Response of canola (*Brassica napus* L.) to increasing nitrogen application rates in contrasting environments

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Declaration

I, the undersigned, hereby declare that the work contained in this thesis is my own original work and that I have not previously in its entirety or in part submitted it at any other university for a degree

JE van Zyl

22 day of November 2007

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Abstract

Response of canola (*Brassica napus* L.) to increasing nitrogen application rates in contrasting environments

The project consisted of three phases: a controlled greenhouse experiment to determine the response of canola to increasing rates of nitrate in the root zone, a controlled greenhouse experiment to determine the response of canola to increasing rates of nitrate in combination with two levels of soil moisture stress and nitrate leaching and a field experiment to determine the reaction of canola to increasing levels of N in four contrasting field environments that was replicated over two seasons.

Under controlled greenhouse conditions increasing nitrate levels (0, 4.5, 6.75, 9, and 11.25 me L^{-1}) were applied in a 1.5 mS cm^{-1} nutrient solution. Increases of dry matter production (DM), flower stem production and plant length with increasing concentrations of nitrate was profound. A typical S-shaped response curve of DM to NO_3 provided a good (R^2=0.99) fit of the DM to NO_3 rates at both 54 and 90 days after planting (DAP). Thus the reaction of canola to increasing levels of N in the root zone was confirmed.

Under controlled greenhouse conditions increasing levels of nitrate was added as KNO_3 (0, 30, 60 and 90 kg N ha^{-1}) in combination with a high irrigation regime (N leaching with no soil water stress) and low irrigation regime (no N leaching with periods of soil water stress). A log(x) function provided a good fit to the DM data of both high and low irrigation regimes (R^2=0.99 and 0.98 respectively). Although significant amounts of N leached (up to 40.32% of applied N) it was concluded that soil water stress had a greater influence on DM production.

Under field trial conditions increasing levels of N was applied as LAN (0, 30, 60, 90 and 120 kg N ha^{-1}, where 30 kg N ha^{-1} was either placed or broadcast at the time of planting) in four contrasting environments of the high yield potential growing areas of the Western Cape Province (Langgewens, Elsenburg, Welgevallen and Roodebloem). No difference in plant

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counts were observed between treatments where N was placed or broadcast at the time of planting. A good correlation was found between DM and applied N (R^2=0.97) over both seasons. In both years the highest yields, on average for all localities, were obtained with application rates of 90 kg N ha^{-1}. Values of nitrogen use efficiencies for all treatments were generally low, due to low N responses while apparent N recovery rates where high. Protein levels in the seed increased while oil levels decreased with increasing N application rates.

Keywords: Canola, Nitrogen

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Uittreksel

Reaksie van canola (*Brassica napus* L.) op toenemende stikstof vlakke in vier kontrasterende omgewings

Die projek het bestaan uit drie fases: 'n beheerde glashuis eksperiment om die reaksie van canola tot stygende nitraat vlakke in die wortelsone vas te stel, 'n beheerde glashuis eksperiment om die reaksie van canola tot stygende nitraat vlakke in kombinasie met twee vlakke van waterstremming en nitraat loging vas te stel en 'n veld proef om die reaksie van canola teenoor stygende vlakke van N in kontrasterende omgewings vas te stel.

Stygende vlakke van nitraat (0, 4.5, 6.75, 9, and 11.25 me L^{-1}) in 'n 1.5 ms cm^{-1} voedingsoplossing is aangewend onder glashuis toestande. Verhoging van droë materiaalproduksie (DM), blomsteelproduksie en plantlengte met stygende nitraatvlakke was opmerklik. 'n Tipiese s-vormige kurwe het 'n goeie passing (R^2=0.99) op die DM data van 54 en 90 dae na plant (DAP) gelewer en sodoende is die reaksie van canola tot stygende vlakke van nitraat bevestig.

Stygende vlakke van nitraat (0, 30, 60 and 90 kg N ha^{-1}) is toegedien as KNO_3 onder glashuis kondisies in kombinasie met 'n hoë (N loging met geen water stremming) en 'n lae (geen loging met water stremming) besproeiings vlak. 'n Log(x) funksie het goeie passing van die DM data gelewer by beide die hoë en lae besproeiings vlakke (R^2=0.99 en 0.98 onderskeidelik). Alhoewel betekenisvolle hoeveelhede N geloog het (tot 40.32% van toegediende N) is dit vasgestel dat waterstremming 'n groter invloed op DM produksie kan hê as die beskikbaarheid van N *per se*.

