2)

In the second study, fertiliser N sources were evaluated in a randomised block design, with five N sources (treatments) and four replications (Table 3.3). The N source treatment plots were 9 x 2.1 m (planter width). Each source treatment was planted with 25 kg N ha^{-1} and received the topdress application at the beginning of their stem elongation period as indicated in Table 3.4 for Year 1 and Year 2.

Table 3.3 N source treatments as well as their elemental compositions, with regards to N and S content, that was used in the second study.

Fertiliser source	N and S elemental composition
Limestone ammoinium nitrate (LAN)	**28% N**
Ammonium Sulphate (AMS)	**21% N; 24% S**
Kysan (LAN + S)	**24% N; 3% S**
Urea	**46% N**
Urea + urease inhibitor	**46% N**

Table 3.4 Topdressed N rate (kg N ha^{-1}) of the N source study at the different sites included in the study, Year 1 and Year 2. The N rate of the source treatments was determined by consulting several fertiliser experts on N requirement of wheat in CA based rotation systems.

Site	Topdress N rate (kg N ha^{-1})	
	Year 1	Year 2
Riversdale C/W	30	30
Tygerhoek C/W	55	55
Caledon L/W	5	10
Langgewens M/W	48	48
Langgewens C/W	75	75
Porterville M/W	35	35
Porterville C/W	63	63
Darling M/W	35	35
Darling C/W	65	65

Each site and cropping sequence, used in both studies, were treated as a separate trial; therefore, the comparison of different sites or cropping sequences were not relevant for this paper. No comparison between Year 1 and Year 2 was made and the two years were treated as separate from each other for both studies.

3.3 Crop management

3.3.1 Pre-plant activities

Where necessary, a non-selective herbicide (glyphosate) was applied before planting to ensure a weed free seedbed at planting. Sakura™ was applied just before seeding or within three days after seeding to control annual grass weeds, particularly ryegrass (*Lolium rigidum*). Plots were measured and marked prior to planting to take accurate, plot specific soil samples.

3.3.2 Activities at planting

In Year 1, all treatments including the different N sources, were planted with 25 kg N ha^{-1} of which 15 kg N ha^{-1} was applied in the form of a 1:1:1 (N:P:K) fertiliser mix with both the disc- and tine planter and the remaining 10 kg N ha^{-1} was broadcasted in the form 1:0:0 prior to planting. The control plots were planted without N, but they did however receive 15 kg P ha^{-1} in the form of single superphosphate to compensate for the additive P applied on the other trial plots.

The same protocol was followed in Year 2, with the exception being that 5 kg N ha^{-1} was applied with the disc planter and the remaining 20 kg N ha^{-1} was broadcasted. This change was implemented to mitigate any seed burn that might have occurred in Year 1. All the plots, received 300 kg ha^{-1} gypsum at planting to prevent any S deficiency effect that may have occurred in Year 1.

An AusPlow no-tillage tine planter with knife openers was used to establish wheat at Langgewens, Porterville and Darling. Caledon, Tygerhoek and Riversdale, were planted with a double disc planter from Rovic and Leers. Wheat, cultivar SST 056, was planted at a rate of 80 kg seed ha^{-1} on all sites. Due to logistical reasons of transporting the planters, two different planters were used to facilitate optimal planting time at each site.

To prevent lateral N movement between treatments, 2.1 m buffer zones were planted in all trials without any N application. Planting dates for Year 1 are shown in Table 3.5.

Table 3.5 The planting date for all sites during Year 1 and 2.

Site	Year 1	Year 2
Riversdale C/W	27 April	26 April
Tygerhoek C/W	3 May	5 June
Caledon L/W	12 May	22 May
Langgewens M/W	10 May	17 May
Langgewens C/W	10 May	17 May
Porterville M/W	21 April	16 May
Porterville C/W	21 April	18 May
Darling M/W	21 April	16 May
Darling C/W	21 April	18 May

Planting dates in Year 2 were later than in Year 1, due to late rainfall and doubtful seedbed conditions.

3.3.3 In-season activities

Weed and disease management was applied during the growing season using a quadbike sprayer at Riversdale, Tygerhoek, Caledon and Langgewens during Year 1 and Year 2. In Year 1, knapsack sprayers were used at Porterville and Darling to apply herbicides and fungicides. In Year 2 the trials at Porterville and Darling were sprayed using a tractor and 30-meter-wide boomsprayer.

3.4 Data collection

3.4.1 Soil parameters

Soil samples were taken at a depth of 30 cm three months before the anticipated planting date to determine the physical and chemical compositions of the soil at the different sites.

The following methods of soil analyses were used (Non-Affiliated Soil Analysis Work Committee (1990):

- Soil pH in 1:2.5 soil:KCl suspension
- Exchangeable acidity with K_2SO_4 extraction
- Exchangeable Base cations (Ca, Mg, K, Na) in citric acid solution
- Cation exchange capacity (CEC) with the ammonium acetate method
- Extractable P in citric acid solution
- Extractable S in calcium phosphate solution
- Exchangeable Cu, Mn and Zn in di-ammonium EDTA
- Exchangeable B with the hot water method
- Organic C with the Walkley-Black method
- Total C and N contents with a Leco TruspecR analyser.
- Particle size were determined by the hydrometer method (using sodium hexametaphosphate)
- Stone fraction by wet sieving over 2mm sieve.

Table 3.6 and Table 3.7 indicate the particle size and chemical analyses, respectively. Table 3.8 shows the soil C and N content for all aites as well as the C:N ratios, before the trial started.

To monitor the soil mineral N content in the first study, a composite soil sample comprising of 4 subsamples per treatment combination was collected at a depth of 30 cm one day (1) pre-planting, (2) pre-topdress, (3) post-topdress and (4) post-harvest. Samples were air dried as quickly as possible by placing the soil in an open tray as Wienhold and Halvorson (1999) reported that the conversion of ammonium-N to nitrate-N, under field conditions, may occur rapidly under favourable soil conditions. Both the ammonium-N and nitrate-N contents of the soil samples were therefore measured and used to determine the total mineral N (ammonium-N + nitrate-N) as an indicator of inorganic N content. No substantial differences in soil mineral N content were recorded in Year 1; therefore, the pre-plant sampling was not done for every individual treatment in Year 2. Rather, every repitition within the block was included as to give a general indication of the mineral N content of the soil. As can be seen in Table 3.7, soil fertility was within the recommended ranges for wheat, except for a few nutrients, which are outlined below:

The trace element concentration at Darling was sub-optimal during Year 1 and 2. Soil salinity or rather, sodicity (low resistance and high Na concentration), was recorded at Porterville M/W. The S concentration of a soil needs to be above 11 mg kg^{-1} to be considered optimal and a concentration of 9 mg kg^{-1} to be considered marginal 7 (FERTASA, 2016b). The Tygerhoek, Caledon and both Darling sites had sub-optimal S concentrations during Year 1, which could have been a limiting factor for crop growth. The S deficiencies during Year 2 were rectified by the application of gypsum. Fertilisation of P and K at planting were based on the results shown in Table 3.7, and it is therefore expected to be adequate for wheat production.

Table 3.6 The particle size composition of the soil samples taken from the trial plots at all nine sites for both years. The samples were taken to a depth of 30 cm.

Site	Year	Sand (%)			Silt (%)	Clay (%)	Stone (%)
		Coarse	Medium	Fine			
Riversdale C/W	**1**	30	10	28	16	16	70
	2	25	11	33	23	8	44
Tygerhoek C/W	**1**	35	14	16	15	22	65
	2	19	6	29	32	16	33
Caledon L/W	**1**	35	7	27	10	22	57
	2	19	10	33	26	12	41
Langgewens M/W	**1**	19	7	42	11	23	51
	2	24	8	40	18	11	37
Langgewens C/W	**1**	21	7	41	10	22	60
	2	19	8	42	24	8	45
Porterville M/W	**1**	16	9	39	17	20	38
	2	14	8	34	20	24	25
Porterville C/W	**1**	16	9	31	19	26	48
	2	12	8	42	16	22	9
Darling M/W	**1**	34	25	30	6	6	3
	2	53	18	19	6	4	2
Darling C/W	**1**	35	26	31	4	4	3
	2	39	25	26	6	4	1

Table 3.7 Chemical soil analyses taken to a depth of 30 cm, at all the research sites for Year 1 and Year 2.

Site	Year	pH (KCl)	Resistance (ohm)	Ca (mg kg^{-1})	Mg (mg kg^{-1})	Na (mg kg^{-1})	K (mg kg^{-1})	CEC (cmol kg^{-1})	P (mg kg^{-1})	Cu (mg kg^{-1})	Zn (mg kg^{-1})	Mn (mg kg^{-1})	B (mg kg^{-1})	S (mg kg^{-1})	C (%)
Riversdale C/W	**Year 1**	5.6	700	860	146	99	257	6.5	34	0.8	0.9	58	0.4	14	1.1
	Year 2	5.5	750	700	110	31	189	5.2	35	0.6	1.0	53	0.3	9.0	1.0
Tygerhoek C/W	**Year 1**	5.2	780	880	171	41	146	7.0	23	0.8	0.9	81	0.4	6.9	1.1
	Year 2	5.7	492	960	207	130	177	7.4	26	1.2	1.5	123	0.6	11	1.2
Caledon L/W	**Year 1**	5.4	670	760	134	59	227	6.4	34	1.9	1.3	121	0.6	5.7	1.1
	Year 2	5.3	1060	796	112	33	230	6.3	49	1.2	0.8	114	0.4	5	1.2
Langgewens M/W	**Year 1**	5.7	440	940	110	40	141	6.1	51	1.7	2.5	141	0.4	15	0.7
	Year 2	5.1	587	560	73	20	122	4.2	64	1.0	1.6	71	0.4	9.6	1.0
Langgewens C/W	**Year 1**	5.3	500	660	73	24	225	5.0	61	2.0	4.4	150	0.4	21	1.0
	Year 2	5.1	925	600	73	14	113	4.5	62	1.3	1.7	116	0.3	13	1.0
Porterville M/W	**Year 1**	5.4	200	620	183	330	64	6.5	53	2.1	1.9	228	0.9	19	0.7
	Year 2	5.6	210	656	164	190	319	6.3	74	2.0	2.5	189	0.5	17	1.3
Porterville C/W	**Year 1**	5.9	385	760	134	132	81	5.7	53	2.8	1.4	164	0.4	31	0.8
	Year 2	5.0	540	450	71	38	150	4.0	68	3.2	2.7	415	0.5	14	0.9
Darling M/W	**Year 1**	5.8	820	300	73	38	88	2.6	45	0.3	0.6	9.6	0.3	4.5	0.6
	Year 2	4.9	1490	160	49	23	22	1.7	36	0.2	1.0	2.3	0.1	4.3	0.3
Darling C/W	**Year 1**	5.3	1255	180	49	16	43	1.9	44	1.5	1.3	8.1	0.1	4.7	0.2
	Year 2	5.3	1260	238	62	22	29	2.2	52	0.4	1.0	4.6	0.2	6.5	0.3

Table 3.8 Soil C and N content (%) for all the sites during both years. Composite samples were taken to a depth of 30 cm.

Site	Year	C (%)	N (%)	C:N Ratio
Riversdale C/W	**Year 1**	1.15	0.17	6.79
	Year 2	0.89	0.09	10.00
Tygerhoek C/W	**Year 1**	1.33	0.23	5.80
	Year 2	1.42	0.11	13.20
Caledon L/W	**Year 1**	0.20	1.13	5.73
	Year 2	1.33	0.09	14.85
Langgewens M/W	**Year 1**	0.87	0.12	7.06
	Year 2	0.96	0.07	14.05
Langgewens C/W	**Year 1**	0.76	0.11	6.74
	Year 2	0.90	0.07	14.05
Porterville M/W	**Year 1**	0.74	0.12	6.24
	Year 2	0.98	0.08	12.65
Porterville C/W	**Year 1**	0.62	0.10	6.03
	Year 2	0.60	0.05	11.50
Darling M/W	**Year 1**	0.34	0.05	8.77
	Year 2	0.28	0.03	9.88
Darling C/W	**Year 1**	0.30	0.04	9.06
	Year 2	0.30	0.04	8.70

3.4.2 Plant parameters

Seedling population was determined 3 to 4 weeks after emergence by counting the number of seedlings per meter row length and replicated 12 times.

The number of seedlings m^{-1} was converted to seedlings m^{-2} using the following formulas:

- Disc planter (175 mm row spacing) = seedlings m^{-1} / 0.175
- Tine planter (300 mm row spacing) = seedlings m^{-1} / 0.3

Plant samples were collected by cutting four one-meter rows per plot at soil level. The amount of ear bearing tillers (EBT) per m^2 was determined by counting the number of tillers on all the sampled plants within the plot and using the following formulas:

- Disc planter (175 mm row spacing) = (EBT /4m) / 0.175

- Tine planter (300 mm row spacing) = (EBT /4m) / 0.3

The plants were oven dried at 40°C for 72 hours, after which all of the plant samples per plot were weighed. Biomass (kg ha^{-1}) was determined using the following formulas:

- Disc planter (175 mm row spacing) = $\frac{Sample\ weight\ (kg)}{(4 \text{ x } 0.175)}\ x\ 10000$
- Tine planter (300 mm row spacing) = $\frac{Sample\ weight\ (kg)}{(4 \text{ x } 0.3)}\ x\ 10000$

3.4.3 Grain yield

Plots were harvested using a small plot harvester. After harvesting, the grain was cleaned and weighed. Grain yield was determined using the following formulas:

- Disc planter (175 mm row spacing) = $\frac{\left(\frac{(\text{Sample weight (kg) x 10000})}{(1.575 \text{ x } 6)-0.7}\right)}{1000}$
- Tine planter (300 mm row spacing) = $\frac{\left(\frac{(\text{Sample weight (kg) x 10000})}{(1.5 \text{ x } 6)-1.2}\right)}{1000}$

3.4.4 Nitrogen use efficiency

The N use efficiency was calculated using the following formula: $\frac{Grain\ yield\ (kg\ ha^{-1})}{Total\ applied\ N\ (kg\ N\ ha^{-1})}$

3.4.5 Quality parameters

A Cox funnel was used to determine hectolitre mass. Wheat samples were analysed for dry matter and crude protein (at a 12% moisture level) by scanning each sample as duplicates in the reflectance mode between 950 - 1650 nm and recorded as log (1/R) at 2 nm increments of the near-infrared region on a Perten DA7200 Diode Array analyser (Perten Instruments AB, Huddinge, Sweden). Approximately 100 g of each sample in whole seed form was packed into an open rotating sample cup with a diameter of 75 mm - AOAC Official Method 989.03.

Harvest indices were calculated using the following formula: $\frac{Yield\ (kg\ ha^{-1})}{Biomass\ (kg\ ha^{-1})}$

Ten plants per plot were ground and allowed to pass through a 1 mm sieve and analysed for % N content using the Kjeldahl method (AOAC, 2000). The % value was then multiplied by the biomass of each individual plot to determine the amount of N (kg ha^{-1}) taken up into the biomass.

3.5 Statistical analyses

The data was subjected to analysis of variance (ANOVA) using General Linear Models Procedure (PROC GLM) of SAS software (Version 9.2; SAS Institute Inc, Cary, USA). Shapiro-Wilk test was performed on the standardised residuals from the model to verify normality (Shapiro and Wilk, 1965). Fisher's least significant difference was calculated at the 5% level to compare treatment means (Ott, 1998). A probability level of 5% was considered significant for all significance tests.

4 The effect of different fertiliser rates on the grain yield, selected yield components, quality parameters and N use efficiency of wheat.

4.1 Results

Each site's data will be discussed separately in the following order: i) Soil mineral N content, ii) Plant parameters, iii) Grain yield, iv) Nitrogen use efficiency (NUE), and v) Quality parameters. Note that the data from Year 1 and Year 2 was statistically analysed separately and will not be compared with each other.

4.1.1 Riversdale C/W

4.1.1.1 Soil mineral N content

The control treatment had a lower soil mineral N content ($P < 0.05$) than some of the other treatments, at the pre-plant stage for Year 1 (Figure 4.1.1).

The control treatment resulted in the lowest ($P < 0.05$) soil mineral N content, at pre-topdress stage, for both years (Figure 4.1.1 and Figure 4.1.2, respectively). Increasing the fertiliser topdress N rate resulted in a gradual increase ($P < 0.05$) in post-topdressed mineral N content in both years.

The post-harvest soil mineral N content of the different treatments did not differ ($P < 0.05$) in Year 1, except for 165 kg N ha^{-1} which was higher and did not differ from 105 kg N ha^{-1} (Figure 4.1.1). Almost no residual fertiliser N remained in the topsoil after harvesting. The only exception was 165 kg N ha^{-1}, which indicates that the nett input of N to soil was higher than the removal. It will, however, be difficult to determine the fate of the applied N as the sampling depth of 30 cm will not detect deep percolation of leached N.

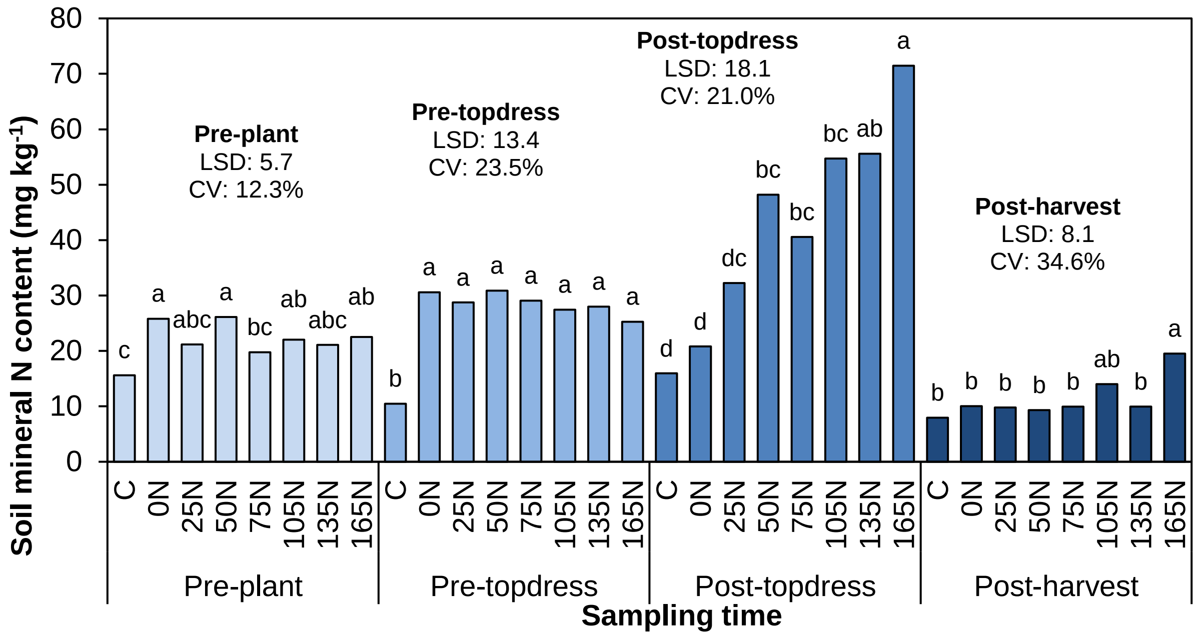


Figure 4.1.1 Total mineral N (mg kg^{-1}) as influenced by topdress N rate (kg ha^{-1}) at Riversdale (Year 1). C = control, 0N, 25N, 50N, 75N, 105N, 135N and 165N = kg N ha^{-1} topdressed. LSD = Least significant difference (P < 0.05); CV = coefficient of variance. Bars with different letters within a specific sampling time indicate significant differences at a 5% level.

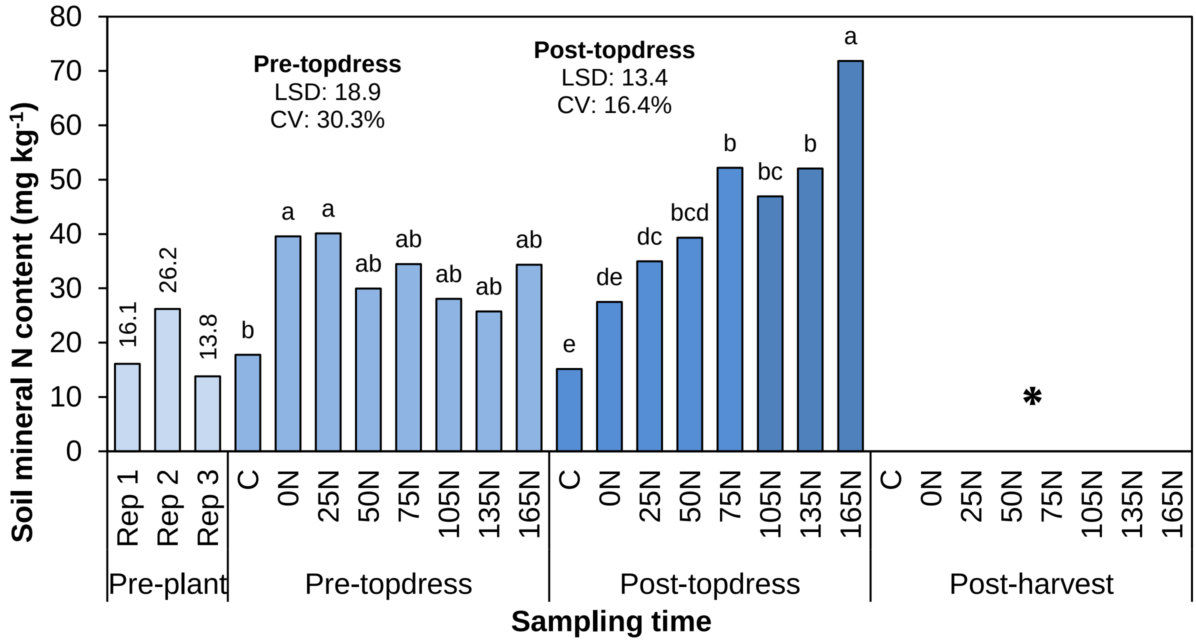


Figure 4.1.2 Total mineral N (mg kg^{-1}) as influenced by topdress N rate (kg ha^{-1}) at Riversdale (Year 2). C = control, 0N, 25N, 50N, 75N, 105N, 135N and 165N = kg N ha^{-1} topdressed. LSD = Least significant difference (P < 0.05); CV = coefficient of variance. Bars with different letters within a specific sampling time indicate significant differences at a 5% level. *Missing data.

The regression between total soil mineral N content and total applied N is described by the equation y = 0.28x + 16.43 (R^2 = 0.80) in Year 1 and y = 0.17x + 32.30 (R^2 = 0.24) in Year 2 (Figure 4.1.3). This indicates a stronger regression between the two variables in Year 1 than Year 2. However, apart from two outliers in Year 2, the response between the two years was similar.

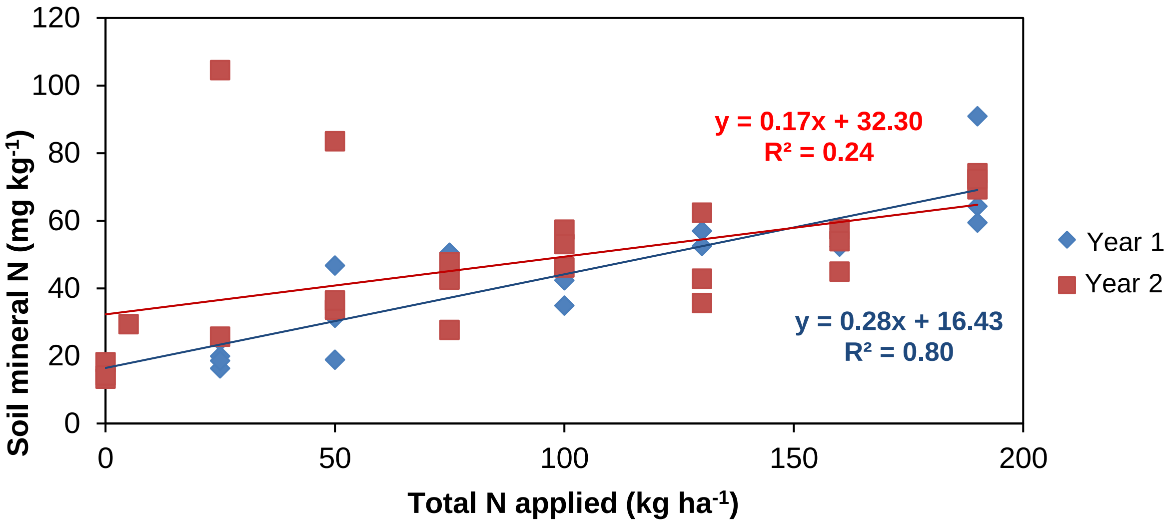


Figure 4.1.3 The response of total soil mineral N at post-topdress stage to total N applied during the growing season at Riversdale for both years as indicated.

4.1.1.2 Plant parameters

No differences ($P > 0.05$) in seedling population were recorded in Year 1 (Table 4.1.1). In Year 2 the 165 kg N ha^{-1} treatment had a higher ($P < 0.05$) seedling population than the 0 and 105 kg ha^{-1} treatments respectively. The number of ear bearing tillers (EBT) in the control was lower ($P < 0.05$) than most of the other treatments in Year 1. In Year 2, the 0 kg N ha^{-1} treatment had a higher ($P < 0.05$) number of EBT than that of the control and the 105 kg N ha^{-1} treatments. The control treatment produced the lowest ($P < 0.05$) biomass compared to the other treatments in Year 1 and lower ($P < 0.05$) than the 0 and 25 kg N ha^{-1} treatments in Year 2.

4.1.1.3 Grain yield

The control treatment resulted in the lowest ($P < 0.05$) grain yield in Year 1 (Figure 4.1.4). In Year 1 yield increased ($P < 0.05$) as topdress N rate was increased to 25 kg N ha^{-1}. However, no differences ($P > 0.05$) in grain yield were recorded for N rates between the 50 and 165 kg N ha^{-1} treatments.

During Year 2 yields increased ($P < 0.05$) with the increasing N rates up until maximum yield was achieved at a topdress rate of 75 kg N ha^{-1}, thereafter a decrease ($P < 0.05$) in grain yield was experienced (Figure 4.1.5).

Table 4.1.1 Seedling population (m^{-2}), number of EBT (m^{-2}) and biomass production (kg ha^{-1}) as influenced by topdressed fertiliser N rate (kg ha^{-1}) at Riversdale during Year 1 and 2 of the study.

				Year 1						
Topdress N rate (kg ha^{-1})	**control**	**0**	**25**	**50**	**75**	**105**	**135**	**165**	**CV (%)**	**LSD**
Seedlings (m^{-2})	106.7 ^{a}	93.3 ^{a}	86.0 ^{a}	106.7 ^{a}	86.0 ^{a}	96.7 ^{a}	92.7 ^{a}	87.3 ^{a}	**15.0**	**27.2**
EBT (m^{-2})	107.1 ^{b}	289.7 ^{a}	322.4 ^{a}	314.3 ^{a}	315.7 ^{a}	250.7 ^{ab}	306.7 ^{a}	357.6 ^{a}	**26.2**	**148.6**
Biomass (kg ha^{-1})	3429 ^{b}	12400 ^{a}	15429 ^{a}	14286 ^{a}	13095 ^{a}	15071 ^{a}	14857 ^{a}	14333 ^{a}	**30.4**	**7783**
				Year 2						
Seedlings (m^{-2})	82.9 ^{ab}	60.0 ^{b}	71.9 ^{ab}	76.7 ^{ab}	71.9 ^{ab}	70.0 ^{b}	77.7 ^{ab}	96.2 ^{a}	**12.8**	**25.3**
EBT (m^{-2})	182.0 ^{bc}	227.1 ^{a}	220.0 ^{ab}	195.7 ^{abc}	205.7 ^{abc}	173.3 ^{c}	190.5 ^{abc}	202.8 ^{abc}	**11.0**	**18.5**
Biomass (kg ha^{-1})	3905 ^{b}	5667 ^{a}	5286 ^{a}	4857 ^{ab}	5048 ^{ab}	4571 ^{ab}	4667 ^{ab}	4571 ^{ab}	**15.2**	**1286**

Means without a common superscripted letter in the same row indicate significant differences at a 5% level.

CV = Coefficient of variance

LSD = Least significant difference

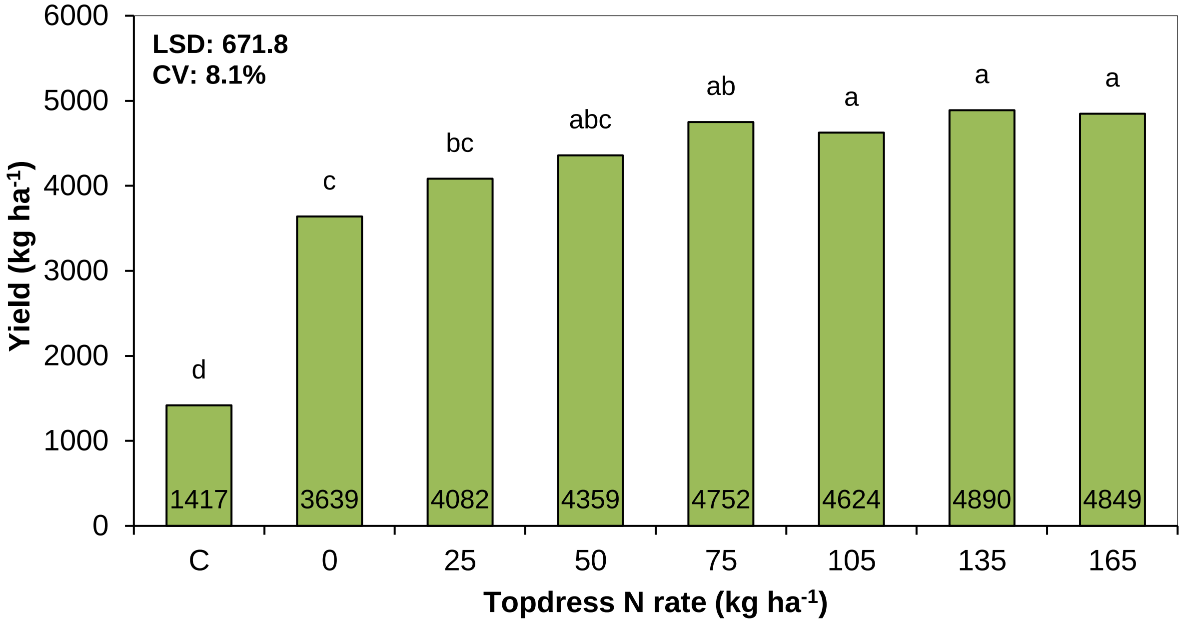


Figure 4.1.4 Grain yield (kg ha^{-1}) as influenced by topdress N rate (kg ha^{-1}) at Riversdale (Year 1). LSD = Least significant difference (P < 0.05); CV = coefficient of variance. Bars with different letters indicate significant differences at a 5% level.

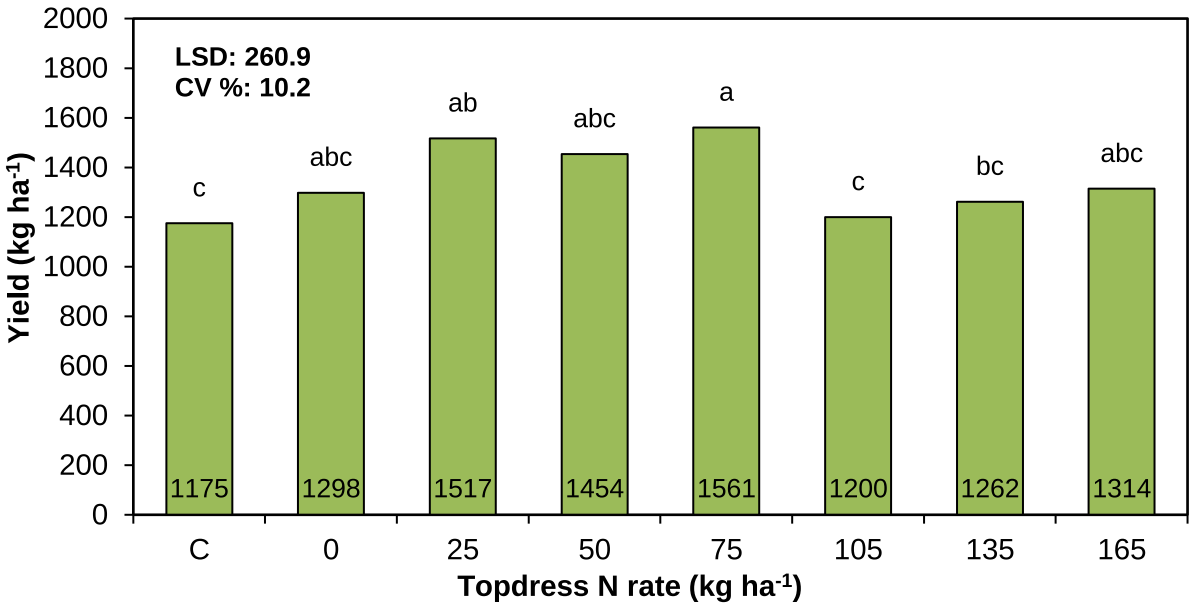


Figure 4.1.5 Grain yield (kg ha^{-1}) as influenced by topdress N rate (kg ha^{-1}) at Riversdale (Year 2). LSD = Least significant difference (P < 0.05); CV = coefficient of variance. Bars with different letters indicate significant differences at a 5% level.

4.1.1.4 Nitrogen use efficiency

Increasing N rates had a negative effect on NUE in both years, where increasing topdress N rate resulted in a decrease in NUE (Figure 4.1.6).

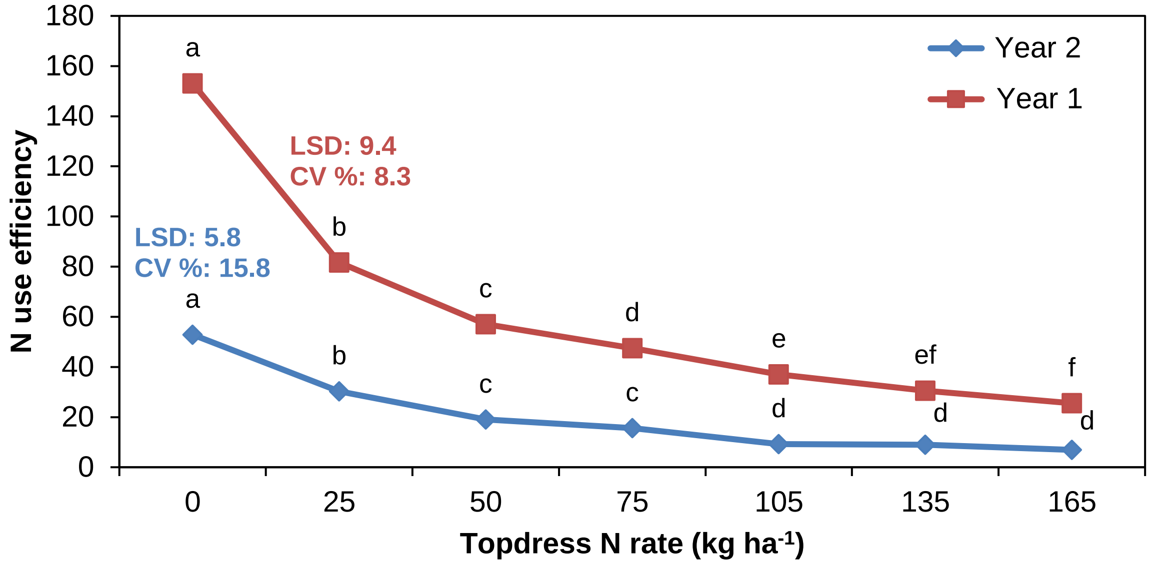


Figure 4.1.6 N use efficiencies per corresponding topdress N rate (kg ha^{-1}) at Riversdale (Year 1 and 2). No common letter within a year indicates significant difference at a 5% level.

4.1.1.5 Quality parameters

There were no differences in hectolitre mass between treatments ($P > 0.05$) in Year 1, but in Year 2, the control treatment had a higher ($P < 0.05$) hectolitre mass than that of the 75, 105 and 165 kg N ha^{-1} treatments (Table 4.1.2). No differences ($P > 0.05$) in harvest index were recorded in either of the years.

Protein content showed a positive response to topdress N rate as there was a gradual increase in protein content in both Year 1 and 2. Other than the control treatment that had a lower ($P < 0.05$) biomass N, no differences ($P > 0.05$) were recorded for either Year 1 or 2.

Table 4.1.2 Hectolitre mass, grain protein content, harvest index and biomass N (kg ha^{-1}) as influenced by topdressed fertiliser N rate (kg ha^{-1}) at Riversdale during Year 1 and 2.

				Year 1						
Topdress N rate (kg ha^{-1})	**control**	**0**	**25**	**50**	**75**	**105**	**135**	**165**	**CV (%)**	**LSD**
Hectolitre mass (g cm^{-3})	*	78.1 ^{a}	78.8 ^{a}	78.8 ^{a}	78.8 ^{a}	78.6 ^{a}	78.8 ^{a}	78.3 ^{a}	**0.8**	**1.2**
Protein content (%)	8.8 ^{d}	8.7 ^{d}	9.5 ^{cd}	9.8 ^{cd}	10.3 ^{bc}	10.8 ^{abc}	11.5 ^{ab}	12.0 ^{a}	**6.3**	**1.3**
Harvest index	0.41 ^{a}	0.31 ^{a}	0.28 ^{a}	0.30 ^{a}	0.47 ^{a}	0.34 ^{a}	0.34 ^{a}	0.34 ^{a}	**28.9**	**0.20**
Biomass N (kg ha^{-1})	30.9 ^{b}	98.9 ^{ab}	148.1 ^{a}	145.6 ^{a}	140.5 ^{a}	156.6 ^{a}	158.7 ^{a}	144.6 ^{a}	**33.4**	**92.5**
				Year 2						
Hectolitre mass (g cm^{-3})	77.7 ^{a}	76.3 ^{ab}	75.7 ^{ab}	76.1 ^{ab}	75.2 ^{b}	74.7 ^{b}	75.7 ^{ab}	75.1 ^{b}	**1.5**	**2.0**
Protein content (%)	10.2 ^{d}	12.1 ^{c}	13.1 ^{bc}	13.4 ^{bc}	13.6 ^{ab}	14.0 ^{ab}	13.9 ^{ab}	14.8 ^{a}	**5.4**	**1.2**
Harvest index	0.33 ^{a}	0.24 ^{a}	0.25 ^{a}	0.30 ^{a}	0.31 ^{a}	0.27 ^{a}	0.31 ^{a}	0.30 ^{a}	**24.7**	**0.12**
Biomass N (kg ha^{-1})	49.4 ^{b}	83.1 ^{a}	78.5 ^{ab}	64.6 ^{ab}	69.7 ^{ab}	74.2 ^{ab}	78.5 ^{ab}	77.5 ^{ab}	**25.3**	**31.8**

Means without a common superscript letter in the same row indicate significant differences at a 5% level.

CV = Coefficient of variance

LSD = Least significant difference

*Missing data

4.1.2 Tygerhoek C/W

4.1.2.1 Soil mineral N content

Soil samples taken at pre-planting stage showed no differences (P > 0.05) in soil mineral N content between N rate treatments in Year 1 (Figure 4.1.7). Except for 165 kg N ha^{-1}, pre-topdress soil samples did not differ (P > 0.05) in total N content in Year 1. In Year 2 no differences (P > 0.05) in soil mineral N content were recorded between treatments at the pre-topdress stage (Figure 4.1.8).

An increase (P < 0.05) in soil mineral N content was found with increasing topdress N rates at post-topdress stage for both Year 1 and 2. No differences (P > 0.05) in soil mineral N were found at post-harvest stage in Year 1. In Year 2, the 165 kg N ha^{-1} treatment had a higher (P < 0.05) soil mineral N content at the post-harvest stage than the 25, 75 and 105 kg N ha^{-1} treatments.

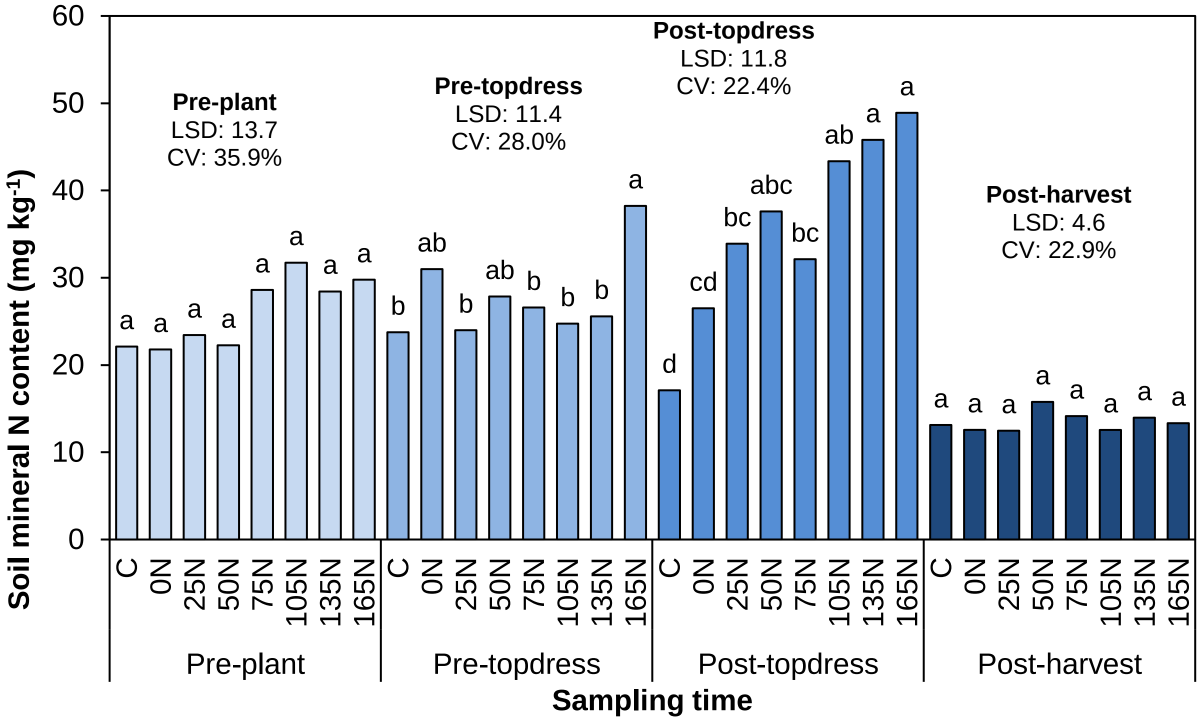


Figure 4.1.7 Total mineral N in the soil as influenced by topdress N rate (kg ha^{-1}) at Tygerhoek (Year 1). LSD = Least significant difference (P < 0.05); CV = coefficient of variance. Bars with different letters within a specific sampling time indicate significant differences at a 5% level.

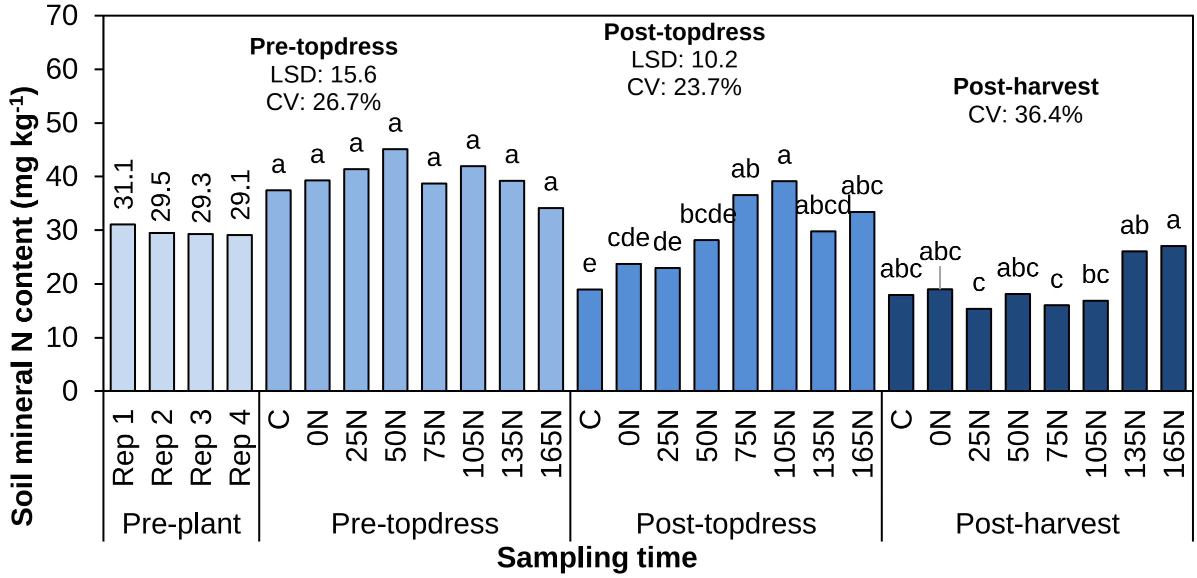


Figure 4.1.8 Total mineral N in the soil as influenced by topdress N rate (kg ha^{-1}) at Tygerhoek (Year 2). LSD = Least significant difference (P < 0.05); CV = coefficient of variance. Bars with different letters within a specific sampling time indicate significant differences at a 5% level.

The regression between total soil mineral N content and total applied N at Tygerhoek is described by the equation y = 0.15x + 21.96 (R^2 = 0.50) in Year 1 and y = 0.08x + 21.73 (R^2 = 0.31) in Year 2 (Figure 4.1.9). There was a stronger regression between soil mineral N and total applied N in Year 1 than Year 2.

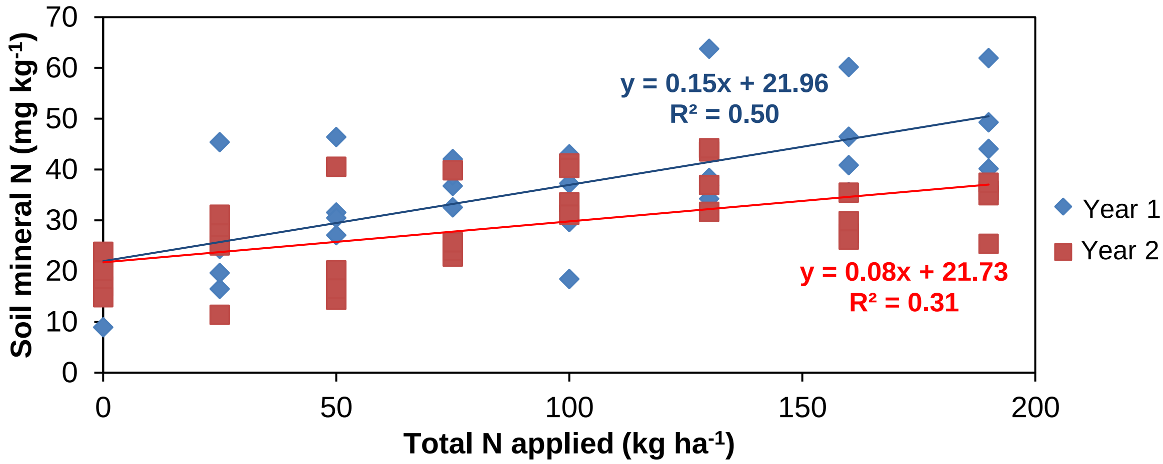


Figure 4.1.9 The response of total soil mineral N at post-topdress stage to total N applied during the growing season at Tygerhoek for the years as indicated.

4.1.2.2 Plant parameters

No differences (P > 0.05) in seedling populations were recorded in either Year 1 and 2 (Table 4.1.3). No differences (P > 0.05) in the number of EBT and biomass production were recorded for treatments when topdress N rates increased above 0 kg N ha^{-1}. During Year 2, N rate had no effect (P > 0.05) on EBT or biomass production.

Table 4.1.3 Seedling population (m^{-2}), number of EBT (m^{-2}) and biomass production ($kg\ ha^{-1}$) as influenced by topdressed fertiliser N rate ($kg\ ha^{-1}$) at Tygerhoek during Year 1 and 2 of the study.

Topdress N rate ($kg\ ha^{-1}$)	control	0	25	50	75	105	135	165	CV (%)	LSD
				Year 1						
Seedlings (m^{-2})	78.4 ^{a}	76.9 ^{a}	75.2 ^{a}	79.5 ^{a}	76.0 ^{a}	71.2 ^{a}	62.9 ^{a}	86.4 ^{a}	**21.9**	**23.6**
EBT (m^{-2})	220.5 ^{b}	283.6 ^{ab}	251.4 ^{ab}	292.9 ^{a}	280.0 ^{ab}	291.8 ^{a}	297.5 ^{a}	298.6 ^{a}	**19.2**	**77.7**
Biomass ($kg\ ha^{-1}$)	8667 ^{b}	11750 ^{a}	10464 ^{ab}	13036 ^{a}	11964 ^{a}	12143 ^{a}	13321 ^{a}	12714 ^{a}	**20.84**	**3560**
				Year 2						
Seedlings (m^{-2})	149.5 ^{a}	145.0 ^{a}	145.5 ^{a}	150.0 ^{a}	155.5 ^{a}	154.5 ^{a}	153.6 ^{a}	162.4 ^{a}	**17.2**	**38.3**
EBT (m^{-2})	305.4 ^{a}	309.3 ^{a}	294.7 ^{a}	327.2 ^{a}	330.4 ^{a}	319.0 ^{a}	327.2 ^{a}	353.6 ^{a}	**13.9**	**65.8**
Biomass ($kg\ ha^{-1}$)	9857 ^{a}	8679 ^{a}	7929 ^{a}	9572 ^{a}	8714 ^{a}	8000 ^{a}	8072 ^{a}	9536 ^{a}	**17.8**	**2303**

Means without a common superscript letter in the same row indicate significant differences at a 5% level.

CV = Coefficient of variance

LSD = Least significant difference

4.1.2.3 Grain yield

No differences ($P > 0.05$) in grain yield were recorded when topdress rates were increased higher than 0 kg ha^{-1} at Tygerhoek, in Year 1 (Figure 4.1.10). No differences ($P > 0.05$) in yield whatsoever were recorded in Year 2 (Figure 4.1.11).

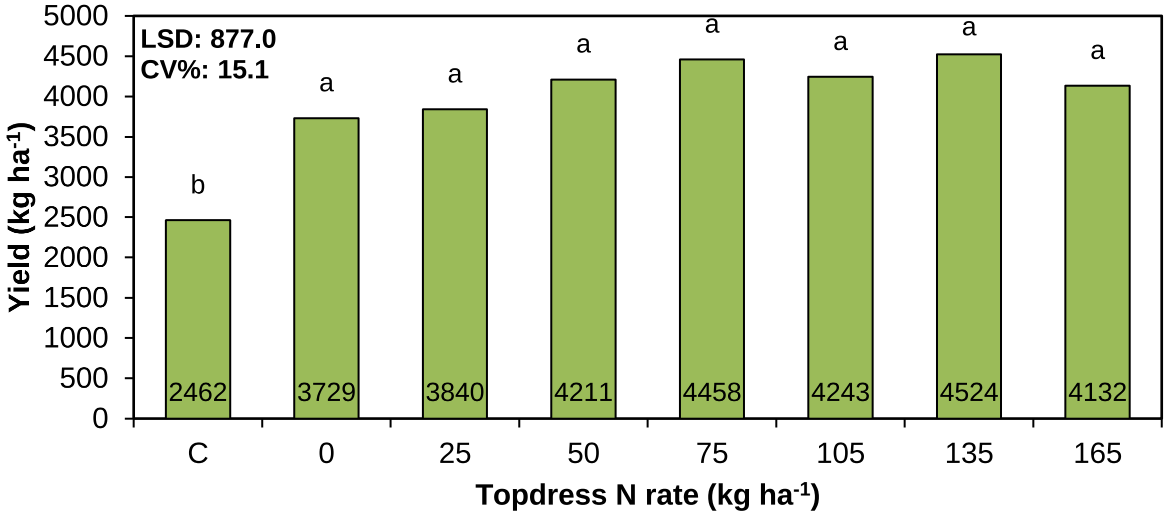


Figure 4.1.10 Grain yield (kg ha^{-1}) as influenced by topdress N rate (kg ha^{-1}) at Tygerhoek (Year 1). LSD = Least significant difference ($P < 0.05$); CV = coefficient of variance. Means without a common letter above bars indicate significant differences at a 5% level.