Onder veld toestande is stygende vlakke van N as KAN toegedien (0, 30, 60, 90 and 120 kg N ha^{-1}, waar 30 kg N ha^{-1} of breedwerpig gestrooi of gebandplaas is met planttyd) in vier kontrasterende omgewings in hoe opbrengs potensiaal gebiede van die Wes-Kaap (Langgewens, Elsenburg, Welgevallen and Roodebloem). Geen verskil in plante tellings is gevind waar N gebandplaas of breedwerpig uitgestrooi is nie. 'n Goeie korrelasie is gevind tussen DM en toegediende N (R^2=0.97) oor beide seisoene. Hoogste opbrengs, gemiddeld

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oor lokaliteite, is in beide jare verkry met toedienings van 90 kg N ha^{-1}. Waardes van N gebruiks effektiewiteit was oor die algemeen laag, vanweë die klein reaksie van canola tot N bemesting, terwyl die skynbare N onginningswaardes hoog was. Proteinvlakke in die saad het verhoog en olievlakke het verlaag met 'n verhoogde toediening van N.

Sleutelwoorde: Canola, Stikstof

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Chapter 1

Introduction

Overview

Since the introduction of canola as a commercial crop about 20 years ago, production in the western and southern Cape Province has increased to a point where 43 300 ha where sown in 2003 (Genis, 2004). Despite the increased area under production, production is still hampered due to low yields. In cultivar trials performed by the Department of Agriculture at Langgewens during 2005 Hyola 61 was the highest yielding cultivar with a yield of 2.9 t ha^{-1} while Tornado TT which is at present a very popular cultivar, yielded 2.0 t ha^{-1}. In similar trials in the Southern Cape (Caledon district) Hyola again was the highest yielding cultivar with a yield of 2.4 t ha^{-1} and the yield for Tornado TT was again only 2.0 t ha^{-1}. Yields obtained by producers are in general much lower and yields of 1.0 to 1.5 tons ha^{-1} are often experienced.

Local research on canola has concentrated on the adaptation of new cultivars and management of the crop by identifying and solving of major practical problems. These include the need for a good seedbed, early sowing, large applications of nitrogenous fertilizer, the control of certain weeds, pests and disease and careful timing of harvest (Hanekom, 1999). High fertilizer applications not only increase production costs, but the injudicious application of large amounts of fertilizers especially nitrogenous fertilizers with high leaching potential is also frowned upon in recent times (Dinnes *et al.*, 2002). In addition to this, reports have been received (Hardy, Hanekom & Langenhoven, 2004) that

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canola shows no response to increasing nitrogen application rates in the western Cape production area. It is for these reasons important to determine the response of canola to N application rates in order to optimize N fertiliser programs for canola in terms of input costs and profit margins for farmers in the production areas of the Western Cape Province.

The role of nitrogen in plants

Nitrogen is the mineral nutrient plants require in the largest amounts (Tiaz & Zaiger, 1998). Nitrogen serves as a constituent of many plant cell components, including amino acids and nucleic acids (Tiaz & Zaiger, 1998), certain hormones (e.g., indole-3-acetic acid; cytokinin), and chlorophyll. The source capacity of plants is primarily determined by leaf area, leaf area duration, rates of photosynthesis, respiration and amino acid synthesis, which are all increased with an increase in nitrogen supply (Novoa & Loomis, 1981).

Nitrogen deficiency rapidly inhibits plant growth. If such a deficiency persists, most species show chlorosis, especially in the older leaves near the base of the plant. Under severe nitrogen deficiency, these leaves become completely yellow and fall of. Younger leaves may not show these symptoms initially, because nitrogen can be mobilized from older leaves (Tiaz & Zaiger, 1998) and transported to the younger parts largely in the form of soluble amines and amides. When nitrogen deficiency develops slowly, plants may have markedly slender and often woody stems. This woodiness may be due a buildup of excess carbohydrates that cannot be used in the synthesis of amino acids or other nitrogen compounds. Carbohydrates not used in nitrogen metabolism may also be used in anthocyanin synthesis, leading to accumulation of the pigment. This condition is manifested as a purple colouration in leaves, petioles and stems of some nitrogen deficient

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plants. Excess nitrogen stimulates abundant growth of the shoot system, favouring a high shoot/root ratio (Tiaz & Zaiger, 1998).