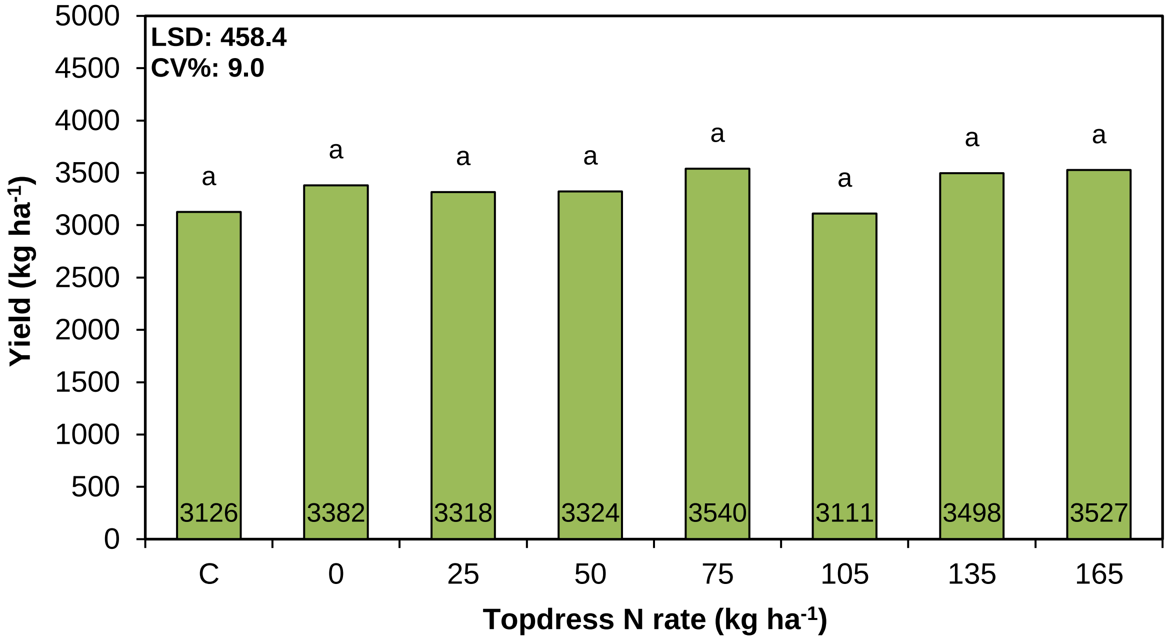


Figure 4.1.11 Grain yield (kg ha^{-1}) as influenced by topdress N rate (kg ha^{-1}) at Tygerhoek (Year 2). LSD = Least significant difference ($P < 0.05$); CV = coefficient of variance. Means without a common letter above bars indicate significant differences at a 5% level.

4.1.2.4 Nitrogen use efficiency

Increasing N rates led to a decrease in NUE, where 0 kg N ha^{-1} had the highest ($P < 0.05$) and 105, 135 and 165 kg N ha^{-1} the lowest ($P < 0.05$) NUE in both years (Figure 4.1.12).

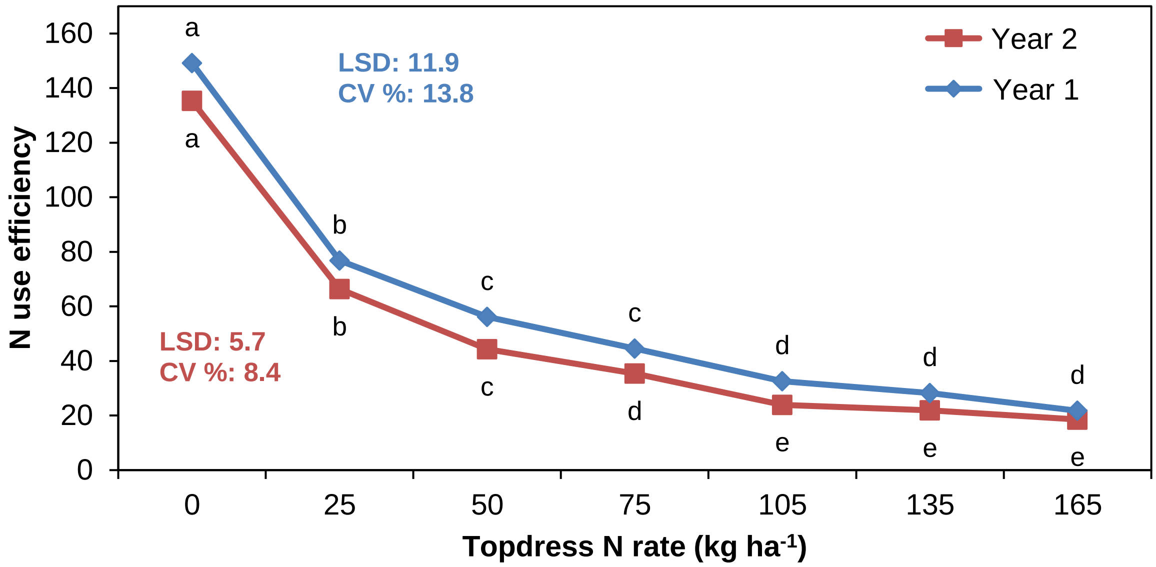


Figure 4.1.12 N use efficiencies per corresponding topdress N rate (kg ha^{-1}) at Tygerhoek (Year 1 and 2). No common letter within a year indicates significant difference at a 5% level.

4.1.2.5 Quality parameters

No differences ($P > 0.05$) in hectolitre mass or harvest index were recorded in Year 1 (Table 4.1.4). In both Year 1 and 2, the increasing topdress N rates led to an increase ($P < 0.05$) in protein content.

Except for the biomass N of the control treatment being lower ($P < 0.05$) than most other N treatments, no other differences in biomass N were recorded.

Table 4.1.4 Hectolitre mass, protein content (%), harvest index and biomass N (kg ha^{-1}) as influenced by topdressed fertiliser N rate (kg ha^{-1}) at Tygerhoek during Year 1 and 2 of the study.

				Year 1						
Topdress N rate (kg ha^{-1})	**control**	**0**	**25**	**50**	**75**	**105**	**135**	**165**	**CV (%)**	**LSD**
Hectolitre mass (g cm^{-3})	76.4 ^{a}	77.0 ^{a}	76.2 ^{a}	76.6 ^{a}	76.9 ^{a}	76.2 ^{a}	77.1 ^{a}	76.4 ^{a}	**1.4**	**1.6**
Protein content (%)	9.9 ^{c}	9.9 ^{c}	10.7 ^{b}	11.1 ^{ab}	11.0 ^{ab}	11.4 ^{ab}	11.6 ^{a}	11.4 ^{ab}	**5.2**	**0.8**
Harvest index	0.31 ^{a}	0.32 ^{a}	0.38 ^{a}	0.32 ^{a}	0.39 ^{a}	0.37 ^{a}	0.34 ^{a}	0.33 ^{a}	**20.9**	**0.11**
Biomass N (kg ha^{-1})	87.7 ^{b}	136.9 ^{ab}	150.5 ^{ab}	193.0 ^{a}	169.4 ^{a}	168.4 ^{a}	206.5 ^{a}	181.9 ^{a}	**26.2**	**76.7**
				Year 2						
Hectolitre mass (g cm^{-3})	75.6 ^{a}	75.7 ^{a}	74.4 ^{ab}	74.7 ^{ab}	74.7 ^{ab}	74.6 ^{ab}	73.5 ^{b}	73.5 ^{b}	**1.3**	**1.5**
Protein content (%)	10.1 ^{e}	11.5 ^{d}	11.6 ^{d}	12.3 ^{cd}	12.8 ^{bc}	13.5 ^{ab}	13.6 ^{ab}	13.9 ^{a}	**4.8**	**0.9**
Harvest index	0.34 ^{a}	0.41 ^{a}	0.43 ^{a}	0.35 ^{a}	0.42 ^{a}	0.41 ^{a}	0.43 ^{a}	0.38 ^{a}	**22.2**	**0.13**
Biomass N (kg ha^{-1})	376.0 ^{ab}	379.2 ^{ab}	331.9 ^{b}	392.0 ^{ab}	385.2 ^{ab}	332.0 ^{b}	335.5 ^{ab}	427.3 ^{a}	**15.6**	**87.5**

Means without a common superscript letter in the same row indicate significant differences at a 5% level.

CV = Coefficient of variance

LSD = Least significant difference

4.1.3 Caledon L/W

4.1.3.1 Soil mineral N content

No differences ($P > 0.05$) in the total mineral N were found at pre-planting stage in Year 1 (Figure 4.1.13). The total mineral N of the 0 kg N ha^{-1} topdress treatment was higher ($P < 0.05$) than most of the other treatments at the pre-topdress stage of Year 1. During Year 2, no differences ($P > 0.05$) in soil mineral N were recorded between treatments at pre-topdress stage (Figure 4.1.14).

Post-topdress samples were not collected in Year 1, due to uneven distribution of seedlings and heavy weed pressure at the time, hence the missing data in Figure 4.1.13. During Year 2 the soil mineral N showed a slight increase ($P < 0.05$) when N rates were increased, with the control and 0 kg N ha^{-1} treatments having the lowest ($P < 0.05$) and the 135 and 165 kg N ha^{-1} the highest ($P < 0.05$) N contents.

Apart from the soil mineral N content at the 165 kg N ha^{-1} treatment being higher ($P < 0.05$) than some, no other differences ($P > 0.05$) in total mineral N were recorded at post-harvest stage in Year 1.

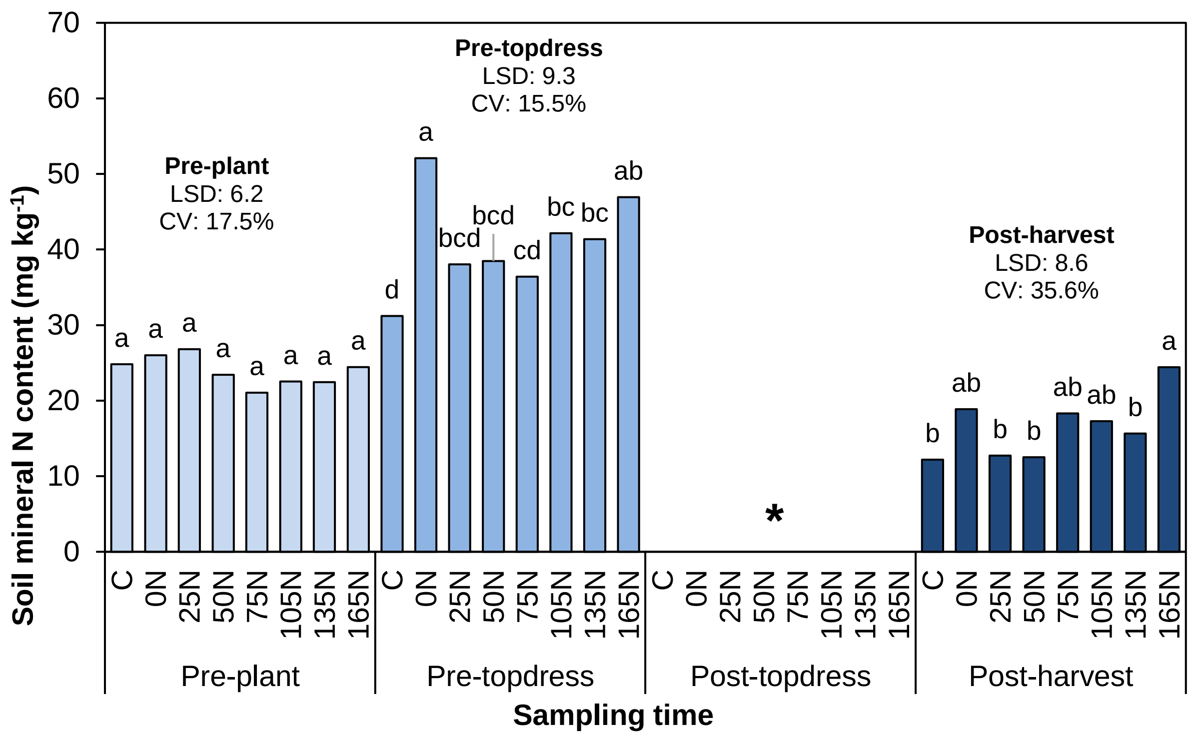


Figure 4.1.13 Total mineral N in the soil as influenced by topdress N rate (kg ha^{-1}) at Caledon (Year 1). LSD = Least significant difference ($P < 0.05$); CV = coefficient of variance. Bars with different letters within a specific sampling time indicate significant differences at a 5% level. *No sampling due to uneven distribution of seedlings

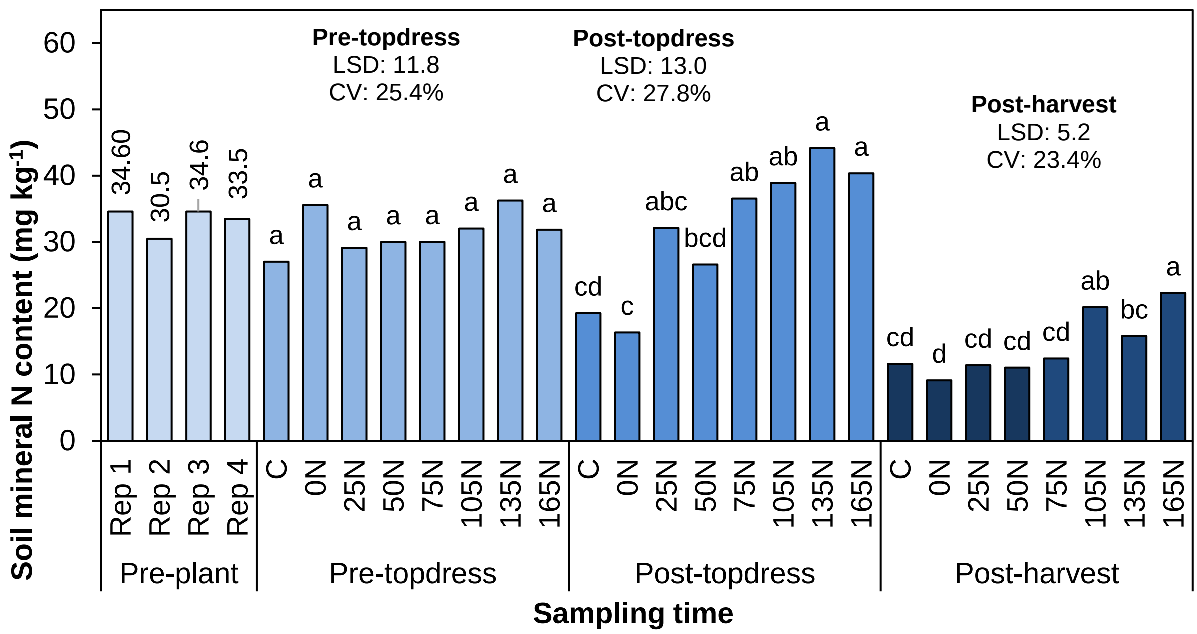


Figure 4.1.14 Total mineral N in the soil as influenced by topdress N rate (kg ha^{-1}) at Caledon (Year 2). LSD = Least significant difference (P < 0.05); CV = coefficient of variance. Bars with different letters within a specific sampling time indicate significant differences at a 5% level.

The regression between total soil mineral N content and total applied N at Caledon is described by the equation y = 0.17x + 32.30 (R^2 = 0.24) in Year 2 (Figure 4.1.15). Regression analysis between the variables could not be performed for Year 1, because post-topdress soil samples were not collected.

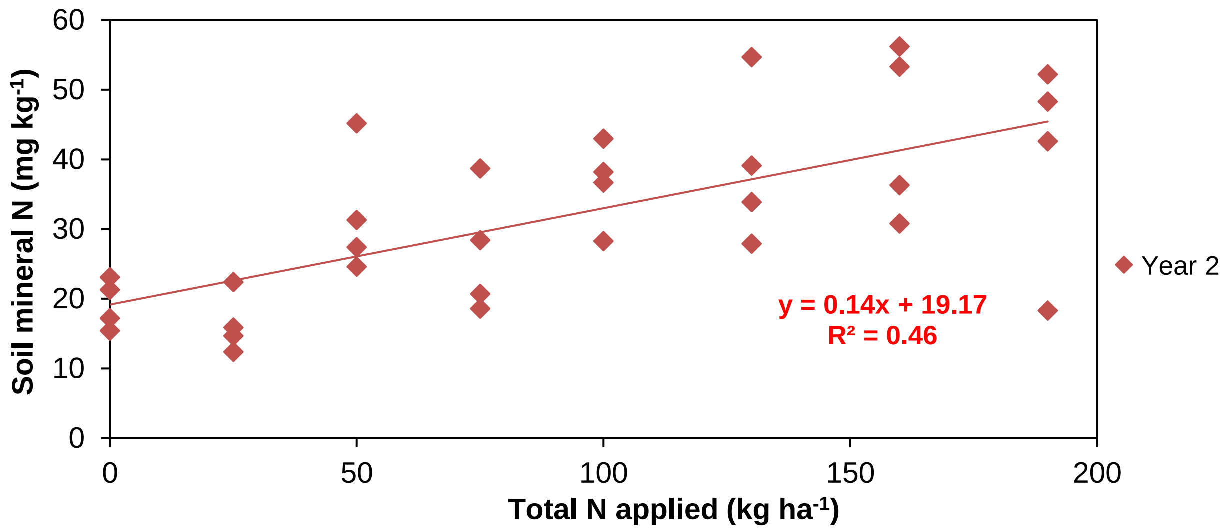


Figure 4.1.15 The response of total soil mineral N at post-topdress stage to total N applied during the growing season at Caledon for Year 2.

4.1.3.2 Plant parameters

The seedling population of the control treatment was higher ($P < 0.05$) than that of the 0, 75, 135 and 165 kg N ha^{-1} treatments (Table 4.1.5). Some differences ($P < 0.05$) were recorded in plant populations in Year 2. Nitrogen rates did not influence ($P > 0.05$) the number of EBT in Year 1, but in Year 2 the control treatment had a lower amount EBT than the 135 kg N ha^{-1} treatment. No differences ($P > 0.05$) in biomass were recorded for either Year 1 or 2 of the study at Caledon.

4.1.3.3 Grain yield

No differences ($P > 0.05$) in yield, as influenced by topdress N rate were recorded in either Year 1 or 2 (Figure 4.1.16 and Figure 4.1.17, respectively).

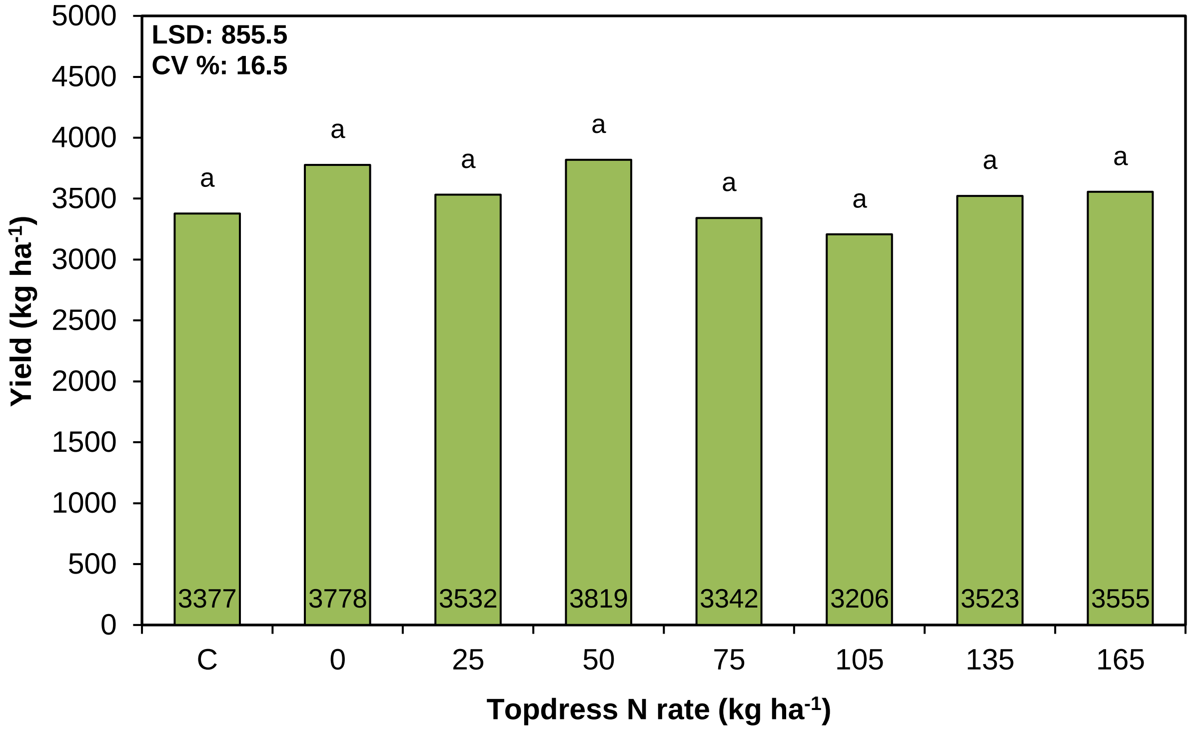


Figure 4.1.16 Grain yield (kg ha^{-1}) as influenced by topdress N rate (kg ha^{-1}) at Caledon (Year 1). LSD = Least significant difference ($P < 0.05$); CV = coefficient of variance. Means without a common letter above bars indicate significant differences at a 5% level.

Table 4.1.5 Seedling population (m^{-2}), number of EBT (m^{-2}) and biomass production (kg ha^{-1}) as influenced by topdressed fertiliser N rate (kg ha^{-1}) at Caledon during Year 1 and 2 of the study.

Topdress N rate (kg ha^{-1})	control	0	25	50	75	105	135	165	CV (%)	LSD
					Year 1					
Seedlings (m^{-2})	125.1 ^{a}	98.8 ^{c}	111.0 ^{abc}	115.0 ^{ab}	103.6 ^{bc}	110.5 ^{abc}	108.1 ^{bc}	98.1 ^{c}	**9.1**	**14.6**
EBT (m^{-2})	327.1 ^{a}	258.2 ^{a}	252.9 ^{a}	286.4 ^{a}	275.0 ^{a}	247.1 ^{a}	292.5 ^{a}	302.9 ^{a}	**17.8**	**73.2**
Biomass (kg ha^{-1})	9429 ^{a}	9036 ^{a}	9143 ^{a}	10393 ^{a}	9000 ^{a}	8357 ^{a}	9036 ^{a}	10476 ^{a}	**17.7**	**2424**
					Year 2					
Seedlings (m^{-2})	118.8 ^{ab}	116.9 ^{ab}	121.0 ^{ab}	130.3 ^{a}	110.7 ^{b}	130.7 ^{a}	123.3 ^{ab}	117.7 ^{ab}	**9.9**	**17.6**
EBT (m^{-2})	235.4 ^{b}	251.1 ^{ab}	277.5 ^{ab}	245.0 ^{ab}	269.0 ^{ab}	258.0 ^{ab}	301.1 ^{a}	265.7 ^{ab}	**15.1**	**58.3**
Biomass (kg ha^{-1})	7393 ^{a}	8857 ^{a}	8322 ^{a}	7679 ^{a}	7643 ^{a}	8143 ^{a}	9215 ^{a}	8357 ^{a}	**16.9**	**2036**

Means without a common superscript letter in the same row indicate significant differences at a 5% level.

CV = Coefficient of variance

LSD = Least significant difference

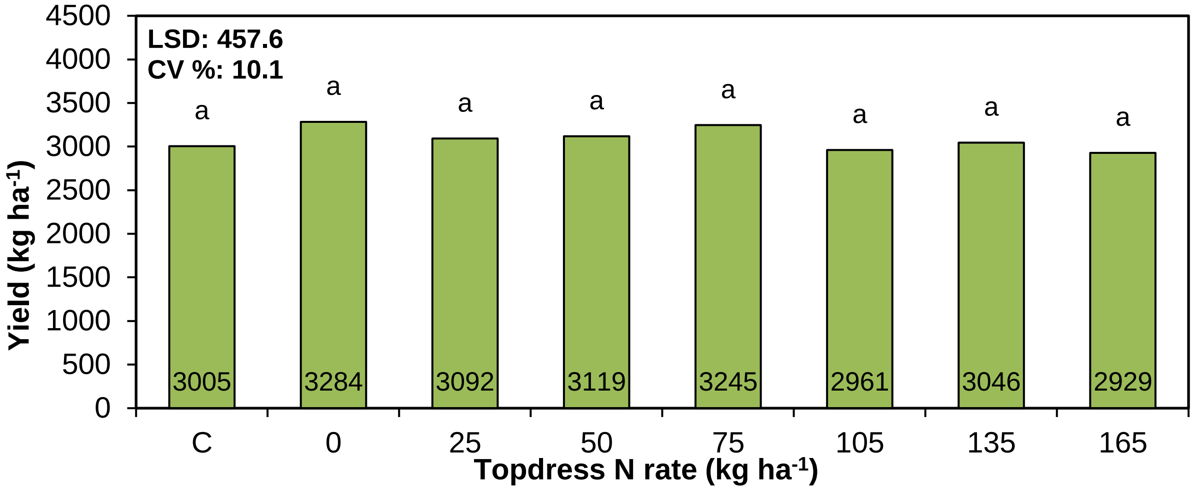


Figure 4.1.17 Grain yield (kg ha^{-1}) as influenced by topdress N rate (kg ha^{-1}) at Caledon (Year 2). LSD = Least significant difference (P < 0.05); CV = coefficient of variance. Means without a common letter above bars indicate significant differences at a 5% level.

4.1.3.4 Nitrogen use efficiency

Increasing N rate has led to a decrease in NUE in both years (Figure 4.1.18).

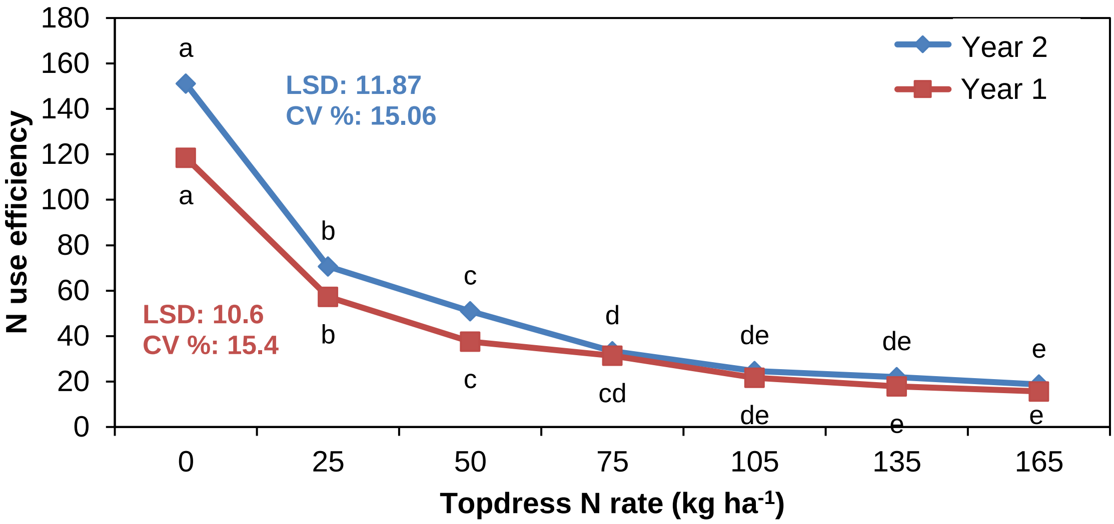


Figure 4.1.18 N use efficiencies per corresponding topdress N rate (kg ha^{-1}) at Caledon (Year 1 and 2). No common letter within a year indicates significant difference at a 5% level.

4.1.3.5 Quality parameters

An increase in topdress N rate led to a decrease (P < 0.05) in hectolitre mass, in both years (Table 4.1.6). In Year 1 the increasing N rates led to a consequent increase (P < 0.05) in protein content, but in Year 2, no increase (P > 0.05) in protein content was recorded between treatments. No differences (P > 0.05) in harvest index were recorded in either Year 1 or 2. Other than the 165 kg N ha^{-1} which had a higher (P < 0.05) biomass N than some treatments, no other differences (P > 0.05) in biomass N were recorded in Year 1 at Caledon. No differences in biomass N were recorded in Year 2.

Table 4.1.6 Hectolitre mass, protein content (%), harvest index and biomass N (kg ha^{-1}) as influenced by topdressed fertiliser N rate (kg ha^{-1}) at Caledon during Year 1 and 2 of the study.

					Year 1					
Topdress N rate (kg ha^{-1})	**control**	**0**	**25**	**50**	**75**	**105**	**135**	**165**	**CV (%)**	**LSD**
Hectolitre mass (g cm^{-3})	78.1 ^{ab}	78.8 ^{a}	77.7 ^{ab}	77.0 ^{bc}	77.0 ^{bc}	76.7 ^{bc}	76.0 ^{c}	76.0 ^{c}	**1.4**	**1.6**
Protein content (%)	12.1 ^{bc}	11.8 ^{c}	12.7 ^{bc}	13.1 ^{ab}	13.1 ^{ab}	13.2 ^{ab}	13.9 ^{a}	14.2 ^{a}	**6.2**	**1.2**
Harvest index	0.35 ^{a}	0.42 ^{a}	0.40 ^{a}	0.38 ^{a}	0.37 ^{a}	0.39 ^{a}	0.40 ^{a}	0.35 ^{a}	**15.4**	**0.09**
Biomass N (kg ha^{-1})	131.0 ^{ab}	123.1 ^{b}	123.6 ^{b}	140.8 ^{ab}	126.9 ^{b}	122.0 ^{b}	140.7 ^{ab}	165.7 ^{a}	**18.9**	**37.3**
					Year 2					
Hectolitre mass (g cm^{-3})	79.1 ^{a}	78.0 ^{ab}	77.6 ^{bc}	76.7 ^{bcd}	76.6 ^{cd}	75.8 ^{de}	76.7 ^{bcd}	75.1 ^{e}	**1.2**	**1.4**
Protein content (%)	13.5 ^{a}	14.0 ^{a}	13.0 ^{a}	12.7 ^{a}	13.5 ^{a}	14.2 ^{a}	14.1 ^{a}	13.8 ^{a}	**12.1**	**2.4**
Harvest index	0.41 ^{a}	0.38 ^{a}	0.37 ^{a}	0.42 ^{a}	0.44 ^{a}	0.37 ^{a}	0.34 ^{a}	0.35 ^{a}	**18.8**	**0.11**
Biomass N (kg ha^{-1})	113.0 ^{a}	124.1 ^{a}	123.0 ^{a}	112.6 ^{a}	144.0 ^{a}	123.1 ^{a}	150.7 ^{a}	129.0 ^{a}	**21.3**	**39.9**

Means without a common superscript letter in the same row indicate significant differences at a 5% level.

CV = Coefficient of variance

LSD = Least significant difference

4.1.4 Langgewens M/W

4.1.4.1 Soil mineral N content

Except for the 75 kg N ha^{-1} treatment, no differences (P > 0.05) between treatments were found at the pre-planting stage for Year 1 (Figure 4.1.19).

The total soil mineral N at pre-topdress stage in Year 1, without any influence of the topdress treatments, was higher than expected. This might be due to the high amount of residual N stored in the soil by the previous year's medics. During Year 2, no differences (P > 0.05) in soil mineral N content were recorded between the different treatments (Figure 4.1.20).

Higher topdress N rates mostly led to an increase (P < 0.05) in total mineral N in the soil at the post-topdress stage, for Year 1 and 2.

Total mineral N present in the soil after harvest was highest, although not always significantly so, for the 105, 135 and 165 kg N ha^{-1} treatments compared to the other treatments.

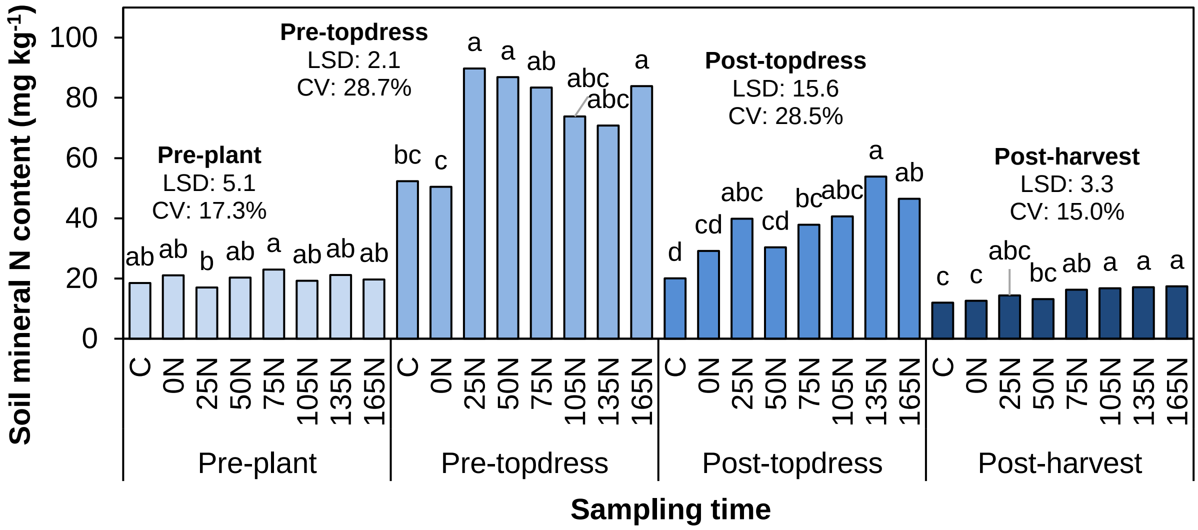


Figure 4.1.19 Total mineral N in the soil as influenced by topdress N rate (kg ha^{-1}) at Langgewens M/W (Year 1). LSD = Least significant difference (P < 0.05); CV = coefficient of variance. Bars with different letters within a specific sampling time indicate significant differences at a 5% level.

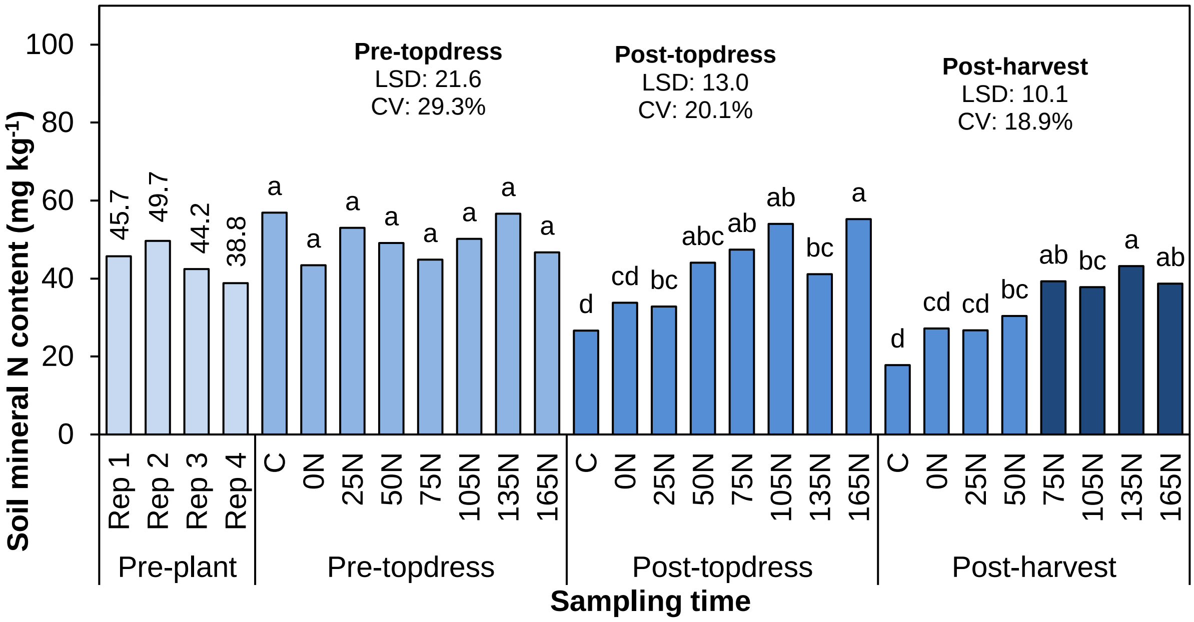


Figure 4.1.20 Total mineral N in the soil as influenced by topdress N rate (kg ha^{-1}) at Langgewens M/W (Year 2). LSD = Least significant difference ($P < 0.05$); CV = coefficient of variance. Bars with different letters within a specific sampling time indicate significant differences at a 5% level.

The regression between topdressed N application rate and post-topdress mineral N content is described by the equation $y = 0.14x + 24.51$ ($R^2 = 0.38$) in Year 1 and $y = 0.13x + 29.87$ ($R^2 = 0.39$) in Year 2 (Figure 4.1.21). The R^2 values for the two years are similar, indicating a similar regression between increase in N rate and its effect on the soil mineral N content.

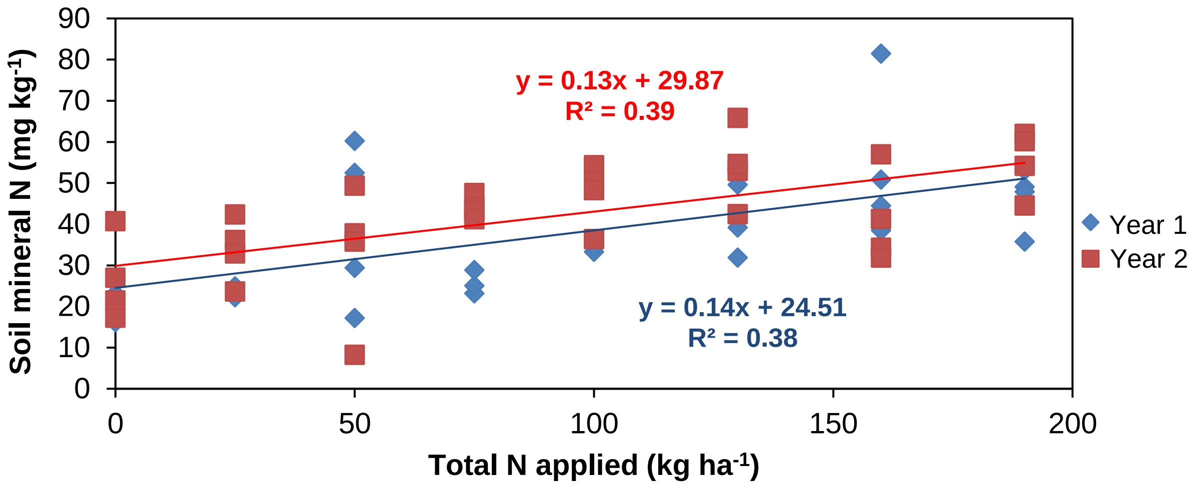


Figure 4.1.21 The response of total soil mineral N at post-topdress stage to total N applied during the growing season at Langgewens M/W for the years as indicated.

4.1.4.2 *Plant parameters*

Table 4.1.7 shows that no differences (P > 0.05) in seedling populations were recorded in Year 1 at Langgewens M/W. In Year 2 some differences (P < 0.05) in seedling populations did occur, however not to such an extent as to influence the crop development of treatments relative to each other. Except for 105 kg N ha^{-1} having more (P < 0.05) EBT than the control treatment, no other differences in EBT were recorded in Year 1. During Year 2, the 135 kg N ha^{-1} treatment had more (P < 0.05) EBT than the 50, 75 and 105 kg N ha^{-1} treatments. The 105 kg N ha^{-1} produced a higher (P < 0.05) amount of biomass than the control and 0 kg N ha^{-1} treatments in Year 1, whilst no differences (P > 0.05) in biomass production were recorded in Year 2.

4.1.4.3 *Grain yield*

During Year 1, the control treatment produced a lower (P < 0.05) yield than all the N topdress treatments, except for 105 kg N ha^{-1} (Figure 4.1.22). Applying N as topdress treatment did not lead to any increases (P > 0.05) in yield, i.e. the yield of the 0 kg N ha^{-1} treatment did not differ from any treatments that received additional N at topdress. No differences (P > 0.05) in yield, as influenced by topdress N rate, were recorded in Year 2 (Figure 4.1.23).

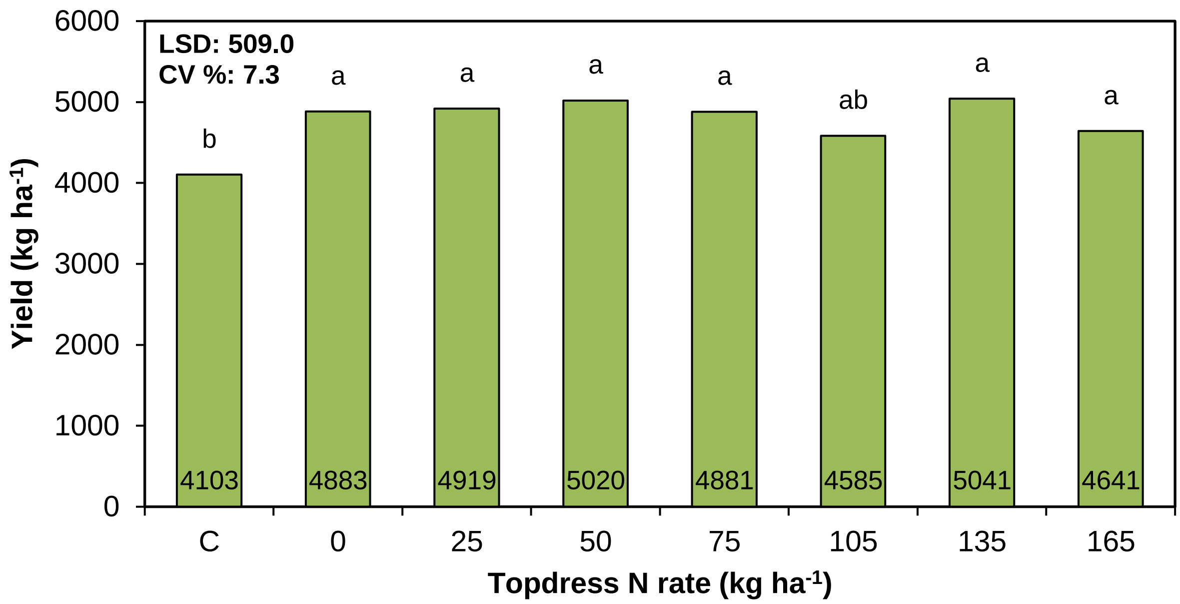


Figure 4.1.22 Grain yield (kg ha^{-1}) as influenced by topdress N rate (kg ha^{-1}) at Langgewens M/W (Year 1). LSD = Least significant difference (P < 0.05); CV = coefficient of variance. Means without a common letter above bars indicate significant differences at a 5% level.

Table 4.1.7 Seedling population (m^{-2}), number of EBT (m^{-2}) and biomass production (kg ha^{-1}) as influenced by topdressed fertiliser N rate (kg ha^{-1}) at Langgewens M/W during Year 1 and 2 of the study.

Topdress N rate (kg ha^{-1})	control	0	25	50	75	105	135	165	CV (%)	LSD
				Year 1						
Seedlings (m^{-2})	71.9 ^{a}	76.3 ^{a}	75.2 ^{a}	76.9 ^{a}	84.3 ^{a}	76.4 ^{a}	78.7 ^{a}	79.0 ^{a}	**19.1**	**21.7**
EBT (m^{-2})	202.9 ^{b}	231.3 ^{ab}	227.9 ^{ab}	260.0 ^{ab}	255.8 ^{ab}	280.4 ^{a}	246.7 ^{ab}	261.0 ^{ab}	**16.6**	**59.9**
Biomass (kg ha^{-1})	8813 ^{c}	9708 ^{bc}	10854 ^{ab}	10750 ^{ab}	10438 ^{ab}	11667 ^{a}	11063 ^{ab}	10521 ^{ab}	**8.9**	**1371**
				Year 2						
Seedlings (m^{-2})	98.8 ^{a}	92.1 ^{ab}	93.8 ^{ab}	92.1 ^{ab}	91.0 ^{a}	87.8 ^{b}	93.2 ^{ab}	88.1 ^{b}	**7.0**	**9.4**
EBT (m^{-2})	210.6 ^{ab}	205.0 ^{ab}	220.2 ^{ab}	177.7 ^{bc}	155.83 ^{c}	178.8 ^{bc}	225.2 ^{a}	189.6 ^{abc}	**16.0**	**46.0**
Biomass (kg ha^{-1})	6396 ^{a}	6396 ^{a}	6479 ^{a}	6458 ^{a}	6104 ^{a}	6458 ^{a}	7208 ^{a}	6437 ^{a}	**11.8**	**1126**

Means without a common superscript letter in the same row indicate significant differences at a 5% level.

CV = Coefficient of variance

LSD = Least significant difference

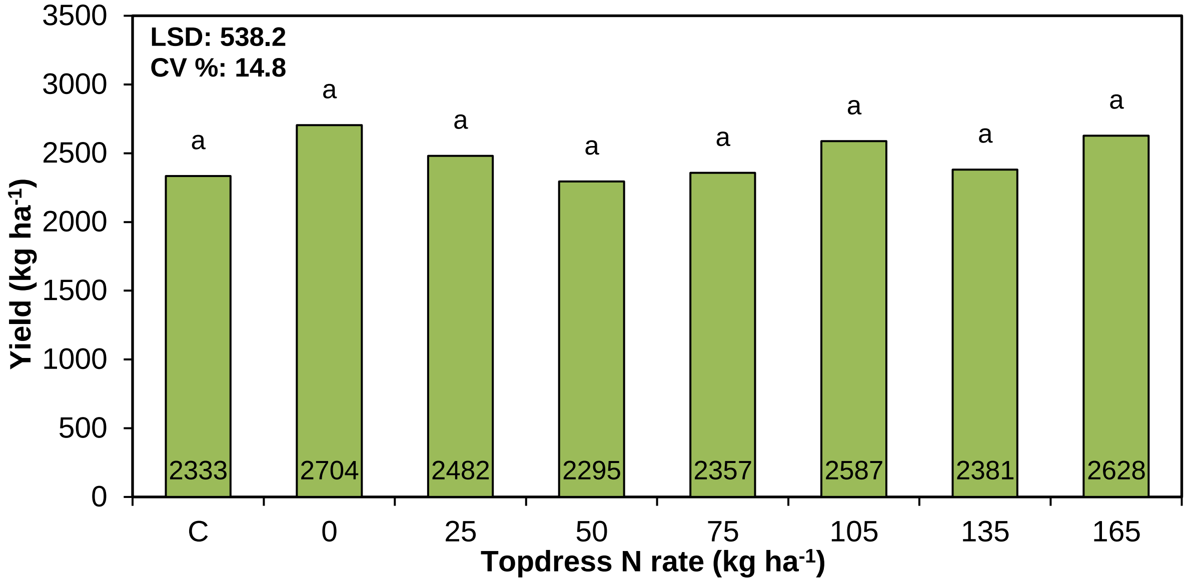


Figure 4.1.23 Grain yield (kg ha^{-1}) as influenced by topdress N rate (kg ha^{-1}) at Langgewens M/W (Year 2). LSD = Least significant difference ($P < 0.05$); CV = coefficient of variance. Means without a common letter above bars indicate significant differences at a 5% level.

4.1.4.4 Nitrogen use efficiency

Increasing N rates led to a decrease ($P < 0.05$) in NUE in both years (Figure 4.1.24).

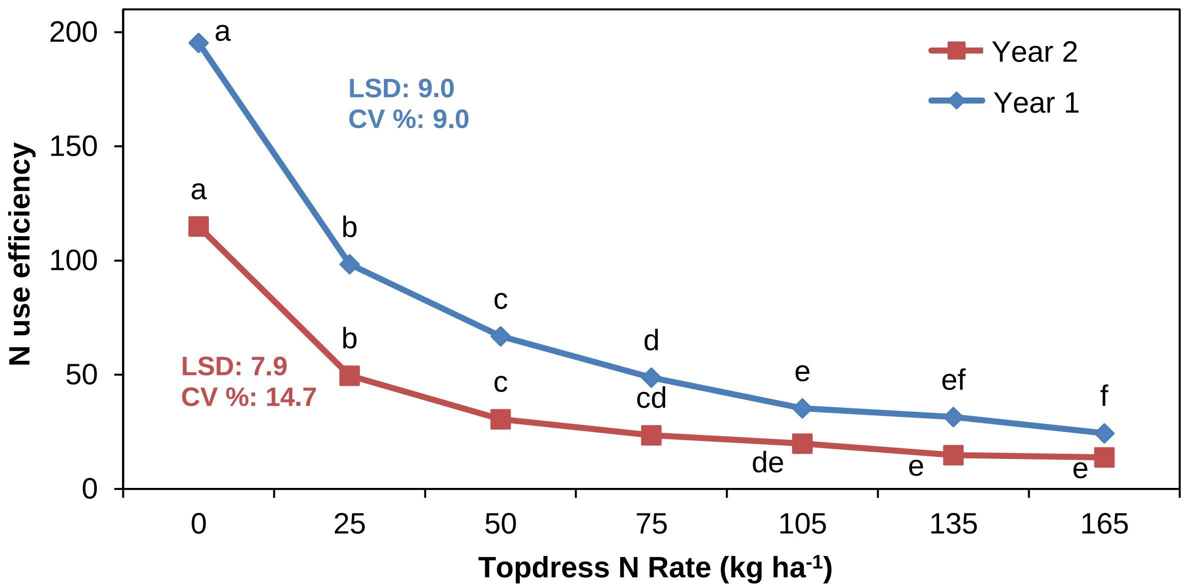


Figure 4.1.24 N use efficiencies per corresponding topdress N rate (kg ha^{-1}) at Langgewens M/W (Year 1 and 2). No common letter within a year indicates significant difference at a 5% level.

4.1.4.5 Quality parameters

During Year 1, an increase in topdress N rate have led to a decrease ($P < 0.05$) in hectolitre mass, where the control, 0 and 25 kg N ha^{-1} treatments had the highest ($P < 0.05$) hectolitre mass (Table 4.1.8). No differences ($P > 0.05$) in hectolitre mass, as influenced by treatments, were recorded in Year 2.

The increasing N rate led to an increase ($P < 0.05$) in protein content, with 165 kg N ha^{-1} being the highest ($P < 0.05$) in Year 1. In Year 2, the increase in protein content with increasing N rates was less apparent, but in some treatments still significant.

The only difference ($P < 0.05$) in harvest index for Year 1 was that of the 105 kg N ha^{-1} treatment being lower than most other treatments. No difference ($P > 0.05$) in harvest index occurred between treatments in Year 2.

No differences ($P > 0.05$) in the amount of N absorbed by the biomass were recorded for Year 1 at Langgewens M/W. In Year 2, the 135 kg N ha^{-1} had a higher ($P < 0.05$) biomass N than that of the 0 and 75 kg N ha^{-1} treatments.

Table 4.1.8 Hectolitre mass, protein content (%), harvest index and biomass N (kg ha^{-1}) as influenced by topdressed fertiliser N rate (kg ha^{-1}) at Langgewens M/W during Year 1 and 2 of the study.

				Year 1						
Topdress N rate (kg ha^{-1})	**control**	**0**	**25**	**50**	**75**	**105**	**135**	**165**	**CV (%)**	**LSD**
Hectolitre mass (g cm^{-3})	79.9 ^{a}	79.7 ^{a}	79.5 ^{a}	78.2 ^{b}	78.3 ^{b}	77.0 ^{c}	77.5 ^{bc}	76.7 ^{c}	**0.9**	**1.1**
Protein content (%)	11.1 ^{d}	11.4 ^{cd}	11.4 ^{cd}	11.7 ^{c}	11.8 ^{b}	11.7 ^{b}	11.8 ^{b}	12.2 ^{a}	**1.9**	**0.3**
Harvest index	0.47 ^{a}	0.50 ^{a}	0.45 ^{a}	0.47 ^{ab}	0.47 ^{a}	0.39 ^{b}	0.46 ^{a}	0.44 ^{ab}	**9.3**	**0.06**
Biomass N (kg ha^{-1})	162.5 ^{a}	145.2 ^{a}	160.1 ^{a}	170.5 ^{a}	185.2 ^{a}	170.3 ^{a}	185.3 ^{a}	190.4 ^{a}	**9.4**	**81.3**
				Year 2						
Hectolitre mass (g cm^{-3})	78.9 ^{a}	78.5 ^{a}	78.3 ^{a}	78.0 ^{a}	78.7 ^{a}	78.7 ^{a}	77.9 ^{a}	77.9 ^{a}	**0.9**	**1.0**
Protein content (%)	15.9 ^{b}	16.1 ^{b}	16.7 ^{ab}	16.6 ^{ab}	16.9 ^{ab}	16.5 ^{ab}	16.9 ^{ab}	17.3 ^{a}	**4.8**	**1.2**
Harvest index	0.37 ^{a}	0.42 ^{a}	0.38 ^{a}	0.36 ^{a}	0.39 ^{a}	0.40 ^{a}	0.33 ^{a}	0.42 ^{a}	**18.9**	**0.11**
Biomass N (kg ha^{-1})	123.8 ^{abc}	107.6 ^{bc}	123.1 ^{abc}	120.0 ^{abc}	104.8 ^{c}	129.4 ^{ab}	138.6 ^{a}	120.8 ^{abc}	**13.7**	**24.4**

Means without a common superscript letter in the same row indicate significant differences at a 5% level.

CV = Coefficient of variance

LSD = Least significant difference

4.1.5 Langgewens C/W

4.1.5.1 Soil mineral N content

As expected, there were no differences (P > 0.05) in total mineral soil mineral N content at pre-plant stage in Year 1, as topdress N rate treatments had not been applied at that stage (Figure 4.1.25).

Low early-season rainfall in Year 1 led to bad crop establishment therefore, pre-topdress soil samples were not collected. In Year 2 the soil mineral N content of the 50 kg N ha^{-1} treatment was higher (P < 0.05) than most other treatments at the pre-topdress stage and the 0 and 75 kg N ha^{-1} treatments had higher (P < 0.05) soil mineral N contents than the control and 105 kg N ha^{-1} treatments (Figure 4.1.26).

At post-topdress stage the results were as expected, where an increase in topdress N rate led to an increase (P < 0.05) in total mineral N content in the soil, with the control treatment being the lowest (P < 0.05) and the 165 kg N ha^{-1} treatment the highest (P < 0.05) for both years.

No differences (P > 0.05) in total soil mineral N content were present in the soil after harvest in Year 1 and in Year 2, the 105, 135 and 165 kg N ha^{-1} treatments had higher (P < 0.05) soil mineral N contents than the control, 0 and 25 kg N ha^{-1} treatments.

The regression between topdressed N application rate and post-topdress mineral N content is described by the equation $y = 0.22x + 17.67$ ($R^2 = 0.68$) in Year 1 and $y = 0.16x + 9.21$ ($R^2 = 0.73$) in Year 2 (Figure 4.1.27). The similarity between the R^2 values of the two years may indicate that the application of N to the soil had a similar effect on soil mineral N content during both years.

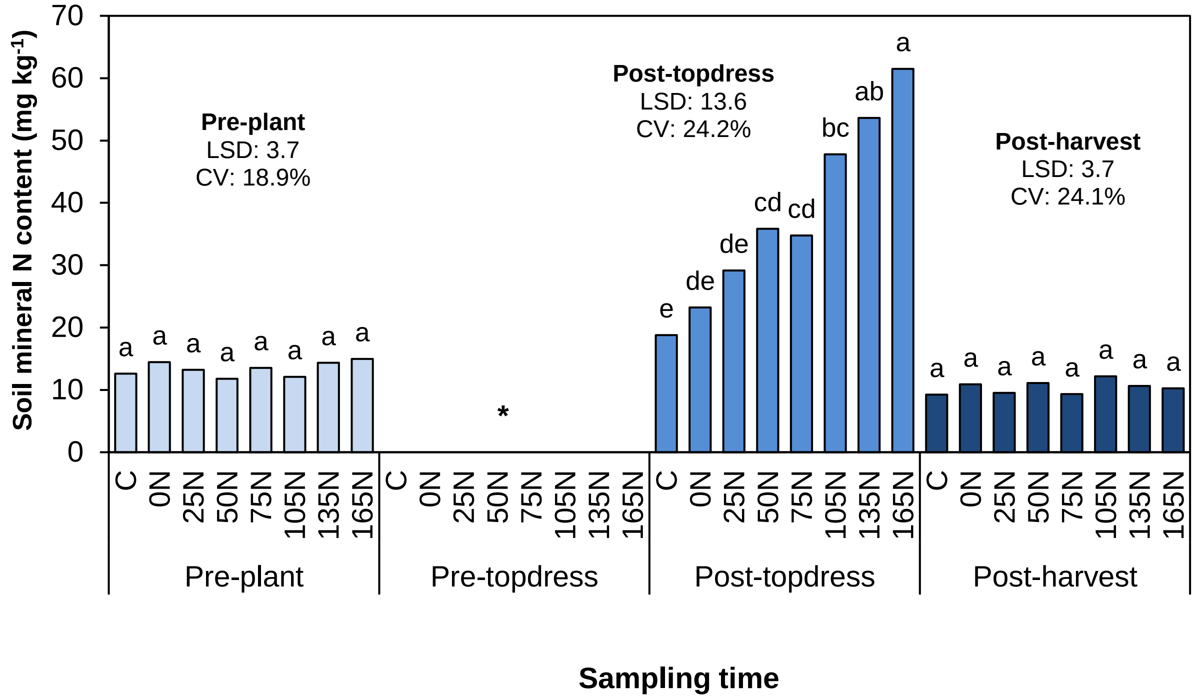


Figure 4.1.25 Total mineral N in the soil as influenced by topdress N rate (kg ha^{-1}) at Langgewens C/W (Year 1). LSD = Least significant difference (P < 0.05); CV = coefficient of variance. Bars with different letters within a specific sampling time indicate significant differences at a 5% level. *No sampling due to uneven distribution of seedlings.

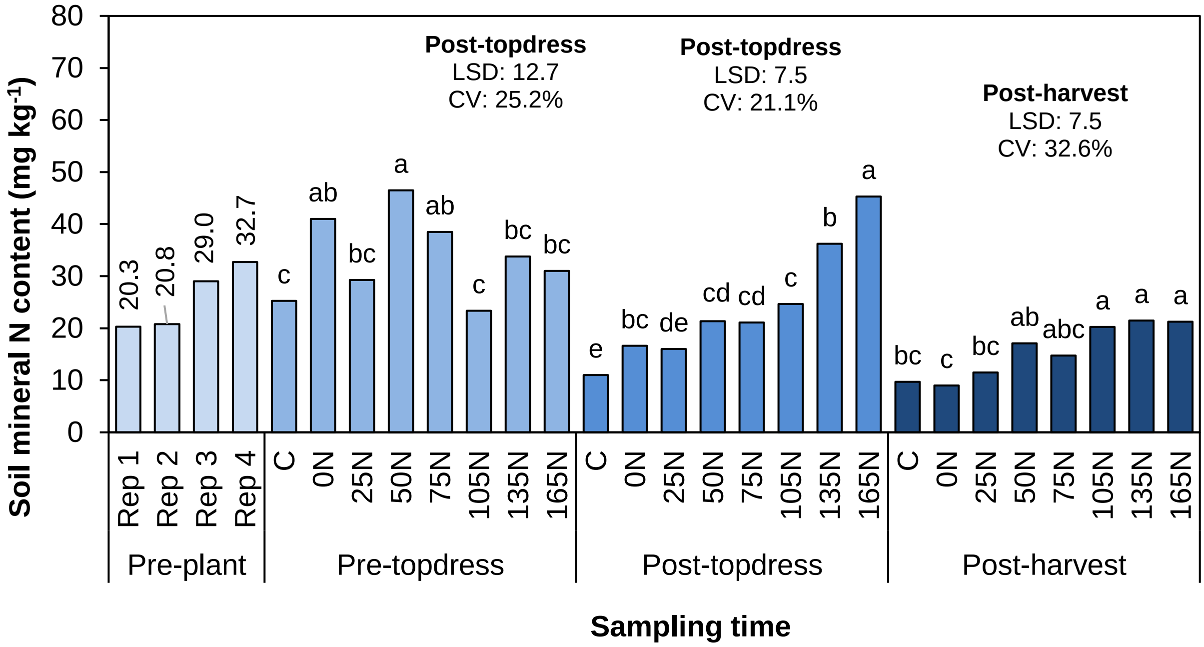


Figure 4.1.26 Total mineral N in the soil as influenced by topdress N rate (kg ha^{-1}) at Langgewens C/W (Year 2). LSD = Least significant difference (P < 0.05); CV = coefficient of variance. Bars with different letters within a specific sampling time indicate significant differences at a 5% level.

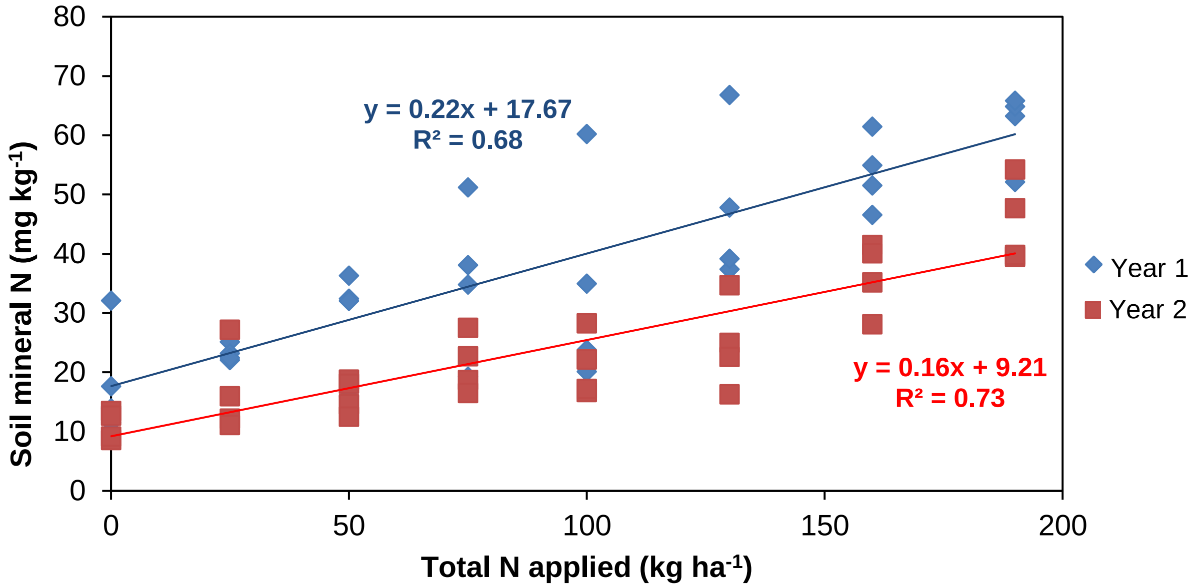


Figure 4.1.27 The response of total soil mineral N at post-topdress stage to total N applied during the growing season at Langgewens C/W for the years as indicated.

4.1.5.2 Plant parameters

Seedling populations were not determined in Year 1, due to poor emergence and uneven distribution of seedlings. In Year 2 the 25 kg N ha^{-1} treatment had higher ($P < 0.05$) seedling populations than the 50 and 165 kg N ha^{-1} treatments (Table 4.1.9). Apart from 105 kg N ha^{-1} being higher ($P < 0.05$) than some treatments, no other differences ($P > 0.05$) in EBT were found for Year 1 of the study at Langgewens for C/W (Table 4.1.9).

Increasing topdress N rates (kg ha^{-1}) led to a slight increase ($P < 0.05$) in biomass (kg ha^{-1}), with 75, 105, 135 and 165 kg N ha^{-1} being the highest. During Year 2, no differences ($P > 0.05$) in the number of EBT or biomass produced occurred between treatments.

4.1.5.3 Grain yield

Whilst the control treatment had a lower ($P < 0.05$) yield than most treatments in Year 1, increasing the topdress N rate above 0 kg N ha^{-1} did not result in any increases ($P > 0.05$) in yield (**Error! Reference source not found.**). Not many differences in yield, as affected by treatments were recorded in Year 2. The only apparent difference was that the 25 kg N ha^{-1} treatment achieved a higher ($P < 0.05$) yield than the 0, 75, 105 and 135 kg N ha^{-1} treatments (Figure 4.1.29).

Table 4.1.9 Seedling population (m^{-2}), number of EBT (m^{-2}) and biomass production (kg ha^{-1}) as influenced by topdressed fertiliser N rate (kg ha^{-1}) at Langgewens C/W during Year 1 and 2 of the study.

Topdress N rate (kg ha^{-1})	control	0	25	50	75	105	135	165	CV (%)	LSD
				Year 1						
Seedlings (m^{-2})	*	*	*	*	*	*	*	*	*	*
EBT (m^{-2})	180.2 ^{b}	200.4 ^{ab}	159.8 ^{b}	170.4 ^{b}	170.8 ^{b}	272.7 ^{a}	202.9 ^{ab}	212.1 ^{ab}	**25.9**	**74.5**
Biomass (kg ha^{-1})	7042 ^{b}	8542 ^{ab}	8354 ^{ab}	8313 ^{ab}	10542 ^{a}	10271 ^{a}	10750 ^{a}	9979 ^{a}	**18.8**	**2551**
				Year 2						
Seedlings (m^{-2})	94.7 ^{ab}	91.3 ^{ab}	103.3 ^{a}	86.8 ^{b}	88.2 ^{ab}	94.2 ^{ab}	91.4 ^{ab}	87.4 ^{b}	**11.7**	**15.9**
EBT (m^{-2})	161.7 ^{a}	186.9 ^{a}	193.1 ^{a}	179.2 ^{a}	188.2 ^{a}	170.7 ^{a}	176.7 ^{a}	184.0 ^{a}	**15.5**	**41.0**
Biomass (kg ha^{-1})	4854 ^{a}	5500 ^{a}	5021 ^{a}	5417 ^{a}	5334 ^{a}	5021 ^{a}	5708 ^{a}	5500 ^{a}	**12.5**	**976**

Means without a common superscript letter in the same row indicate significant differences at a 5% level.

CV = Coefficient of variance

LSD = Least significant difference

*missing values due to bad and uneven seedling populations during early season of Year 1.

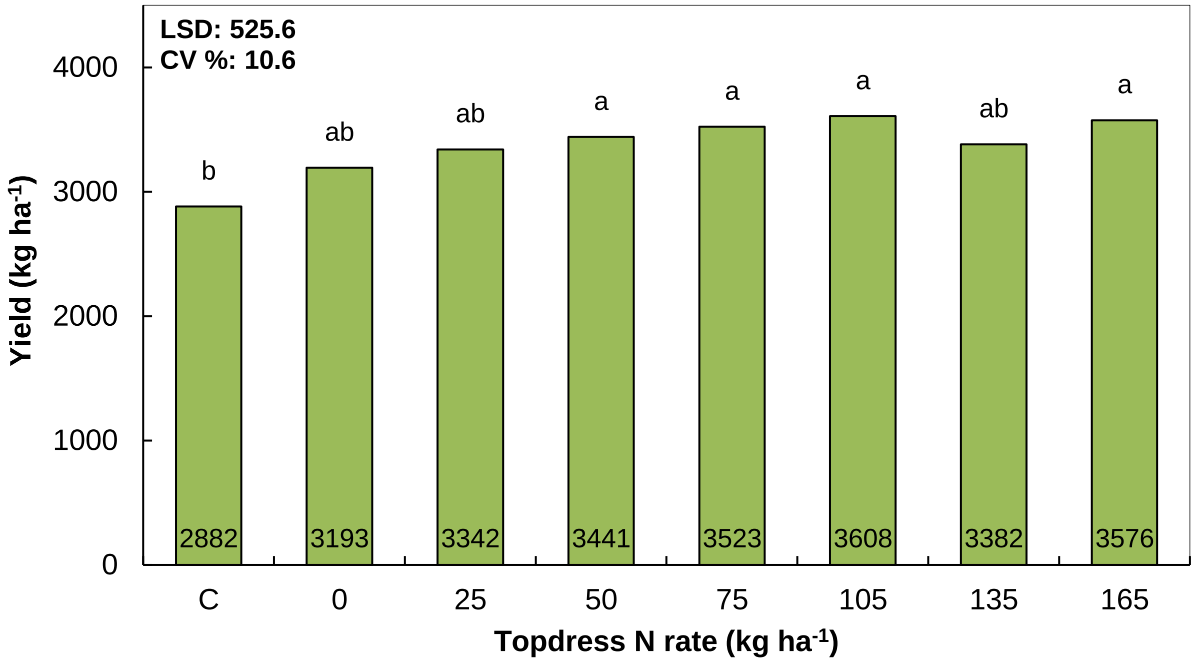


Figure 4.1.28 Grain yield (kg ha^{-1}) as influenced by topdress N rate (kg ha^{-1}) at Langgewens C/W (Year 1). LSD = Least significant difference (P < 0.05); CV = coefficient of variance. Means without a common letter above bars indicate significant differences at a 5% level.

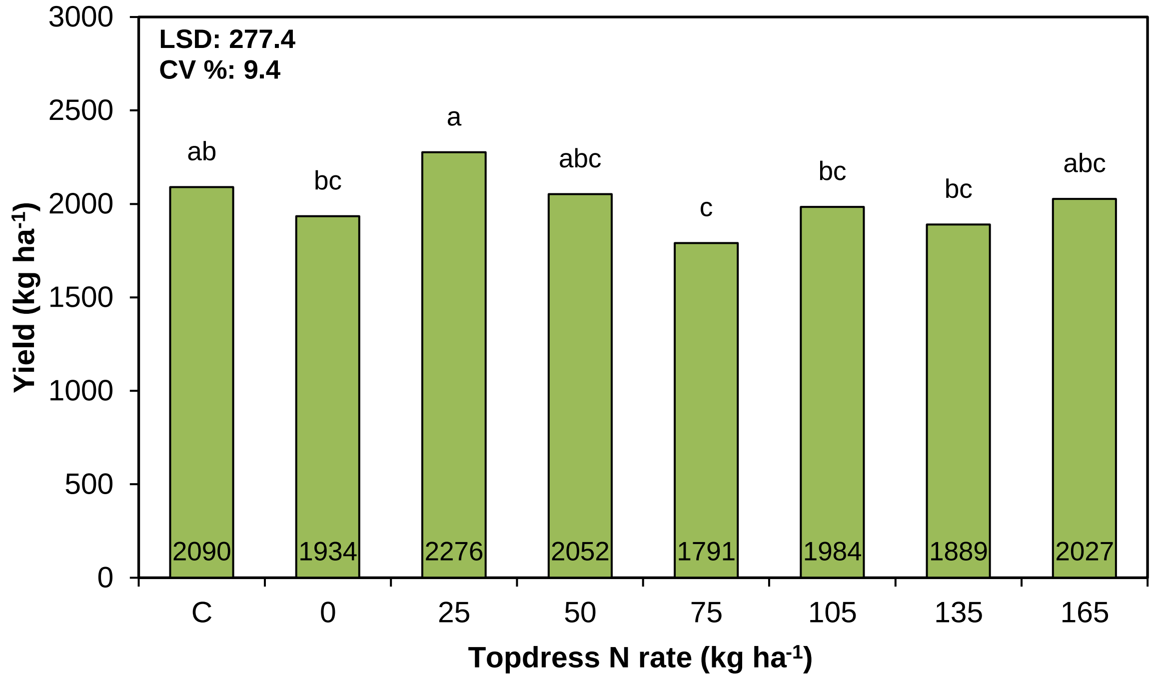


Figure 4.1.29 Grain yield (kg ha^{-1}) as influenced by topdress N rate (kg ha^{-1}) at Langgewens C/W (Year 2). LSD = Least significant difference (P < 0.05); CV = coefficient of variance. Means without a common letter above bars indicate significant differences at a 5% level.

4.1.5.4 Nitrogen use efficiency

Increasing N rates had a negative effect on NUE, where 0 kg N ha^{-1} had the highest ($P < 0.05$) and 135 and 165N ha^{-1} the lowest ($P < 0.05$) NUE in both years (Figure 4.1.30).

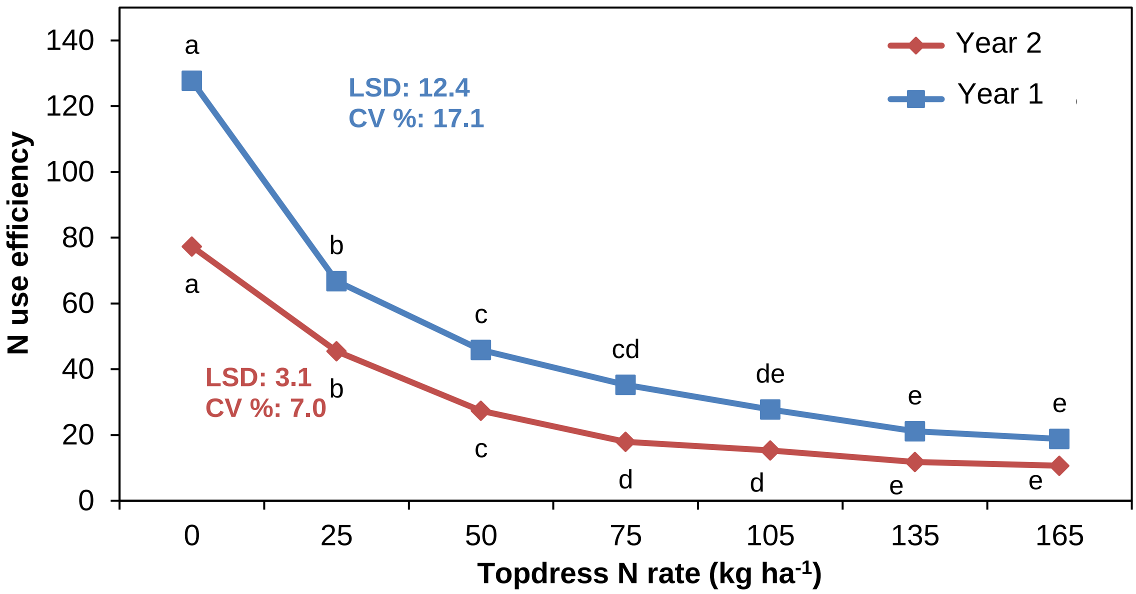


Figure 4.1.30 N use efficiencies per corresponding topdress N rate (kg ha^{-1}) at Langgewens C/W (Year 1 and 2). Points with different letters above or below them within a year indicate significant differences at a 5% level.

4.1.5.5 Quality parameters

Increasing the topdress N rate led to a decrease in hectolitre mass, with the 165 kg N ha^{-1} treatment being the lowest ($P < 0.05$) in Year 1 and 2 (Table 4.1.10.). Protein content increased with an increase in topdress N rate, where the 165 kg N ha^{-1} was the highest ($P < 0.05$) in both Year 1 and 2.

No differences in harvest index, as influenced by topdress N rates, were recorded for Year 1 at Langgewens C/W. In Year 2, conflicting results in harvest index were recorded and no trend was observed.

The same effect of N rate on biomass N was recorded in both years, where an increasing N rate led to an increase ($P < 0.05$) in biomass N.

Table 4.1.10 Hectolitre mass, protein content (%), harvest index and biomass N (kg ha^{-1}) as influenced by topdressed fertiliser N rate (kg ha^{-1}) at Langgewens C/W during Year 1 and 2 of the study.

				Year 1						
Topdress N rate (kg ha^{-1})	**control**	**0**	**25**	**50**	**75**	**105**	**135**	**165**	**CV (%)**	**LSD**
Hectolitre mass (g cm^{-3})	81.2 ^{a}	81.1 ^{a}	80.4 ^{ab}	80.9 ^{a}	80.2 ^{ab}	79.5 ^{bc}	79.4 ^{bc}	78.9 ^{c}	**1.0**	**1.3**
Protein content (%)	10.8 ^{f}	11.1 ^{ef}	11.2 ^{def}	12.0 ^{bcd}	11.8 ^{cde}	12.8 ^{ab}	12.6 ^{abc}	13.2 ^{a}	**4.4**	**0.8**
Harvest index	0.42 ^{a}	0.38 ^{a}	0.40 ^{a}	0.42 ^{a}	0.37 ^{a}	0.36 ^{a}	0.34 ^{a}	0.38 ^{a}	**17.5**	**0.10**
Biomass N (kg ha^{-1})	84.1 ^{c}	109.6 ^{bc}	103.3 ^{bc}	125.5 ^{abc}	169.8 ^{a}	142.3 ^{ab}	163.5 ^{a}	151.1 ^{a}	**23.9**	**49.1**
				Year 2						
Hectolitre mass (g cm^{-3})	79.2 ^{a}	76.5 ^{bc}	78.4 ^{a}	76.6 ^{bc}	75.9 ^{bc}	76.7 ^{b}	75.5 ^{bc}	75.4 ^{c}	**1.1**	**1.3**
Protein content (%)	12.1 ^{d}	14.0 ^{c}	14.1 ^{c}	16.0 ^{b}	16.8 ^{ab}	16.2 ^{b}	17.4 ^{a}	18.0	**6.3**	**1.4**
Harvest index	0.44 ^{ab}	0.36 ^{c}	0.46 ^{a}	0.38 ^{bc}	0.34 ^{c}	0.40 ^{abc}	0.33 ^{c}	0.38 ^{bc}	**13.5**	**0.08**
Biomass N (kg ha^{-1})	60.4 ^{c}	79.3 ^{bc}	76.9 ^{bc}	79.02 ^{bc}	97.0 ^{ab}	85.9 ^{ab}	106.3 ^{a}	102.7 ^{a}	**17.9**	**22.6**

Means without a common superscript letter in the same row indicate significant differences at a 5% level.

CV = Coefficient of variance

LSD = Least significant difference

4.1.6 Porterville M/W

4.1.6.1 Soil mineral N content

No differences ($P > 0.05$) in soil mineral N content were present before planting in Year 1 (Figure 4.1.31). No differences ($P > 0.05$) in soil mineral N contents, as affected by N treatments, were recorded for both years at the pre-topdress stage (Figure 4.1.31 and Figure 4.1.32).

Due to poor seedling establishment and low seedling populations, no soil samples were collected at the post-topdress stage for Year 1. In Year 2, increasing the topdress N rates from control to 75 kg N ha^{-1}, led to an increase ($P < 0.05$) in soil mineral N content (Figure 4.1.32).

At the post-harvest stage in Year 1, the 165 kg N ha^{-1} had the highest ($P < 0.05$) amount of mineral N present in the soil. In Year 2, at the same stage, the 165 kg N ha^{-1} treatment had a higher ($P < 0.05$) soil mineral N content than the 25 kg N ha^{-1} treatment, no other differences ($P > 0.05$) were recorded.

The response of total soil mineral N content to total applied N at Porterville C/W is described by the equation $y = 0.25x + 47.31$ ($R^2 = 0.27$) in Year 2 (Figure 4.1.33). The response curve between the variables was not drawn up for Year 1, because post-topdress soil samples were not collected.

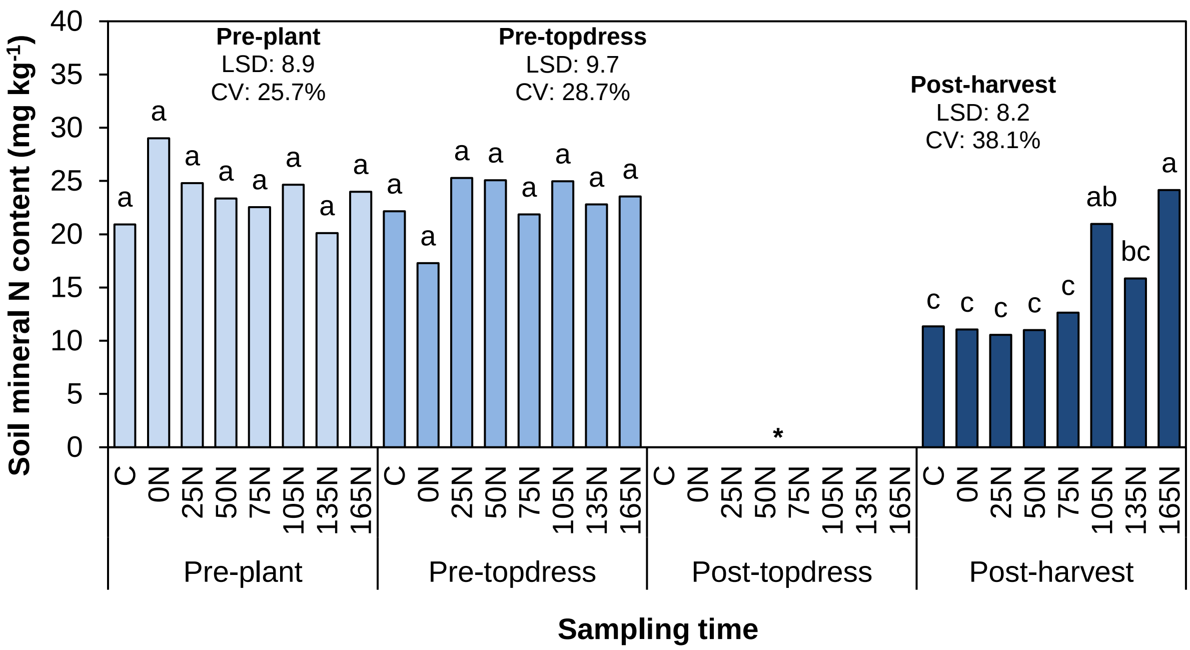


Figure 4.1.31 Total mineral N in the soil as influenced by topdress N rate (kg ha^{-1}) at Porterville M/W (Year 1). LSD = Least significant difference ($P < 0.05$); CV = coefficient of variance. Bars with different letters within a specific sampling time indicate significant differences at a 5% level. *No sampling due to uneven distribution of seedlings.

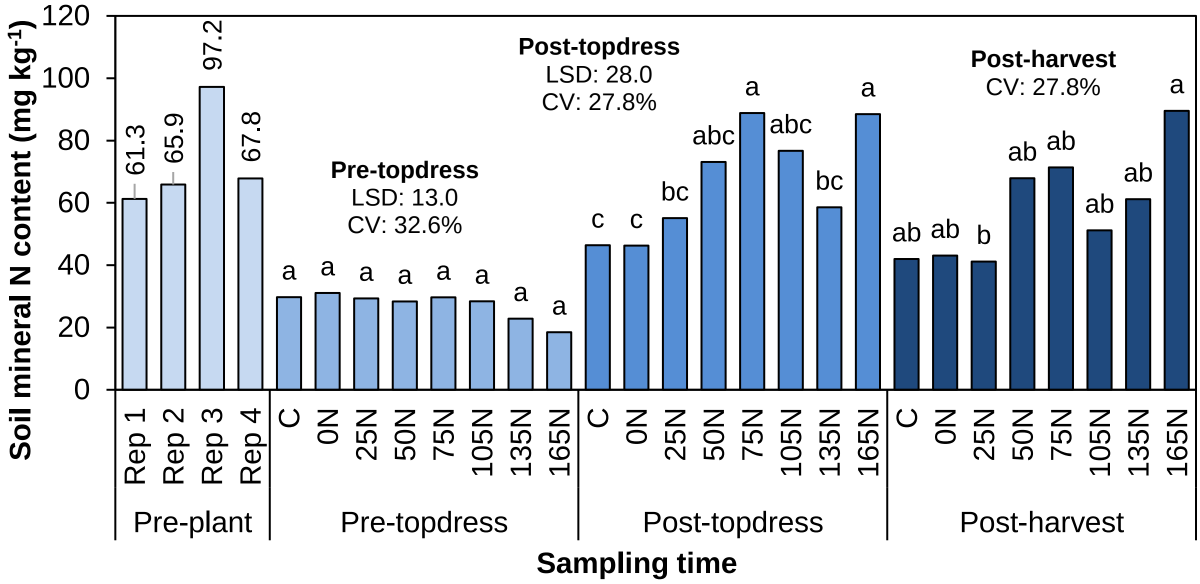


Figure 4.1.32 Total mineral N in the soil as influenced by topdress N rate (kg ha^{-1}) at Porterville M/W (Year 2). LSD = Least significant difference (P < 0.05); CV = coefficient of variance. Bars with different letters within a specific sampling time indicate significant differences at a 5% level.

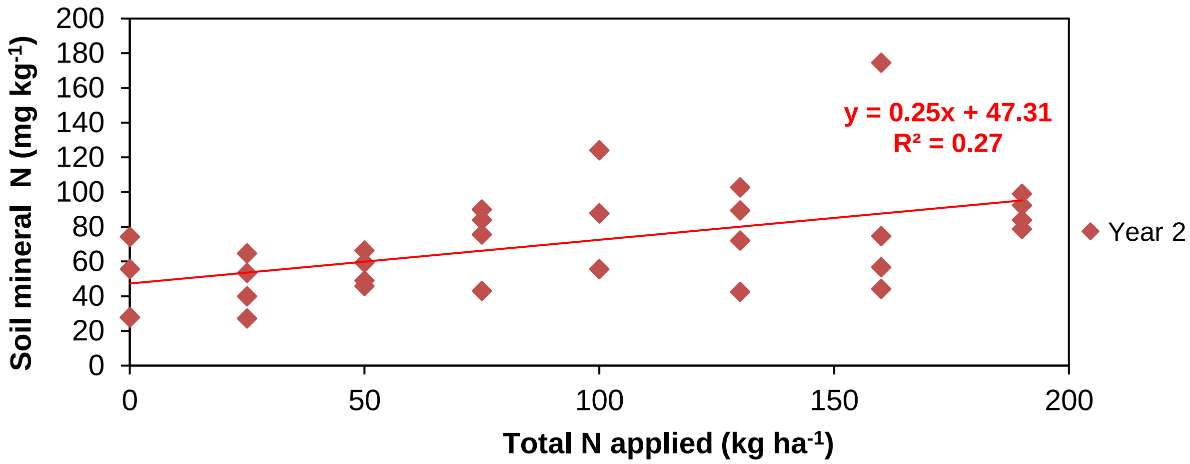


Figure 4.1.33 The response of total soil mineral N at post-topdress stage to total N applied during the growing season at Porterville M/W for the years as indicated.

4.1.6.2 Plant parameters

For Year 1, the control treatment had fewer (P < 0.05) seedlings than some of the other treatments (Table 4.1.11). In Year 2, the 50 kg N ha^{-1} treatment had a higher (P < 0.05) seedling population than the 75 kg N ha^{-1}.

No clear relationship between the number of EBT and topdress N rate was found, with 135 kg N ha^{-1} having the lowest (P < 0.05) number and 25 kg N ha^{-1} the highest (P < 0.05) number. During Year 2, the 25 and 50 kg N ha^{-1} treatments had higher (P < 0.05) numbers of EBT than the 105 and 135 kg N ha^{-1} treatments. The only clear difference in biomass in Year 1 was that the 50 kg N ha^{-1} produced less (P < 0.05) than the 135 kg N ha^{-1} treatment, whilst no differences (P > 0.05) were recorded in Year 2.

4.1.6.3 Grain yield

Apart from the control treatment being the lowest (P < 0.05), no other differences (P > 0.05) in yield were recorded for Year 1 (Figure 4.1.34). An increase in topdress N rate above 0 kg N ha^{-1} did not lead to an increase (P > 0.05) in yield. During Year 2, no differences (P > 0.05) in yield were recorded (Figure 4.1.35).

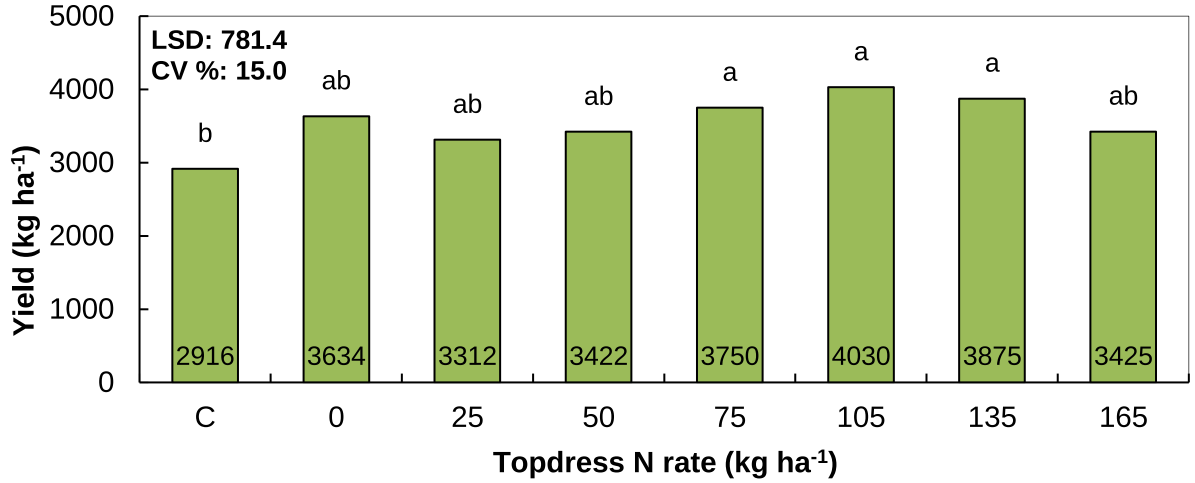


Figure 4.1.34 Grain yield (kg ha^{-1}) as influenced by topdress N rate (kg ha^{-1}) at Porterville M/W (Year 1). LSD = Least significant difference (P < 0.05); CV = coefficient of variance. Means without a common letter above bars indicate significant differences at a 5% level.

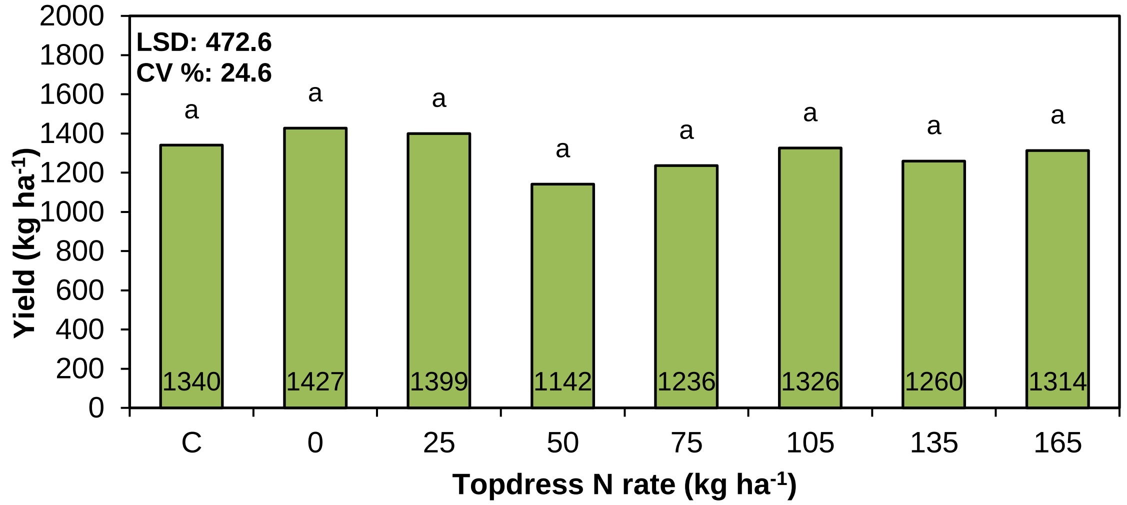


Figure 4.1.35 Grain yield (kg ha^{-1}) as influenced by topdress N rate (kg ha^{-1}) at Porterville M/W (Year 2). LSD = Least significant difference (P < 0.05); CV = coefficient of variance. Means without a common letter above bars indicate significant differences at a 5% level.

Table 4.1.11 Seedling population (m^{-2}), number of EBT (m^{-2}) and biomass production (kg ha^{-1}) as influenced by topdressed fertiliser N rate (kg ha^{-1}) at Porterville M/W during Year 1 and 2 of the study.

Topdress N rate (kg ha^{-1})	control	0	25	50	75	105	135	165	CV (%)	LSD
				Year 1						
Seedlings (m^{-2})	49.1 ^{b}	64.0 ^{ab}	70.1 ^{a}	72.1 ^{a}	69.6 ^{a}	64.4 ^{ab}	64.4 ^{ab}	71.1 ^{ab}	**17.3**	**16.6**
EBT (m^{-2})	165.0 ^{cd}	187.9 ^{bcd}	250.6 ^{a}	210.0 ^{ab}	222.3 ^{ab}	205.6 ^{bc}	197.5 ^{d}	219.8 ^{ab}	**13.8**	**44.3**
Biomass (kg ha^{-1})	7667 ^{ab}	8938 ^{ab}	7854 ^{ab}	7563 ^{b}	8271 ^{ab}	9062 ^{ab}	9687 ^{a}	8292 ^{ab}	**16.9**	**2086**
				Year 2						
Seedlings (m^{-2})	67.1 ^{ab}	68.5 ^{ab}	71.7 ^{ab}	81.1 ^{a}	58.6 ^{b}	74.5 ^{ab}	65.6 ^{ab}	73.8 ^{ab}	**16.6**	**17.1**
EBT (m^{-2})	197.3 ^{ab}	196.1 ^{ab}	220.6 ^{a}	221.5 ^{a}	192.7 ^{ab}	174.0 ^{b}	176.7 ^{b}	183.6 ^{ab}	**14.7**	**42.3**
Biomass (kg ha^{-1})	4938 ^{a}	5500 ^{a}	5521 ^{a}	5521 ^{a}	5896 ^{a}	5104 ^{a}	5792 ^{a}	5500 ^{a}	**14.4**	**1159**

Means without a common superscript letter in the same row indicate significant differences at a 5% level.

CV = Coefficient of variance

LSD = Least significant difference

4.1.6.4 Nitrogen use efficiency

Increasing N rates led to a negative effect on NUE in both years (Figure 4.1.36).

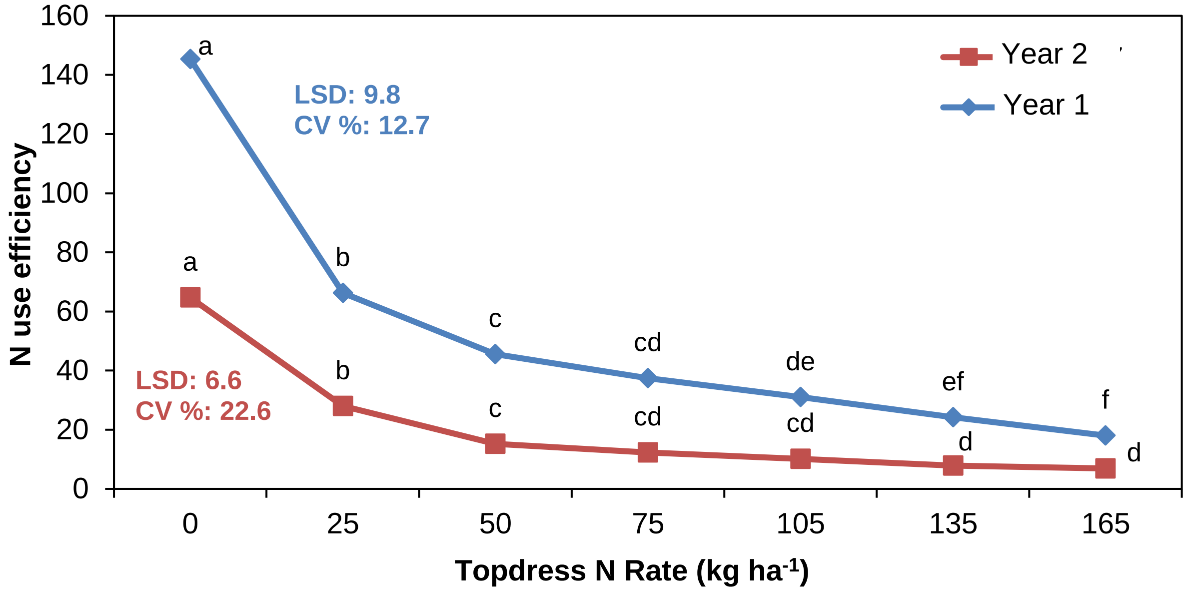


Figure 4.1.36 N use efficiencies per corresponding topdress N rate (kg ha^{-1}) at Porterville M/W (Year 1 and 2). LSD = Least significant difference (P < 0.05); CV = coefficient of variance. No common letter within a year indicates significant difference at a 5% level.

4.1.6.5 Quality parameters

No clear relationship between topdress N rate and hectolitre mass was found for Year 1 (Table 4.1.12). The only differences being that 105 and 135 kg N ha^{-1} had lower (P < 0.05) hectolitre mass than the 0 kg N ha^{-1} treatment. In Year 2, the 75 kg N ha^{-1} treatment had a lower (P < 0.05) hectolitre mass than the control treatment. Protein content increased (P < 0.05) with increasing topdress N rates in Year 1 at Porterville M/W but showed no differences (P > 0.05) between treatments in Year 2.

The harvest indices of the 25 and 50 kg N ha^{-1} were lower than those of the 75 and 105 kg N ha^{-1}, but no other differences were found for Year 1 and did not differ at all (P > 0.05) in Year 2. Apart from the control treatment having lower (P < 0.05) biomass N than most, no other differences were recorded in Year 2.

Table 4.1.12 Hectolitre mass, protein content (%), harvest index and biomass N (kg ha^{-1}) as influenced by topdressed fertiliser N rate (kg ha^{-1}) at Porterville M/W during Year 1 and 2 of the study.

				Year 1						
Topdress N rate (kg ha^{-1})	**control**	**0**	**25**	**50**	**75**	**105**	**135**	**165**	**CV (%)**	**LSD**
Hectolitre mass (g cm^{-3})	77.8 ^{ab}	80.1 ^{a}	77.7 ^{ab}	77.9 ^{ab}	77.0 ^{ab}	76.2 ^{b}	76.5 ^{b}	77.0 ^{ab}	**3.0**	**3.4**
Protein content (%)	12.0 ^{bc}	11.6 ^{c}	12.1 ^{bc}	12.4 ^{abc}	13.2 ^{ab}	13.8 ^{a}	13.5 ^{ab}	13.5 ^{ab}	**7.9**	**1.5**
Harvest index	0.38 ^{ab}	0.41 ^{ab}	0.36 ^{b}	0.45 ^{b}	0.46 ^{a}	0.45 ^{a}	0.41 ^{ab}	0.37 ^{ab}	**13.8**	**0.09**
Biomass N (kg ha^{-1})	*	*	*	*	*	*	*	*	*	*
				Year 2						
Hectolitre mass (g cm^{-3})	73.6 ^{a}	72.4 ^{ab}	72.3 ^{ab}	71.8 ^{ab}	70.3 ^{b}	71.6 ^{ab}	71.8 ^{ab}	70.8 ^{ab}	**2.8**	**2.9**
Protein content (%)	18.2 ^{a}	18.1 ^{a}	18.3 ^{a}	17.8 ^{a}	17.7 ^{a}	18.5 ^{a}	17.6 ^{a}	18.2 ^{a}	**5.7**	**1.5**
Harvest index	0.28 ^{a}	0.26 ^{a}	0.26 ^{a}	0.21 ^{a}	0.22 ^{a}	0.27 ^{a}	0.22 ^{a}	0.24 ^{a}	**25.3**	**0.09**
Biomass N (kg ha^{-1})	77.6 ^{b}	100.1 ^{a}	95.7 ^{ab}	112.0 ^{a}	110.1 ^{a}	94.4 ^{ab}	100.0 ^{a}	101.2 ^{a}	**12.9**	**18.8**

Means without a common superscript letter in the same row indicate significant differences at a 5% level.

CV = Coefficient of variance

LSD = Least significant difference

*Missing data

4.1.7 Porterville C/W

4.1.7.1 Soil mineral N content

Soil samples taken before planting showed little or no differences (P > 0.05) in soil mineral N, where the only difference was that 50 kg N ha^{-1} had more (P < 005) mineral N present in the soil than the treatments that received 135 and 165 kg N ha^{-1} (Figure 4.1.37). Due to this, the pre-plant soil samples were not taken for every individual treatment in Year 2, but rather per block to give a general indication of the mineral N content of the soil.

Before the topdress stage in Year 1 and 2, the control treatment (receiving no N at plant) had the lowest (P < 0.05) mineral N content present in the soil (Figure 4.1.37 and Figure 4.1.38). No other differences (P > 0.05) were recorded in either of the two years.

Soil samples collected after topdress in Year 1 showed an increase in total soil mineral N content, with increasing topdress N rates, where 135 kg N ha^{-1} was the highest (P < 0.05). In Year 2 at the post-topdress stage, no differences (P > 0.05) in soil mineral N content was recorded, but this might also be explained by the high coefficient of variance (CV) (Figure 4.1.38).

No differences (P > 0.05) in the soil mineral N content were found in the samples collected after harvest in Year 1.

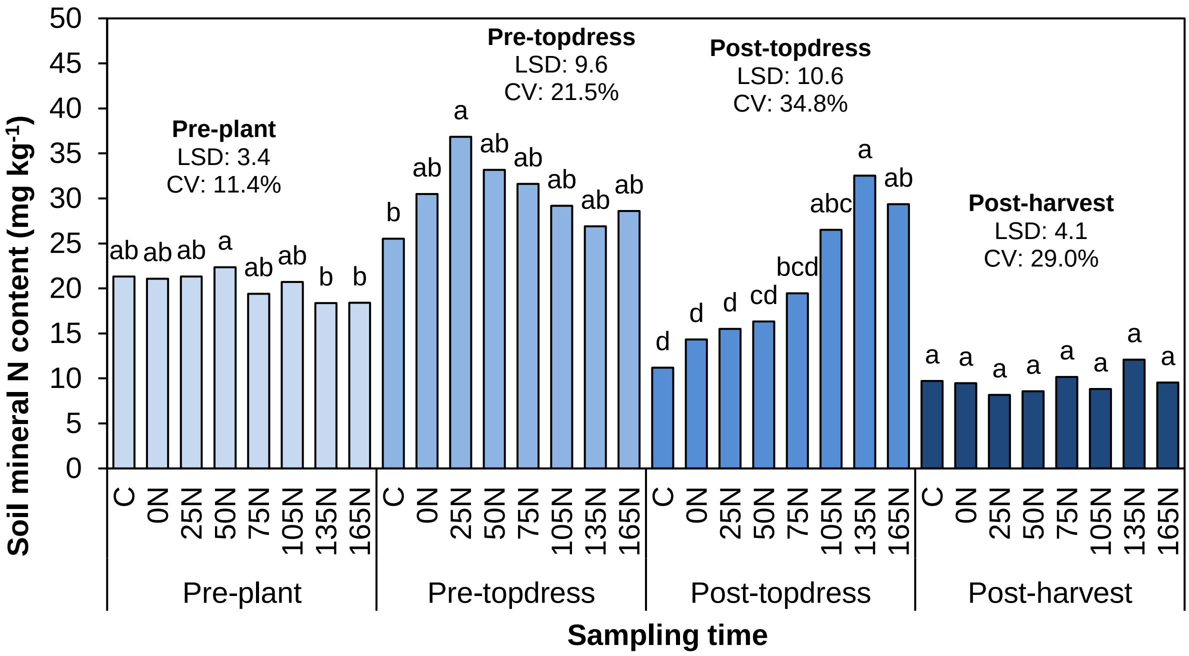


Figure 4.1.37 Total mineral N in the soil as influenced by topdress N rate (kg ha^{-1}) at Porterville C/W (Year 1). LSD = Least significant difference (P < 0.05); CV = coefficient of variance. Bars with different letters within a specific sampling time indicate significant differences at a 5% level.