Nitrogen uptake

The uptake of nitrate is influenced by many factors including temperature, pH, and nitrate concentration of the external solution, the rate of transpiration and the presence of ammonium is also important. Nitrate uptake increases with increasing temperature and decreases with increasing pH. An increase in transpiration may increase uptake by enhancing transport across the cortex or to reduce the internal concentration by increasing transport to the shoot. The effect of transpiration will be enhanced when passive uptake is dominant (Novoa & Loomis, 1981).

In aerated soils nitrate is the dominant form in plant nutrition. It is absorbed first through the free-space (cell wall spaces) and then across membranes into the cells themselves. Membrane transport may be passive by diffusion across electrochemical gradients or, active through the expenditure of metabolic energy. Ammonium can enter into the amino acid synthesis directly, but nitrate must first be reduced to the ammonium form (Novoa & Loomis, 1981).

The supply of nitrogen is influenced by soil conditions. Leaching, denitrification, immobilization of nitrogen in the biomass of microorganisms and then in humus, and mineralization of organic matter are important and are also influenced by water (Van Keulen, 1981).

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Novoa & Loomis (1981) showed results where, under optimum soil water conditions wheat yielded 24 kg grain kg N applied^{-1} but only 11 kg grain kg N applied^{-1} when water was limiting. The recovered nitrogen in the grain decreased from around 20 percent to 4 percent when water supply was restricted. In such experiments water supply would effect production in two ways, by decreasing the growth rate as well as nitrogen supply.

Since nitrate is a highly soluble anion and not strongly held by soil colloids, applications in the form of nitrate may lead to increased leaching losses. Ammonium on the other hand is a single charged cation that behaves analogous to potassium in the soil. In a comparison of leaching losses between nitrate and ammonium fertilizers performed by Mancino and Troll (1990) it was found that 0.09% of applied N was lost when applied as $(NH_4)SO_4$ compared to 4.13% when applied as NH_4NO_3.

In a review by Dinnes *et al.* (2002) it is stated that timing of application and nitrogen rates are important factors for increasing nitrogen use efficiency. Where nitrate applications are split across the growing season the nitrates have a better chance of staying in the rhizosphere for longer thus, giving the plant a longer time for assimilation of the nitrogen.

Small emissions (<4% of N applied) of NH_3 have been measured following the application of ammonium nitrate (Harison & Webb, 2001). The amount volatilized will be less if the pH is buffered below 7 (Harrison & Webb, 2001) and even less if waterlogged conditions do not occur (Sommer, Schjoerring & Denmead, 2004).

Nitrogen and canola

Nitrogen is an important macro nutrient that affects the growth and yield of non-legume crops such as canola. Nitrogen nutrition has no significant effect on the rate of development but growth is affected through protein synthesis, leaf expansion (Wright, Smith & Woodroofe, 1988, Schjoerring *et al.,* 1995) and growth of all components of the crop. An increase in canola seed yield due to increasing nitrogen application rates has been reported by Hocking *et al.* (1997). Nitrogen nutrition also affects seed quality. High nitrogen content within the plant tends to reduce oil content while increasing protein content (Kimber & McGregor, 1995). A plentiful supply of both nitrogen and sulphur may however lead to a high glucosinolate content, which can adversely affect the feeding value of canola meal (Kimber & McGregor, 1995).

Canola has a high nitrogen requirement (Hocking, Randall & DeMarco, 1997). In Australia yields of commercially grown Canola crops were well below the genetically potential yields of the cultivars and this could be partly attributed to inadequate application or poor management of nitrogen. According to Kimber and McGregor (1995) a canola crop accumulates 50-60 kg of nitrogen for every ton of seed produced. In the report by the Canola Working Group of the Western Cape (2001) it is reported that 40 kg N ha^{-1} is removed for each ton of grain produced. From the results obtained by Hocking *et al.* (1997) it became clear that with a grain yield of 3.5 t ha^{-1} the grain yield response curve starts to flatten at 150 kg N ha^{-1} at the cooler wetter sites (540 mm rainfall) and no response in yield due to nitrogen was found in the warmer, drier sites (430 mm rainfall) with yields of less than 0.5 t ha^{-1}. Hocking *et al.* (1997) also noted large increases in dry matter production in response to N fertilizer, but these differences were not reflected in the grain yield. The absence of this reflection was attributed to moisture stress during the seed

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filling stage. Seed oil concentrations at 8.5% moisture did not decline significantly for treatments receiving 25 to 150 kg N ha^{-1}. However, the protein percentage of the seeds increased significantly for treatments receiving more than 25 kg N ha^{-1}.