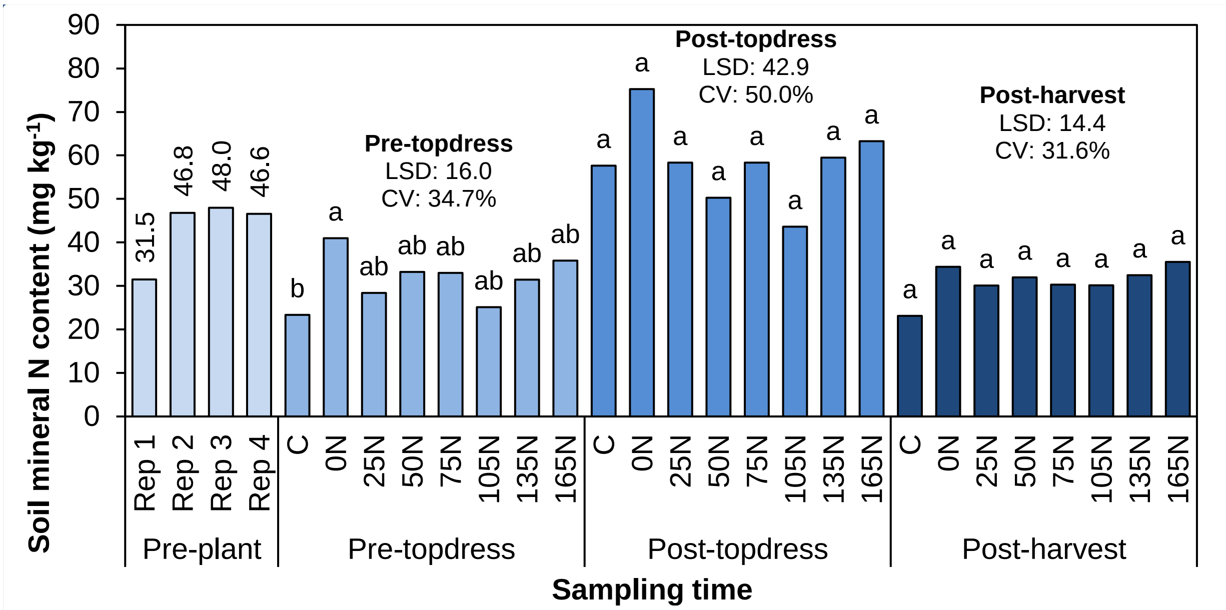


Figure 4.1.38 Total mineral N in the soil as influenced by topdress N rate (kg ha^{-1}) at Porterville C/W (Year 2). LSD = Least significant difference (P < 0.05); CV = coefficient of variance. Bars with different letters within a specific sampling time indicate significant differences at a 5% level.

The regression between topdressed N application rate and post-topdress mineral N content is described by the equation y = 0.11x + 10.39 (R^2 = 0.52) in Year 1 and y = -0.04x + 61.62 (R^2 = 0.01) in Year 2 (Figure 4.1.39).

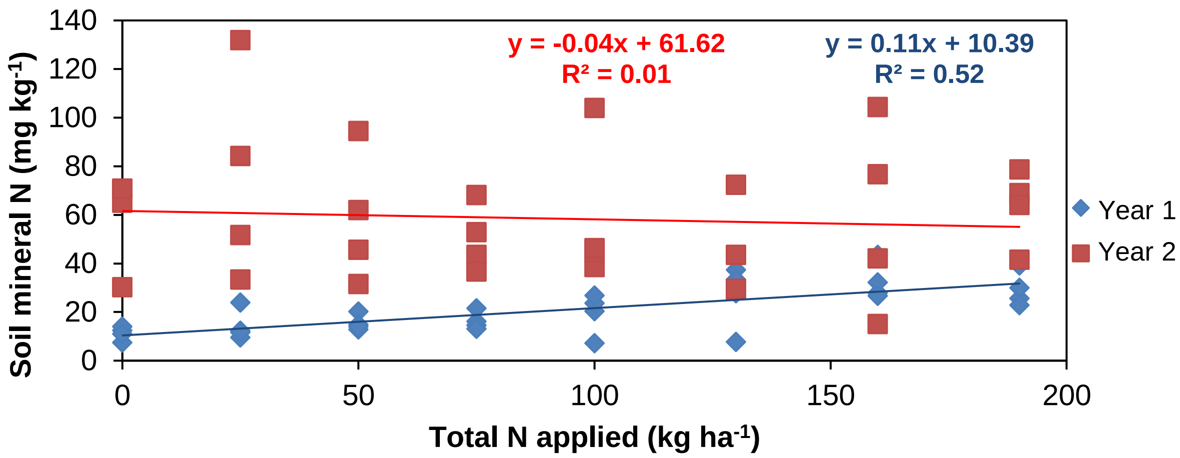


Figure 4.1.39 The response of total soil mineral N at post-topdress stage to total N applied during the growing season at Porterville C/W for the years as indicated.

4.1.7.2 Plant parameters

No differences (P > 0.05) in seedling population were found between N rate treatments for Year 1 and 2 (Table 4.1.13). Except for 165 kg N ha^{-1} having a higher (P < 0.05) number of EBT than some treatments, only intermediary differences (P > 0.05) were found in Year 1 and no differences ($P > 0.05$) in Year 2. The control treatment produced the lowest ($P < 0.05$) amount of biomass in Year 1, whilst no differences ($P > 0.05$) in biomass were recorded in Year 2.

4.1.7.3 Grain yield

An upward trend in yield, as topdress N rate was increased, was observed in Year 1 (Figure 4.1.40). Increasing the N rate above 50 kg N ha^{-1} did not, however, led to a further increase in yield. The only difference in Year 2 was that the control treatment achieved a higher ($P < 0.05$) yield than that of the 135 kg N ha^{-1} treatment (Figure 4.1.41).

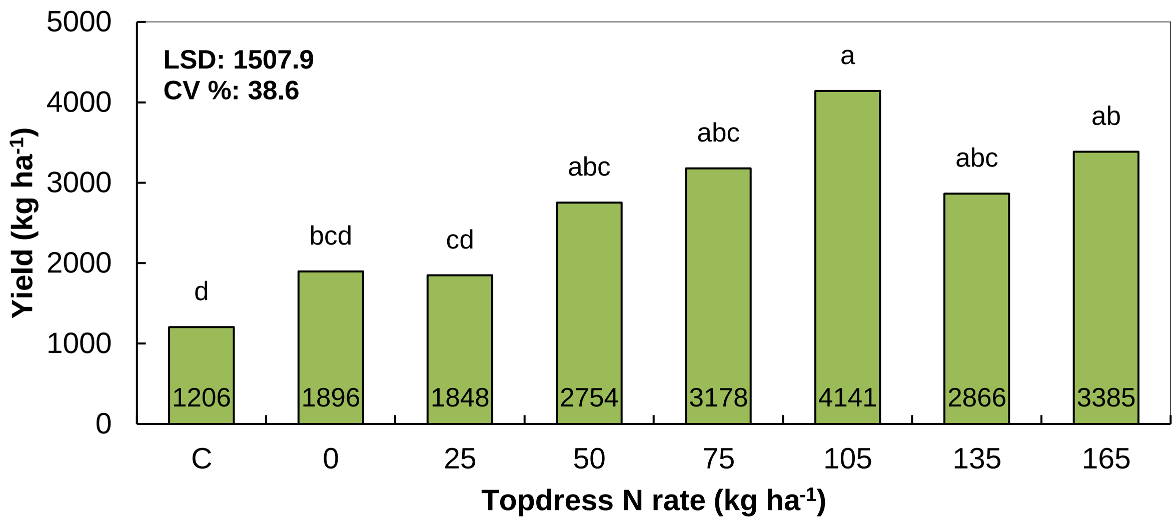


Figure 4.1.40 Grain yield (kg ha^{-1}) as influenced by topdress N rate (kg ha^{-1}) at Porterville C/W (Year 1). LSD = Least significant difference ($P < 0.05$); CV = coefficient of variance. Means without a common letter above bars indicate significant differences at a 5% level.

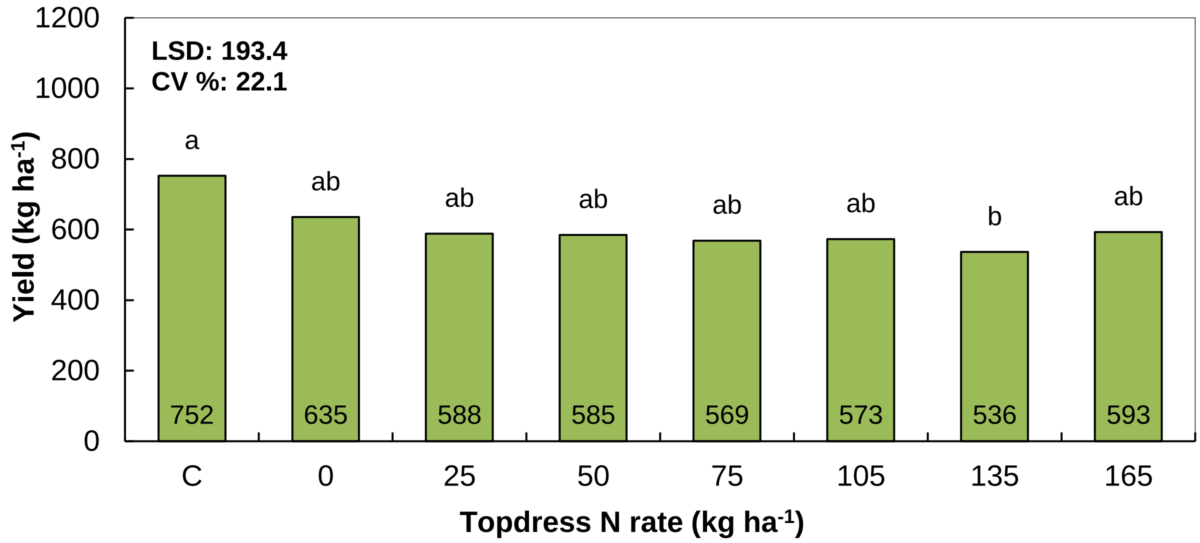


Figure 4.1.41 Grain yield (kg ha^{-1}) as influenced by topdress N rate (kg ha^{-1}) at Porterville C/W (Year 2). LSD = Least significant difference ($P < 0.05$); CV = coefficient of variance. Means without a common letter above bars indicate significant differences at a 5% level.

Table 4.1.13 Seedling population (m^{-2}), number of EBT (m^{-2}) and biomass production (kg ha^{-1}) as influenced by topdressed fertiliser N rate (kg ha^{-1}) at Porterville C/W during Year 1 and 2 of the study.

Topdress N rate (kg ha^{-1})	**control**	**0**	**25**	**50**	**75**	**105**	**135**	**165**	**CV (%)**	**LSD**
					Year 1					
Seedlings (m^{-2})	96.5 ^{a}	102.4 ^{a}	93.0 ^{a}	82.2 ^{a}	90.8 ^{a}	89.9 ^{a}	103.0 ^{a}	112.8 ^{a}	**24.0**	**34.3**
EBT (m^{-2})	206.0 ^{b}	242.7 ^{ab}	222.9 ^{ab}	205.4 ^{b}	214.8 ^{ab}	261.7 ^{ab}	205.4 ^{ab}	269.6 ^{a}	**17.3**	**58.8**
Biomass (kg ha^{-1})	4208 ^{b}	6229 ^{ab}	6500 ^{ab}	6396 ^{ab}	7458 ^{a}	8583 ^{a}	7333 ^{a}	8583 ^{a}	**24.3**	**2465**
					Year 2					
Seedlings (m^{-2})	75.7 ^{a}	67.6 ^{a}	69.6 ^{a}	59.7 ^{a}	71.4 ^{a}	72.5 ^{a}	75.9 ^{a}	71.0 ^{a}	**15.6**	**16.1**
EBT (m^{-2})	160.6 ^{a}	175.9 ^{a}	159.6 ^{a}	181.5 ^{a}	168.8 ^{a}	152.7 ^{a}	149.6 ^{a}	175.4 ^{a}	**14.6**	**35.6**
Biomass (kg ha^{-1})	3500 ^{a}	3521 ^{a}	3375 ^{a}	3625 ^{a}	3521 ^{a}	3312 ^{a}	3354 ^{a}	3646 ^{a}	**15.5**	**792**

Means without a common superscript letter in the same row indicate significant differences at a 5% level.

CV = Coefficient of variance

LSD = Least significant difference

4.1.7.4 Nitrogen use efficiency

Increasing the topdress N rate decreased (P < 0.05) the NUE for both years (Figure 4.1.42).

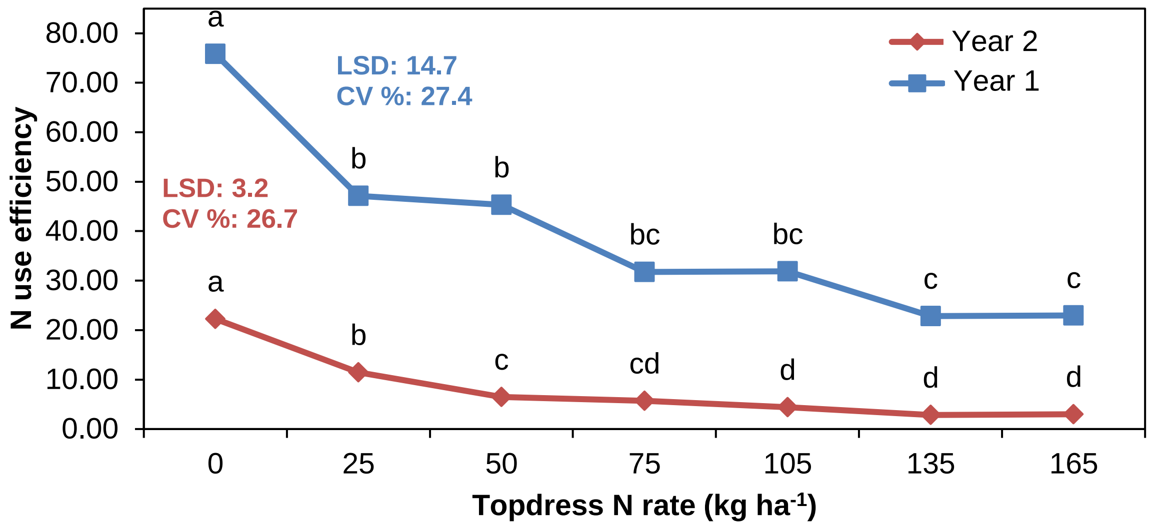


Figure 4.1.42 N use efficiencies per corresponding topdress N rate (kg ha^{-1}) at Porterville C/W (Year 1 and 2). LSD = Least significant difference (P < 0.05); CV = coefficient of variance. No common letter within a year indicates significant difference at a 5% level.

4.1.7.5 Quality parameters

No differences (P > 0.05) in hectolitre mass were recorded in Year 1 (Table 4.1.14). During Year 2, the control treatment had a higher (P < 0.05) hectolitre mass than the 75 kg N ha^{-1} treatment. No differences (P > 0.05) in protein content was recorded in Year 2.

Except for the 105 kg N ha^{-1} having a higher (P < 0.05) harvest index than the control, 0 and 25 kg N ha^{-1} treatments, not many other differences in harvest index were recorded in Year 1. In Year 2, the control treatment had the lowest (P < 0.05) harvest index.

Biomass N content seemed to be positively correlated to increasing topdress N rates, where an increase in N rate led to an increase (P < 0.05) in biomass N content of the wheat crop. During Year 2, this was not the case, as no differences (P > 0.05) in biomass N were recorded between treatments.

Table 4.1.14 Hectolitre mass, protein content (%), harvest index and biomass N (kg ha^{-1}) as influenced by topdressed fertiliser N rate (kg ha^{-1}) at Porterville C/W during Year 1 and 2 of the study.

Topdress N rate (kg ha^{-1})	control	0	25	50	75	105	135	165	CV (%)	LSD
				Year 1						
Hectolitre mass (g cm^{-3})	80.8 ^{a}	80.8 ^{a}	81.0 ^{a}	80.7 ^{a}	81.0 ^{a}	80.5 ^{a}	80.6 ^{a}	80.5 ^{a}	**0.5**	**0.7**
Protein content (%)	*	*	*	*	*	*	*	*	*	*
Harvest index	0.28 ^{c}	0.31 ^{bc}	0.28 ^{c}	0.41 ^{abc}	0.43 ^{ab}	0.49 ^{a}	0.37 ^{abc}	0.36 ^{abc}	**27.0**	**0.15**
Biomass N (kg ha^{-1})	47.8 ^{d}	64.0 ^{cd}	77.5 ^{bcd}	81.6 ^{bcd}	83.2 ^{bcd}	113.0 ^{ab}	93.7 ^{bc}	137.5 ^{a}	**28.2**	**40.5**
				Year 2						
Hectolitre mass (g cm^{-3})	**	**	**	**	**	**	**	**	**	**
Protein content (%)	17.9 ^{a}	18.8 ^{a}	18.2 ^{a}	18.1 ^{a}	18.3 ^{a}	18.7 ^{a}	18.1 ^{a}	18.3 ^{a}	**4.6**	**1.2**
Harvest index	0.22 ^{a}	0.18 ^{ab}	0.18 ^{ab}	0.16 ^{b}	0.16 ^{b}	0.18 ^{ab}	0.13 ^{b}	0.16 ^{b}	**20.5**	**0.05**
Biomass N (kg ha^{-1})	60.0 ^{a}	69.0 ^{a}	65.2 ^{a}	71.2 ^{a}	73.1 ^{a}	68.8 ^{a}	69.7 ^{a}	74.0 ^{a}	**17.8**	**18.5**

Means without a common superscript letter in the same row indicate significant differences at a 5% level.

CV = Coefficient of variance

LSD = Least significant difference

* Missing data

**Too little grain at the end of season to determine hectolitre mass

4.1.8 Darling M/W

4.1.8.1 Soil mineral N content

Soil samples collected at the pre-planting stage showed no differences ($P < 0.05$) in the total amount of mineral N present in the soil (Figure 4.1.43).

The 75 kg N ha^{-1} treatment had a higher ($P < 0.05$) mineral N content present in the soil than most other treatments at the pre-topdress stage, while not many other differences ($P > 0.05$) were recorded at this stage in Year 1. No differences ($P > 0.05$) in soil mineral N content was recorded at the pre-topdress stage in Year 2 (Figure 4.1.44).

At the post-topdress stage, a clear upwards trend in total mineral N with increasing N rates was present in Year 1, with 105, 135 and 165 kg N ha^{-1} having the highest ($P < 0.05$) amount of mineral N in the soil. The same trend was recorded in Year 2, but increasing N rates only led to an increase ($P < 0.05$) in soil mineral N content from the control to the 75 kg N ha^{-1} treatment, thereafter no further increases ($P > 0.05$) in soil mineral N content were recorded.

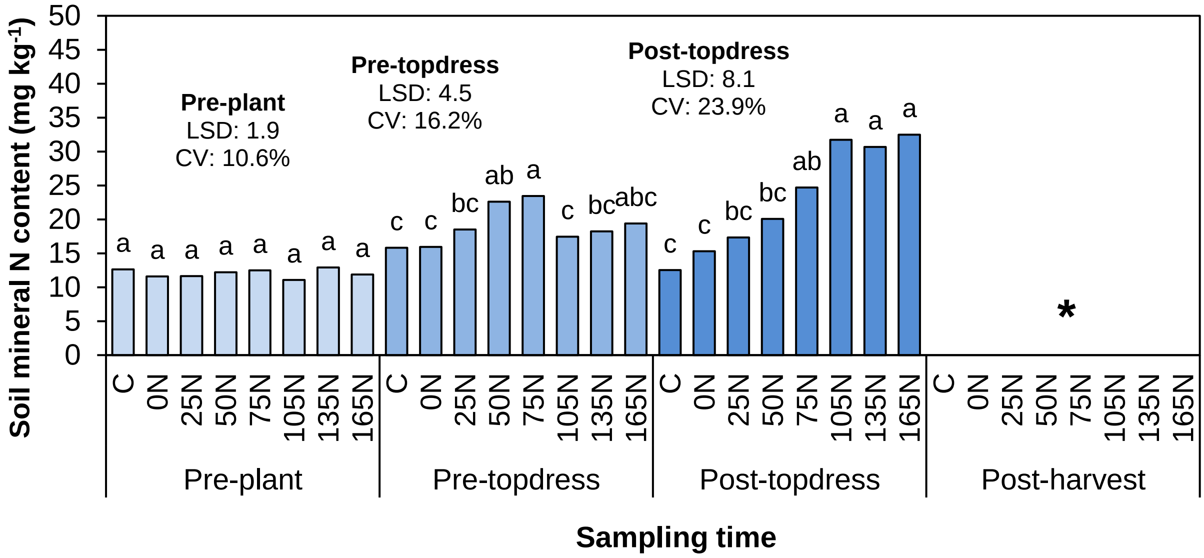


Figure 4.1.43 Total mineral N in the soil as influenced by topdress N rate (kg ha^{-1}) at Darling M/W (Year 1). LSD = Least significant difference ($P < 0.05$); CV = coefficient of variance. Bars with different letters within a specific sampling time indicate significant differences at a 5% level. *No sampling due to logistical transport problems.

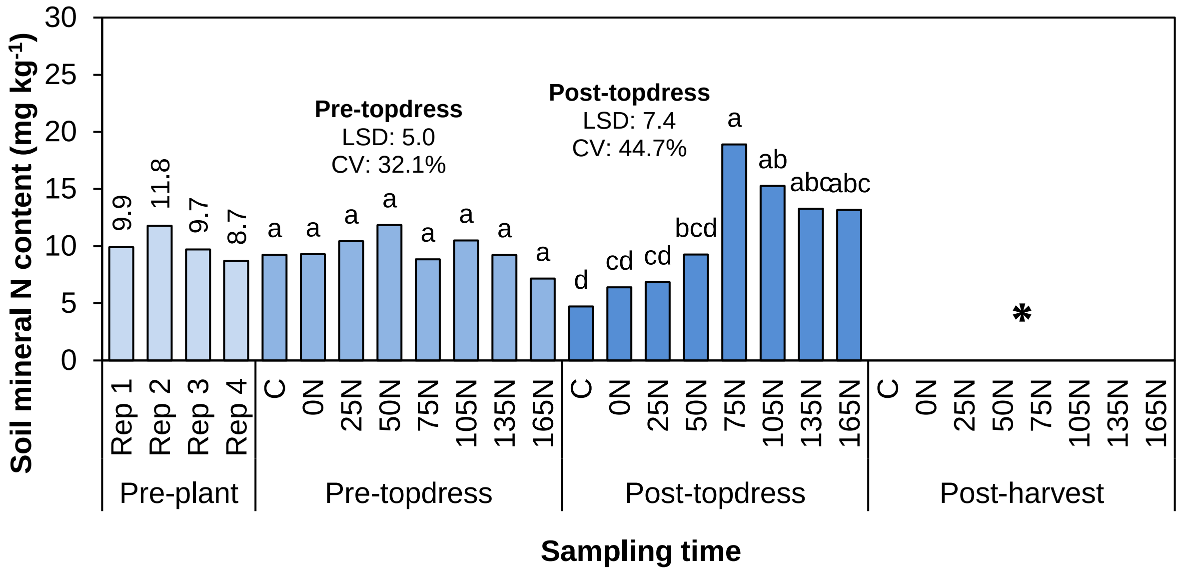


Figure 4.1.44 Total mineral N in the soil as influenced by topdress N rate (kg ha^{-1}) at Darling M/W (Year 2). LSD = Least significant difference (P < 0.05); CV = coefficient of variance. Bars with different letters within a specific sampling time indicate significant differences at a 5% level. *Missing.

The regression between topdressed N application rate and post-topdress mineral N content is described by the equation y = 0.12x + 12.53 (R^2 = 0.60) in Year 1 and y = 0.0069x + 11.48 (R^2 = 0.0023) in Year 2 (Figure 4.1.45).

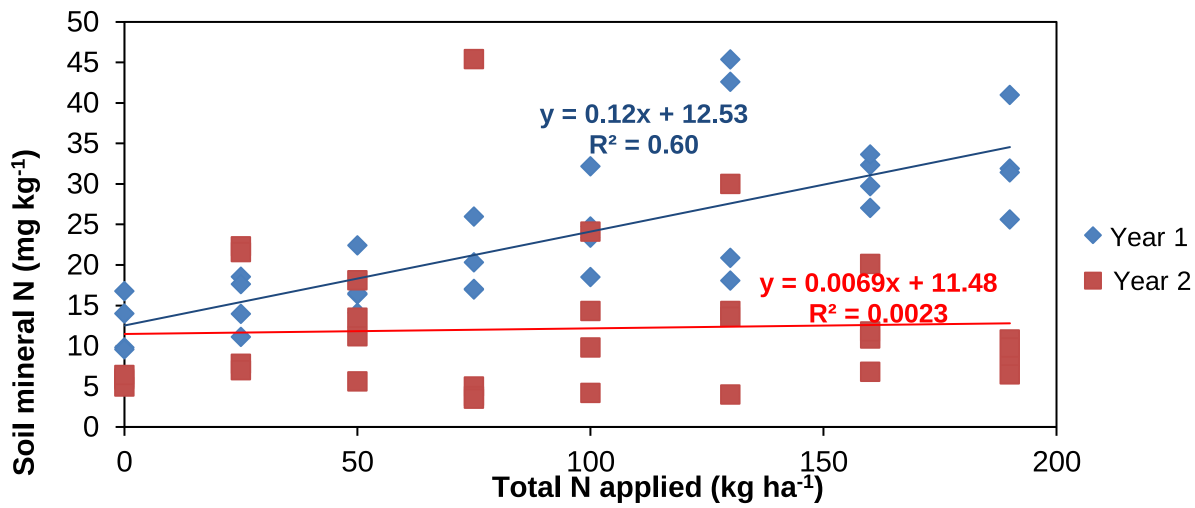


Figure 4.1.45 The response of total soil mineral N at post-topdress stage to total N applied during the growing season at Darling M/W for the years as indicated.

4.1.8.2 Plant parameters

There were no differences (P> 0.05) in the seedlings populations between treatments for Year 1 at Darling M/W (Table 4.1.15). In Year 2 the 0 and 75 kg N ha^{-1} treatments had higher (P < 0.05) seedling populations than that of the 105 and 165 kg N ha^{-1} treatments. During Year 1, no differences (P > 0.05) in the number of EBT were present as the topdress N rate was increased above 50 kg N ha^{-1}. Increasing the topdress N rate from 75 kg N ha^{-1} to 165 kg N ha^{-1} yielded no increase (P > 0.05) in biomass production in Year 1. No differences (P > 0.05) in biomass production or the number of EBT were recorded between treatments in Year 2.

4.1.8.3 Grain yield

An increase in topdress N rate led to a corresponding increase in grain yield (up to the 50 kg N ha^{-1} treatment) in Year 1 (Figure 4.1.46). Increasing the N rate above 50 kg N ha^{-1} did not further influence (P > 0.05) grain yield. Topdress N rate treatments had no effect (P > 0.05) on grain yield in Year 2 (Figure 4.1.47).

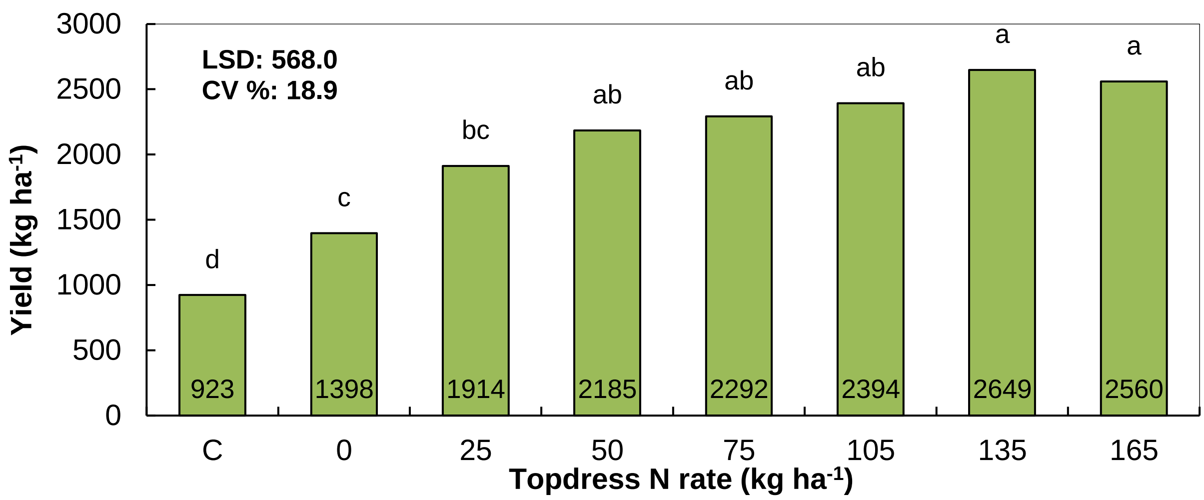


Figure 4.1.46 Grain yield (kg ha^{-1}) as influenced by topdress N rate (kg ha^{-1}) at Darling M/W (Year 1). LSD = Least significant difference (P < 0.05); CV = coefficient of variance. Means without a common letter above bars indicate significant differences at a 5% level.

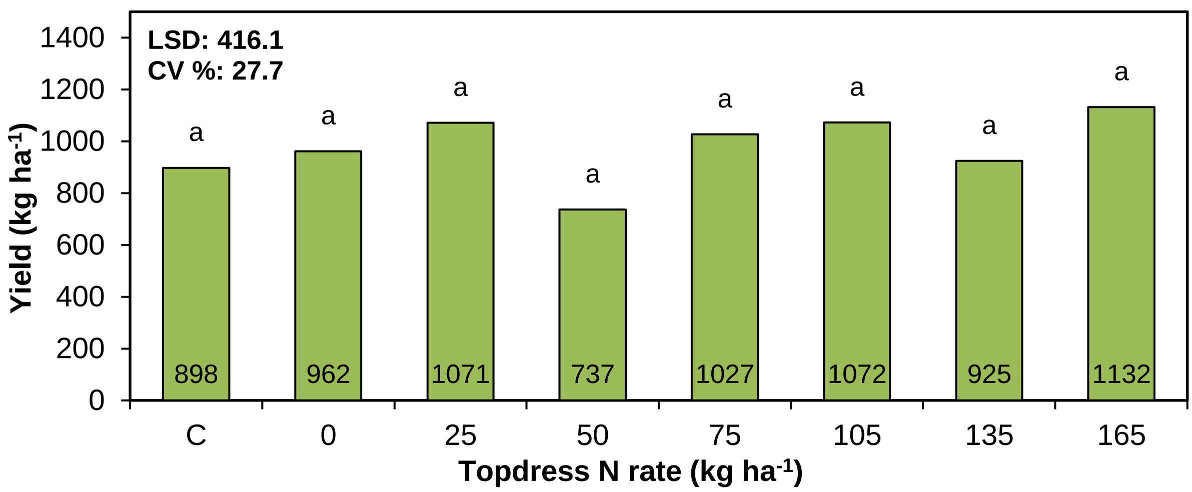


Figure 4.1.47 Grain yield (kg ha^{-1}) as influenced by topdress N rate (kg ha^{-1}) at Darling M/W (Year 2). LSD = Least significant difference (P < 0.05); CV = coefficient of variance. Means without a common letter above bars indicate significant differences at a 5% level.

Table 4.1.15 Seedling population (m^{-2}), number of EBT (m^{-2}) and biomass production (kg ha^{-1}) as influenced by topdressed fertiliser N rate (kg ha^{-1}) at Darling M/W during Year 1 and 2 of the study.

Topdress N rate (kg ha^{-1})	control	0	25	50	75	105	135	165	CV (%)	LSD
				Year 1						
Seedlings (m^{-2})	135.9 ^{a}	149.3 ^{a}	139.3 ^{a}	154.3 ^{a}	140.1 ^{a}	144.0 ^{a}	142.1 ^{a}	142.8 ^{a}	**13.1**	**27.6**
EBT (m^{-2})	145.0 ^{d}	222.3 ^{bc}	214.6 ^{c}	255.4 ^{abc}	284.2 ^{ab}	298.1 ^{a}	286.5 ^{ab}	304.8 ^{a}	**18.0**	**66.4**
Biomass (kg ha^{-1})	2500 ^{e}	4271 ^{d}	4896 ^{cd}	5292 ^{bcd}	6229 ^{abc}	6438 ^{ab}	6875 ^{a}	6500 ^{a}	**18.2**	**1451**
				Year 2						
Seedlings (m^{-2})	82.2 ^{ab}	89.0 ^{a}	81.4 ^{ab}	77.0 ^{ab}	88.3 ^{a}	67.8 ^{b}	74.7 ^{ab}	65.1 ^{b}	**17.3**	**19.9**
EBT (m^{-2})	116.7 ^{a}	137.1 ^{a}	142.9 ^{a}	153.9 ^{a}	120.4 ^{a}	136.5 ^{a}	133.8 ^{a}	126.5 ^{a}	**21.5**	**42.3**
Biomass (kg ha^{-1})	2709 ^{a}	2604 ^{a}	3083 ^{a}	2854 ^{a}	2854 ^{a}	3333 ^{a}	2979 ^{a}	3646 ^{a}	**27.9**	**1233**

Means without a common superscript letter in the same row indicate significant differences at a 5% level.

CV = Coefficient of variance

LSD = Least significant difference

4.1.8.4 Nitrogen use efficiency

For Year 1, increasing topdress N rates had a negative effect on NUE, where 0 kg N ha^{-1} had the highest (P < 0.05) and 165 kg N ha^{-1} the lowest (P < 0.05) NUE. In Year 2, the increasing topdress N rates, again, led to an initial decrease in NUE. The curve levelled out at a rate of 50 kg N ha^{-1}, and further increase in topdress N rates did not lead to a decrease in NUE (Figure 4.1.48).

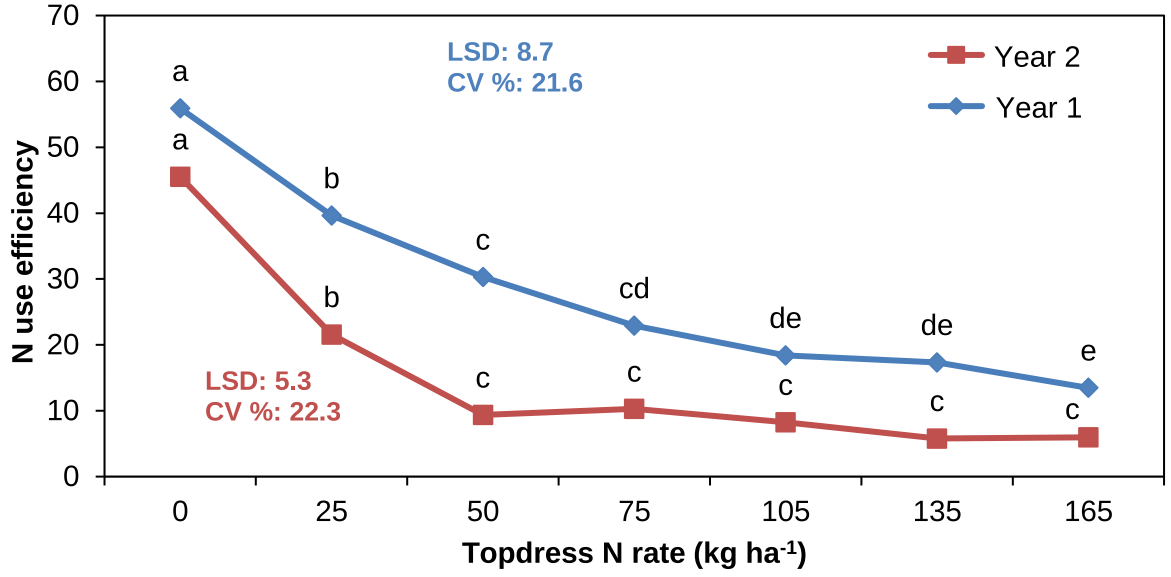


Figure 4.1.48 N use efficiencies per corresponding topdress N rate (kg ha^{-1}) at Darling M/W (Year 1 and 2). LSD = Least significant difference (P < 0.05); CV = coefficient of variance. No common letter within a year indicates significant difference at a 5% level.

4.1.8.5 Quality parameters

Increasing the topdress N rate led to a consequent decrease in hectolitre mass, with 75, 105, 135 and 165 kg N ha^{-1} all portraying low amounts (P < 0.05) in Year 1 and a slight decrease (P < 0.05) in Year 2. The grain protein content, however, increased as the topdress N rates were increased, with 165 kg N ha^{-1} having the highest (P < 0.05) protein content in Year 1 (Table 4.1.16). In Year 2, however, no increase in protein content (P < 0.05) was experienced whith increasing N rates.

No differences (P > 0.05) in harvest index, as influenced by the topdress N rates, occurred in Year 1 or 2. Increasing N rates led to an increase in biomass N, with 135 and 165 kg N ha^{-1} both being the highest (P < 0.05) in Year 1. For Year 2, no specific response of biomass N to N treatments were recorded.

Table 4.1.16 Hectolitre mass, protein content (%), harvest index and biomass N (kg ha^{-1}) as influenced by topdressed fertiliser N rate (kg ha^{-1}) at Darling M/W during Year 1 and 2 of the study.

Topdress N rate (kg ha^{-1})	control	0	25	50	75	105	135	165	CV (%)	LSD
Year 1										
Hectolitre mass (g cm^{-3})	78.1 ^{a}	77.5 ^{ab}	75.7 ^{c}	76.0 ^{bc}	73.7 ^{d}	73.9 ^{d}	73.1 ^{d}	72.7 ^{d}	**1.4**	**1.6**
Protein content (%)	11.2 ^{e}	11.5 ^{e}	12.7 ^{d}	12.7 ^{d}	13.6 ^{c}	14.0 ^{bc}	14.5 ^{ab}	15.0 ^{a}	**3.7**	**0.7**
Harvest index	0.34 ^{a}	0.33 ^{a}	0.40 ^{a}	0.41 ^{a}	0.38 ^{a}	0.37 ^{a}	0.39 ^{a}	0.39 ^{a}	**17.2**	**0.09**
Biomass N (kg ha^{-1})	32.0 ^{e}	54.5 ^{de}	69.0 ^{cd}	75.9 ^{bcd}	103.6 ^{ab}	97.1 ^{abc}	110.9 ^{a}	118.1 ^{a}	**22.2**	**28.8**
Year 2										
Hectolitre mass (g cm^{-3})	74.7 ^{ab}	76.0 ^{a}	74.6 ^{b}	73.9 ^{bc}	74.0 ^{bc}	72.1 ^{d}	72.9 ^{cd}	73.6 ^{bc}	**0.9**	**1.4**
Protein content (%)	13.5 ^{b}	14.9 ^{ab}	14.9 ^{ab}	14.0 ^{b}	15.1 ^{ab}	18.2 ^{a}	14.7 ^{b}	14.8 ^{ab}	**16.1**	**3.6**
Harvest index	0.43 ^{a}	0.39 ^{a}	0.29 ^{a}	0.36 ^{a}	0.36 ^{a}	0.30 ^{a}	0.37 ^{a}	0.31 ^{a}	**52.2**	**0.28**
Biomass N (kg ha^{-1})	40.2 ^{abc}	28.8 ^{c}	36.1 ^{bc}	46.8 ^{abc}	36.94 ^{abc}	61.0 ^{a}	50.2 ^{abc}	59.1 ^{ab}	**37.3**	**24.6**

Means without a common superscript letter in the same row indicate significant differences at a 5% level.

CV = Coefficient of variance

LSD = Least significant difference

4.1.9 Darling C/W

4.1.9.1 Soil mineral N content

Except for the 25 kg N ha^{-1} having lower ($P < 0.05$) mineral N in the soil compared to the 75 kg N ha^{-1}, no further differences ($P > 0.05$) were recorded at pre-plant stage (Figure 4.1.49).

As expected the control treatment, receiving no N at planting, had the lowest ($P < 0.05$) mineral N content at the pre-topdress stage in Year 1. No differences ($P > 0.05$) in soil mineral N content were recorded at the pre-topdress stage of Year 2 (Figure 4.1.50).

The different treatments ranging from the control to the 105 kg N ha^{-1} treatment had no differences ($P > 0.05$) in soil mineral N content at the post-topdress stage of Year 1, but substantially higher ($P < 0.05$) N contents were recorded for both the 135 and 165 kg N ha^{-1} treatments. In Year 2 at the post-topdress stage, an increase in N rates led to an increase ($P < 0.05$) in soil mineral N content, resulting in a strong positive response.

After harvest soil samples of Year 1 indicated no differences ($P > 0.05$) in total mineral N content between 0 and 135 kg N ha^{-1} treatments. The 165 kg N ha^{-1} treatment, however, had a higher ($P < 0.05$) mineral N content present in the soil than the control treatment.

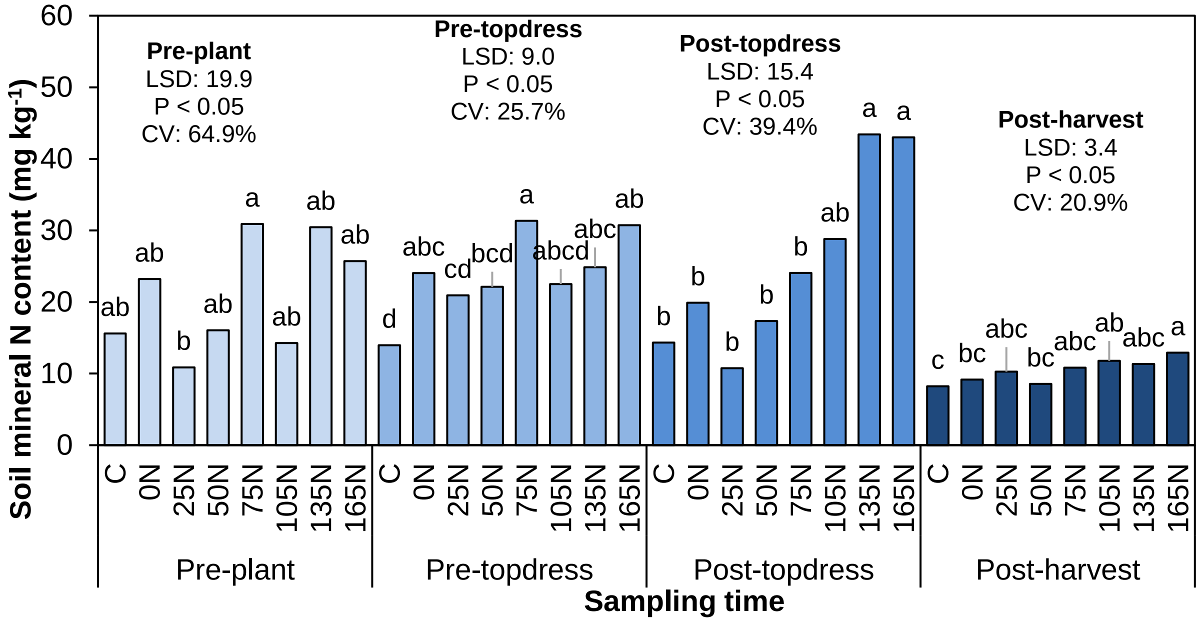


Figure 4.1.49 Total mineral N in the soil as influenced by topdress N rate (kg ha^{-1}) at Darling C/W (Year 1). LSD = Least significant difference ($P < 0.05$); CV = coefficient of variance. Bars with different letters within a specific sampling time indicate significant differences at a 5% level.

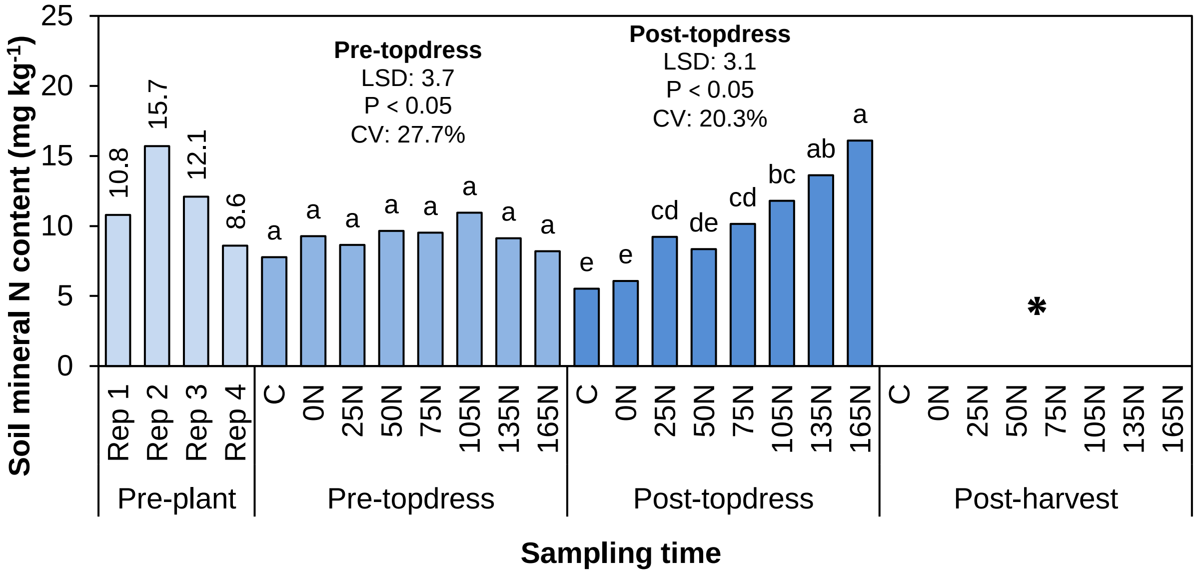


Figure 4.1.50 Total mineral N in the soil as influenced by topdress N rate (kg ha^{-1}) at Darling C/W (Year 2). LSD = Least significant difference (P < 0.05); CV = coefficient of variance. Bars with different letters within a specific sampling time indicate significant differences at a 5% level. *Missing data.

The regression between topdressed N application rate and post-topdress mineral N content is described by the equation y = 0.17x + 9.75 (R^2 = 0.53) in Year 1 and y = 0.058x + 5.24 (R^2 = 0.62) in Year 2 (Figure 4.1.51).

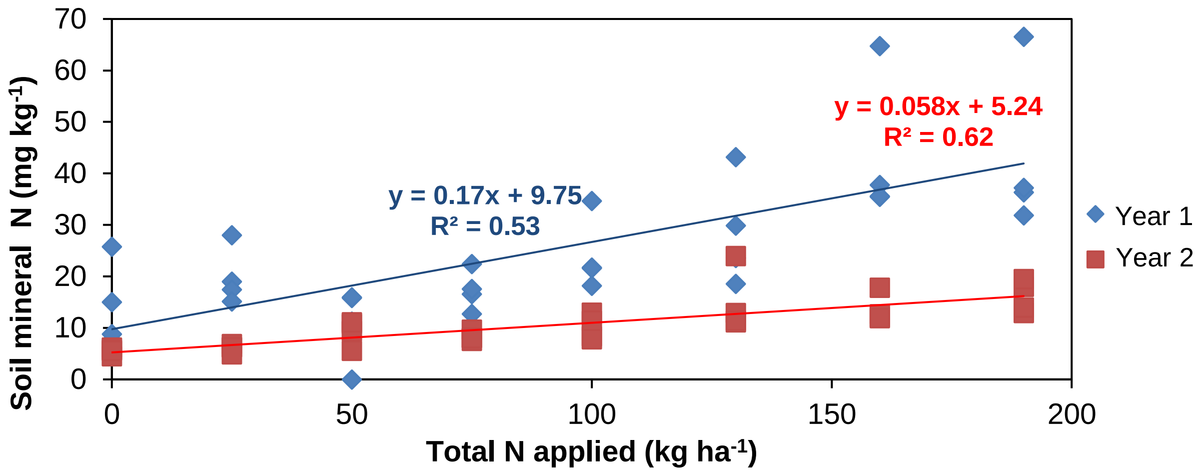


Figure 4.1.51 The response of total soil mineral N at post-topdress stage to total N applied during the growing season at Darling C/W for the years as indicated.

4.1.9.2 Plant parameters

No differences (P > 0.05) in seedling populations were recorded between the different N topdress treatments for Year 1 and 2 at Darling C/W (Table 4.1.17). The 25, 50, 75, 105 and 165 kg N ha^{-1} treatments did not differ (P > 0.05) in the number of EBT they produced, but the 135 kg N ha^{-1} treatment produced more (P < 0.05) EBT than the control and 0 kg N ha^{-1} treatments in Year 1. No differences (P > 0.05) in the number of EBT produced were recorded in Year 2. Except for the control being lower ($P < 0.05$) than most treatments, no other differences ($P > 0.05$) in biomass, as influenced by topdress N rate were recorded in Year 1.

4.1.9.3 Grain yield

In Year 1, the control treatment had the lowest ($P < 0.05$) yield of all the treatments and no further differences ($P > 0.05$) occurred after the N rates were increased above a rate of 0 kg N ha^{-1} (Figure 4.1.52). The yields for Year 2 are shown in Figure 4.1.53. No apparent trends were visible in the data, but the 0 kg N ha^{-1} treatment achieved a higher ($P < 0.05$) yield than the 50, 135 and 165 kg N ha^{-1} treatments. During Year 2, the control and 0 kg N ha^{-1} produced less ($P < 0.05$) biomass than the 75 kg N ha^{-1} treatment.

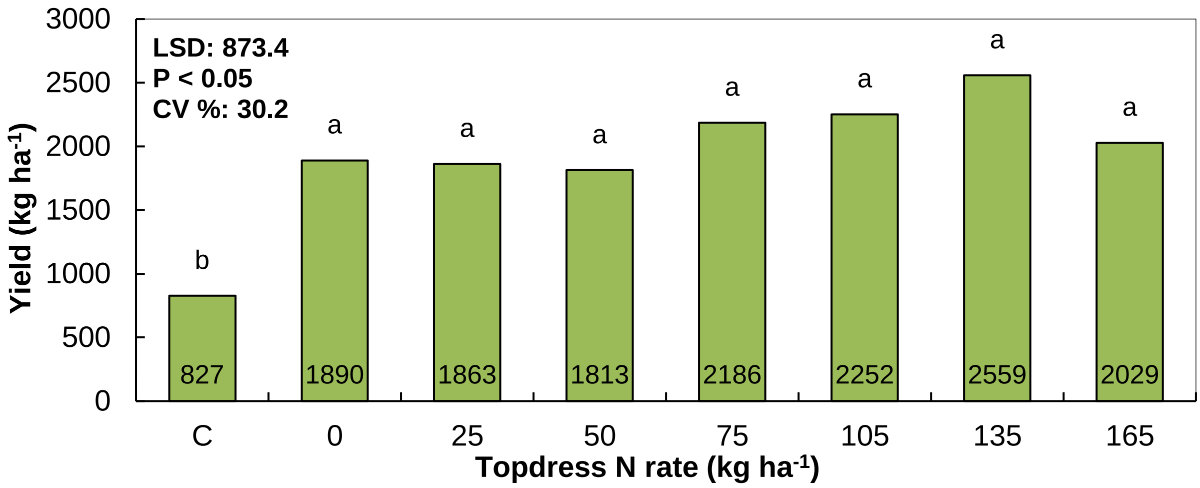


Figure 4.1.52 Grain yield (kg ha^{-1}) as influenced by topdress N rate (kg ha^{-1}) at Darling C/W (Year 1). LSD = Least significant difference ($P < 0.05$); CV = coefficient of variance. Means without a common letter above bars indicate significant differences at a 5% level.

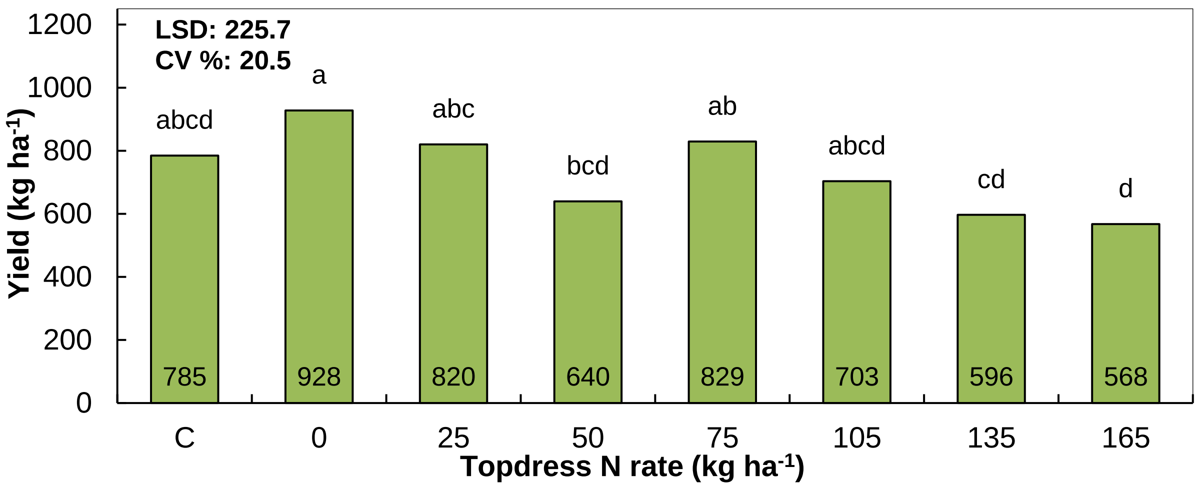


Figure 4.1.53 Grain yield (kg ha^{-1}) as influenced by topdress N rate (kg ha^{-1}) at Darling C/W (Year 2). LSD = Least significant difference ($P < 0.05$); CV = coefficient of variance. Means without a common letter above bars indicate significant differences at a 5% level.

Table 4.1.17 Seedling population (m^{-2}), number of EBT (m^{-2}) and biomass production (kg ha^{-1}) as influenced by topdressed fertiliser N rate (kg ha^{-1}) at Darling C/W during Year 1 and 2 of the study.

Topdress N rate (kg ha^{-1})	**control**	**0**	**25**	**50**	**75**	**105**	**135**	**165**	**CV (%)**	**LSD**
					Year 1					
Seedlings (m^{-2})	137.2 ^{a}	129.2 ^{a}	129.9 ^{a}	147.1 ^{a}	130.0 ^{a}	142.6 ^{a}	139.6 ^{a}	134.1 ^{a}	**12.8**	**25.8**
EBT (m^{-2})	173.3 ^{c}	179.6 ^{c}	230.0 ^{abc}	218.8 ^{bc}	244.6 ^{abc}	269.2 ^{ab}	298.1 ^{a}	198.6 ^{abc}	**22.8**	**77.5**
Biomass (kg ha^{-1})	3000 ^{b}	5396 ^{a}	5333 ^{a}	4938 ^{ab}	5938 ^{a}	5938 ^{a}	7083 ^{a}	6667 ^{a}	**27.6**	**2273**
					Year 2					
Seedlings (m^{-2})	115.1 ^{a}	114.9 ^{a}	119.2 ^{a}	118.2 ^{a}	101.2 ^{a}	104.9 ^{a}	104.0 ^{a}	113.5 ^{a}	**12.8**	**20.9**
EBT (m^{-2})	166.7 ^{a}	148.1 ^{a}	153.4 ^{a}	153.4 ^{a}	170.6 ^{a}	172.7 ^{a}	176.5 ^{a}	172.3 ^{a}	**15.5**	**37.8**
Biomass (kg ha^{-1})	2459 ^{b}	2646 ^{b}	2937 ^{ab}	2854 ^{ab}	3229 ^{a}	2959 ^{ab}	2792 ^{ab}	2833 ^{ab}	**13.7**	**573**

Means without a common superscript letter in the same row indicate significant differences at a 5% level.

CV = Coefficient of variance

LSD = Least significant difference

4.1.9.4 Nitrogen use efficiency

Increasing N rates led to a decrease in NUE, where 0 kg N ha^{-1} had the highest (P < 0.05) and 105, 135 and 165 kg N ha^{-1} the lowest (P < 0.05) NUE for Year 1 (Figure 4.1.54). The same trend was shown in Year 2, where 0 kg N ha^{-1} had the highest (P < 0.05) and both 135 and 165 kg N ha^{-1} the lowest (P < 0.05) NUE.

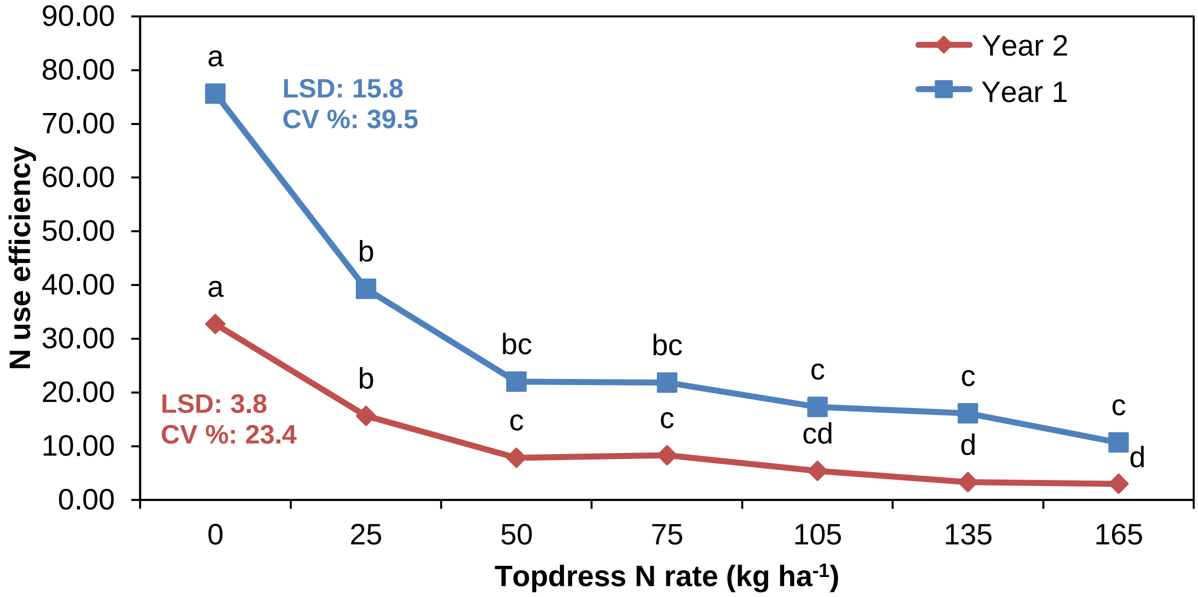


Figure 4.1.54 N use efficiencies per corresponding topdress N rate (kg ha^{-1}) at Darling C/W (Year 1 and 2). LSD = Least significant difference (P < 0.05); CV = coefficient of variance. No common letter within a year indicates significant difference at a 5% level.

4.1.9.5 Quality parameters

The only difference in hectolitre mass was that 105 kg N ha^{-1} was lower (P < 0.05) than most other treatments in Year 1 (Table 4.1.18). During Year 2, the increasing N rates led to a decrease (P < 0.05) in hectolitre mass. Grain protein content for the control, 0, 25 and 50 kg N ha^{-1} treatments was the lower (P < 0.05) than some of the higher N rate treatments for Year 1, hence showing an increase in grain protein content with increasing N rates. In Year 2, the different N treatments did not influence (P > 0.05) protein content.

Except for the control treatment being lower (P < 0.05) than 105 kg N ha^{-1}, no other differences (P > 0.05) in harvest index were recorded for Year 1. No differences (P > 0.05) in hectolitre mass were recorded in Year 2. The control treatment absorbed the lowest (P < 0.05) amount of N into its biomass in Year 1. Increasing N rates led to an increase (P < 0.05) in N taken up by the biomass in Year 2.

Table 4.1.18 Hectolitre mass, protein content (%), harvest index and biomass N (kg ha^{-1}) as influenced by topdressed fertiliser N rate (kg ha^{-1}) at Darling C/W during Year 1 and 2 of the study.

				Year 1						
Topdress N rate (kg ha^{-1})	**control**	**0**	**25**	**50**	**75**	**105**	**135**	**165**	**CV (%)**	**LSD**
Hectolitre mass (g cm^{-3})	76.0 ^{a}	74.9 ^{a}	76.1 ^{a}	76.3 ^{a}	73.9 ^{a}	61.9 ^{b}	72.6 ^{ab}	70.6 ^{ab}	**9.7**	**11.5**
Protein content (%)	10.5 ^{d}	11.9 ^{cd}	11.6 ^{d}	11.9 ^{cd}	13.2 ^{bc}	14.4 ^{ab}	14.1 ^{ab}	14.8 ^{a}	**7.2**	**1.4**
Harvest index	0.28 ^{b}	0.35 ^{ab}	0.34 ^{ab}	0.36 ^{ab}	0.36 ^{ab}	0.40 ^{a}	0.37 ^{ab}	0.33 ^{ab}	**21.5**	**0.11**
Biomass N (kg ha^{-1})	29.0 ^{c}	82.2 ^{abc}	63.3 ^{abc}	59.4 ^{bc}	68.6 ^{abc}	92.7 ^{ab}	107.5 ^{ab}	117.0 ^{a}	**37.4**	**56.3**
				Year 2						
Hectolitre mass (g cm^{-3})	*	*	*	*	*	*	*	*	*	*
Protein content (%)	18.1 ^{a}	17.3 ^{a}	17.2 ^{a}	16.6 ^{a}	18.7 ^{a}	18.4 ^{a}	18.2 ^{a}	18.4 ^{a}	10.4	2.8
Harvest index	0.30 ^{a}	0.23 ^{a}	0.26 ^{a}	0.30 ^{a}	0.19 ^{a}	0.30 ^{a}	0.27 ^{a}	0.25 ^{a}	**30.8**	**0.12**
Biomass N (kg ha^{-1})	37.1 ^{c}	45.1 ^{bc}	48.9 ^{abc}	55.2 ^{ab}	59.3 ^{a}	53.7 ^{ab}	59.5 ^{a}	57.0 ^{ab}	**15.8**	**12.1**

Means without a common superscript letter in the same row indicate significant differences at a 5% level.

CV = Coefficient of variance

LSD = Least significant difference

*Too little grain at the end of season to determine hectolitre mass

4.2 Discussion

4.2.1 Soil mineral N

Pre-plant soil samples were expected to show no differences ($P > 0.05$) in their soil mineral N contents as no N fertiliser treatments were applied at that stage. As expected, most of the sites showed no differences ($P > 0.05$) in soil mineral N content at that stage in Year 1. The rationale for taking pre-plant soil samples on every plot in Year 1 was to use the pre-plant soil mineral N content as a co-variate in analyses of variance to detect differences. Although differences ($P < 0.05$) in pre-plant soil mineral N content were seen at the Riversdale and Darling C/W sites, they were unsubstantial and were therefore not analysed as a covariate. Pre-plant, soil mineral N content was not expected to have an influence on crop growth or soil mineral N later in the season and for that reason, only one representative sample of pre-plant soil mineral N was taken per block in Year 2.

Pre-plant soil samples indicated that most of the sites during both years did not have limiting mineral N content before the planting season commenced. The adequate soil mineral N range considered for wheat production is higher than 25 to 50 mg N kg^{-1}. When soil mineral N content falls below this range, it may become a limiting factor to crop growth (Carson and Phillips, 2017). According to Cui et al. (2007), 30 to 52% of the residual nitrate N in the soil could be taken up by wheat. Furthermore, Miao et al. (2015) found that wheat plants take up ammonium-N, nitrate-N and mineralised-N from organic C during the growing season. This leads to the conclusion that soil mineral N could, to a large extent, decrease the fertiliser requirement of the wheat crop and N mineralisation should form part of N fertiliser recommendations (Miransari and Mackenzie, 2011).

In Year 1, both the Langgewens C/W and the Darling wheat after medic sites had low soil mineral N content at the pre-planting stage. In Year 2, the Riversdale and both Darling sites had low soil mineral N content at the pre-planting stage. In the case of the Riversdale and Langgewens C/W soil plots, inadequate soil mineral N could be due to the removal thereof by the previous year's canola crop. At Darling, the soil is prone to N leaching due to the soil's sandy texture (Cheng et al., 2008; Dang et al., 2009; Miransari and Mackenzie, 2011; Wang et al., 2007).

Since the control plot received no N at the planting stage compared to the other treatment plots that were planted with 25 kg N ha^{-1}, it was expected that the control plots would have a lower soil mineral N content than that of the other treatments at the pre-topdress stage. This was the case for both years at the Riversdale and Porterville C/W sites. The soil of the control plots also had the lowest ($P < 0.05$) mineral N content at Langgewens M/W and Darling C/W in Year 1. The soil mineral N content at the pre-topdress stage for Langgewens M/W was higher than expected in Year 1. This could have been due to the N fixed by the previous year's annual medics or fertiliser N that remained in the soil profile leading to a boosted crop performance and yield. López-Bellido and López-Bellido (2001) found that crop rotations that contained faba beans or chickpea crops generally have a higher soil mineral N content. This may offer an explanation to the effect that medics may have on the soil mineral N content. Most of the residual N in the soil is in the form of nitrate-N. Ammonium-N present in the soil may be rapidly converted to nitrate-N (Miao et al., 2015; Wienhold and Halvorson, 1999). The accumulated nitrate-N is at a risk for leaching (Cheng et al., 2008; Dang et al., 2009; Miransari and Mackenzie, 2011; Wang et al., 2007). This may mean that leaching losses at Langgewens M/W were high during Year 1.

The soil samples taken at post-topdress stage during both years showed a good response to N fertilisation. Increased N topdress rates led to an increased ($P < 0.05$) soil mineral N content at almost all the sites. The soil mineral N content of soils under continuous CA may experience an increase in mineral N content due to mineralisation. When the nitrate-N content of a soil reaches excessive levels due to over-fertilisation, the effects of the residual N from the previous year's annual medics might have had no effect on crop yields (Miao et al., 2015).

The post-harvest soil samples indicated that low levels of mineral N were present in the soil at the end of the season as most sites had no differences ($P > 0.05$) between treatments. The only reoccurring difference was that the 165 kg N ha^{-1} treatment had the highest soil mineral N content at post-harvest stage for Riversdale, Caledon, Langgewens M/W, Porterville M/W and Darling C/W. There is a strong probability that N build-up might have occurred at the 165 kg N ha^{-1} treatments; which, in turn, may lead to detrimental environmental effects. This is in agreement with the findings by Cheng et al. (2008), Dang et al. (2009), Miransari and Mackenzie (2011) and Wang et al. (2007), who especially noted the high leachability of nitrate-N throughout the growing season. Considering the low soil mineral N content at the end of the season alongside the low NUE, may very well indicate that the applied N was not taken up by the wheat throughout the season but was rather lost to the environment. This could be indicative to the potential water pollution that occurs in cultivated fields. The potential for improvement in N use efficiencies for wheat production systems exists. It also emphasises that N programmes must be developed to ensure that all N applied is used by the crop, as oversupply of N will leave relative high levels of N in soil prone to leaching and contamination of natural resources.

4.2.2 *Plant parameters*

A seedling population of 150 to 175 wheat seedlings m^{-2} is optimal in the dryland production systems of the Western Cape and marginal at 120 seedlings m^{-2} (A. Agenbag, personal communication, December 11, 2017). During Year 1, low seedling populations were recorded at all the sites in this study. The two Darling sites, however, had acceptable seedling populations (Table 4.19). In Year 2, the seedling populations at most of the locations were found to be low once again, but were found to be optimal at Tygerhoek and marginal at Caledon. All sites received the same N rate at planting stage during both years, meaning that the topdress N was not applied and did not influence seedling populations. The low seedling counts for both years may be due to late onset of rainfall in Year 1 and even later onset of rainfall in Year 2. This may have caused crop establishment problems and could have had a negative impact on yield, especially in Year 2.

Table 4.19 Average seedling populations (m^{-2}) at all the sites for both Year 1 and 2. Very low seedling populations are marked in red.

Site	Year 1	Year 2
Riversdale C/W	93	73
Tygerhoek C/W	73	152
Caledon L/W	109	121
Langgewens M/W	77	92
Langgewens C/W	Not recorded	92
Porterville M/W	65	70
Porterville C/W	97	70
Darling M/W	143	78
Darling C/W	138	111

During Year 1, the number of EBT at Tygerhoek, Langgewens C/W and both the Darling sites showed a positive response to increased N topdress rates. A high number of EBT is desirable, due to the positive correlation between a high number of EBT and high yields (Norwood, 2000). Similar studies by Abbate et al. (1995), Fischer (2007) and Salvagiotti and Miralles (2008) showed a similar response in the number of EBT increased alongside increased topdress N rate. However, the remaining sites in Year 1 and all the sites in Year 2 showed no tendency to produce more EBT as N rate was increased.

The increase in topdress N rate had no effect ($P > 0.05$) on the biomass production of the different treatments during both years, with the only difference being that of both the Langgewens sites, Porterville C/W and Darling M/W, where there was a slight, but sometimes statistically significant increase ($P < 0.05$) in biomass production with increasing topdress N rates during Year 1. Even though Year 1 received more rainfall than Year 2 (Section 3.1), the amount of rainfall during the growing season was considered low for both years. The low rainfall, could have influenced biomass production to such an extent that topdress N rates had a negligible influence on biomass production. The lack of response that biomass had to increasing topdress N rates is in contrast to findings by Halvorson et al. (2004). They found a consistent positive correlation in increased biomass production in response to increased topdress N rates. The low rainfall conditions during the two years of this study and the potential increase in soil mineral N due to CA, especially at the lower N rate treatments, may have influenced the biomass production data to such an extent as not to show a response to the different N rate treatments.

4.2.3 Grain yield

Year 1 was a relatively high yielding year for all sites whereas Year 2 was a very low yielding year for most sites, the exception being Caledon and Tygerhoek. Late and erratic rainfall was experienced during both years and could have affected grain yield. The sites at Darling and Porterville experienced very dry conditions early in the season, causing potential stress on the developing crops (Section 3.1). While many of the sites were in areas that received very little rainfall late in the growing season for Year 2, resulting in sub-optimal conditions during the grain filling stage of wheat and a consequent decrease in yield (Section 3.1).

Jackson (2006) and Rawluk et al. (2000) reported that an increasing topdress N rate results in increasing yield. However, that was not the case for most of the sites included in this study. All the sites in both Year 1 and 2, apart from Riversdale, Porterville C/W and Darling M/W in Year 1, showed no increase ($P > 0.05$) in yield with increasing topdress N rates; from rates as low as 0 kg N ha^{-1} (Table 4.20). The lack of yield response to topdress N rates could be due to the severe drought experienced in the Western Cape region, which is characteristic of Mediterranean-type climates; thus, causing wheat to cut off the grain filling stage prematurely that leads to physiological maturity early. Halvorson et al. (2004) reported that the lack of late-season rain could influence crop yields and cause the inability of higher topdress N rates to influence crop yield. For Year 1, increasing the total N rate to 75 kg N ha^{-1} (25 kg N ha^{-1} at plant + topdress 50 kg N ha^{-1}) at both the Darling sites respectively, resulted in an increase in yield. This is in agreement with the findings of Salvagiotti and Miralles (2008) who reported an increase in yield with increasing topdress N rates up to 80 kg N ha^{-1}. However, Salvagiotti et al. (2009) found increases in yield up to topdress N rates of 90 kg ha^{-1}.

The current wheat guidelines (FERTASA 2016b) are principally based on N rate according to a specific yield target which is, in turn, determined by rainfall during the production season. This rate could then subsequently be adapted according to the production record, soil texture and the previous crop in rotation. For instance, it is recommended that the fertiliser N requirement is reduced by 50% for the first year of wheat following annual medics. The contribution of plant nutrition to the total production cost for wheat in the Swartland region may be well more than 30% (DAFF, 2016). Any reductions in this cost can lead to the production of wheat with a larger profit margin.

Table 4.20 The topdress N rates that marks the point at with increasing topdress N rates had no further ($P > 0.05$) effect on crop yield, for all sites during both years.

Site	Year 1	Year 2
Riversdale C/W	25	0
Tygerhoek C/W	0	control
Caledon L/W	control	control
Langgewens M/W	0	control
Langgewens C/W	0	control
Porterville M/W	0	control
Porterville C/W	50	control
Darling M/W	50	control
Darling C/W	0	control

When comparing the yield results of the current study (Table 4.20) to recommendations made according to current guidelines by fertiliser experts (Table 4.21), it becomes apparent that producers in the regions might be over-fertilising as no substantial yield response to N fertilisation was recorded. It should, however, be noted that further data analysis is necessary before guidelines and recommendations can be made. The adverse climate of the two years of this study should also be considered in this line of thinking.

Table 4.21 The optimal total N rate (25 kg N ha^{-1} at plant + topdress N), as prescribed by several fertiliser experts in the Western Cape, for all sites during both years.

	Total N rate (kg N ha^{-1})	
Site	**Year 1**	**Year 2**
Riversdale C/W	55	55
Tygerhoek C/W	80	78
Caledon L/W	30	35
Langgewens M/W	73	58
Langgewens C/W	100	85
Porterville M/W	60	60
Porterville C/W	88	88
Darling M/W	60	60
Darling C/W	90	90

4.2.4 Nitrogen use efficiency (NUE)

Increasing topdress N rates led to a drastic decrease in NUE at all sites for both years, which is a common finding throughout the world (Doyle and Holford 1993, Halvorson et al. 2004, López-Bellido and López-Bellido 2001, McDonald 1992, Timsina et al. 2001). Ju et al. (2009) also stated that when N fertiliser rates surpass the crop demand for N, it will lead to a decrease in NUE. Therefore, applying excessive amounts of N fertiliser will result in the inability of the crop to utilise all of the N and that in turn may cause environmental problems (Miao et al. 2015).

Nitrogen use efficiencies in the 15 to 44% range, are considered too low (EU Nitrogen Expert Panel, 2015). Although the South African climate differs substantially from that of Europe, the European NUE guidelines were consulted as a comparative measure, as local guideline of optimal NUE are not available. This limiting NUE range was exceeded (Table 4.22) at most of the sites during the study for topdress N rates lower than the optimal recommended rates of each site (Table 4.21). When the NUE fall within this low range, producers lead the risk of polluting nearby water sources. Maintaining a high NUE might be the key to mitigating potential N pollution risks (Alva et al., 2006; Cassman et al., 2003; Salvagiotti et al., 2009).

Table 4.22 The N topdress rates that mark the point at with increasing topdress N rates lead to sub-optimal NUE levels (below 44%) for all sites during both years.

	Topdress N rate (kg N ha^{-1})	
Site	**Year 1**	**Year 2**
Riversdale C/W	105	25
Tygerhoek C/W	75	50
Caledon L/W	75	50
Langgewens M/W	105	50
Langgewens C/W	50	25
Porterville M/W	50	25
Porterville C/W	50	0
Darling M/W	25	25
Darling C/W	25	0

During Year 1, six of the nine sites reported NUE higher than 100% at topdress N rates of 0 kg N ha^{-1} (25 kg N ha^{-1} total). This leads to the conclusion that more N was taken up by the plant than fertiliser N applied. During Year 2, the number of sites where NUE was above 100% at a topdress N rate of 0 kg N ha^{-1} was limited to three of the nine sites. Similar results were reported by Halvorson et al. (2004) during four of their nine year study. Although this result might not be sustainable in commercial scale agriculture, it is indicative of the soil's capacity to sustain crop growth and lower fertiliser requirement through the mineralisation of N.

4.2.5 Grain quality parameters

During Year 1 at Caledon, both Langgewens sites and Darling M/W the hectolitre mass of wheat grain decreased ($P < 0.05$) with increasing topdress N rates. The hectolitre mass at the other sites showed no response to the topdress N rate. During Year 2, the Riversdale, Tygerhoek, Langgewens C/W, and Darling wheat after medic sites showed a slight decrease in hectolitre mass with increasing topdress N rates, whilst the Caledon site showed a clear decrease ($P < 0.05$) with increasing topdress N rates. The recommended hectolitre mass, to ensure high quality wheat in South Africa, needs to be between 76 and 77 g cm^{-3} (DAFF, 2016). The lower range of hectolitre mass is between 70 and 74 g cm^{-3}. The average hectolitre masses for all the sites were at, or close to, optimum levels in Year 1, the exception being that of the two Darling sites (Table 4.23). During Year 2 and possibly due to the drought conditions, most of the research sites had low average hectolitre masses, with only the Caledon and both Langgewens sites having optimal hectolitre masses.

Table 4.23 Average hectolitre mass (g cm^{-3}) at all the sites and both years of the study. Hectolitre masses falling within the lower range of the spectrum are marked in red. *Not enough grain to sample for hectolitre mass

Site	Year 1	Year 2
Riversdale C/W	78.6	75.5
Tygerhoek C/W	76.6	74.6
Caledon L/W	77.1	76.9
Langgewens M/W	78.3	78.2
Langgewens C/W	80.3	76.9
Porterville M/W	77.5	71.8
Porterville C/W	80.7	*
Darling M/W	75.0	74.0
Darling C/W	72.5	*

Protein content increased (P < 0.05) in response to increasing topdress N rates at all of the sites in Year 1. In Year 2, increases (P < 0.05) in protein content were recorded at four of the nine sites, namely; Riversdale, Tygerhoek and both Langgewens sites. This is in agreement with many previous studies that linked an increase in N fertiliser rate to an increase in grain protein content (Gooding et al., 2007a, 2007b; Halvorson et al., 2004; Jackson, 2006; Lázzari et al., 2007; Rawluk et al., 2000; Uhart and Andrade, 1995). As previously mentioned, Halvorson et al. (2004) concluded their nine year study by reporting a strong positive correlation of protein to increasing topdress N rates, where the highest topdress N rate treatment produced wheat with the highest grain protein content.

The harvest indices of the treatments for most sites during both years showed no clear response to topdress N rates. The exception being at the Porterville C/W site where Year 1 showed an increase in harvest index with increased topdress N rates. However, the results from the same site for Year 2 agreed with López-Bellido and López-Bellido (2001), who recorded a drop in the harvest index of dryland wheat as topdress N rates were increased.

The biomass N content at the Langgewens C/W and the Darling C/W sites increased (P < 0.05) with an increased topdress N rate in Year 1. In Year 2, an increased topdress N rate led to an increase (P < 0.05) in N taken up by the biomass at the Porterville C/W and Darling M/W sites. This result was also found to correspond with previous studies done by Cassman et al. (1992), Ehdaie and Waines (2001) and Salvagiotti et al. (2009).

5 The effect of a late-season foliar N application, in the form of urea ammonium nitrate (UAN), on the yield and grain protein content of wheat.

5.1 Results

The effect that a late season foliar N application had on the grain yield and protein content of wheat at each site will be discussed separately in the following order: i) Grain yield, and ii) Protein content. Note that the data from Year 1 and Year 2 was statistically analysed separately, and will not be compared with each other.

5.1.1 Riversdale C/W

5.1.1.1 Grain yield

Yields were not influenced ($P > 0.05$) by a foliar N application in Year 1, except for the control treatment for which a foliar N application resulted in a higher yield ($P < 0.05$) (Figure 5.1.1). In Year 2, the same observation was made, but the 105 kg N ha^{-1} treatment also showed higher yield with a foliar N application (Figure 5.1.2).

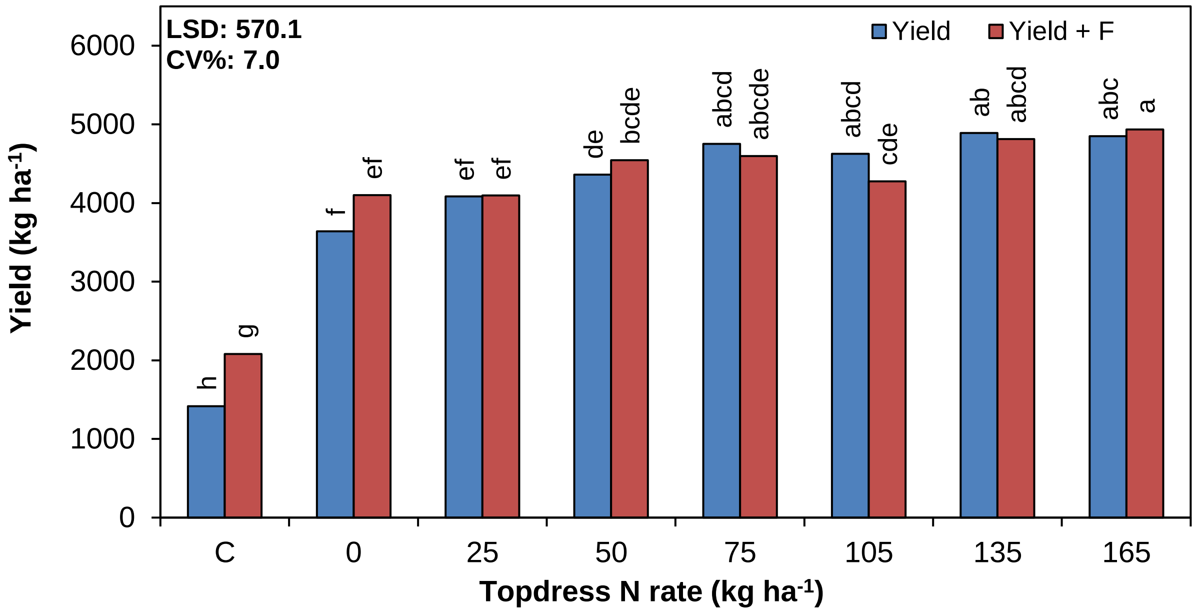


Figure 5.1.1 Grain yield (kg ha^{-1}) of topdress N treatments with and without additional foliar N at Riversdale (Year 1). LSD = Least significant difference ($P < 0.05$); CV = coefficient of variance. Means within each topdress treatment without a common letter above bars indicate significant differences at a 5% level.

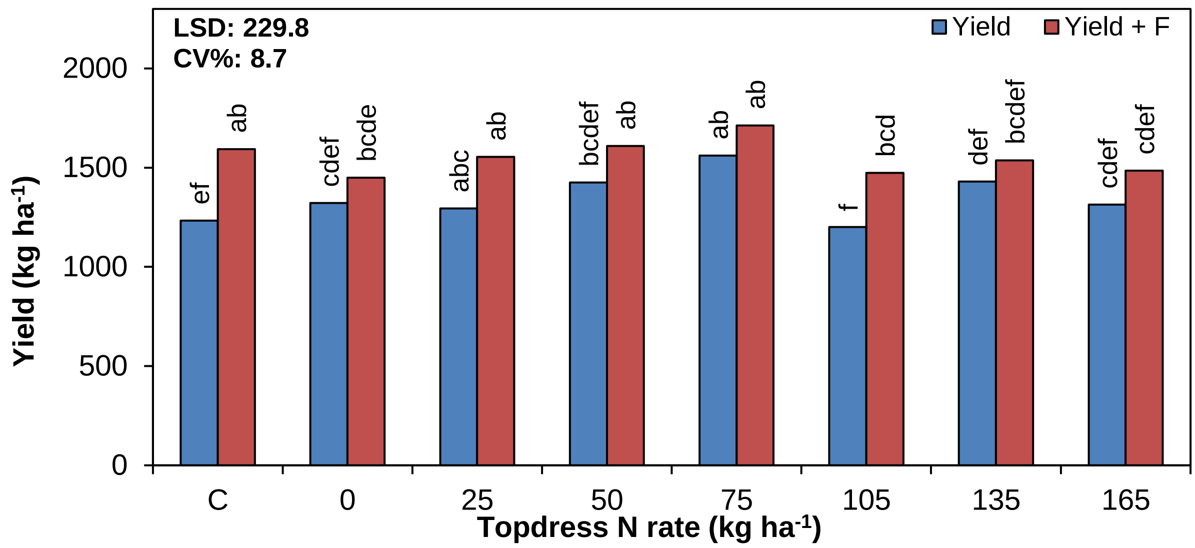


Figure 5.1.2 Grain yield (kg ha^{-1}) of topdress N treatments with and without additional foliar N at Riversdale (Year 2). LSD = Least significant difference (P < 0.05); CV = coefficient of variance. Means within each topdress treatment without a common letter above bars indicate significant differences at a 5% level.

5.1.1.2 Protein content

Foliar N application during the flag leaf stage resulted in higher (P < 0.05) mean grain protein content (10.8%) compared to no foliar N (10.2%) in Year 1 (Figure 5.1.3). For the respective N rates, no differences (P > 0.05) in protein content between the different foliar N application treatments were found for topdress N rates, except for topdress N rates 75 and 105 kg ha^{-1}, where an additional foliar N application led to higher (P < 0.05) protein content. During Year 2, only the control treatment showed an increase (P < 0.05) in protein content with foliar N application (Figure 5.1.4).

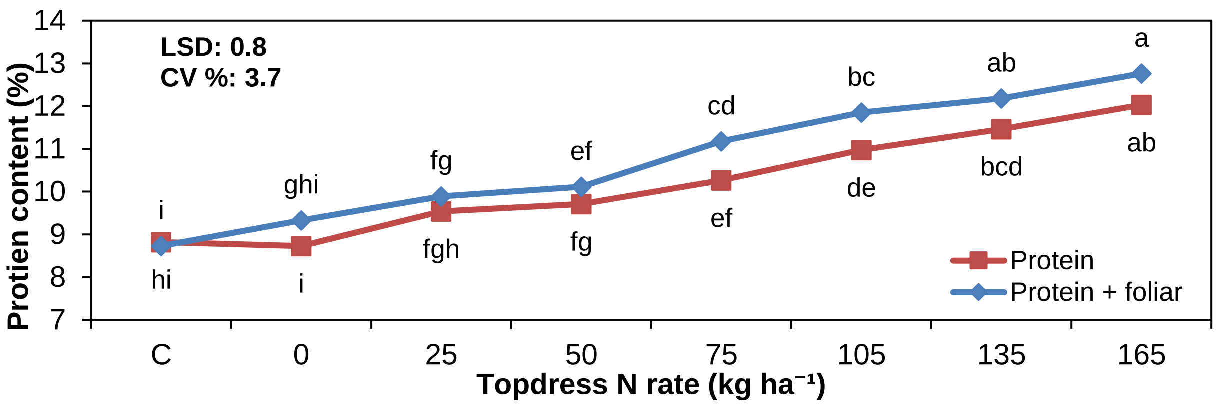


Figure 5.1.3 Grain protein (%) for topdress N treatments with and without additional foliar N at Riversdale (Year 1). LSD = Least significant difference (P < 0.05); CV = coefficient of variance. Means without a common letter above or below points indicate significant differences at a 5% level.

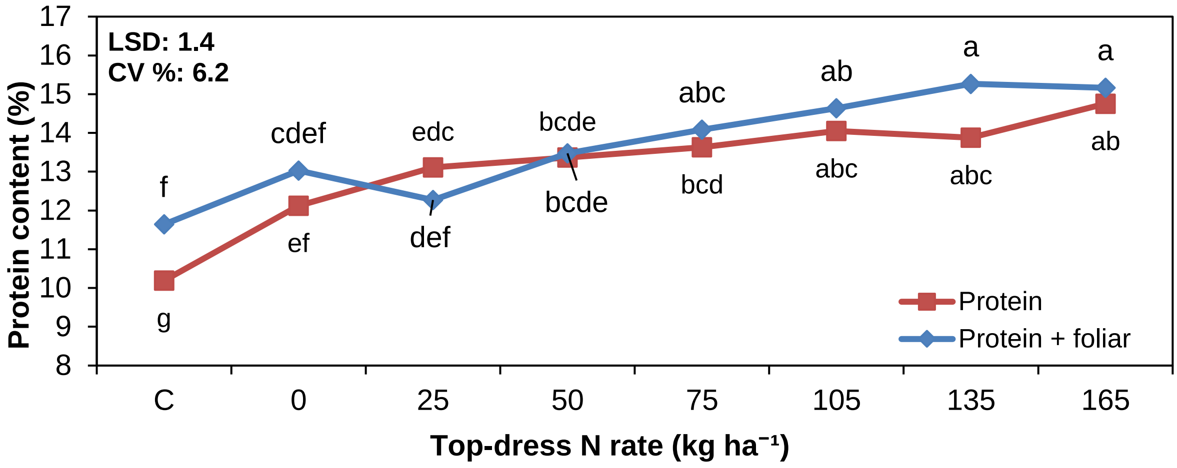


Figure 5.1.4 Grain protein (%) for topdress N treatments with and without additional foliar N at Riversdale (Year 2). LSD = Least significant difference (P < 0.05); CV = coefficient of variance. Means without a common letter above or below points indicate significant differences at a 5% level.

5.1.2 Tygerhoek C/W

5.1.2.1 Grain yield

Except for the 135 kg N ha^{-1} treatment, no increase in yield was recorded with the addition of a foliar N application in Year 1 (Figure 4.2.7). Foliar N application did not affect (P > 0.05) grain yield in Year 2 (Figure 5.1.6).

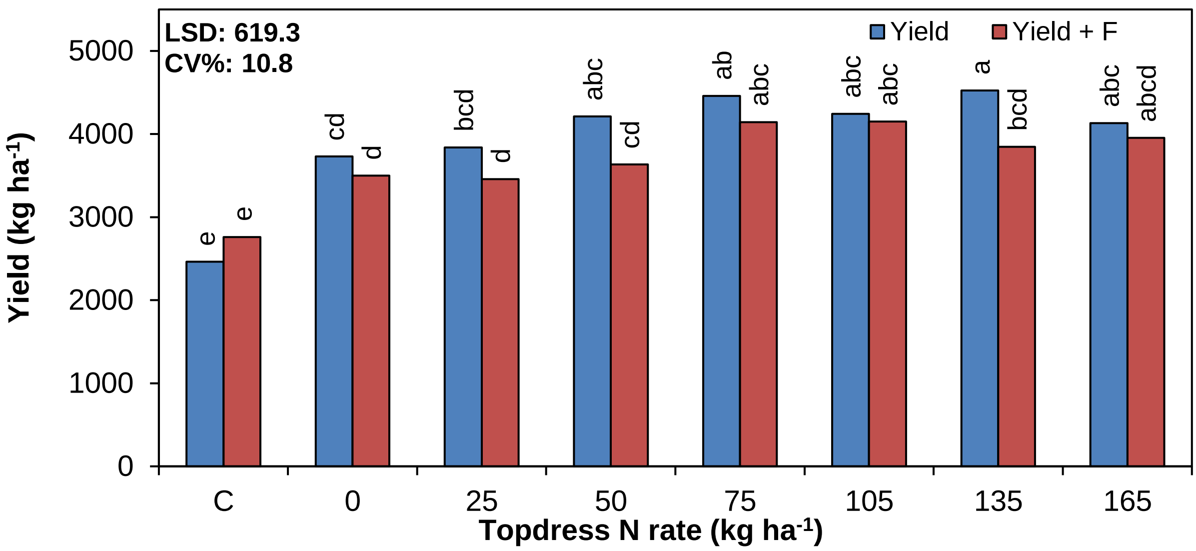


Figure 5.1.5 Grain yield (kg ha^{-1}) of topdress N treatments with and without additional foliar N at Tygerhoek (Year 1). LSD = Least significant difference (P < 0.05); CV = coefficient of variance. Means within each topdress treatment without a common letter above bars indicate significant differences at a 5% level.

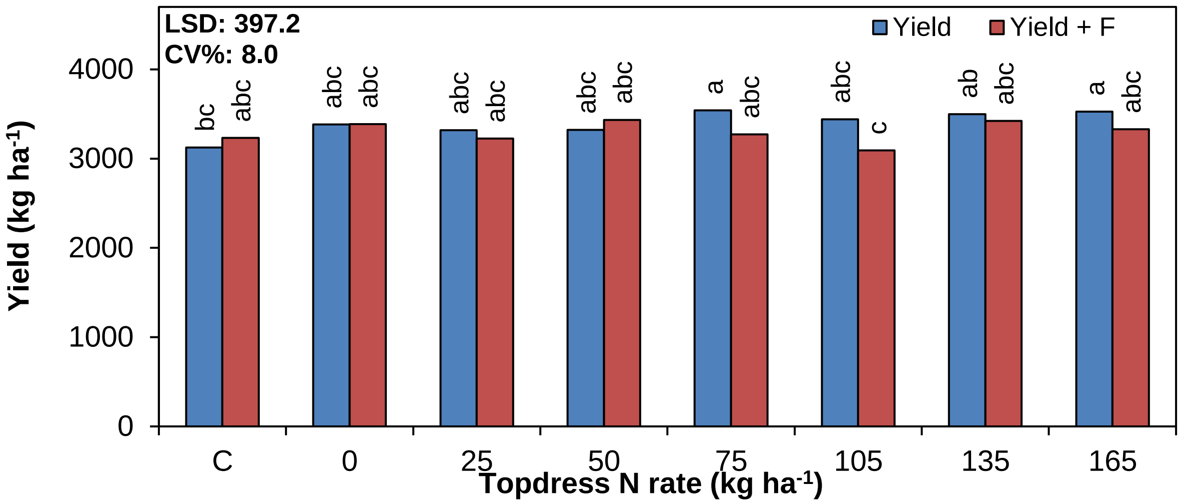


Figure 5.1.6 Grain yield (kg ha^{-1}) of topdress N treatments with and without additional foliar N at Tygerhoek (Year 2). LSD = Least significant difference (P < 0.05); CV = coefficient of variance. Means within each topdress treatment without a common letter above bars indicate significant differences at a 5% level.

5.1.2.2 Protein content

During Year 1, foliar N application resulted in higher (P < 0.05) mean grain protein content (11.8%) compared to no foliar N (10.9%). Treatments receiving an additional foliar N application were higher (P < 0.05) in protein than those without any foliar N, all except the 135 kg N ha^{-1} topdress treatment in Year 1, which had similar protein contents with- and without additional foliar N (Figure 5.1.7). The control was the only treatment that increased (P < 0.05) in protein content with an additional foliar N application in Year 1 (Figure 5.1.8).

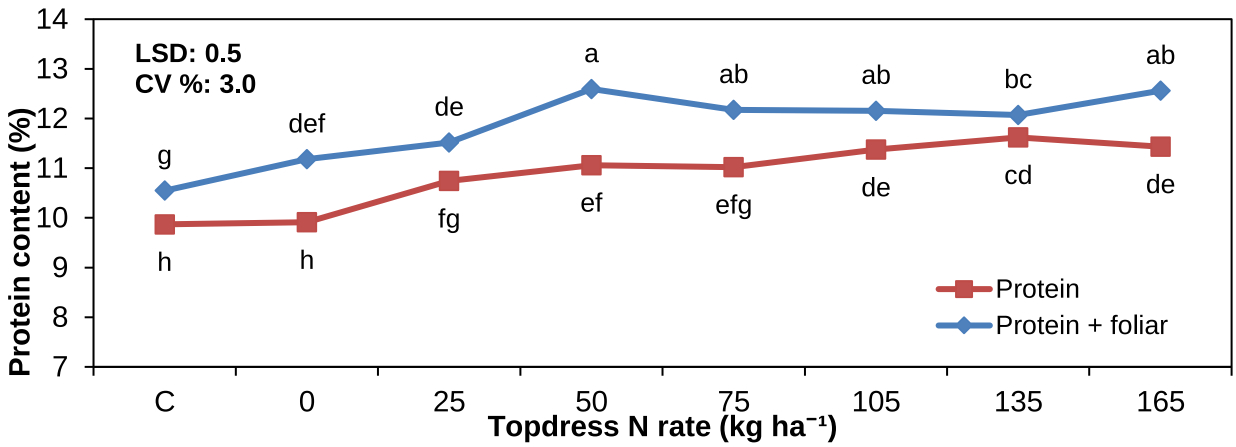


Figure 5.1.7 Grain protein (%) for topdress N treatments with and without additional foliar N at Tygerhoek (Year 1). LSD = Least significant difference (P < 0.05); CV = coefficient of variance. Means without a common letter above or below points indicate significant differences at a 5% level.

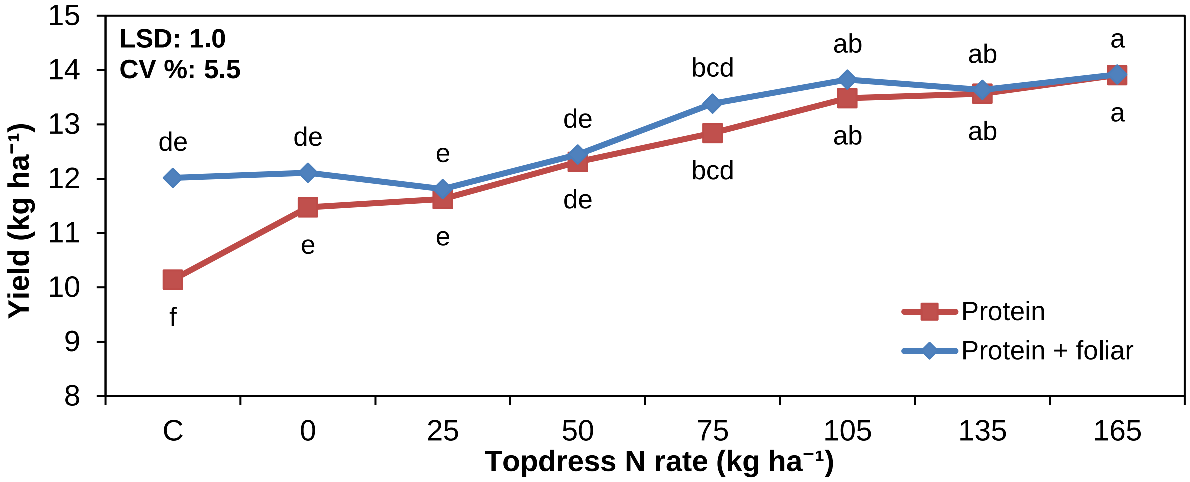


Figure 5.1.8 Grain protein (%) for topdress N treatments with and without additional foliar N at Tygerhoek (Year 2). LSD = Least significant difference (P < 0.05); CV = coefficient of variance. Means without a common letter above or below points indicate significant differences at a 5% level.

5.1.3 Caledon L/W

5.1.3.1 Grain yield

Apart from the 165 kg N ha^{-1} treatment in Year 2, the addition of foliar N did not lead to consistent increases (P < 0.05) in yield (Figure 5.1.9 and Figure 5.1.10).

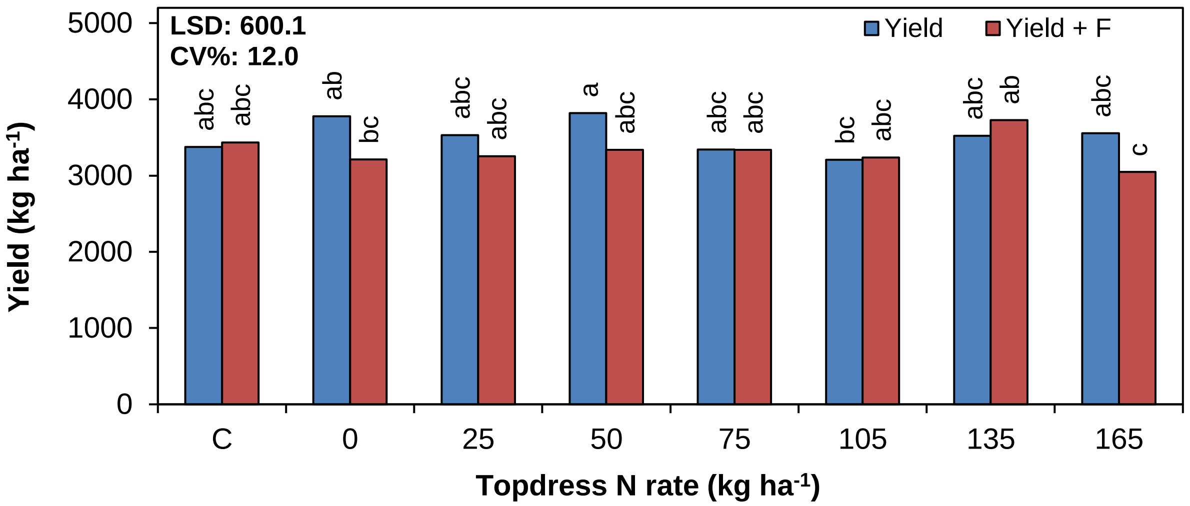


Figure 5.1.9 Grain yield (kg ha^{-1}) of topdress N treatments with and without additional foliar N at Caledon (Year 1). LSD = Least significant difference (P < 0.05); CV = coefficient of variance. Means within each topdress treatment without a common letter above bars indicate significant differences at a 5% level.

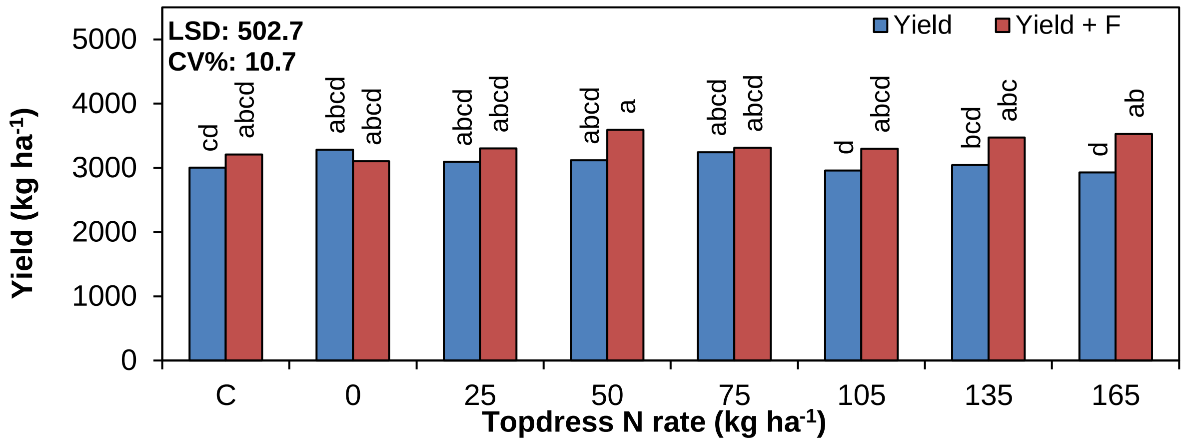


Figure 5.1.10 Grain yield (kg ha^{-1}) of topdress N treatments with and without additional foliar N at Caledon (Year 2). LSD = Least significant difference (P < 0.05); CV = coefficient of variance. Means within each topdress treatment without a common letter above bars indicate significant differences at a 5% level.

5.1.3.2 Protein content

There was no difference (P > 0.05) between treatments receiving foliar N (13.2%) and those without foliar N (13.0%) in Year 1. During Year 1, the control treatment that received an additional foliar N application had higher (P < 0.05) protein content than the control treatment without foliar N (Figure 5.1.11). No other differences (P > 0.05) within each topdress treatment were recorded for Year 1 of the study at Caledon. During Year 2, only the 25 kg N ha^{-1} showed an increase (P < 0.05) in protein content with additional foliar N.

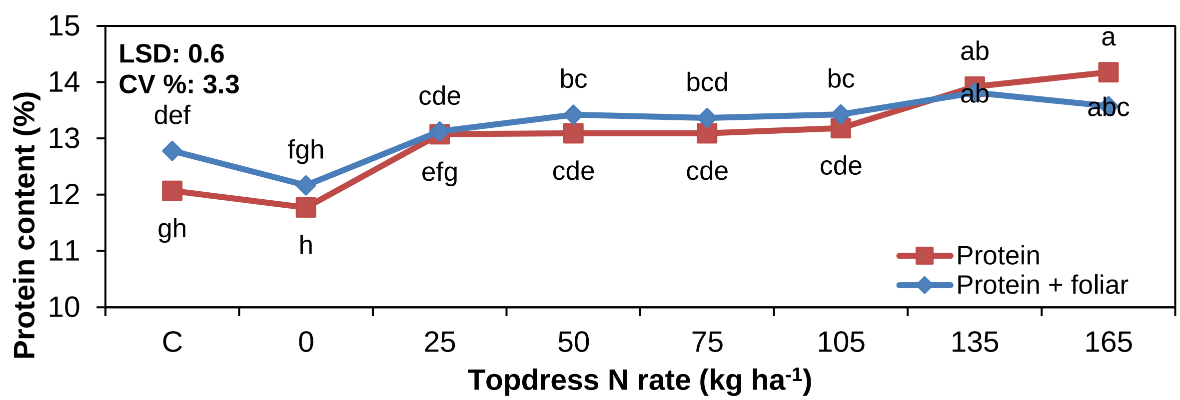


Figure 5.1.11 Grain protein (%) for topdress N treatments with and without additional foliar N at Caledon (Year 1). LSD = Least significant difference (P < 0.05); CV = coefficient of variance. Means without a common letter above or below points indicate significant differences at a 5% level.