To improve the yields of canola it is important to maximize the nitrogen recovery efficiency of canola, because it has been reported that canola has a very low nitrogen recovery efficiency rate (Kimber & McGregor, 1995; Hocking *et al.*, 1997; Santonoceto *et al.*, 2002) and drought stress may further reduce recovery (Smith, Wright & Woodroofe, 1988; Schjoering *et al.*, 1995). Nitrogen recovery efficiencies as low as 50% (Kimber & McGregor, 1995) and values close to 100% (Hocking *et al.*, 1997; Santonoceto *et al.*, 2002) has been reported, with the trend being that nitrogen recovery efficiency generally decrease with increasing N application rates. Nitrogen use efficiencies of 26 kg seed kg N accumulated^{-1} and agronomic efficiencies of 43 kg seed kg N applied^{-1} have been reported by Hocking *et al,* (1997) for application rates 10 g N ha^{-1} and agronomic efficiency decreased to 8 kg seed kg N applied^{-1} where 150 kg N ha^{-1} was applied.

Nitrogen is immediately available to the plants when applied in the form of nitrate although it has been shown that canola can utilize the ammoniacle form (Kimber & McGregor, 1995). Timing applications to coincide with growth stages where the plant has a high N accumulation rate may also lead to reduced nitrate leaching hence the possibility of higher N recovery efficiencies. Hocking *et al.* (1997) states that contrasting results have been found with regard to the growth stage of greatest N accumulation. Some reports state that 56% of N is accumulated before anthesis, 33% during flowering and 11% after flowering, while other reports propose that more N is accumulated during and after flowering than the period before anthesis. The time of greatest uptake will also be highly dependant on the soil water status according to Van Keulen (1981). In a trial by Schjoering *et al.,* (1995)

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irrigation increased seed and straw yields only with high N supply, indicating that growth at low N supply was more inhibited by N deficiency than water deficiency. In the report by the Canola Working Group of the Western Cape (2001) it is said that the splitting of nitrogen applications should receive special attention. The guideline is that heavier soils should receive 40 to 60% of N at the time of planting and the rest before stem elongation. On sandy soils subject to leaching 40% N should be applied at the time of planting and the rest should be top dressed and that this application can be split in two at 30 days and 65 days after emergence.

Hocking *et al.* (1997) found that seed oil concentrations were reduced where nitrogen was top dressed at the start of flowering this however was offset by the increase in oil yield ha^{-1}.

Aim

The main focus of this study was to determine the response of dry matter production, grain yield and quality of canola to nitrogen applications in different growing environments. Three distinctly different trials were designed to illustrate the response on canola to increasing N application rates. These trails were conducted in pots in a fully controlled environment (glasshouse) to avoid any stress conditions which might affect the response; with different levels of water supply and lastly under field conditions in four different soil and climatic environments.

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Chapter 2

Reaction of canola (*Brassica napus* L.) to increasing levels of nitrate under glasshouse conditions

Aim

A greenhouse trial was conducted to determine the vegetative growth and flowering response of canola (B*rassica napus* L., cv Thunder TT) to different levels of nitrate applied under optimum growth conditions. The experiments attempted to establish what concentrations of nitrate in the soil solution inhibits growth, which levels fall within the optimum range of NO_3 concentration in solution and at what levels no further response is expected.

Materials and methods

Canola was grown hydroponically in pots filled with coarse sand in a temperature (20/15°C day/night) controlled glasshouse. No. 1 acid washed sand acquired from Consol Minerals that was used as a growth medium, can be classified as a coarse sand (Table 2.1) and contain very little nutrients (Table 2.2).