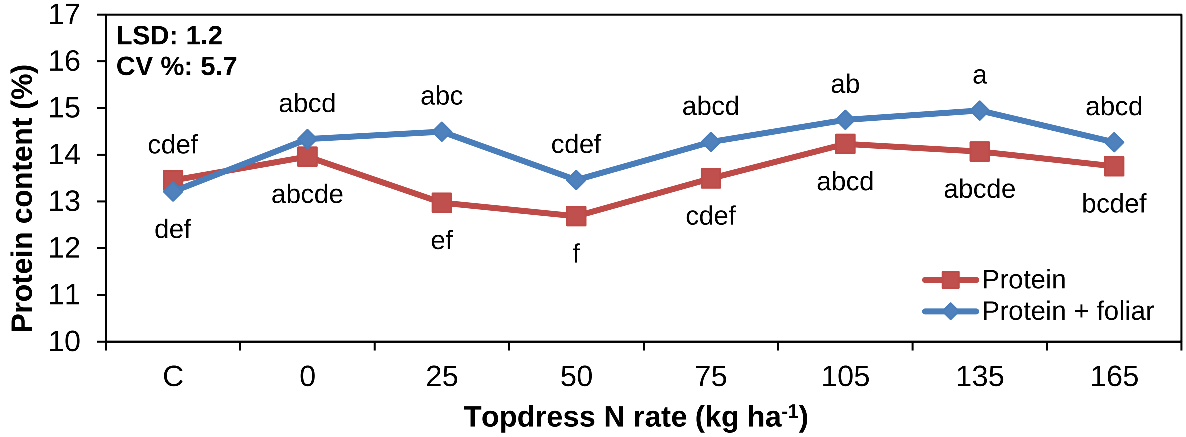


Figure 5.1.12 Grain protein (%) for topdress N treatments with and without additional foliar N at Caledon (Year 2). LSD = Least significant difference ($P < 0.05$); CV = coefficient of variance. Means without a common letter above or below points indicate significant differences at a 5% level.

5.1.4 Langgewens M/W

5.1.4.1 Grain yield

Foliar N application did not increase ($P > 0.05$) yields in Year 1 (Figure 5.1.13). During Year 2, the addition of a foliar N application did not lead to any consistent increases ($P > 0.05$) in yield at most of the treatments, but led to an increase ($P < 0.05$) in yields of the 50 and 135 kg N ha^{-1} treatments (Figure 5.1.14).

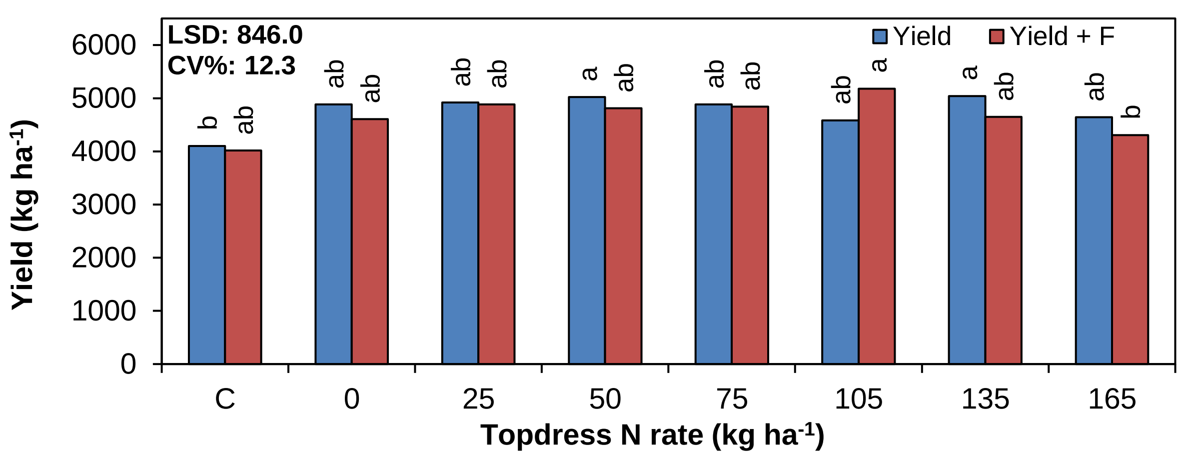


Figure 5.1.13 Grain yield (kg ha^{-1}) of topdress N treatments with and without additional foliar N at Langgewens M/W (Year 1). LSD = Least significant difference ($P < 0.05$); CV = coefficient of variance. Means within each topdress treatment without a common letter above bars indicate significant differences at a 5% level.

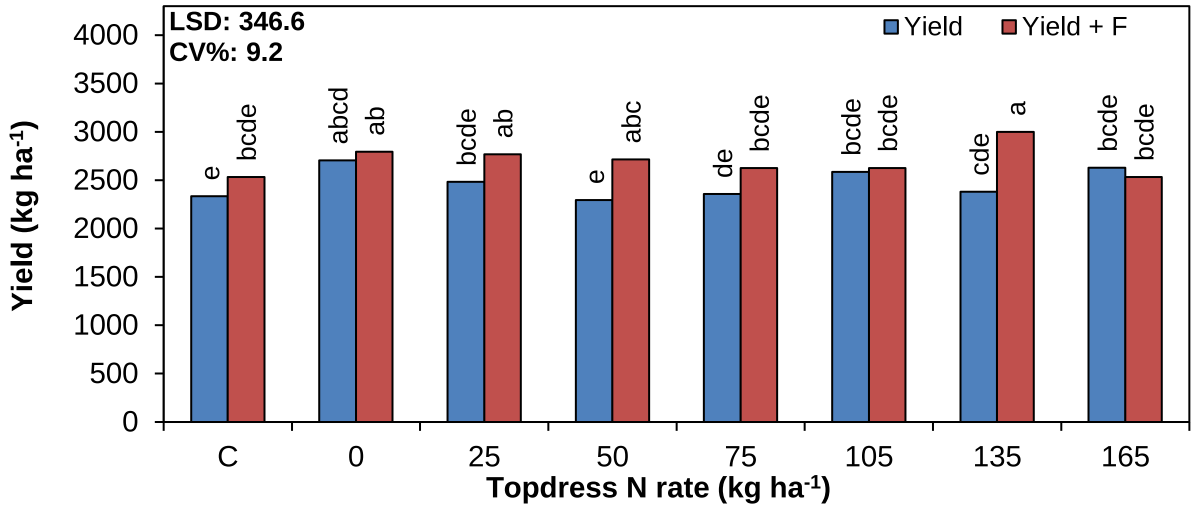


Figure 5.1.14 Grain yield (kg ha^{-1}) of topdress N treatments with and without additional foliar N at Langgewens M/W (Year 2). LSD = Least significant difference ($P < 0.05$); CV = coefficient of variance. Means within each topdress treatment without a common letter above bars indicate significant differences at a 5% level

5.1.4.2 Protein content

The protein content of treatments receiving a foliar N application (12.6%) was higher ($P < 0.05$) than those that did not receive foliar N (11.7%). All treatments that received an additional foliar N application in Year 1 had higher ($P < 0.05$) protein content than those without additional N (Figure 5.1.15). In Year 2, no treatments, apart from the control, increased in protein content with the application of additional foliar N (Figure 5.1.16).

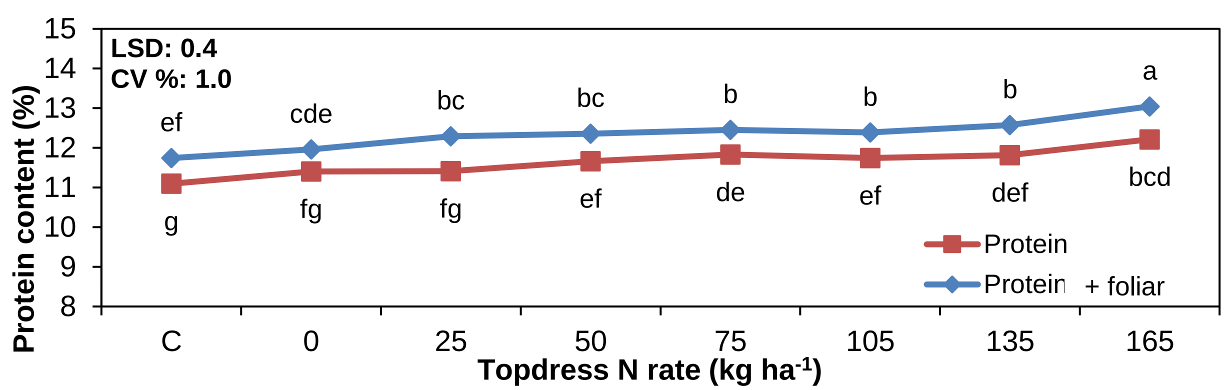


Figure 5.1.15 Grain protein (%) for topdress N treatments with and without additional foliar N at Langgewens M/W (Year 1). LSD = Least significant difference ($P < 0.05$); CV = coefficient of variance. Means without a common letter above or below points indicate significant differences at a 5% level.

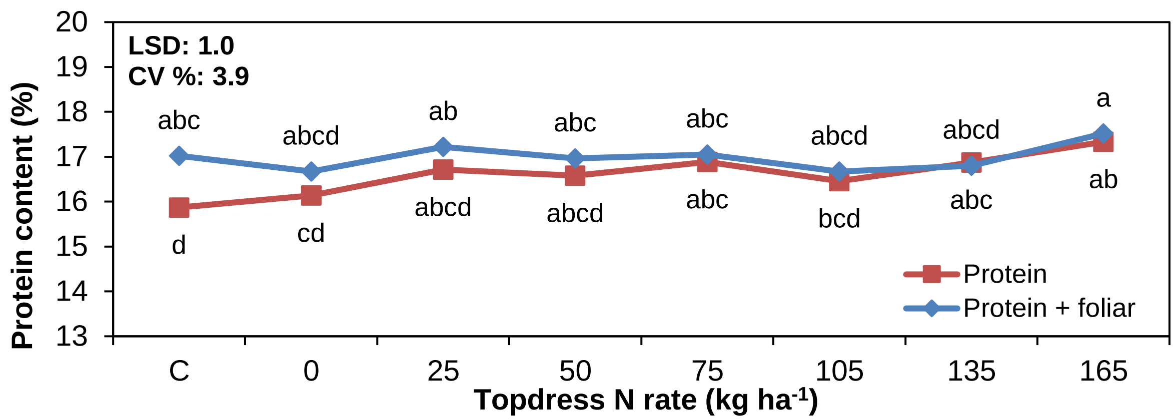


Figure 5.1.16 Grain protein (%) for topdress N treatments with and without additional foliar N at Langgewens M/W (Year 2). LSD = Least significant difference (P < 0.05); CV = coefficient of variance. Means without a common letter above or below points indicate significant differences at a 5% level.

5.1.5 Langgewens C/W

5.1.5.1 Grain yield

Foliar N did not lead to an increase (P > 0.05) in yield at most treatments in Year 1, but increased (P < 0.05) yields were recorded at the 25, 75 and 135 kg N ha^{-1} treatments (Figure 5.1.17) and led to increased (P < 0.05) yields at most N treatments in Year 2 (Figure 5.1.18).

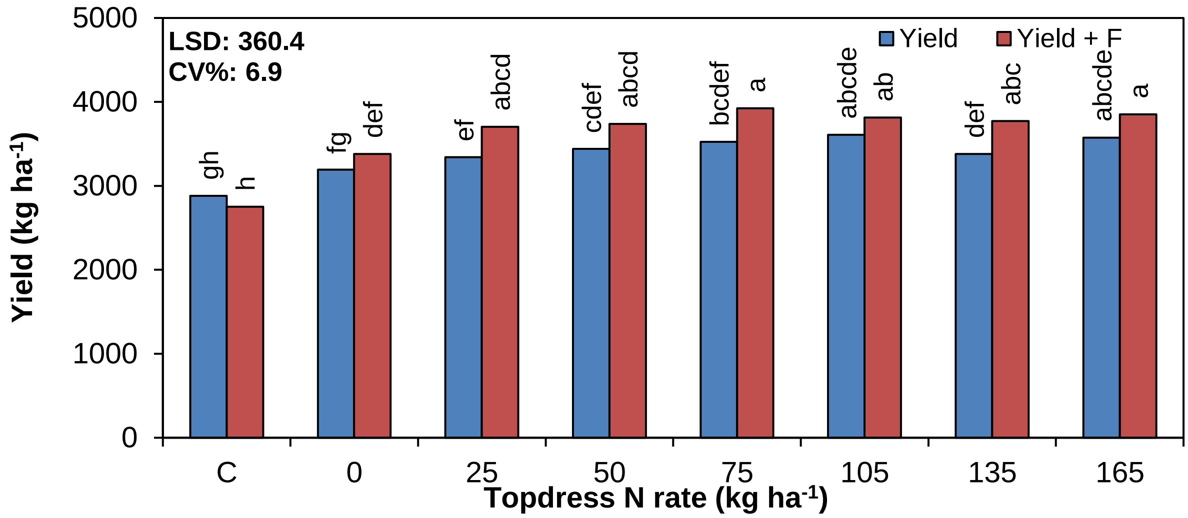


Figure 5.1.17 Grain yield (kg ha^{-1}) of topdress N treatments with and without additional foliar N at Langgewens C/W (Year 1). LSD = Least significant difference (P < 0.05); CV = coefficient of variance. Means within each topdress treatment without a common letter above bars indicate significant differences at a 5% level.

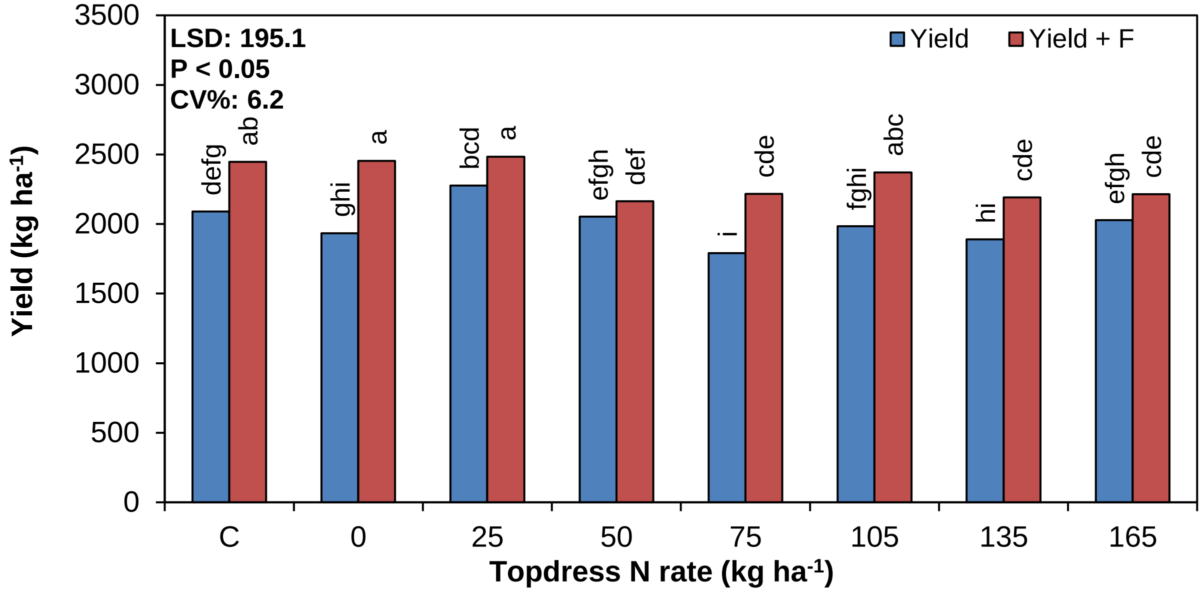


Figure 5.1.18 Grain yield (kg ha^{-1}) of topdress N treatments with and without additional foliar N at Langgewens C/W (Year 2). LSD = Least significant difference ($P < 0.05$); CV = coefficient of variance. Means within each topdress treatment without a common letter above bars indicate significant differences at a 5% level. *Statistical analysis failure due to insufficient data.

5.1.5.2 Protein content

The 50 kg N ha^{-1} treatment that received an additional foliar N application resulted in a higher ($P < 0.05$) grain protein content than the 50 kg N ha^{-1} without a foliar N application (Figure 5.1.19). No other differences ($P > 0.05$) were recorded in Year 1. In Year 2, the protein content of the control and 0 kg N ha^{-1} treatments with additional foliar N was higher ($P < 0.05$) than those without (Figure 5.1.20).

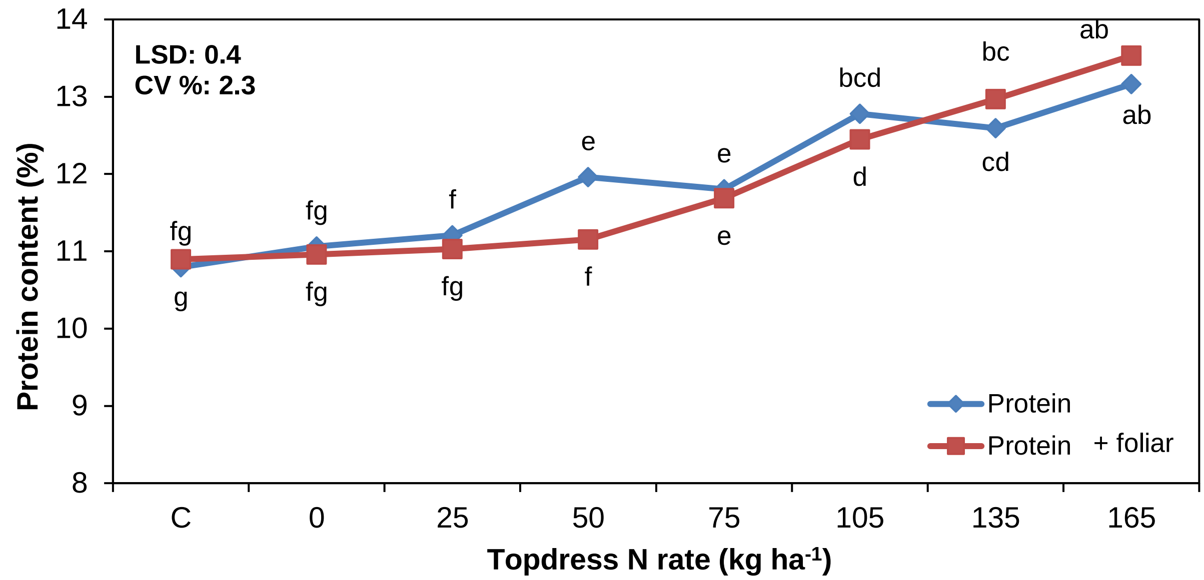


Figure 5.1.19 Grain protein (%) for topdress N treatments with and without additional foliar N at Langgewens C/W (Year 1). LSD = Least significant difference (P < 0.05); CV = coefficient of variance. Means without a common letter above or below points indicate significant differences at a 5% level.

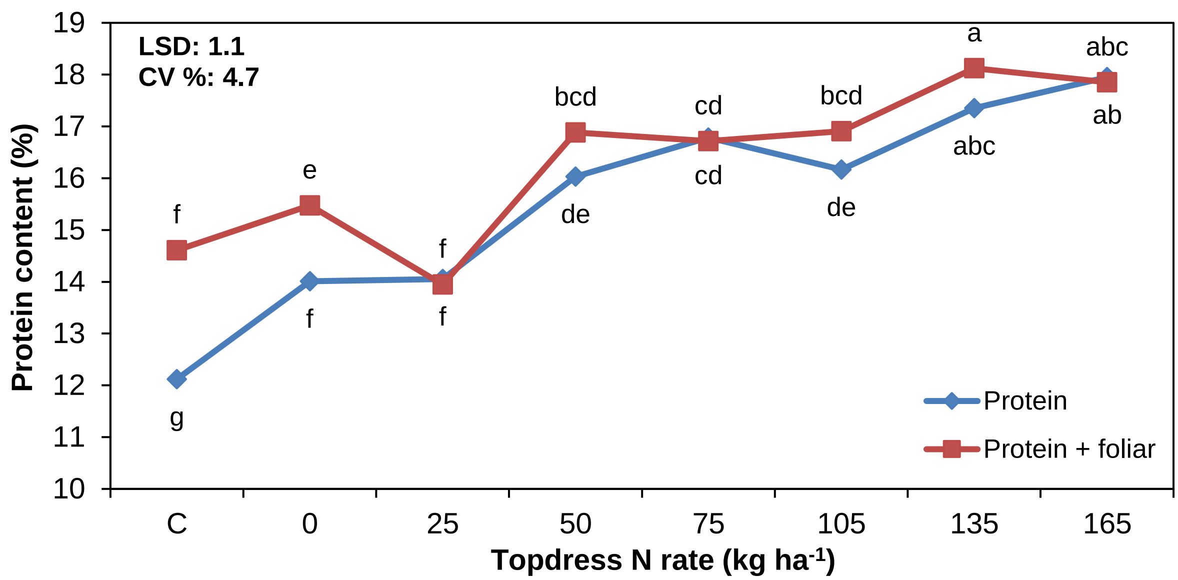


Figure 5.1.20 Grain protein (%) for topdress N treatments with and without additional foliar N at Langgewens C/W (Year 2). LSD = Least significant difference (P < 0.05); CV = coefficient of variance. Means without a common letter above or below points indicate significant differences at a 5% level.

5.1.6 Porterville M/W

5.1.6.1 Grain yield

No increase (P > 0.05) in yield was recorded between treatments in Year 1 (Figure 5.1.21). In Year 2, foliar N application led to an increase (P < 0.05) in yield at almost all treatments and a marginal increase in yield at the 75 kg N ha^{-1} treatment (Figure 5.1.22).

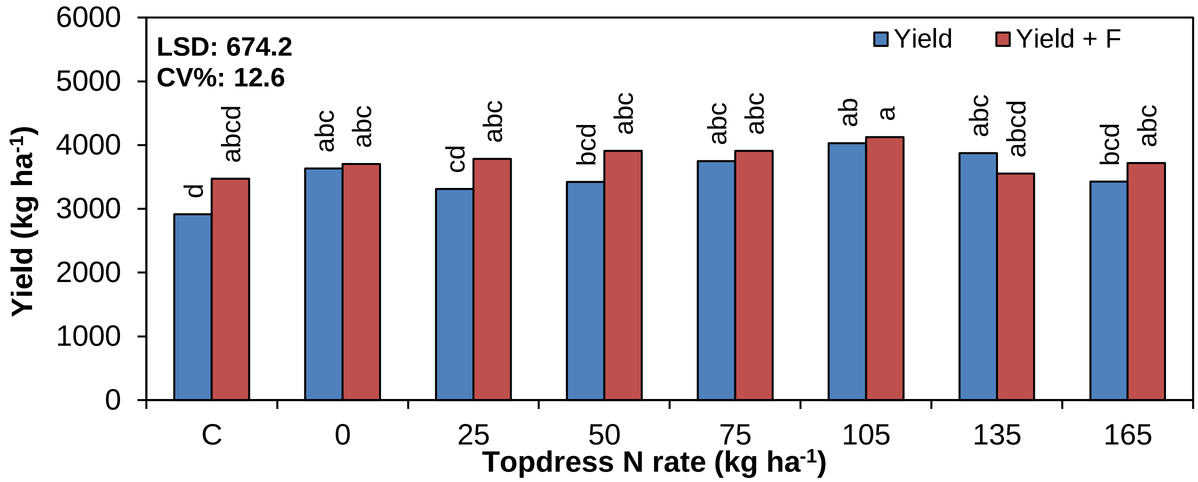


Figure 5.1.21 Grain yield (kg ha^{-1}) of topdress N treatments with and without additional foliar N at Porterville M/W (Year 1). LSD = Least significant difference (P < 0.05); CV = coefficient of variance. Means within each topdress treatment without a common letter above bars indicate significant differences at a 5% level.

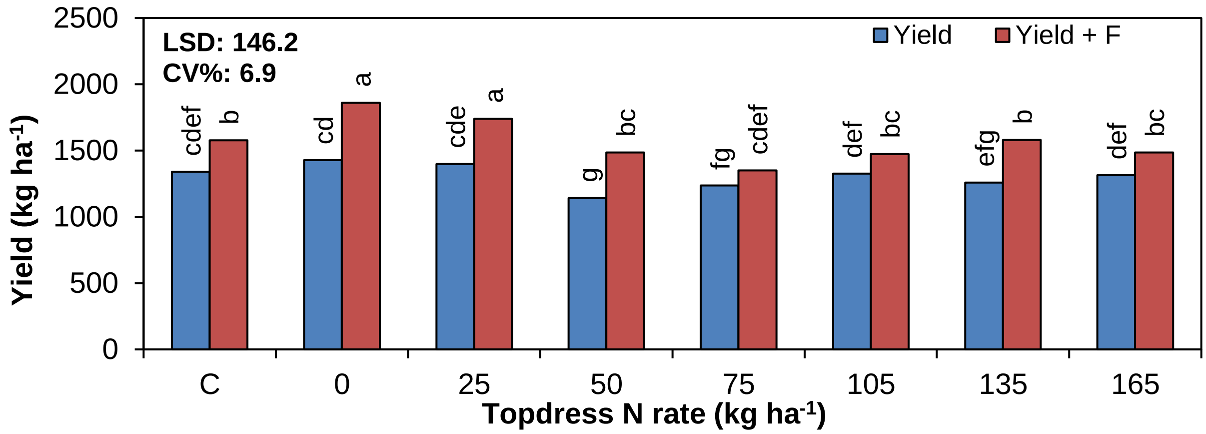


Figure 5.1.22 Grain yield (kg ha^{-1}) of topdress N treatments with and without additional foliar N at Porterville M/W (Year 2). LSD = Least significant difference (P < 0.05); CV = coefficient of variance. Means within each topdress treatment without a common letter above bars indicate significant differences at a 5% level.

5.1.6.2 Protein content

No differences (P > 0.05) between the two foliar treatments were recorded in either Year 1 or 2 (Figure 5.1.23 and 5.1.24, respectively).

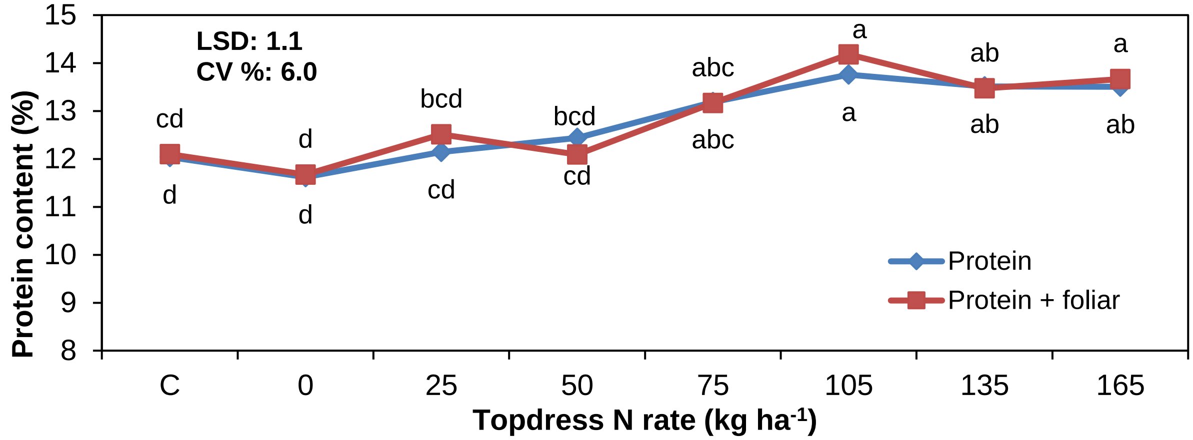


Figure 5.1.23 Grain protein (%) for topdress N treatments with and without additional foliar N at Porterville M/W (Year 1). LSD = Least significant difference (P < 0.05); CV = coefficient of variance. Means without a common letter above or below points indicate significant differences at a 5% level.

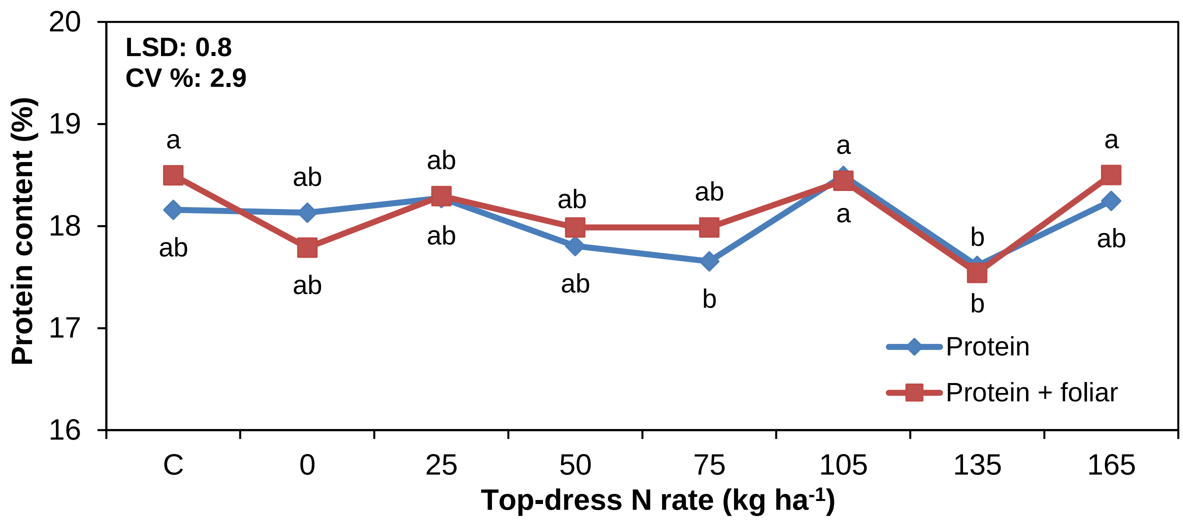


Figure 5.1.24 Grain protein (%) for topdress N treatments with and without additional foliar N at Porterville M/W (Year 2). LSD = Least significant difference (P < 0.05); CV = coefficient of variance. Means without a common letter above or below points indicate significant differences at a 5% level.

5.1.7 Porterville C/W

5.1.7.1 Grain yield

No differences (P > 0.05) in yield, because of foliar N application, were recorded in Year 1 (Figure 5.1.25). In Year 2, the application of foliar N led to increased yields at the 105 and 135 kg N ha^{-1} treatments, but not at the other treatments (Figure 5.1.26).

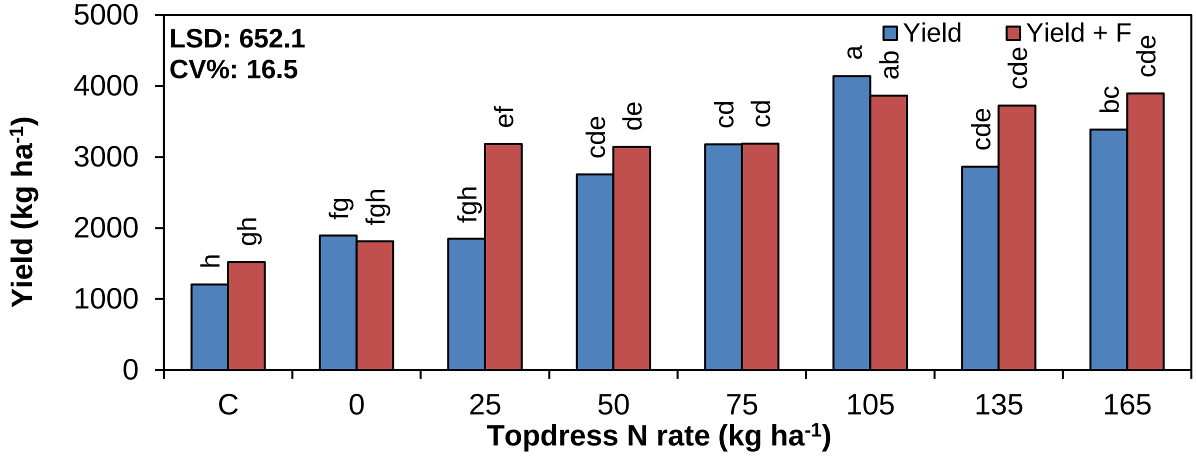


Figure 5.1.25 Grain yield (kg ha^{-1}) of topdress N treatments with and without additional foliar N at Porterville C/W (Year 1). LSD = Least significant difference (P < 0.05); CV = coefficient of variance. Means within each topdress treatment without a common letter above bars indicate significant differences at a 5% level.

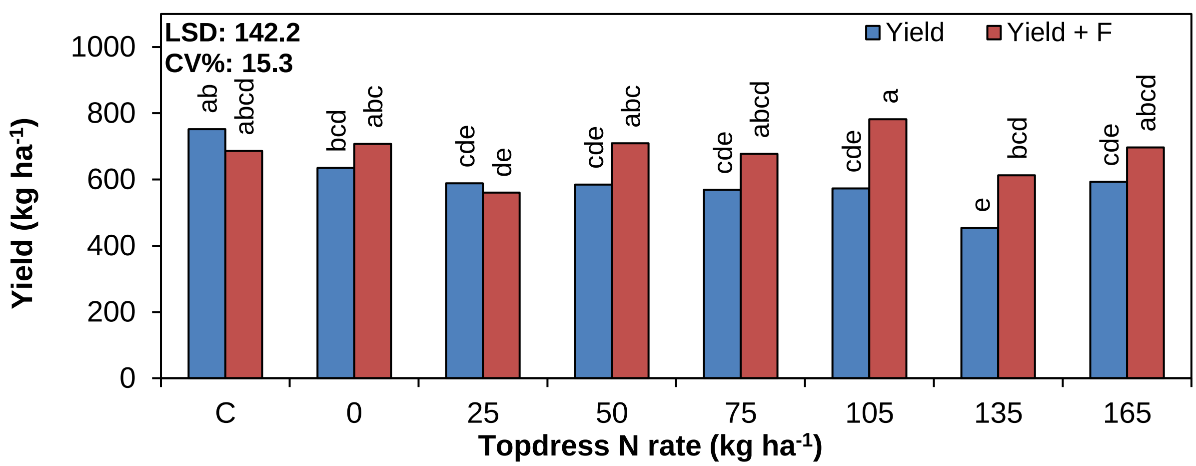


Figure 5.1.26 Grain yield (kg ha^{-1}) of topdress N treatments with and without additional foliar N at Porterville C/W (Year 2). LSD = Least significant difference (P < 0.05); CV = coefficient of variance. Means within each topdress treatment without a common letter above bars indicate significant differences at a 5% level.

5.1.7.2 Protein content

Although protein samples were collected in Year 1, samples were lost during analysis. No differences (P > 0.05) in protein content were recorded between foliar N application treatments in Year 2 (Figure 5.1.27).

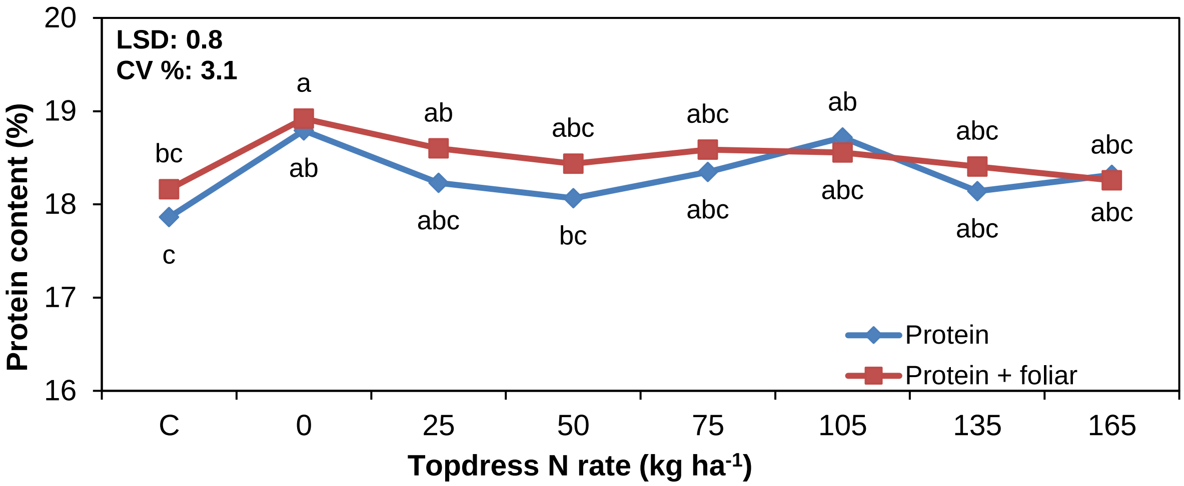


Figure 5.1.27 Grain protein (%) for topdress N treatments with and without additional foliar N at Porterville C/W (Year 2). LSD = Least significant difference (P < 0.05); CV = coefficient of variance. Means without a common letter above or below points indicate significant differences at a 5% level.

5.1.8 Darling M/W

5.1.8.1 Grain yield

In Year 1, foliar N application led to an increase (P < 0.05) in yield of the control and 0 kg N ha^{-1} treatments (Figure 5.1.28). During Year 2, the addition of foliar N to the wheat crops did not lead to an increase (P > 0.05) in yield in any of the treatments (Figure 5.1.29).

5.1.8.2 Protein content

During Year 1, foliar N application led to an increase (P < 0.05) in grain protein content of the 50 kg N ha^{-1} treatment. No other differences (P > 0.05) were recorded in Year 1 (Figure 5.1.30). No differences (P > 0.05) in protein content were recorded in Year 2 (Figure 5.1.31).

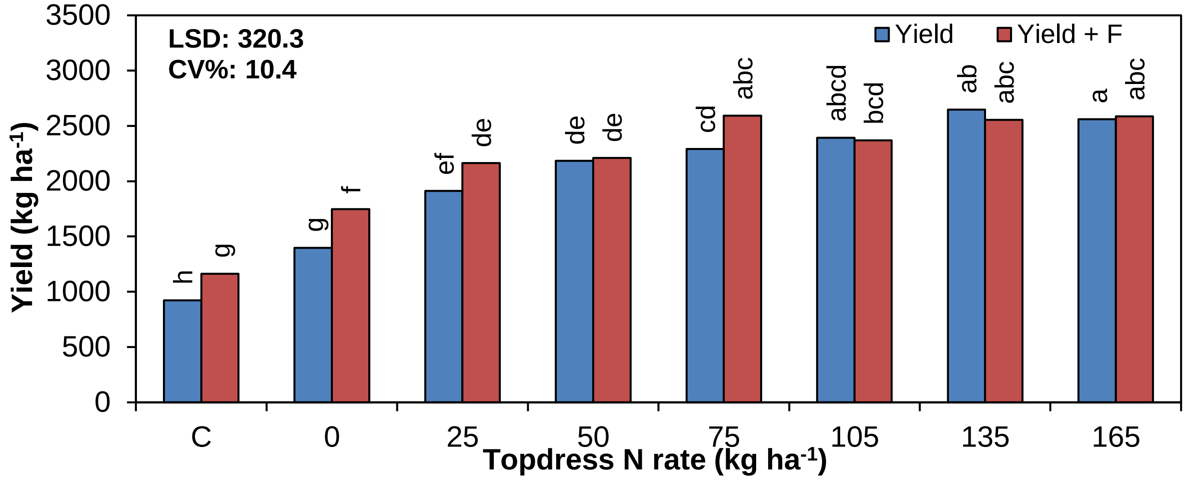


Figure 5.1.28 Grain yield (kg ha^{-1}) of topdress N treatments with and without additional foliar N at Darling M/W (Year 1). LSD = Least significant difference (P < 0.05); CV = coefficient of variance. Means within each topdress treatment without a common letter above bars indicate significant differences at a 5% level.

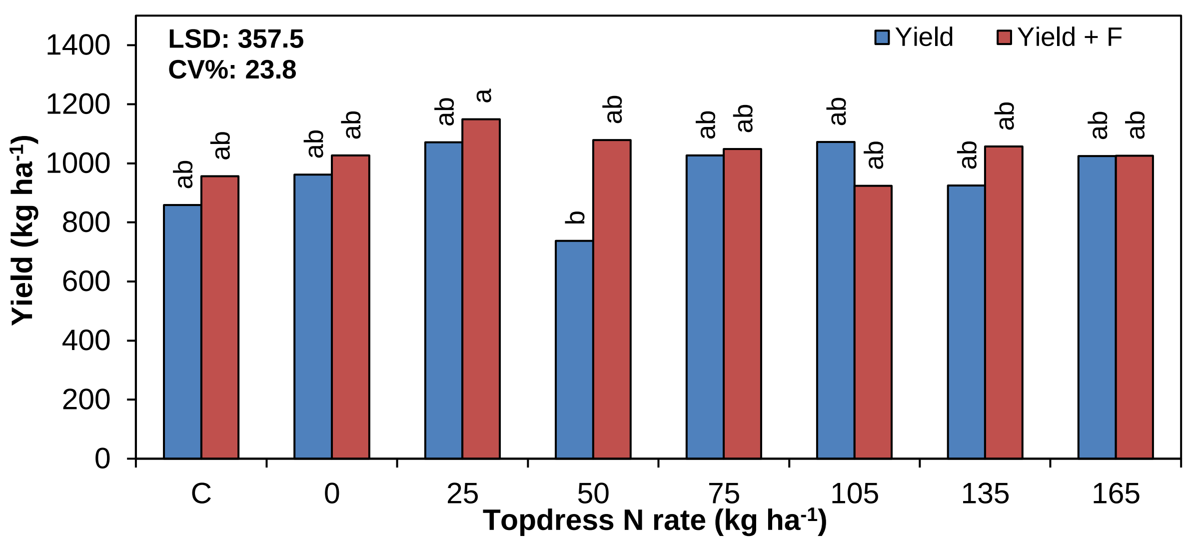


Figure 5.1.29 Grain yield (kg ha^{-1}) of topdress N treatments with and without additional foliar N at Darling M/W (Year 2). LSD = Least significant difference (P < 0.05); CV = coefficient of variance. Means within each topdress treatment without a common letter above bars indicate significant differences at a 5% level.

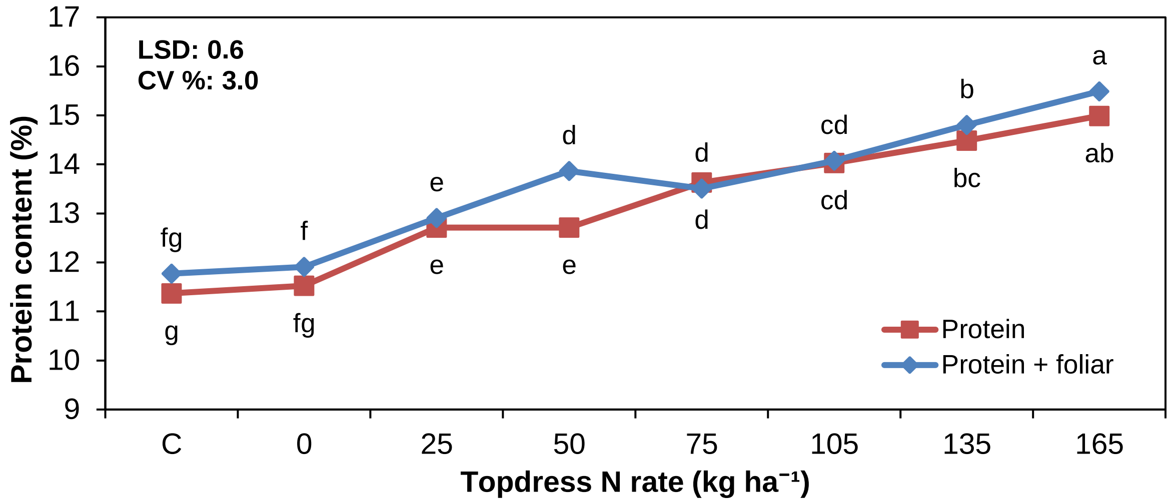


Figure 5.1.30 Grain protein (%) for topdress N treatments with and without additional foliar N at Darling M/W (Year 1). LSD = Least significant difference ($P < 0.05$); CV = coefficient of variance. Means without a common letter above or below points indicate significant differences at a 5% level.

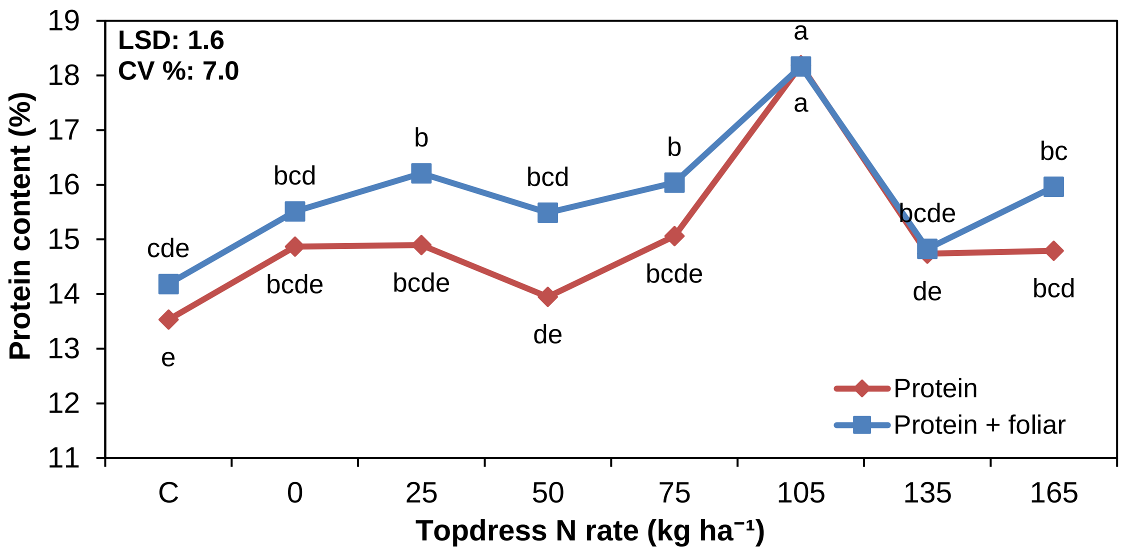


Figure 5.1.31 Grain protein (%) for topdress N treatments with and without additional foliar N at Darling M/W (Year 2). LSD = Least significant difference ($P < 0.05$); CV = coefficient of variance. Means without a common letter above or below points indicate significant differences at a 5% level.

5.1.9 Darling C/W

5.1.9.1 Grain yield

During Year 1, foliar N application did not increase (P > 0.05) the yields of any treatments, except for 135 kg N ha^{-1} (Figure 5.1.32). At most of the treatments in Year 2, application of foliar N did not result in any increases (P > 0.05) in yield, with the only increases (P < 0.05) in yield being recorded at the 135 and 165 kg N ha^{-1} treatments (Figure 5.1.33).

5.1.9.2 Protein content

The 50, 135 and 165 kg N ha^{-1} treatments all benefited from an additional foliar N application, as it led to higher (P < 0.05) grain protein content in Year 1 (Figure 5.1.34). Apart from the 25 and 50 kg N ha^{-1} having higher (P < 0.05) protein contents with the addition of foliar N, no other differences (P > 0.05) were recorded between foliar treatments in Year 2 (Figure 5.1.35).

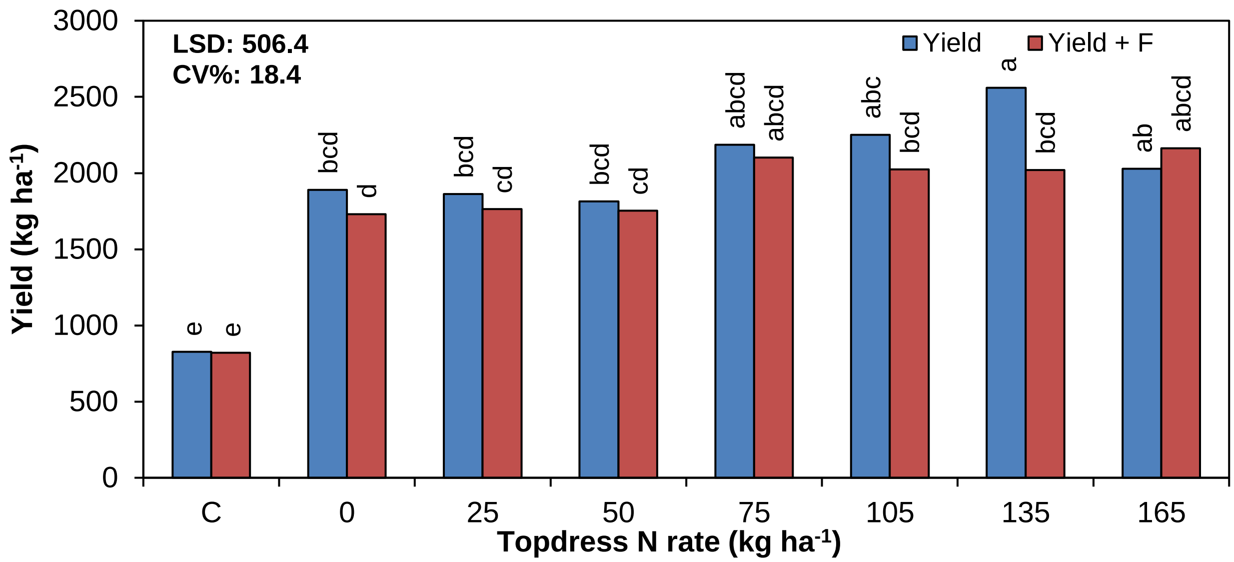


Figure 5.1.32 Grain yield (kg ha^{-1}) of topdress N treatments with and without additional foliar N at Darling C/W (Year 1). LSD = Least significant difference (P < 0.05); CV = coefficient of variance. Means within each topdress treatment without a common letter above bars indicate significant differences at a 5% level.

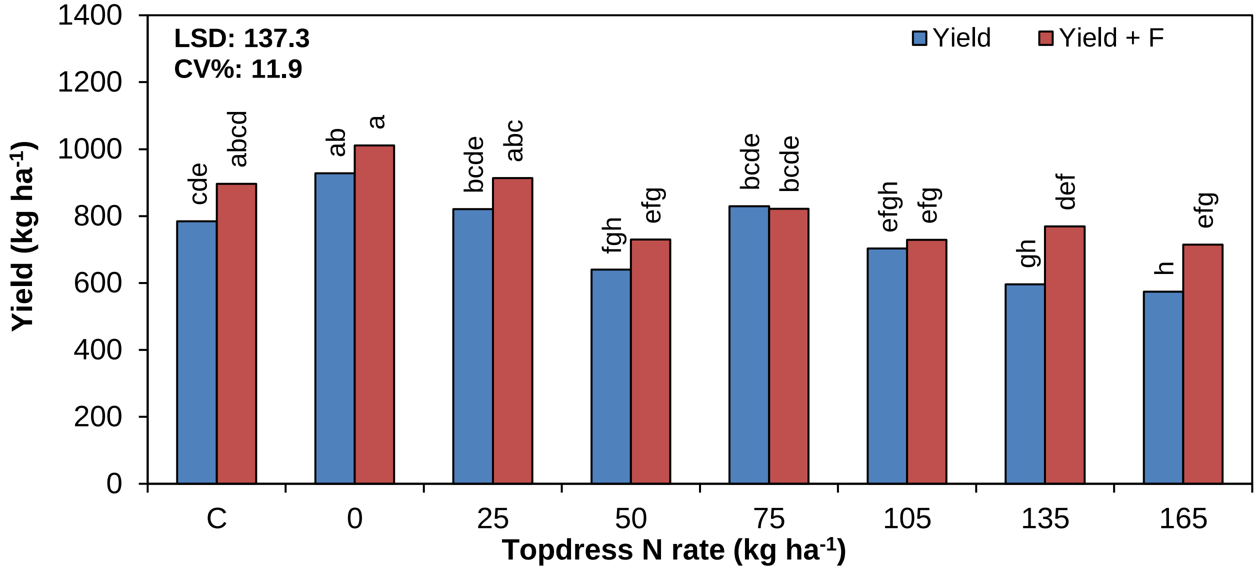


Figure 5.1.33 Grain yield (kg ha^{-1}) of topdress N treatments with and without additional foliar N at Darling C/W (Year 2). LSD = Least significant difference (P < 0.05); CV = coefficient of variance. Means within each topdress treatment without a common letter above bars indicate significant differences at a 5% level.

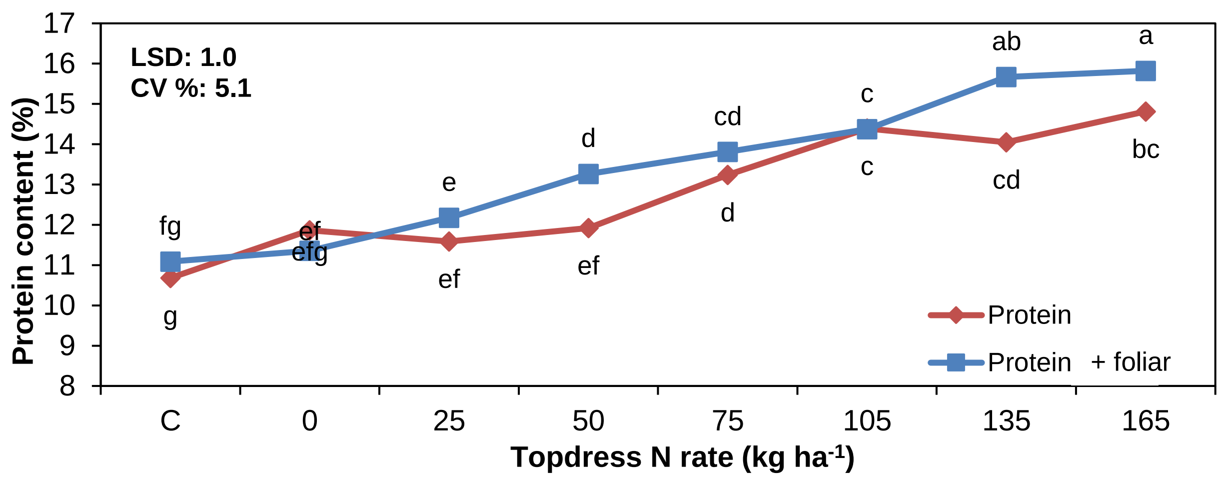


Figure 5.1.34 Grain protein (%) for topdress N treatments with and without additional foliar N at Darling C/W (Year 1). LSD = Least significant difference (P < 0.05); CV = coefficient of variance. Means without a common letter above or below points indicate significant differences at a 5% level.

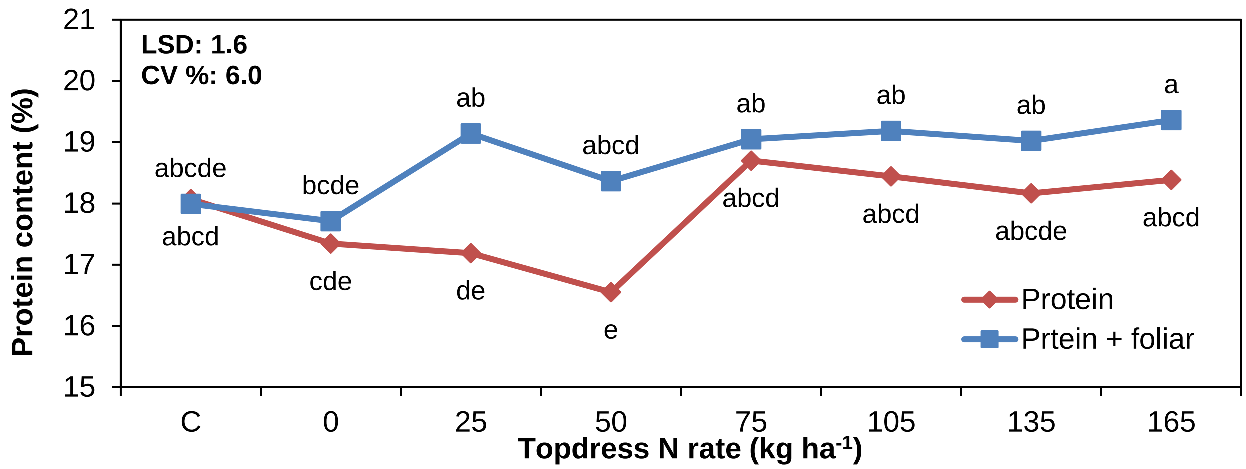


Figure 5.1.35 Grain protein (%) for topdress N treatments with and without additional foliar N at Darling C/W (Year 2). LSD = Least significant difference (P < 0.05); CV = coefficient of variance. Means without a common letter above or below points indicate significant differences at a 5% level.

5.2 Discussion

The late-season foliar N application in the form of urea ammonium nitrate (UAN) did not lead to consistent increases (P < 0.05) in yield at any of the nine sites during Year 1 and only two of the nine sites in Year 2. This was the expected result, as late-season N applications normally play a more substantial role in increasing grain protein content rather than yield. However, during Year 1, two sites showed a yield response (P < 0.05) to foliar N application, namely: the Langgewens C/W and Porterville M/W sites. Although late-season foliar N applications are more effective in increasing grain protein, it may increase yields in N deficient plants (Brown et al., 2005; Orloff et al., 2012).

During Year 1, at the Riversdale, Tygerhoek and Langgewens M/W sites foliar N application at anthesis led to increased grain protein content of the wheat crop. Similar results were previously reported by Bly and Woodard (2003), Gooding and Davies (1992), Otteson et al. (2007), Rawluk et al. (2000) and Woolfolk et al. (2002). This increase in grain protein content with an additional foliar N application is important in wheat production (Otteson et al., 2007) as the increase in grain protein content leads to the production of better quality wheat which can consequently be sold at more profitable prices. This is an important factor to consider.

The Caledon, Langgewens C/W, Porterville M/W and both Darling sites in Year 1 and all of the sites in Year 2 showed no consistent protein increase with foliar N application, thus contradicting the findings of Bly and Woodard (2003), Gooding and Davies (1992), Otteson et al. (2007), Rawluk et al. (2000) and Woolfolk et al. (2002). The lack of grain protein increase in response to an additional late-season foliar N application at the Caledon, Porterville- and Darling M/W sites could have been due to the N-fixation by the previous year's lucerne and medic crops. This can be supported by Staggenborg et al. (2003) as they found that wheat response to N was influenced by the preceding crop. The inability of a late-season application of foliar N to increase grain protein content could result in a less profitable harvest, because of the extra expense on the foliar N without reaping any benefits from it.

6 The effect of different N sources on crop growth, yield and quality of wheat.

6.1 Results

The data from each site will be discussed separately in the following order: i) Plant parameters, ii) Grain yield, and iii) Quality parameters. Note that the data from Year 1 and Year 2 was statistically analysed separately, and will not be compared with each other.

6.1.1 Riversdale C/W

6.1.1.1 Plant parameters

In Year 1 lower ($P < 0.05$) seedling populations were recorded for urea with urease inhibitor (urea + I) compared to limestone ammonium nitrate with added sulphur (LAN + S). However, seedling populations for urea + I did not differ ($P > 0.05$) from urea, ammonium sulphate (AMS) and limestone ammonium nitrate (LAN) (Table 6.1.1). In Year 2 no differences ($P > 0.05$) in seedling populations were recorded between N source treatments. No differences ($P > 0.05$) in the number of EBT or biomass production occurred between the different N source treatments in Year 1 or 2.

Table 6.1.1 Seedling population (m^{-2}), number of EBT (m^{-2}) and biomass production (kg ha^{-1}) as influenced by fertiliser N sources at Riversdale during Year 1 and 2.

	Year 1						
N source	**Urea**	**Urea + I**	**AMS**	**LAN**	**LAN + S**	**CV (%)**	**LSD**
Seedlings (m^{-2})	87.3 ^{ab}	85.7 ^{b}	96.5 ^{ab}	89.5 ^{ab}	108.9 ^{a}	**12.9**	**22.7**
EBT (m^{-2})	284.3 ^{a}	285.2 ^{a}	270.5 ^{a}	311.0 ^{a}	282.9 ^{a}	**13.3**	**72.0**
Biomass (kg ha^{-1})	12143 ^{a}	12619 ^{a}	12048 ^{a}	15000 ^{a}	12810 ^{a}	**21.6**	**5260**
	Year 2						
Seedlings (m^{-2})	74.3 ^{a}	77.7 ^{a}	80.5 ^{a}	92.4 ^{a}	70.5 ^{a}	**10.8**	**23.7**
EBT (m^{-2})	220.5 ^{a}	212.4 ^{a}	234.3 ^{a}	210.5 ^{a}	206.2 ^{a}	**14.2**	**57.8**
Biomass (kg ha^{-1})	5190 ^{a}	4524 ^{a}	5667 ^{a}	4476 ^{a}	4714 ^{a}	**18.8**	**1736**

Means without a common superscript letter in the same row indicate significant differences at a 5% level.

CV = Coefficient of variance

LSD = Least significant difference

6.1.1.2 Grain yield

In Year 1, AMS resulted in lower ($P < 0.05$) grain yield than urea + I and LAN + S (Figure 6.1.1), but the opposite result was observed in Year 2 (Figure 6.1.2), where the AMS treatment had a higher ($P < 0.05$) yield than urea + I and LAN + S.

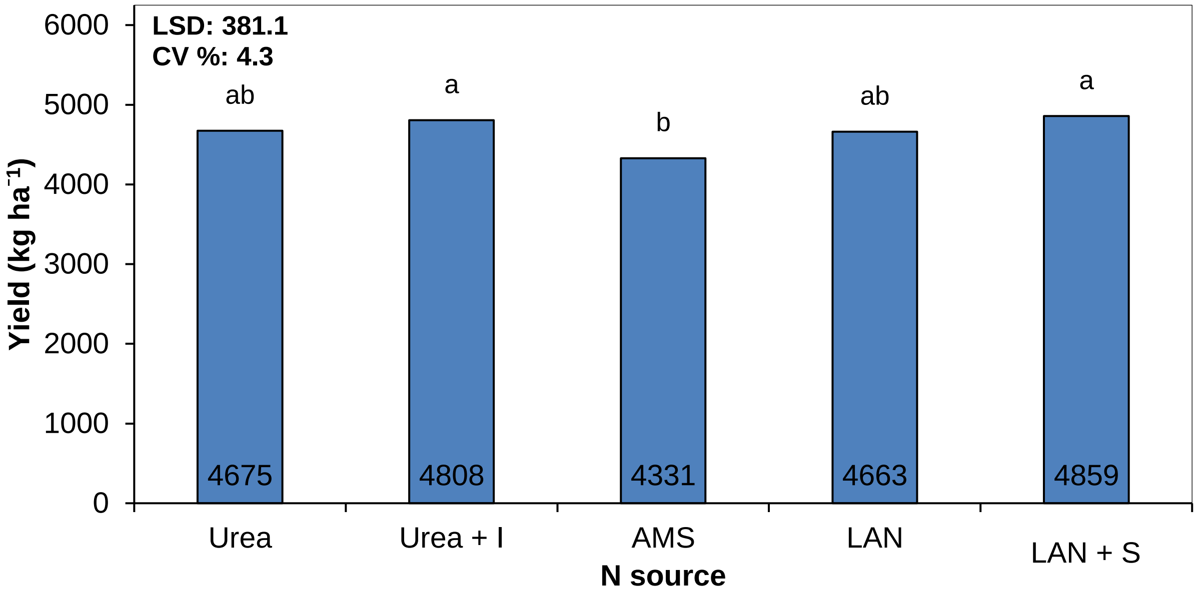


Figure 6.1.1 Grain yield (kg ha^{-1}) as influenced by fertiliser N source at Riversdale (Year 1). LSD = Least significant difference ($P < 0.05$); CV = coefficient of variance. Bars with different letters indicate significant differences at a 5% level.

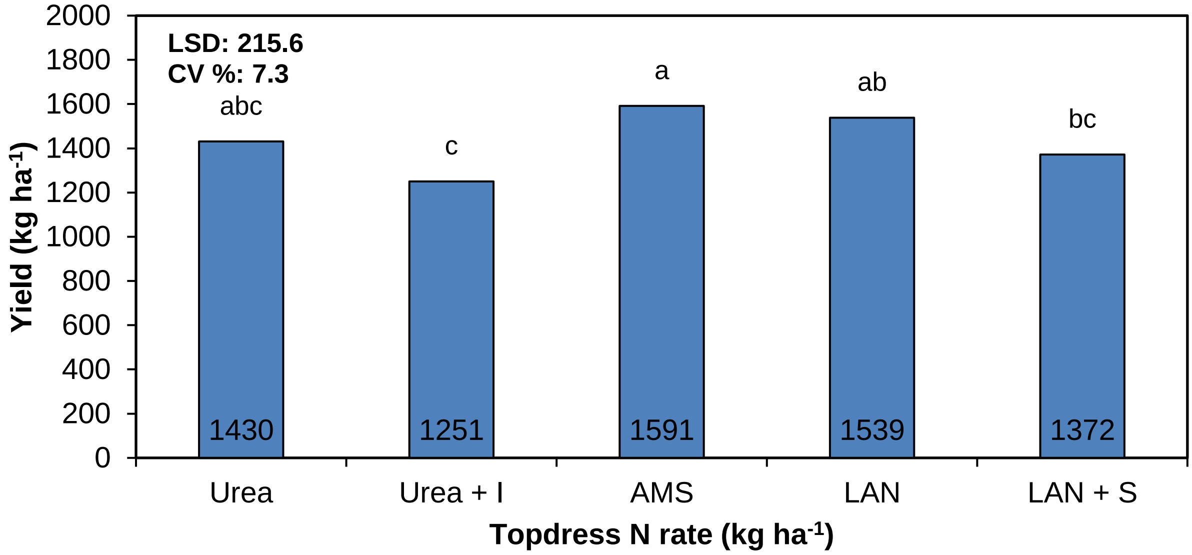


Figure 6.1.2 Grain yield (kg ha^{-1}) as influenced by fertiliser N source at Riversdale (Year 2). LSD = Least significant difference ($P < 0.05$); CV = coefficient of variance. Bars with different letters indicate significant differences at a 5% level.

6.1.1.3 Quality parameters

Urea + I and urea had higher ($P < 0.05$) hectolitre mass than LAN and AMS, but did not differ ($P > 0.05$) from that of LAN + S in Year 1 (Table 6.1.2). During Year 2, urea produced a higher ($P < 0.05$) hectolitre mass than AMS, LAN and LAN + S, but did not differ ($P > 0.05$) from urea + I. No differences ($P > 0.05$) in harvest index were recorded for the different treatments in either Year 1 or 2. No differences ($P > 0.05$) in protein content were found between the different N sources in either Year 1 or 2.

Table 6.1.2 Hectolitre mass and grain protein content (%) as influenced by fertiliser N sources at Riversdale during Year 1 and 2 of the study.

				Year 1			
N source	**Urea**	**Urea + I**	**AMS**	**LAN**	**LAN + S**	**CV (%)**	**LSD**
Hectolitre mass (g cm^{-3})	78.8 ^{a}	78.9 ^{a}	78.1 ^{b}	77.9 ^{b}	78.4 ^{ab}	**0.5**	**0.7**
Harvest index	39.6 ^{a}	38.8 ^{a}	35.9 ^{a}	32.3 ^{a}	39.0 ^{a}	**18.8**	**13.2**
Protein content (%)	9.6 ^{a}	9.6 ^{a}	9.5 ^{a}	9.6 ^{a}	9.6 ^{a}	**4.6**	**0.8**
				Year 2			
Hectolitre mass (g cm^{-3})	75.9 ^{a}	75.3 ^{ab}	74.0 ^{b}	74.4 ^{b}	73.9 ^{b}	**1.1**	**1.5**
Harvest index	0.28 ^{a}	0.32 ^{a}	0.30 ^{a}	0.34 ^{a}	0.29 ^{a}	**19.3**	**0.11**
Protein content (%)	13.1^{a}	13.8^{a}	13.7^{a}	13.9^{a}	13.4^{a}	**3.4**	**0.9**

Means without a common superscript letter in the same row indicate significant differences at a 5% level.

CV = Coefficient of variance

LSD = Least significant difference

6.1.2 Tygerhoek C/W

6.1.2.1 Plant parameters

No differences ($P > 0.05$) in the seedling population occurred between the source treatments in Year 1 and 2 (Table 6.1.3). Urea + I produced more ($P < 0.05$) EBT than urea and LAN + S, but did not differ from AMS and LAN in Year 1. The different N sources resulted in no differences ($P > 0.05$) in EBT or biomass production in Year 2. During Year 1 LAN produced higher ($P < 0.05$) biomass than LAN + S and urea.

6.1.2.2 Grain yield

No differences ($P > 0.05$) in yield were observed between the different N sources at Tygerhoek, during Year 1 (Figure 6.1.3) or 2 (Figure 6.1.4).

Table 6.1.3 Seedling population (m^{-2}), number of EBT (m^{-2}) and biomass production (kg ha^{-1}) as influenced by fertiliser N sources at Tygerhoek during Year 1 and 2 of the study.

N source	Urea	Urea + I	AMS	LAN	LAN + S	CV (%)	LSD
Year 1							
Seedlings (m^{-2})	74.1 ^{a}	62.9 ^{a}	84.8 ^{a}	72.6 ^{a}	83.6 ^{a}	**19.6**	**22.8**
EBT (m^{-2})	217.9 ^{c}	323.2 ^{a}	287.5 ^{ab}	290.0 ^{ab}	252.1 ^{bc}	**14.9**	**62.7**
Biomass (kg ha^{-1})	9464 ^{b}	11393 ^{ab}	11714 ^{ab}	12857 ^{a}	9786 ^{b}	**15.8**	**2687**
Year 2							
Seedlings (m^{-2})	144.3 ^{a}	141.7 ^{a}	166.7 ^{a}	151.7 ^{a}	152.9 ^{a}	**16.8**	**39.2**
EBT (m^{-2})	291.1 ^{a}	288.2 ^{a}	329.7 ^{a}	330.0 ^{a}	324.7 ^{a}	**16.0**	**76.9**
Biomass (kg ha^{-1})	8750 ^{a}	7429 ^{a}	9357 ^{a}	8929 ^{a}	8893 ^{a}	**16.3**	**2181**

Means without a common superscript letter in the same row indicate significant differences at a 5% level.

CV = Coefficient of variance

LSD = Least significant difference

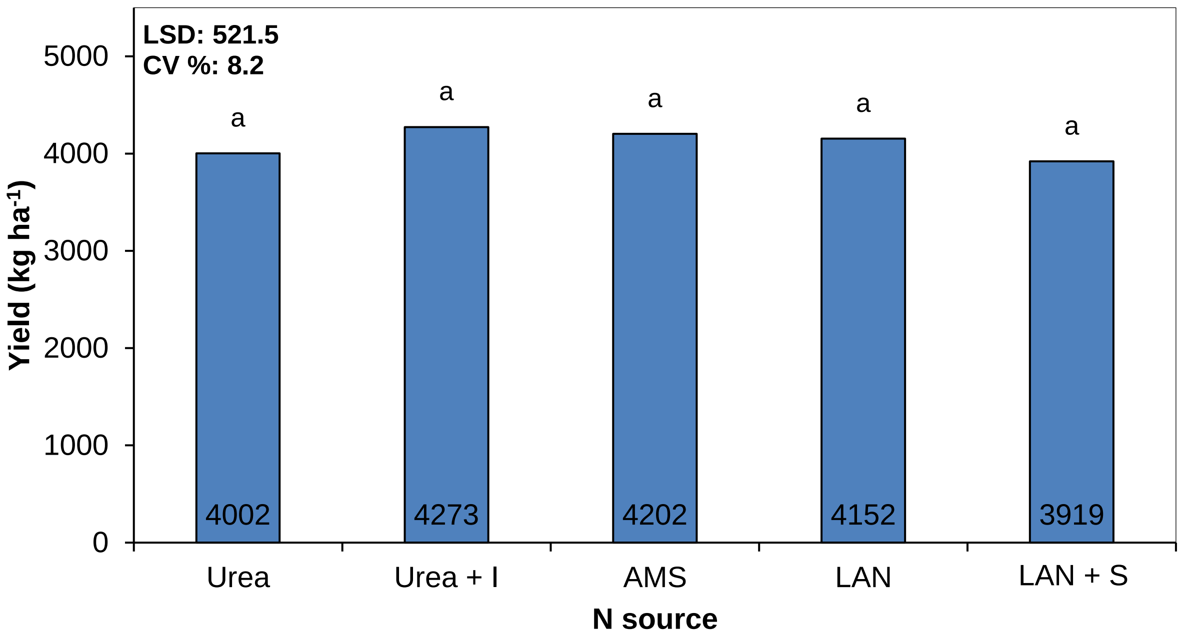


Figure 6.1.3 Grain yield (kg ha^{-1}) as influenced by fertiliser N source at Tygerhoek (Year 1). LSD = Least significant difference ($P < 0.05$); CV = coefficient of variance. Means without a common letter above bars indicate significant differences at a 5% level.

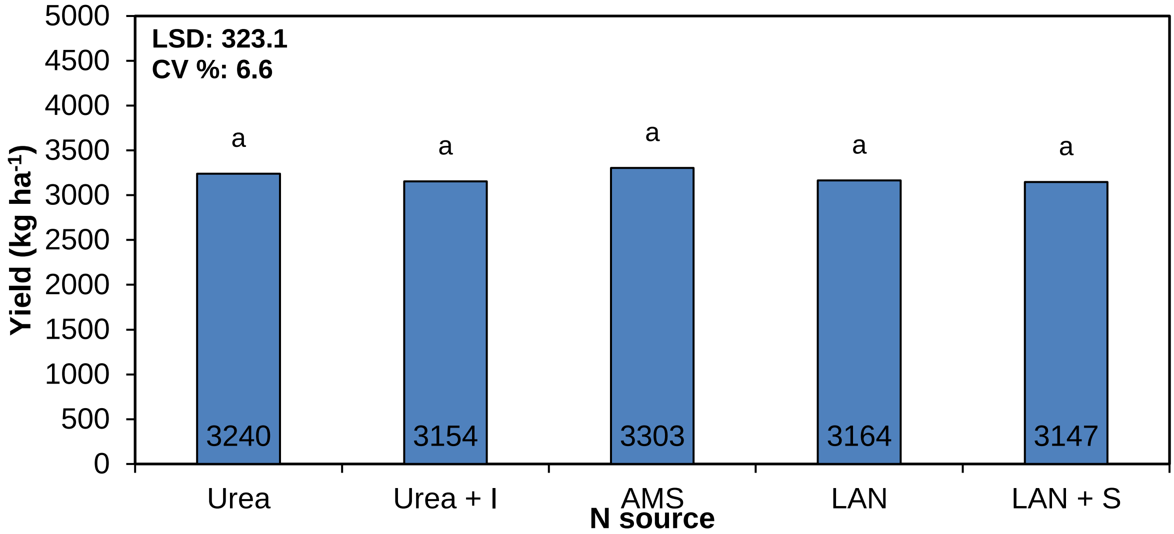


Figure 6.1.4 Grain yield (kg ha^{-1}) as influenced by fertiliser N source at Tygerhoek (Year 2). LSD = Least significant difference (P < 0.05); CV = coefficient of variance. Means without a common letter above bars indicate significant differences at a 5% level.

6.1.2.3 Quality parameters

No differences (P > 0.05) in hectolitre mass and harvest index between the different N sources were recorded in either Year 1 or 2 of the study (Table 6.1.4). Protein contents did not differ (P > 0.05) between N rate treatments in Year 1, but Urea + I had a higher (P < 0.05) protein content than Urea and LAN + S in Year 2.

Table 6.1.4 Hectolitre mass, harvest index and protein content (%) as influenced by fertiliser N sources at Tygerhoek during Year 1 and 2 of the study.

	Year 1						
N source	**Urea**	**Urea + I**	**AMS**	**LAN**	**LAN + S**	**CV (%)**	**LSD**
Hectolitre mass (g cm^{-3})	76.0 ^{a}	76.6 ^{a}	76.2 ^{a}	76.4 ^{a}	76.5 ^{a}	**1.2**	**1.4**
Harvest index	0.44 ^{a}	0.38 ^{a}	0.36 ^{a}	0.33 ^{a}	0.40 ^{a}	**18.7**	**0.11**
Protein content (%)	10.7 ^{a}	10.8 ^{a}	10.6 ^{a}	10.5 ^{a}	10.7 ^{a}	**2.7**	**0.5**
	Year 2						
Hectolitre mass (g cm^{-3})	74.2 ^{a}	73.5 ^{a}	74.0 ^{a}	73.5 ^{a}	73.6 ^{a}	**0.9**	**1.0**
Harvest index	0.38 ^{a}	0.44 ^{a}	0.36 ^{a}	0.36 ^{a}	0.39 ^{a}	**21.6**	**0.13**
Protein content (%)	12.9 ^{b}	13.7 ^{a}	13.4 ^{ab}	13.5 ^{ab}	13.1 ^{b}	**2.7**	**2.2**

Means without a common superscript letter in the same row indicate significant differences at a 5% level.

CV = Coefficient of variance

LSD = Least significant difference

6.1.3 Caledon L/W

6.1.3.1 Plant parameters

The source treatments indicated no differences ($P > 0.05$) in seedling populations for either Year 1 or 2 (Table 6.1.5). No differences ($P > 0.05$) in EBT were recorded in Year 1 or 2. In Year 1, source treatments had no effect on biomass production, while AMS produced a higher ($P < 0.05$) biomass than urea and LAN + S in Year 2.

Table 6.1.5 Seedling population (m^{-2}), number of EBT (m^{-2}) and biomass production (kg ha^{-1}) as influenced by fertiliser N sources at Caledon during Year 1 and 2 of the study.

N Source	Urea	Urea + I	AMS	LAN	LAN + S	CV (%)	LSD
Year 1							
Seedlings (m^{-2})	106.9 ^{a}	107.9 ^{a}	106.9 ^{a}	100.7 ^{a}	112.1 ^{a}	**7.9**	**12.9**
EBT (m^{-2})	285.4 ^{a}	284.6 ^{a}	263.9 ^{a}	229.6 ^{a}	259.6 ^{a}	**17.9**	**73.1**
Biomass (kg ha^{-1})	8786 ^{a}	8964 ^{a}	9393 ^{a}	8321 ^{a}	8929 ^{a}	**15.5**	**2116**
Year 2							
Seedlings (m^{-2})	125.7 ^{a}	113.3 ^{a}	118.4 ^{a}	112.9 ^{a}	128.6 ^{a}	**11.6**	**21.5**
EBT (m^{-2})	247.2 ^{a}	255.7 ^{a}	283.2 ^{a}	254.7 ^{a}	247.2 ^{a}	**11.3**	**44.6**
Biomass (kg ha^{-1})	8036 ^{b}	9000 ^{ab}	9500 ^{a}	8357 ^{ab}	7821 ^{b}	**11.0**	**1444**

Means without a common superscript letter in the same row indicate significant differences at a 5% level.
CV = Coefficient of variance
LSD = Least significant difference

6.1.3.2 Grain yield

No differences ($P > 0.05$) in yield were recorded for Year 1 or 2 at Caledon between N sources (Figure 6.1.5 and Figure 6.1.6, respectively).

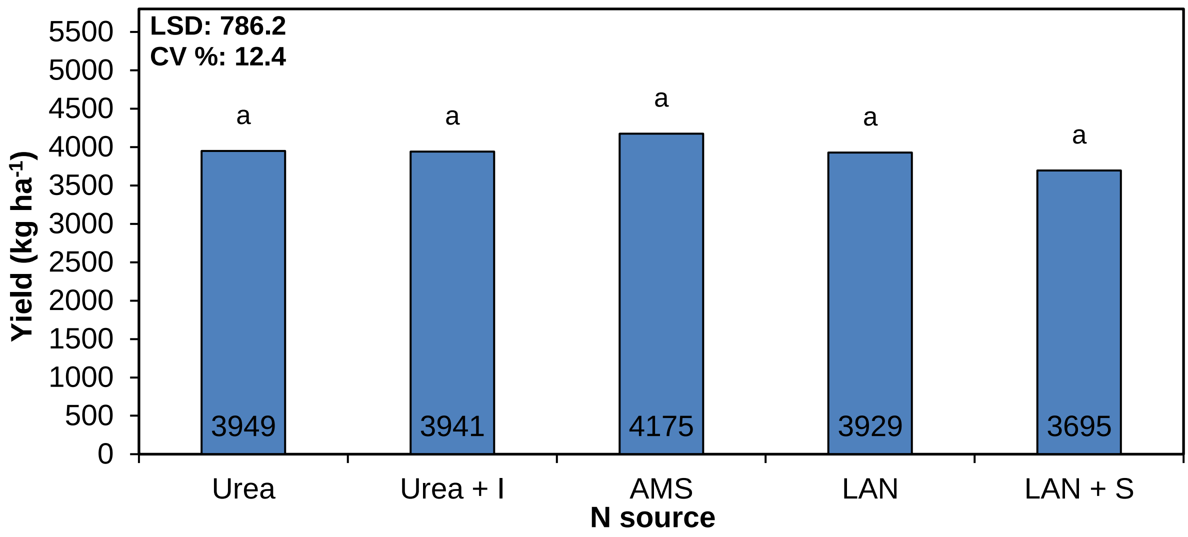


Figure 6.1.5 Grain yield (kg ha^{-1}) as influenced by fertiliser N source at Caledon (Year 1). LSD = Least significant difference ($P < 0.05$); CV = coefficient of variance. Means without a common letter above bars indicate significant differences at a 5% level.

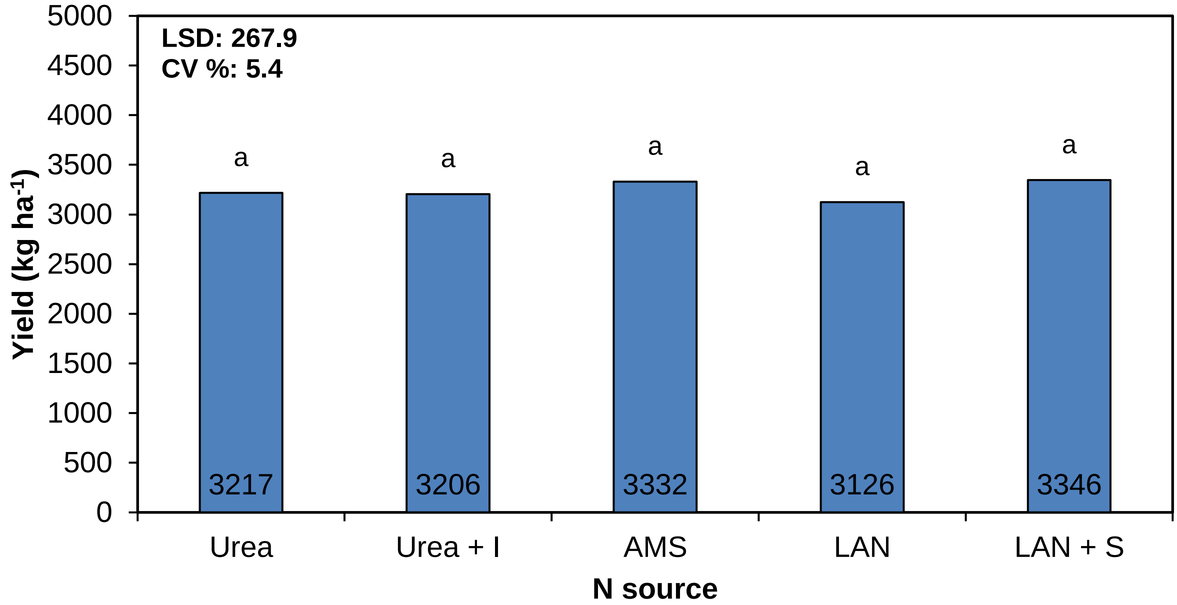


Figure 6.1.6 Grain yield (kg ha^{-1}) as influenced by fertiliser N source at Caledon (Year 2). LSD = Least significant difference ($P < 0.05$); CV = coefficient of variance. Means without a common letter above bars indicate significant differences at a 5% level.

6.1.3.3 Quality parameters

Table 6.1.6 shows that no differences ($P > 0.05$) in hectolitre mass, harvest index and protein content (%), as influenced by N sources, were recorded in Year 1 at Caledon. During Year 2, LAN had a higher ($P < 0.05$) hectolitre mass than urea, while LAN + S had a higher harvest index than urea + I and AMS, but no differences in protein ($P > 0.05$) was recorded.

Table 6.1.6 Hectolitre mass, harvest index and protein content (%) as influenced by fertiliser N sources at Caledon during Year 1 and 2 of the study.

N Source	Urea	Urea + I	AMS	LAN	LAN + S	CV (%)	LSD
Year 1							
Hectolitre mass (g cm^{-3})	77.0 ^{a}	76.7 ^{a}	77.6 ^{a}	77.2 ^{a}	77.3 ^{a}	**1.4**	**1.7**
Harvest index	0.48 ^{a}	0.46 ^{a}	0.45 ^{a}	0.48 ^{a}	0.44 ^{a}	**17.5**	**0.13**
Protein content (%)	12.8 ^{a}	12.5 ^{a}	12.3 ^{a}	13.0 ^{a}	12.4 ^{a}	**4.2**	**0.8**
Year 2							
Hectolitre mass (g cm^{-3})	76.7 ^{b}	77.3 ^{ab}	76.9 ^{ab}	77.5 ^{a}	77.3 ^{ab}	**0.6**	**0.7**
Harvest index	0.40 ^{ab}	0.36 ^{b}	0.36 ^{b}	0.37 ^{ab}	0.43 ^{a}	**10.4**	**0.06**
Protein content (%)	13.6 ^{a}	13.6 ^{a}	13.9 ^{a}	13.8 ^{a}	13.5 ^{a}	**4.1**	**0.9**

Means without a common superscript letter in the same row indicate significant differences at a 5% level.

CV = Coefficient of variance

LSD = Least significant difference

6.1.4 Langgewens M/W

6.1.4.1 Plant parameters

No differences ($P > 0.05$) in seedling population, number of EBT and biomass for the N source treatments were found for Year 1 (Table 6.1.7). In Year 2 no differences ($P > 0.05$) in seedling populations were found between source treatments. The AMS treatment produced more ($P < 0.05$) EBT and a higher ($P < 0.05$) biomass than the LAN and LAN + S treatments in Year 2.

6.1.4.2 Grain yield

LAN + S achieved a higher ($P < 0.05$) yield than urea, urea + I and LAN in Year 1 at Langgewens M/W (Figure 6.1.7). During Year 2, LAN had a higher yield ($P < 0.05$) than urea (Figure 6.1.8).

Table 6.1.7 Seedling population (m^{-2}), number of EBT (m^{-2}) and biomass production (kg ha^{-1}) as influenced by fertiliser N sources at Langgewens M/W during Year 1 and 2 of the study.

N Source	Urea	Urea + I	AMS	LAN	LAN + S	CV (%)	LSD
Year 1							
Seedlings (m^{-2})	88.0 ^{a}	82.6 ^{a}	89.0 ^{a}	95.2 ^{a}	99.1 ^{a}	**13.4**	**18.8**
EBT (m^{-2})	235.8 ^{a}	230.0 ^{a}	241.9 ^{a}	257.1 ^{a}	241.0 ^{a}	**15.9**	**58.9**
Biomass (kg ha^{-1})	10458 ^{a}	11438 ^{a}	11292 ^{a}	10854 ^{a}	11375 ^{a}	**10.5**	**1792**
Year 2							
Seedlings (m^{-2})	92.9 ^{a}	90.8 ^{a}	87.8 ^{a}	94.3 ^{a}	84.1 ^{a}	**12.1**	**16.8**
EBT (m^{-2})	207.1 ^{ab}	200.8 ^{abc}	238.8 ^{a}	158.3 ^{c}	177.3 ^{bc}	**14.3**	**43.3**
Biomass (kg ha^{-1})	6042 ^{ab}	5771 ^{ab}	6479 ^{a}	5646 ^{b}	5313 ^{b}	**8.7**	**786**

Means without a common superscript letter in the same row indicate significant differences at a 5% level.

CV = Coefficient of variance

LSD = Least significant difference

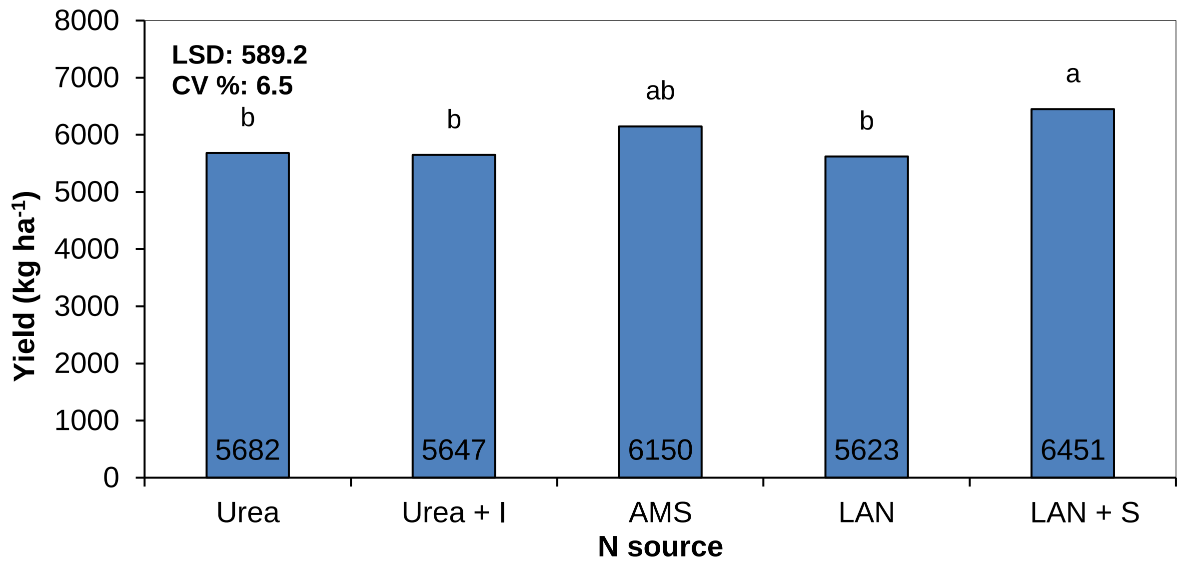


Figure 6.1.7 Grain yield (kg ha^{-1}) as influenced by fertiliser N source at Langgewens M/W (Year 1). LSD = Least significant difference ($P < 0.05$); CV = coefficient of variance. Means without a common letter above bars indicate significant differences at a 5% level.

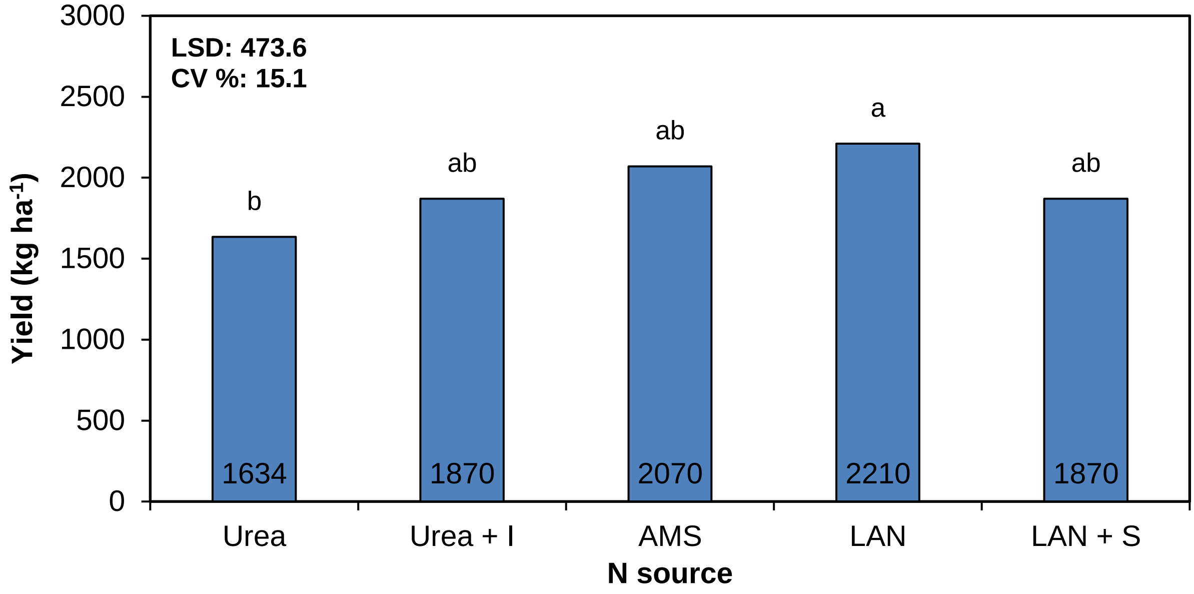


Figure 6.1.8 Grain yield (kg ha^{-1}) as influenced by fertiliser N source at Langgewens M/W (Year 2). LSD = Least significant difference (P < 0.05); CV = coefficient of variance. Means without a common letter above bars indicate significant differences at a 5% level.

6.1.4.3 Quality parameters

Table 6.1.8 shows that no differences (P > 0.05) in hectolitre mass were recorded in Year 1, whilst that of LAN was higher than urea in Year 2. No differences (P > 0.05) in harvest index between N source treatments occurred in Year 1 or 2 at the Langgewens wheat after medic site. The urea treatment resulted in grain with higher (P < 0.05) protein content (%) than urea + I and LAN in Year 1, while LAN + S had a higher (P < 0.05) protein content than LAN and urea in Year 2.

Table 6.1.8 Hectolitre mass, harvest index and protein content (%) as influenced by fertiliser N sources at Langgewens M/W during Year 1 and 2 of the study.

N Source	Urea	Urea + I	AMS	LAN	LAN + S	CV (%)	LSD
Year 1							
Hectolitre mass (g cm^{-3})	78.7 ^{a}	79.4 ^{a}	79.1 ^{a}	78.4 ^{a}	78.7 ^{a}	**1.1**	**1.4**
Harvest index	0.55 ^{a}	0.50 ^{a}	0.55 ^{a}	0.52 ^{a}	0.57 ^{a}	**9.7**	**0.08**
Protein content (%)	11.8 ^{a}	11.6 ^{bc}	11.8 ^{ab}	11.6 ^{c}	11.7 ^{abc}	**1.0**	**0.2**
Year 2							
Hectolitre mass (g cm^{-3})	76.7 ^{b}	77.3 ^{ab}	76.9 ^{ab}	77.5 ^{a}	77.3 ^{ab}	**0.6**	**0.7**
Harvest index	0.31 ^{a}	0.31 ^{a}	0.31 ^{a}	0.31 ^{a}	0.31 ^{a}	**16.8**	**0.09**
Protein content (%)	17.4 ^{b}	17.8 ^{ab}	17.7 ^{ab}	17.4 ^{b}	18.1 ^{a}	**2.1**	**0.6**

Means without a common superscript letter in the same row indicate significant differences at a 5% level.

CV = Coefficient of variance

LSD = Least significant difference

6.1.5 Langgewens C/W

6.1.5.1 Plant parameters

Seedling populations were not recorded in Year 1, due to poor establishment. In Year 2, no differences ($P > 0.05$) in seedling populations were recorded (Table 6.1.9). No differences ($P > 0.05$) in the number of EBT were recorded in Year 1 or 2. Urea + I treatment produced a higher ($P < 0.05$) biomass than the LAN treatment in Year 1 and no differences ($P > 0.05$) between treatments were recorded in Year 2.

6.1.5.2 Grain yield

As can be seen in Figure 6.1.9 and Figure 6.1.10, no differences ($P > 0.05$) in yield (kg ha^{-1}) were recorded between the N source treatments in either Year 1 or 2.

Table 6.1.9 Seedling population (m^{-2}), number of EBT (m^{-2}), biomass production (kg ha^{-1}) as influenced by fertiliser N sources at Langgewens C/W during Year 1 and 2 of the study.

N Source	Urea	Urea + I	AMS	LAN	LAN + S	CV (%)	LSD
Year 1							
Seedlings (m^{-2})	*	*	*	*	*	*	*
EBT (m^{-2})	210.6 ^{a}	227.3 ^{a}	221.9 ^{a}	199.8 ^{a}	251.5 ^{a}	**24.2**	**82.7**
Biomass (kg ha^{-1})	9458 ^{ab}	11722 ^{a}	11000 ^{ab}	8292 ^{b}	10271 ^{ab}	**19.9**	**3221**
Year 2							
Seedlings (m^{-2})	96.7 ^{a}	92.6 ^{a}	85.7 ^{a}	85.1 ^{a}	83.8 ^{a}	**12.2**	**16.7**
EBT (m^{-2})	195.2 ^{a}	186.9 ^{a}	212.9 ^{a}	189.4 ^{a}	172.3 ^{a}	**21.3**	**62.8**
Biomass (kg ha^{-1})	5834 ^{a}	6167 ^{a}	5896 ^{a}	5834 ^{a}	5459 ^{a}	**16.1**	**1445**

Means without a common superscript letter in the same row indicate significant differences at a 5% level.

CV = Coefficient of variance

LSD = Least significant difference

*missing values due to bad and uneven seedling populations during early season of Year 1.

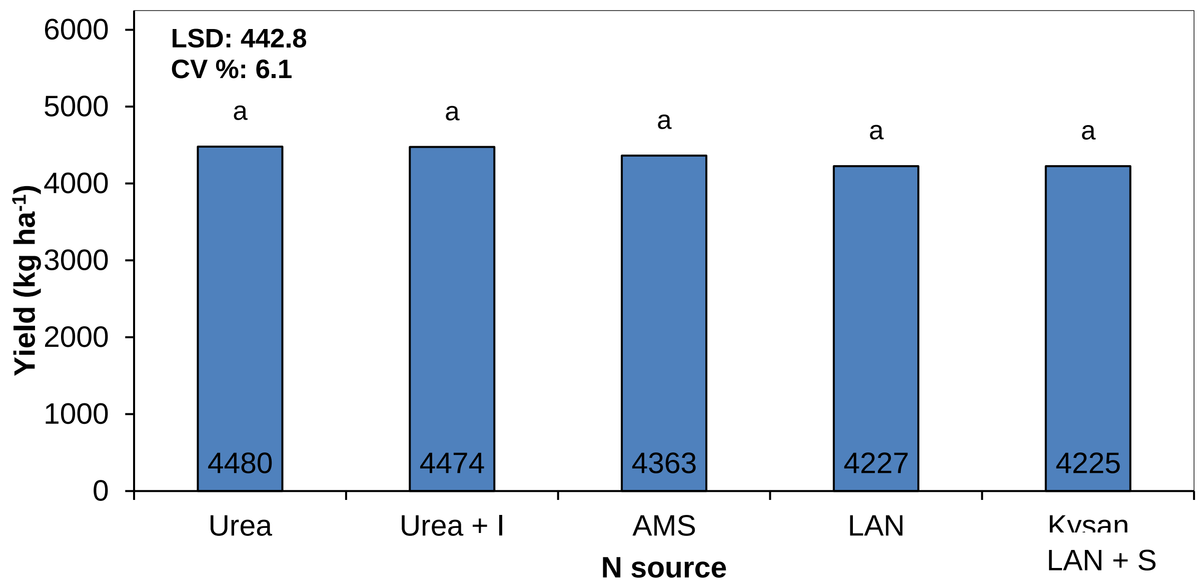


Figure 6.1.9 Grain yield (kg ha^{-1}) as influenced by fertiliser N source at Langgewens C/W (Year 1). LSD = Least significant difference ($P < 0.05$); CV = coefficient of variance. Means without a common letter above bars indicate significant differences at a 5% level.

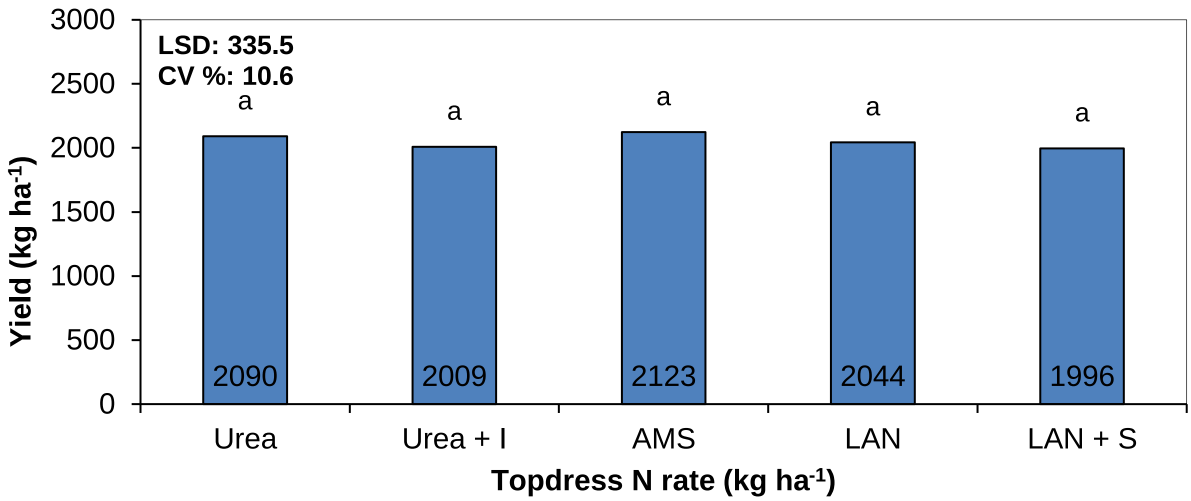


Figure 6.1.10 Grain yield (kg ha^{-1}) as influenced by fertiliser N source at Langgewens C/W (Year 2). LSD = Least significant difference (P < 0.05); CV = coefficient of variance. Means without a common letter above bars indicate significant differences at a 5% level.

6.1.5.3 Quality parameters

Urea and LAN + S had a higher (P < 0.05) hectolitre mass than AMS, whilst there were no differences (P > 0.05) in harvest index and protein content (%) for the different N sources in Year 1 (Table 6.1.10). During Year 2, no differences (P > 0.05) in hectolitre mass, harvest index or protein content were recorded for the different treatments.

Table 6.1.10 Hectolitre mass, harvest index and protein content (%) as influenced by fertiliser N sources at Langgewens C/W during Year 1 and 2 of the study.

	Year 1						
N Source	**Urea**	**Urea + I**	**AMS**	**LAN**	**LAN + S**	**CV (%)**	**LSD**
Hectolitre mass (g cm^{-3})	80.7 ^{a}	80.4 ^{ab}	80.0 ^{b}	80.5 ^{ab}	80.6 ^{a}	**0.4**	**0.5**
Harvest index	0.47 ^{a}	0.39 ^{a}	0.42 ^{a}	0.51 ^{a}	0.46 ^{a}	**17.7**	**0.14**
Protein content (%)	11.8 ^{a}	12.1 ^{a}	11.9 ^{a}	12.0 ^{a}	11.6 ^{a}	**3.0**	**0.6**
	Year 2						
Hectolitre mass (g cm^{-3})	76.2 ^{a}	76.0 ^{a}	76.8 ^{a}	76.9 ^{a}	76.6 ^{a}	**0.8**	**1.0**
Harvest index	0.37 ^{a}	0.34 ^{a}	0.36 ^{a}	0.35 ^{a}	0.38 ^{a}	**10.9**	**0.06**
Protein content (%)	17.1 ^{a}	16.8 ^{a}	16.7 ^{a}	17.2 ^{a}	17.0 ^{a}	**3.6**	**0.9**

Means without a common superscript letter in the same row indicate significant differences at a 5% level.

CV = Coefficient of variance

LSD = Least significant difference

6.1.6 Porterville M/W

6.1.6.1 Plant parameters

No differences (P > 0.05) in plant populations, the number of EBT and amount of biomass production between the different N sources were recorded for Year 1 or 2 (Table 6.1.11).

Table 6.1.11 Seedling population (m^{-2}), number of EBT (m^{-2}) and biomass production (kg ha^{-1}) as influenced by fertiliser N sources at Porterville M/W during Year 1 and 2 of the study.

N Source	Urea	Urea + I	AMS	LAN	LAN + S	CV (%)	LSD
Year 1							
Seedlings (m^{-2})	47.5 [a]	51.8 [a]	53.6 [a]	48.1 [a]	51.7 [a]	**17.8**	**13.9**
EBT (m^{-2})	247.1 [a]	258.3 [a]	229.7 [a]	246.0 [a]	234.2 [a]	**20.8**	**88.7**
Biomass (kg ha^{-1})	8750 [a]	10646 [a]	10500 [a]	9396 [a]	10271 [a]	**14.9**	**2274**
Year 2							
Seedlings (m^{-2})	68.5 [a]	70.0 [a]	72.7 [a]	70.4 [a]	59.9 [a]	**17.1**	**18.0**
EBT (m^{-2})	215.2 [a]	215.2 [a]	215.2 [a]	215.2 [a]	215.2 [a]	**13.3**	**40.1**
Biomass (kg ha^{-1})	5333 [a]	5230 [a]	5187 [a]	5375 [a]	5104 [a]	**10.6**	**860**

Means without a common superscript letter in the same row indicate significant differences at a 5% level.

CV = Coefficient of variance

LSD = Least significant difference

6.1.6.2 Grain yield

When wheat was fertilised with urea it had a higher (P < 0.05) yield than when fertilised with LAN + S in Year 1 (Figure 6.1.11). Only intermediate differences (P > 0.05) between the other source treatments were further recorded. No differences in yield were recorded between source treatments in Year 2 (Figure 6.1.12).

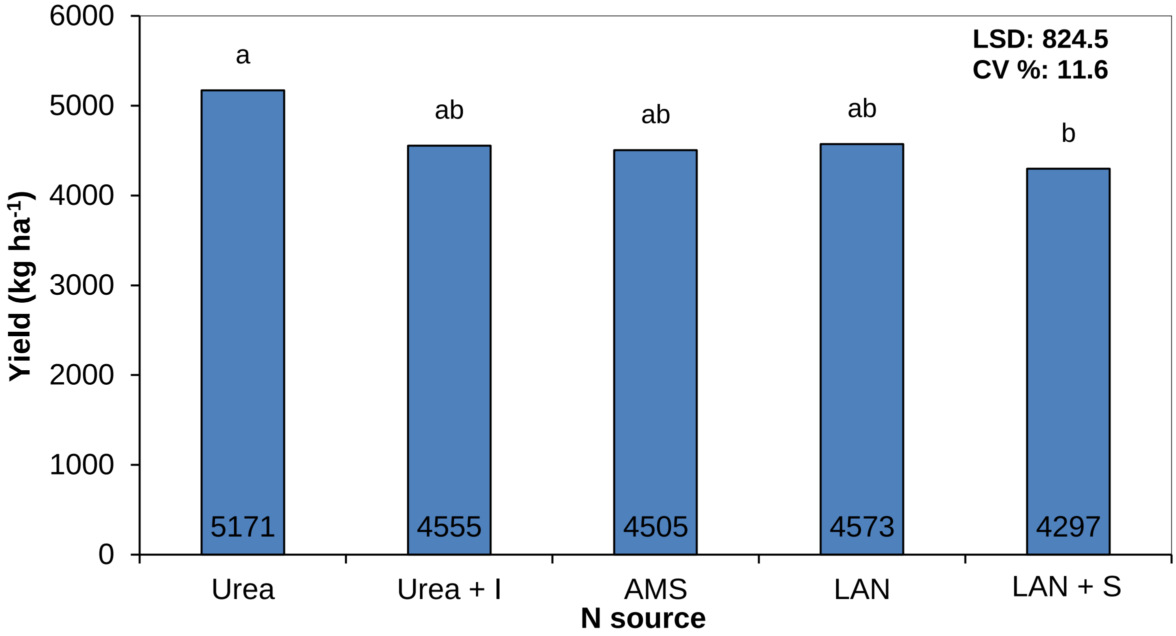


Figure 6.1.11 Grain yield (kg ha^{-1}) as influenced by fertiliser N source at Porterville M/W (Year 1). LSD = Least significant difference (P < 0.05); CV = coefficient of variance. Means without a common letter above bars indicate significant differences at a 5% level.

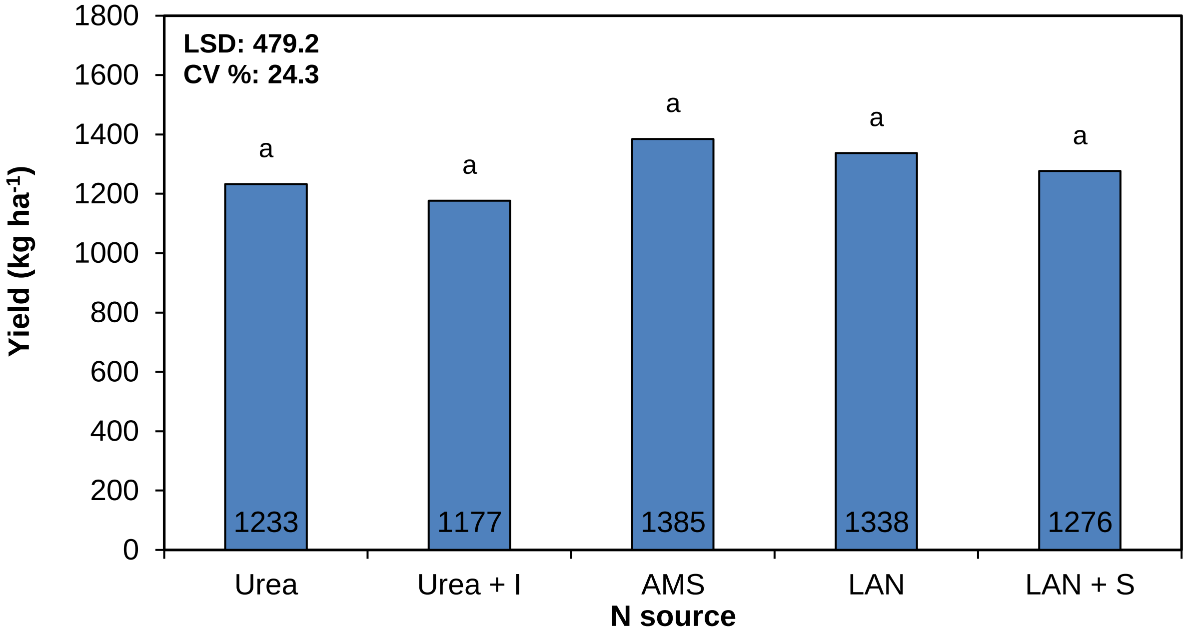


Figure 6.1.12 Grain yield (kg ha^{-1}) as influenced by fertiliser N source at Porterville M/W (Year 2). LSD = Least significant difference (P < 0.05); CV = coefficient of variance. Means without a common letter above bars indicate significant differences at a 5% level.

6.1.6.3 Quality parameters

No differences (P > 0.05) in hectolitre mass or grain protein content, as influenced by different N sources, were recorded for Year 1 at Porterville M/W (Table 6.1.12). Urea + I and AMS had a higher (P < 0.05) hectolitre mass than urea in Year 2. Apart from urea having a higher (P < 0.05) harvest index than LAN + S and urea + I, only intermediate differences (P > 0.05) were further recorded in Year 1 and no differences (P > 0.05) were recorded in Year 2. No differences (P > 0.05) in protein content were recorded in Year 2.

Table 6.1.12 Hectolitre mass, harvest index and protein content (%) as influenced by fertiliser N sources at Porterville M/W during Year 1 and 2 of the study.

	Year 1						
N Source	**Urea**	**Urea + I**	**AMS**	**LAN**	**LAN + S**	**CV (%)**	**LSD**
Hectolitre mass (g cm^{-3})	78.3 ^{a}	76.8 ^{a}	77.1 ^{a}	77.3 ^{a}	77.5 ^{a}	**1.8**	**2.1**
Harvest index	0.63 ^{a}	0.44 ^{b}	0.44 ^{ab}	0.49 ^{ab}	0.42 ^{b}	**25.8**	**0.19**
Protein content (%)	12.2 ^{a}	12.7 ^{a}	12.4 ^{a}	12.5 ^{a}	12.7 ^{a}	**4.1**	**0.8**
	Year 2						
Hectolitre mass (g cm^{-3})	75.6 ^{b}	76.8 ^{a}	76.7 ^{a}	76.1 ^{ab}	76.2 ^{ab}	**0.7**	**0.9**
Harvest index	0.23 ^{a}	0.23 ^{a}	0.26 ^{a}	0.25 ^{a}	0.26 ^{a}	**17.5**	**0.07**
Protein content (%)	18.2 ^{a}	18.1 ^{a}	17.6 ^{a}	18.2 ^{a}	18.5 ^{a}	**4.0**	**2.0**

Means without a common superscript letter in the same row indicate significant differences at a 5% level.

CV = Coefficient of variance

LSD = Least significant difference

6.1.7 Porterville C/W

6.1.7.1 Plant parameters

Seedling populations and EBT did not differ (P > 0.05) during either Year 1 or 2. LAN + S produced a higher (P < 0.05) biomass than the LAN treatment in Year 1, but no differences (P > 0.05) in biomass were recorded in Year 2 (Table 6.1.13).

6.1.7.2 Grain yield

As presented in Figure 6.1.13, the AMS source treatment achieved a higher (P < 0.05) yield than that of the LAN treatment in Year 1. No differences (P > 0.05) in yield, as influenced by N source treatment, were recorded in Year 2 (Figure 6.1.14).

Table 6.1.13 Seedling population (m^{-2}), number of EBT (m^{-2}) and biomass production (kg ha^{-1}) as influenced by fertiliser N sources at Porterville C/W during Year 1 and 2 of the study.

N Source	Urea	Urea + I	AMS	LAN	LAN + S	CV (%)	LSD
Year 1							
Seedlings (m^{-2})	85.1 ^{a}	77.5 ^{a}	71.3 ^{a}	88.1 ^{a}	59.6 ^{a}	**22.9**	**29.2**
EBT (m^{-2})	237.9 ^{a}	230.8 ^{a}	217.5 ^{a}	213.3 ^{a}	231.1 ^{a}	**16.5**	**62.6**
Biomass (kg ha^{-1})	8167 ^{ab}	8500 ^{ab}	8500 ^{ab}	7042 ^{b}	8917 ^{a}	**11.6**	**1594**
Year 2							
Seedlings (m^{-2})	65.0 ^{a}	66.8 ^{a}	75.5 ^{a}	65.7 ^{a}	76.4 ^{a}	**16.0**	**17.3**
EBT (m^{-2})	172.3 ^{a}	156.9 ^{a}	181.9 ^{a}	172.1 ^{a}	176.3 ^{a}	**14.5**	**38.3**
Biomass (kg ha^{-1})	3750 ^{a}	3417 ^{a}	3812 ^{a}	3604 ^{a}	4042 ^{a}	**21.8**	**1249**

Means without a common superscript letter in the same row indicate significant differences at a 5% level.

CV = Coefficient of variance

LSD = Least significant difference

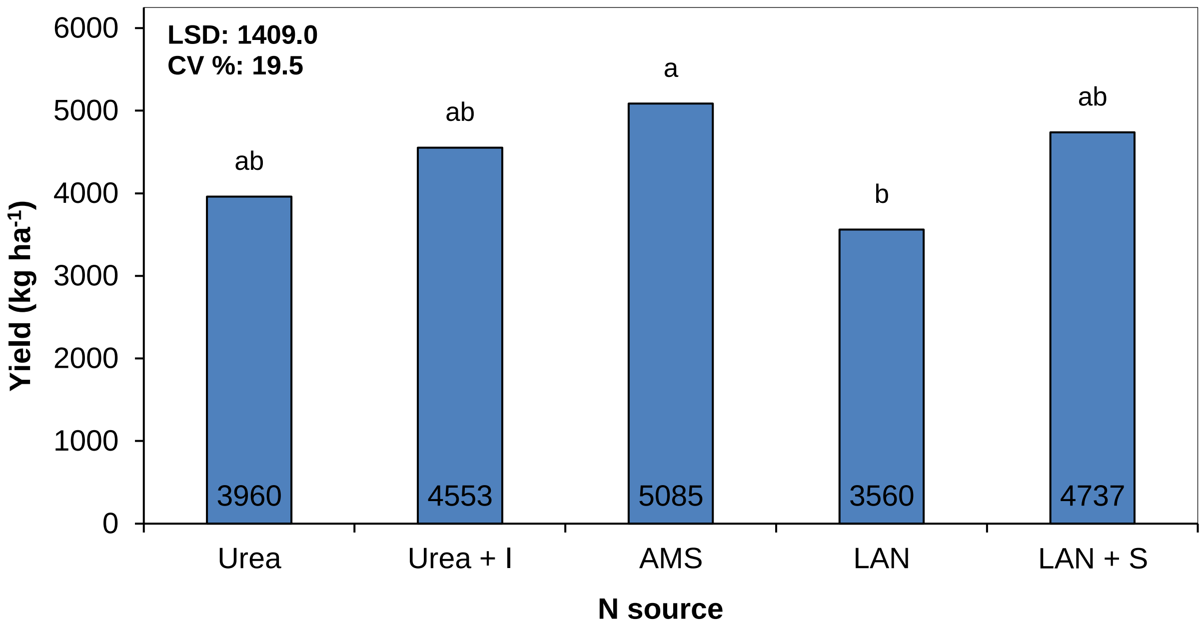


Figure 6.1.13 Grain yield (kg ha^{-1}) as influenced by fertiliser N source at Porterville C/W (Year 1). LSD = Least significant difference ($P < 0.05$); CV = coefficient of variance. Means without a common letter above bars indicate significant differences at a 5% level.

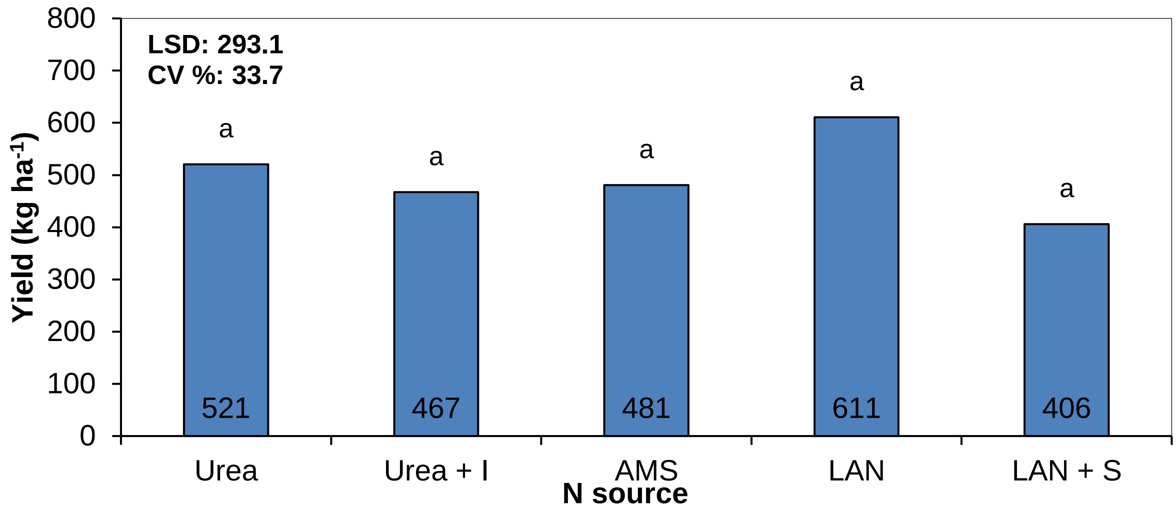


Figure 6.1.14 Grain yield (kg ha^{-1}) as influenced by fertiliser N source at Porterville C/W (Year 2). LSD = Least significant difference (P < 0.05); CV = coefficient of variance. Means without a common letter above bars indicate significant differences at a 5% level.

6.1.7.3 Quality parameters

No differences (P > 0.05) in hectolitre mass and harvest index, as influenced by N source treatment, were found in Year 1 or 2 at Porterville C/W (Table 6.1.14). Source treatments had no effect (P > 0.05) on protein content in Year 2.

Table 6.1.14 Hectolitre mass, harvest index and protein content (%) as influenced by fertiliser N sources at Porterville C/W during Year 1 and 2 of the study.

				Year 1			
N Source	**Urea**	**Urea + I**	**AMS**	**LAN**	**LAN + S**	**CV (%)**	**LSD**
Hectolitre mass (g cm^{-3})	81.0 ^{a}	80.6 ^{a}	80.5 ^{a}	81.0 ^{a}	80.5 ^{a}	**0.7**	**0.9**
Harvest index	47.46 ^{a}	51.54 ^{a}	49.22 ^{a}	50.77 ^{a}	44.70 ^{a}	**23.4**	**17.58**
Protein content (%)	*	*	*	*	*	*****	*****
				Year 2			
Hectolitre mass (g cm^{-3})	73.6 ^{a}	73.0 ^{a}	73.9 ^{a}	73.8 ^{a}	73.0 ^{a}	**2.0**	**3.5**
Harvest index	0.14 ^{a}	0.14 ^{a}	0.19 ^{a}	0.17 ^{a}	0.14 ^{a}	**41.4**	**0.10**
Protein content (%)	18.7 ^{a}	19.2 ^{a}	18.8 ^{a}	18.6 ^{a}	18.9 ^{a}	**4.4**	**1.3**

Means without a common superscript letter in the same row indicate significant differences at a 5% level.

CV = Coefficient of variance

LSD = Least significant difference

*Protein content samples were taken, prepared and sent away for sampling, but got lost in lab

6.1.8 Darling M/W

6.1.8.1 Plant parameters

No differences (P > 0.05) in the seedling population were recorded in Year 1 or 2 (Table 6.1.15). Urea + I produced more (P < 0.05) EBT than LAN in Year 1, whilst the amount of biomass produced by the different N sources did not differ (P > 0.05) in Year 1 or 2.

Table 6.1.15 Seedling population (m^{-2}), number of EBT (m^{-2}) and biomass production (kg ha^{-1}) as influenced by fertiliser N sources at Darling M/W during Year 1 and 2 of the study.

N Source	Urea	Urea + I	AMS	LAN	LAN + S	CV (%)	LSD
			Year 1				
Seedlings (m^{-2})	156.9 ^{a}	153.5 ^{a}	140.0 ^{a}	143.6 ^{a}	148.2 ^{a}	**7.4**	**16.8**
EBT (m^{-2})	270.0 ^{ab}	292.9 ^{a}	253.6 ^{ab}	233.8 ^{b}	249.2 ^{ab}	**11.5**	**46.9**
Biomass (kg ha^{-1})	5313 ^{a}	6375 ^{a}	4861 ^{a}	5146 ^{a}	5917 ^{a}	**14.3**	**1669**
			Year 2				
Seedlings (m^{-2})	74.7 ^{a}	93.6 ^{a}	77.8 ^{a}	78.6 ^{a}	79.5 ^{a}	**20.7**	**46.5**
EBT (m^{-2})						**19.2**	**0**
Biomass (kg ha^{-1})	3584 ^{a}	3250 ^{a}	3167 ^{a}	3250 ^{a}	3625 ^{a}	**12.2**	**1143**

Means without a common superscript letter in the same row indicate significant differences at a 5% level.

CV = Coefficient of variance

LSD = Least significant difference

6.1.8.2 Grain yield

In Year 1 at Darling M/W, urea + I produced a higher (P < 0.05) yield than AMS, LAN and LAN + S (Figure 6.1.15). As shown in Figure 6.1.16, no differences (P > 0.05) in yield were recorded between N source treatments in Year 2.

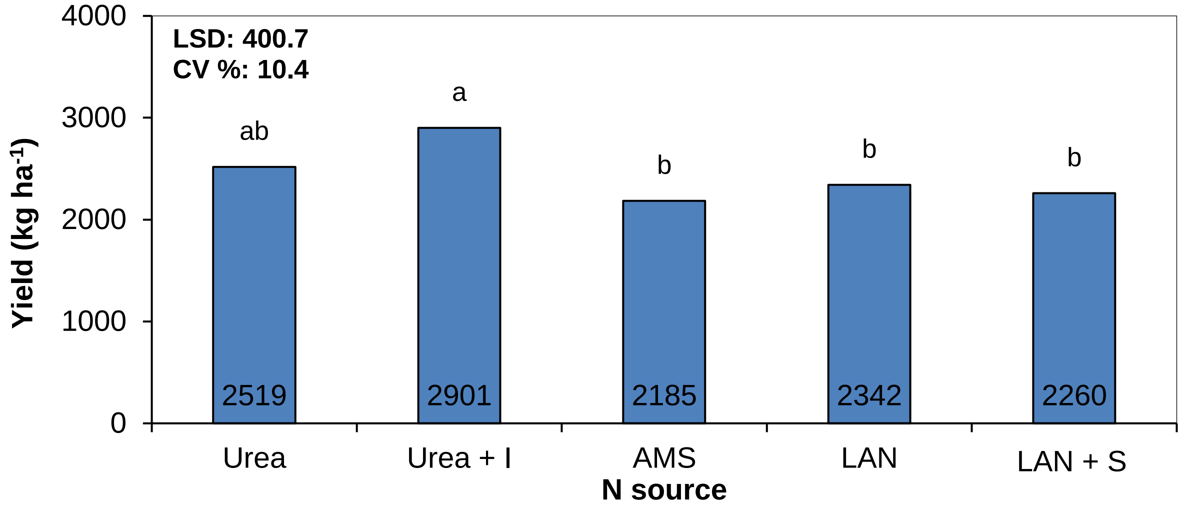


Figure 6.1.15 Grain yield (kg ha^{-1}) as influenced by fertiliser N source at Darling M/W (Year 1). LSD = Least significant difference ($P < 0.05$); CV = coefficient of variance. Means without a common letter above bars indicate significant differences at a 5% level.

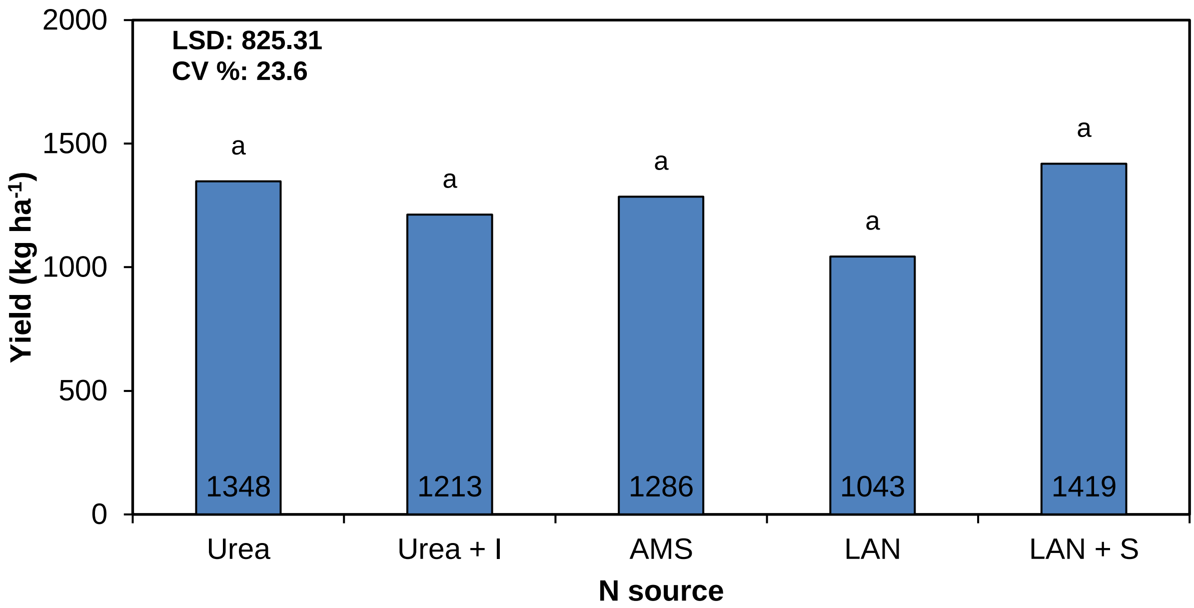


Figure 6.1.16 Grain yield (kg ha^{-1}) as influenced by fertiliser N source at Darling M/W (Year 2). LSD = Least significant difference ($P < 0.05$); CV = coefficient of variance. Means without a common letter above bars indicate significant differences at a 5% level.

6.1.8.3 Quality parameters

During Year 1 and 2 at Darling M/W, N sources did not lead to any differences ($P > 0.05$) in either hectolitre mass, harvest index or protein content (Table 6.1.16).

Table 6.1.16 Hectolitre mass, harvest index and protein content (%) as influenced by fertiliser N sources at Darling M/W during Year 1 and 2 of the study.

N Source	Urea	Urea + I	AMS	LAN	LAN + S	CV (%)	LSD
			Year 1				
Hectolitre mass (g cm^{-3})	75.7 ^{a}	75.7 ^{a}	76.8 ^{a}	77.0 ^{a}	76.5 ^{a}	**2.1**	**2.4**
Harvest index	0.48 ^{a}	0.48 ^{a}	0.46 ^{a}	0.46 ^{a}	0.40 ^{a}	**13.9**	**0.10**
Protein content (%)	13.1 ^{a}	12.7 ^{a}	12.2 ^{a}	12.5 ^{a}	12.5 ^{a}	**3.6**	**0.7**
			Year 2				
Hectolitre mass (g cm^{-3})	74.1 ^{a}	73.7 ^{a}	74.8 ^{a}	73.6 ^{a}	75.0 ^{a}	**1.3**	**2.6**
Harvest index	0.38 ^{a}	0.37 ^{a}	0.42 ^{a}	0.31 ^{a}	0.40 ^{a}	**18.8**	**0.19**
Protein content (%)	14.9 ^{a}	16.0 ^{a}	14.5 ^{a}	15.9 ^{a}	14.8 ^{a}	**6.6**	**2.8**

Means without a common superscript letter in the same row indicate significant differences at a 5% level.

CV = Coefficient of variance

LSD = Least significant difference

6.1.9 Darling C/W

6.1.9.1 Plant parameters

As seen in Table 6.1.17, no differences (P > 0.05) in seedling population, number of EBT and biomass production between treatments were recorded for Year 1 or 2.

6.1.9.2 Grain yield

No differences (P > 0.05) in yield, as influenced by different N sources, were recorded for either Year 1 or 2 (Figure 6.1.17 and Figure 6.1.18).

Table 6.1.17 Seedling population (m^{-2}), number of EBT (m^{-2}) and biomass production (kg ha^{-1}) as influenced by fertiliser N sources at Darling C/W during Year 1 and 2 of the study.

N Source	Urea	Urea + I	AMS	LAN	LAN + S	CV (%)	LSD
Year 1							
Seedlings (m^{-2})	141.9 ^{a}	139.6 ^{a}	144.4 ^{a}	127.5 ^{a}	135.7 ^{a}	**10.8**	**22.7**
EBT (m^{-2})	263.8 ^{a}	235.4 ^{a}	301.9 ^{a}	222.5 ^{a}	244.2 ^{a}	**29.5**	**116.6**
Biomass (kg ha^{-1})	5583 ^{a}	5479 ^{a}	6556 ^{a}	5667 ^{a}	4778 ^{a}	**30.3**	**2643**
Year 2							
Seedlings (m^{-2})	117.6 ^{a}	122.0 ^{a}	129.3 ^{a}	127.1 ^{a}	117.8 ^{a}	**6.5**	**12.3**
EBT (m^{-2})	192.3 ^{a}	149.8 ^{a}	175.6 ^{a}	162.1 ^{a}	175.2 ^{a}	**16.7**	**43.9**
Biomass (kg ha^{-1})	2896 ^{a}	2542 ^{a}	3104 ^{a}	3063 ^{a}	2667 ^{a}	**15.9**	**698**

Means without a common superscript letter in the same row indicate significant differences at a 5% level.

CV = Coefficient of variance

LSD = Least significant difference

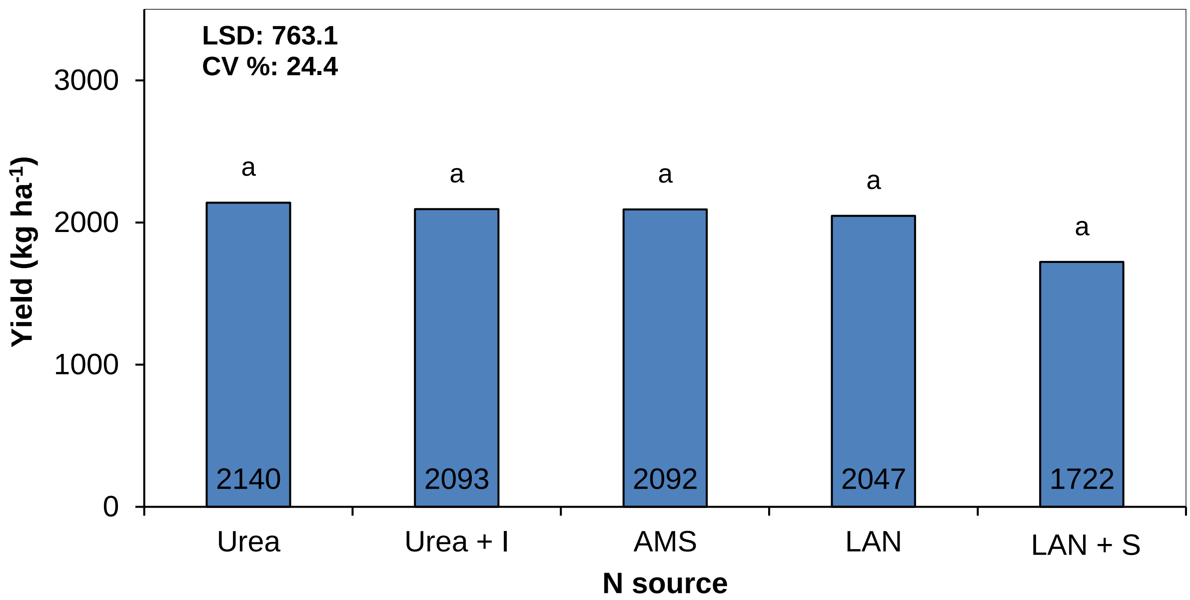


Figure 6.1.17 Grain yield (kg ha^{-1}) as influenced by fertiliser N source at Darling C/W (Year 1). LSD = Least significant difference ($P < 0.05$); CV = coefficient of variance. Means without a common letter above bars indicate significant differences at a 5% level.

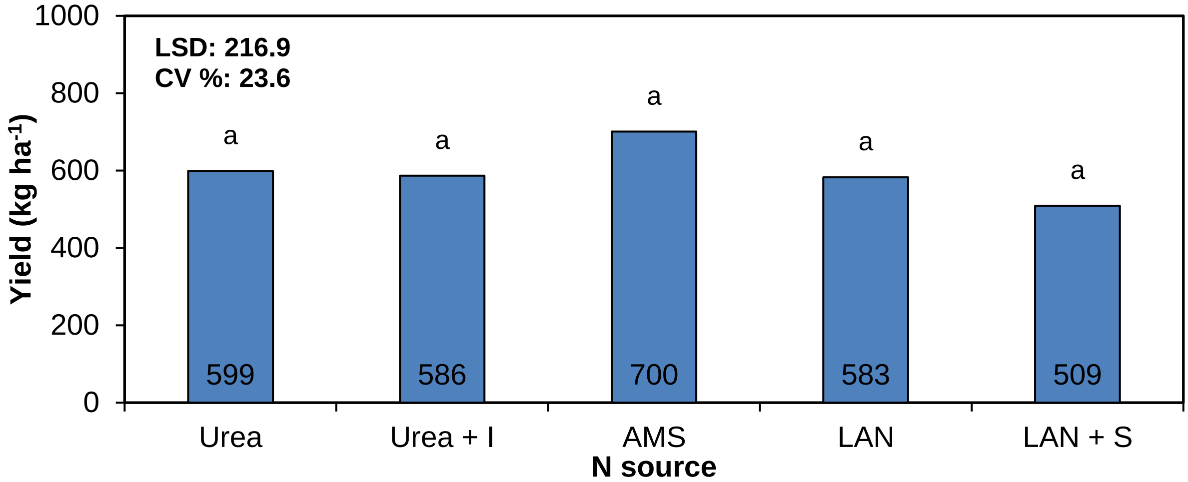


Figure 6.1.18 Grain yield (kg ha^{-1}) as influenced by fertiliser N source at Darling C/W (Year 2). LSD = Least significant difference ($P < 0.05$); CV = coefficient of variance. Means without a common letter above bars indicate significant differences at a 5% level.

6.1.9.3 Quality parameters

LAN + S produced higher ($P < 0.05$) hectolitre mass than urea in Year 1 (Table 6.1.18). The AMS treatment had a lower ($P < 0.05$) harvest index than all other treatments. The grain protein content (%) of the urea source treatment was higher ($P < 0.05$) than that of LAN + S, but did not differ ($P > 0.05$) from that of urea + I, AMS or LAN in Year 1. In Year 2, urea produced a lower ($P < 0.05$) hectolitre mass than urea + I and AMS. No differences ($P > 0.05$) in harvest index and protein content were recorded in Year 2.

Table 6.1.18 Hectolitre mass, harvest index and protein content (%) as influenced by fertiliser N sources at Darling C/W during Year 1 and 2 of the study.

	Year 1						
N Source	**Urea**	**Urea + I**	**AMS**	**LAN**	**LAN + S**	**CV (%)**	**LSD**
Hectolitre mass (g cm^{-3})	71.9 ^{b}	73.8 ^{ab}	73.4 ^{ab}	74.7 ^{ab}	75.3 ^{a}	**2.6**	**2.9**
Harvest index	0.39 ^{a}	0.38 ^{a}	0.26 ^{b}	0.36 ^{a}	0.36 ^{a}	**12.5**	**0.07**
Protein content (%)	13.9 ^{a}	13.0 ^{ab}	13.0 ^{ab}	12.8 ^{ab}	12.4 ^{b}	**6.4**	**1.3**
	Year 2						
Hectolitre mass (g cm^{-3})	75.6 ^{b}	76.8 ^{a}	76.7 ^{a}	76.1 ^{ab}	76.2 ^{ab}	**0.7**	**0.9**
Harvest index	0.18 ^{a}	0.22 ^{a}	0.21 ^{a}	0.20 ^{a}	0.25 ^{a}	**31.0**	**0.10**
Protein content (%)	19.4 ^{a}	19.4 ^{a}	19.3 ^{a}	19.3 ^{a}	19.7 ^{a}	**2.2**	**0.7**

Means without a common superscript letter in the same row indicate significant differences at a 5% level.
CV = Coefficient of variance
LSD = Least significant difference

6.2 Discussion

6.2.1 Plant parameters

Contrary to findings by Abbate et al. (1995), Fischer (2007) and Salvagiotti and Miralles (2008), source treatments, containing both N and S, did not consistently lead to an increase in the number of EBT produced at any of the sites during both years. Almost no differences ($P > 0.05$) in the number of EBT, as influenced by source treatment, were recorded at any of the sites.

Salvagiotti and Miralles (2008) found that the addition of S to an N fertiliser programme led to higher biomass of the wheat crop; however, this was not the case for most of the sites during both years, where no differences ($P > 0.05$) in biomass were recorded with the addition of S. During Year 1, however, LAN + S achieved a lower biomass than LAN alone at Tygerhoek, which directly contradicts the findings of Salvagiotti and Miralles (2008). The S concentration present in the soil at Tygerhoek in Year 1 was relatively low, which may explain why LAN + S failed to produce a higher biomass than LAN alone. Porterville C/W was the only site during both years that recorded similar results to that of Salvagiotti and Miralles (2008) where LAN + S achieved a higher biomass than LAN alone.

6.2.2 Grain yield

The S concentration in the soils of Tygerhoek, Caledon and both Darling sites were sub-optimal during Year 1 (Table 3.4). Crops grown in soils with a suboptimal S content normally show a positive response to S fertilisation (Jackson, 2006), but this was not the case at the abovementioned sites where the fertiliser sources with added S did not outperform the other source treatments as expected. Salvagiotti et al. (2009) and Salvagiotti and Miralles (2008) recorded higher wheat yields with the addition of S to the fertiliser programme. The only sites that showed an increase in yield with the addition of S was the Langgewens M/W site in Year 1 where LAN + S achieved a higher yield than LAN, and Porterville C/W in Year 1, where the yield of AMS was higher than that of LAN. Both sites, where a yield response to S containing sources were recorded, had adequate levels of S present in the soil (Table 3.4). The abovementioned S-containing sources had a higher biomass production than the sources without S. This could have influenced the production of higher yielding wheat plants, which is in agreement with Salvagiotti and Miralles (2008) that found that S enhanced grain yield response by producing plants with a greater leaf area index.

None of the sites, during either of the years, displayed any differences ($P > 0.05$) in yield between the urea + I and urea treatments. This same result has previously been recorded by Mohammed et al. (2016). Wang et al. (2015) also found that an ammonium and nitrate fertiliser mix achieved greater yields than that of ammonium alone. The yields of the AMS treatment compared to the LAN + S treatment were contradictory as the Riversdale (Year 2) and Porterville C/W (Year 1) had higher yields for AMS versus LAN + S, whilst Riversdale (Year 1) and Darling M/W (Year 1) showed an increased yield for LAN + S versus AMS; thus, contradicting Wang et al. (2015).

At most of the sites during both years, however, no differences ($P > 0.05$) in yield were recorded between N source treatments.

6.2.3 Quality parameters

The addition of S to N sources regarding its effect on the harvest index of wheat has shown conflicting results in the past. Giller et al. (2004), Ladha et al. (2005) and Salvagiotti and Miralles (2008) found that S had no effect on the harvest index, while Cassman et al. (1992) and Ehdaie and Waines (2001) found that S addition increased the harvest index. In this study the results indicated that the addition of S to an N fertiliser programme had no effect on the harvest index of wheat.

Apart from differences ($P < 0.05$) at Riversdale, Langgewens C/W and Darling C/W, no consistent differences ($P > 0.05$) in hectolitre mass were recorded during Year 1. In agreement with the findings of Mohammed et al. (2016), no differences in protein content were recorded between the urea + I and urea treatments at any of the sites in Year 1. In Year 2, only the Tygerhoek site had a higher ($P < 0.05$) protein content in the urea + I treatment than in urea alone. None of the treatments in Year 1, showed an increase in protein content in response to additional S. This is contradictory to the findings of Jackson (2006). In Year 2, however, the LAN + S treatment at Langgewens M/W had a higher ($P < 0.05$) protein content than that of the LAN treatment, indicating the potential of S to increase protein content. No differences ($P > 0.05$) in protein content were however recorded at most of the sites between source treatments in Year 1 or 2.

The use of different N sources had no profound effect on the yield and quality of dryland wheat produced in this study. This indicates that the optimal N source for wheat production might be the cheapest and most accessible one, which, under the same conditions that prevailed during this study, will be urea.

7 General discussion

There is an optimum planting time for a wheat crop, depending on location and climate (Jackson et al., 1990). Delaying the time of planting past optimal may reduce wheat yield (Anderson and Smith, 1990). Planting earlier may also be a good mitigation tool against excessive nitrate leaching (Addiscott et al., 1991; Ehdaie and Waines, 2001), thus preventing the total soil mineral N content of the soil to reach sub-optimal levels. During Year 2 of the study, planting dates were later than optimal at the different sites (Table 3.4), and that might have had a negative impact on crop development, soil mineral N content and yield. Considering that the optimal planting date in the Western Cape is from late April to early June, the fact that the first substantial rains in Year 1 and two only came in mid-June (Section 3.1) could have also led to lower seedling populations.

The increase ($P < 0.05$) in soil mineral N content with increasing topdress N rates, was expected to carry over and reflect in crop yields as well as in plant and quality parameter data at the end of the season. However, this was not the case in the current study. Bundy and Malone (1988), Fan et al. (2003) and Ferguson et al. (2002) previously found a strong correlation between soil mineral N and crop yield. This strongly supports the theory that the climatic conditions that prevailed during this study could have influenced crop yields to such an extent that the differences in soil mineral N might not have influenced crop yields as expected. This could potentially mean that in the current study, the rotational effect of the preceding medic crop could have been lost at excessive N application rates. This is an unfortunate finding as it has previously been found that soil mineral N is more valuable to crop development than fertiliser N (Miransari and Mackenzie, 2011).

The increase ($P < 0.05$) in the number of EBT, with increasing topdress N rates, at the Tygerhoek, Langgewens C/W and both Darling sites during Year 1, were expected to reflect in crop yields. However, this was not always the case. This disagrees with Brown et al. (2005) and Norwood (2000), who previously found that a higher number of EBT led to higher yields.

Maximum yields, where no further differences ($P > 0.05$) were recorded, were at total fertiliser N rates as low as 0 to 25 kg N ha^{-1}. At these fertiliser N rates, the NUE of the wheat crops were very high for most sites, falling in the range of 80 to above 100%. This is higher than the results recorded in a study by Halvorson et al. (2004) who found NUE levels of 56% at the maximum yielding N rates. There were no clear differences seen in yield as affected by the different crop rotations. This tendency was also found by López-Bellido and López-Bellido (2001).

8 Conclusions and recommendations

8.1 Synopsis

The Western Cape has a typical Mediterranean-type climate with most of the annual rainfall occurring during the cool winter months (June- August). The systems are mostly based on wheat planted in rotation with other crops that have adapted to the climate, i.e. lucerne (*Medicago sativa*), annual medics (*M. trancatula* and *M. polymorpha*), canola (*Brassica napus*), barley (*Hordeum vulgare*) and oats (*Avena sativa*). Because of the profitability associated with wheat production, wheat in South Africa used to be mainly produced in monoculture systems, ensuring the financial benefit of a cash crop every year. This practice has led to nutrient depletion of soils, the development of herbicide resistant weeds (ryegrass (*Lolium rigidum*) and the consequent reduction in wheat yields (Basson et al., 2017). Producers adopted crop rotation systems and minimum-tillage in an attempt to rectify the issues associated with wheat monoculture systems (Basson et al., 2017). Hence the drive toward conservation agriculture, especially in the Western Cape, started.

Nitrogen is one of the most limiting nutrients to crop growth (Provin and Hossner, 2001; Zhu et al., 2013), hence the need to supply adequate amounts of N (neccesary to ensure optimal crop growth) arised (Jansson and Persson, 1982; Shober, 2015; Sinclair et al., 1989). However, this N requirement has led to an increasing trend in N fertiliser usage worldwide, with 80 million tons of N being used annually (Gibbon, 2012). The fertiliser usage in South Africa alone has risen from 1.2 million tons in 1960, to 2.2 million tons in 2017 (FERTASA, 2016a). When wheat is produced from monoculture systems, soils generally contain insufficient amounts of residual N; therefore, the crop is entirely dependant on the application of N fertilisers. Labuschagne and Langenhoven (2012) stated that producers can save up to 50% on N fertiliser costs when rotating wheat with annual medics.

Worldwide, the NUE of cereal crops averages at 33% (Grahmann et al., 2014) which is a pressing issue as the EU Nitrogen Expert Panel (2015) considers NUE within the 15 - 44% range too low. This brings forth the need to establish effective N management programmes and consequently limit environmental impacts of crop production (Jansson and Persson, 1982; Shober, 2015; Sinclair et al., 1989). The growing global population demands to be fed and this burden drives the need for an increase of 50 to 70% in cereal production (Ladha et al., 2005). Improving the NUE by understanding the balance of N supply and crop demand critical growth stages of wheat might be a step in the right direction to ensure optimal N usage while simultaneously limiting N losses to the environment.

Early applications of N fertiliser, i.e. until the booting phase, generally leads to increases in grain yield (Labuschagne and Langenhoven, 2012), while N application post-anthesis can potentially ensure optimal grain protein contents (Bly and Woodard, 2003; Brown and Petrie, 2006; Rawluk et al., 2000). A wheat producer needs to supply optimal amounts of N at early growth stages to ensure that the yield potential is reached while maintaining N fertilisation at later growth stages, thus keeping grain protein intact. Applying N fertilisers in a two-way split where 20 to 30% is applied at planting and the rest at topdress (at stem elongation), is considered general practice in ensuring optimal yields. The addition of soluble urea or urea ammonium nitrate (UAN) post-anthesis may be beneficial in ensuring higher grain protein contents. The effect of post-anthesis foliar N applications on the yield and grain protein content of wheat is relatively untested in the Western Cape and this study could be valuable in assessing whether foliar N applications are feasible.

When a N fertiliser programme is developed, a decision should be made as to which N source to use. The form of N, N concentration (%), release mechanism and additional nutrients added to the fertiliser mix are important factors to consider. For instance, certain sources like ammonium sulphate (AMS) and limestone ammonium sulphate with added sulphur (LAN + S) contain both N and sulphur (S) in their composition. Salvagiotti et al. (2009) found that the additon of S to a fertiliser's composition might lead to higher uptake of N, which may potentially improve crop yields and grain protein (Jones and Olson-Rutz, 2012).

Nitrogen losses from soil by way of leaching may occur if over-fertilisation takes place (Alva et al., 2006; Cassman et al., 2003; Salvagiotti et al., 2009). The climate and soil characteristics of a specific area also play an important role in N loss dynamics from cultivated fields. For instance, leaching losses from the shallow soils of the Western Cape present a pressing issue in terms of N application and environmental pollution. Labuschagne and Langenhoven (2012) found that winter rains can cause N losses of up to 60%. Hence, the importance for soil mineral N tests, determining leachable nitrate-N and making fertiliser recommendations accordingly, arises.

Certain physical, chemical and biological soil properties were changed after implementation of conservation agriculture for a number of years (Grahmann et al., 2014). As soil characteristics influence the behaviour of both applied and residual N, it becomes a necessity to adjust N fertilisation. Current N fertilisation programmes, especially in the Western Cape, were developed for conventional cropping systems involving soil tillage. Since there is a build-up of soil organic matter in the minimum-tillage systems, and a subsequent higher potentially mineralisable N content in soils, it is expected that the current guidelines overestimate the N fertiliser need by crops. Therefore, the rationale for re-evaluating the fertiliser guidelines exists.

The aim of this study was to do a complete analysis of the effect that different preceding crops, topdress N rates, sources of N, and timing of N application would have on the yield, yield components and protein content of wheat, whilst monitoring the effect of different topdress N rates on the soil mineral N concentration throughout the growing season.

8.1.1 Objective 1: To determine the effect of different fertiliser rates on the grain yield, selected yield components, quality parameters and N use efficiency of the wheat crop.

Increasing topdress N rates had a less profound effect on crop yields than expected, where most of the sites in both years showed no increase ($P > 0.05$) in yield with increasing topdress N rate, even from topdress N rates as low as 0 kg N ha^{-1}. In Year 1, four of the nine research sites recorded an increase ($P < 0.05$) in the number of ear bearing tillers (EBT) with increasing topdress N rates. The other five research sites in Year 1 and all of the research sites in Year 2 showed no response ($P > 0.05$) in the number of EBT, as influenced by increasing topdress N rates. Biomass production was not influenced by topdress N rates, and little to no differences ($P > 0.05$) were recorded at all the research sites during both Year 1 and 2.

A decrease ($P < 0.05$) in hectolitre mass with increasing topdress N rates were recorded at four of the research sites in Year 1 and five in Year 2. An increase ($P < 0.05$) in grain protein content with the increasing topdress N rates was recorded at all the research sites in Year 1 and at four of the nine in Year 2. Harvest indices were not consistently influenced by topdress N rates during either of the years. Increasing topdress N rates lead to more ($P < 0.05$) N being taken up in the biomass at only two of the nine research sites during both Year 1 and 2, which indicates that contrary to what was expected, topdress N rates had little effect on biomass N.

The NUE of wheat was negatively influenced by increasing topdress N rates in both years of this study. This is indicative to a certain level of over fertilisation, mostly at topdress N rates of 50 kg N ha^{-1} and lower.

8.1.2 Objective 2: To determine the effect of a late-season foliar N application, in the form of urea ammonium nitrate (UAN), on the yield and grain protein content of the wheat crop.

Late-season foliar N application in the form of UAN failed to consistently increase crop yields at any of the research sites during Year 1 and only at two of the nine sites in Year 2. This was correspondent with previous studies and might indicate that the wheat crop at the two sites, where yield increases were recorded, were N deficient. The late-season foliar N application was expected to increase the protein content of wheat. This was the case at three of the nine sites during Year 1, two of which are situated in the southern Cape region. At the other six sites in Year 1 and all of the sites in Year 2, foliar N applications failed to increase ($P > 0.05$) protein contents of the wheat crop.

8.1.3 Objective 3: To test the effect of different N sources on crop growth, yield and quality of wheat.

It was expected that the sources containing additional S or urease inhibiting bacteria would lead to increased yields and quality, but the use of different N sources had no profound effect on the yield and quality of dryland wheat produced in Year 1 of this study and only at two of the nine sites in Year 2. This might indicate that the optimal N source for wheat production might be the cheapest and most accessible one.

8.2 General conclusion

After doing a complete analysis of the N requirement of wheat produced under conservation agriculture practices and dryland conditions in the Western Cape Province, it was apparent that fertiliser N recommendations will have to be adjusted. The recommended rates of N to produce wheat lead to over-fertilisation in some areas, which may, in turn, lead to environmental pollution and can lead to economic losses. Foliar N application at post-anthesis had limited success in increasing yield and grain protein content of wheat. Determining the optimal N source might entail choosing the most cost-effective and accessible source.

8.3 Limitation of research

Under field conditions, it is difficult to keep the level of variation to a minimum; therefore, it may be beneficial to rather increase the number of blocks. Although the results published in this paper might be indicative to the fact that fertiliser N programmes will have to be adjusted, further studies and analysis of data are needed before any guidelines can be set up.

A broad spectrum of data was collected and analysed during the two years. The data gives one a general understanding of the effects that fertiliser N rate, timing and source will have on wheat development. To truly investigate these effects, separate studies into fertiliser N rate, timing and source are necessary, especially in the Western Cape.

Both growing seasons can be considered as relatively dry seasons as the first substantial rainfall occurring only in June and were accompanied by sporadic seasonal distribution of rainfall. These conditions might have been a limiting factor to crop development; hence, it is difficult to predict the effect of N fertilisation on the growth and development of wheat during a wet season with the data collected in this study.

During the rainy winter months in the Western Cape Province, where nitrate-N leaching potential reaches a maximum, it might be advantageous to extend the depth of soil sampling and monitor how much, if any, nitrate-N leaches from the soil profile and becomes unavailable to crops.

8.4 Recommendations for future research

Future studies into the effect that leaching losses may have on water sources and soil residual N might aid the development of fertiliser N programmes where N use efficiency is at a more optimal level. Applying proper rates of N fertiliser with respect to soil mineral N can be the most economically profitable to the producer and the least harmful to the environment in terms of pollution.

Studying the rate of conversion from ammonium-N to nitrate-N under the soil- and climatic conditions of the Western Cape could be indicative as to what effect different fertiliser N sources has on plant available N.

Studying the effect of different rotational crops or catch crops on soil mineral N content and on the performance of the following wheat crop, could yield interesting results. It could also reveal what effect these crops will have on the nutrient- and microbial composition of the soil.

Studies into flag leaf chlorophyll- and/or N content of the wheat crop might determine why foliar N application had no profound effect on increasing grain protein content at all the research sites.

Economic analyses of the parameters included in this study and their impact on large scale farming operations might yield interesting results in terms of the profitability of conservation agriculture’s effect on lowering N fertiliser recommendations.

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