Table 2.1 Particle size analysis for no. 1 sand from Consol Minerals

Particles retained	Particle size (mm)	% retained on mesh
Very coarse sand	2 – 1	11.5
Coarse sand	1 – 0.5	80.7
Medium sand	0.5 – 0.25	7.8
Fine sand	0.25 – 0.1	-
Very fine sand	0.1 – 0.05	-

Table 2.2 Chemical analysis for no.1 sand from Consol Minerals

Compound	%
SiO_2	99.75
Al_2O_3	0.07
Fe_2O_3	0.023
TiO_2	0.024
ZrO_2	0.005
CaO	0.003

The 3 L pots were filled with dry sand after the drainage holes were covered with fine mesh to prevent the sand from washing out. Drip irrigation with two outlets per pot was used and the six irrigation stations (one for each fertiliser rate) were controlled by an electronic irrigation controller. Pots were irrigated five times per day to avoid any water stress and 15% drainage was allowed to prevent build up of salts in the medium.

Eight seeds of canola (B*rassica napus* L., cv Thunder TT) were planted per pot with four seeds spatially arranged round each dripper. During the first two weeks after planting the plants were irrigated with municipal tap water without any fertiliser added. Nitrate treatments (Table 2.3) were started at 15 days after planting (DAP) by raising the EC of the irrigation water to 0.5 mS cm^{-1}. At this stage the plants were thinned out to two plants per pot (one plant per dripper). At 26 DAP the EC was raised to 1.5 mS cm^{-1} from where it remained constant till the end of the experiment. The gradual increase in EC was done to prevent root burning of the young plants. The pH of the nutrient solution was kept at pH 5.5 for the duration of the experiment.

The five nitrate treatments were applied in a randomized block design with six replications. Four pots were used as an experimental unit per treatment in each replication. A standard Steiner (1984) solution was used and ion concentrations balanced due to varying nitrate concentrations as described by Steiner (1984). The ratio of ions for a 2 mS cm^{-1} nutrient solution for different nitrate treatments and the concentration of nitrate in the final 1.5 msScm^{-1} solution is shown Table 2.3.

Table 2.3 Ratio of ions (me L^{-1}) for a 2 mS cm^{-1} nutrient solution for different treatments and the concentration of nitrate in the final 1.5 mS cm^{-1} nutrient solution

Treatment	K^+	Ca^{2+}	Mg^{2+}	NO_3^-	$H_2PO_4^-$	SO_4^{2-}	$[NO_3^-]$ in final solution
1	7	9	4	0	2.5	17.5	0
2	7	9	4	6	1.75	12.25	4.5
3	7	9	4	9	1.38	9.62	6.75
4	7	9	4	12	1	7	9
5	7	9	4	15	0.63	4.37	11.25

For all treatments a 200× concentrate of the 2 mS cm^{-1} solution was prepared in 5 L containers. Some calcium could not be applied to the concentrated solution for treatments 1 and 2, because $CaSO_4$ had to be used as the source of calcium and would precipitate under these concentrations. Thus 0.049 g and 0.021 g $CaSO_4$ had to be added to the final nutrient solution of treatment 1 and 2 respectively for every 1 ml of concentrate solution used. Micronutrients applications were the same for all treatments and the quantities (g) used per 5 litre of 200× concentrate is shown in Table 2.4.

Table 2.4 Micronutrients (g) added to 5 L of a 200 × concentrate solution

Salt	**g per 5 l of 200 × nutrient solution**
Libfer	5.03
$MnSO_4$	1.71
Solubor	1.15
$CuSO_4$	0.14
$ZnSO_4$	1.13
NaMo	0.1

Data collected

Dry matter production was determined by plant samplings at 54 and 90 DAP. During the first sampling two plants (one pot per experimental unit of four pots) per replication of each nitrate treatment were cut at soil surface level, dried at 80 ˚C for 48 hours and weighed. During the final harvesting at 90 DAP the remaining six plants (three pots) were sampled in the same way. At that stage plant heights were also measured and the number of flowering stems per plant counted.

Data analysis

Statistical analysis was done using STATISTICA version 7.0 (Statistica, 2004). One-way analysis of variance was performed on all data. Model fitting on dry matter production was done using non linear estimation. Significance testing was done using the Fisher LSD test and LSD values were calculated using the student's t-LSD (P= 0.05).

Results and discussion

Dry matter production

Mean dry matter (DM) production of canola at 54 and 90 DAP were increased from 0.017 to 3.133 g plant^{-1} and 0.050 to 27.279 g plant^{-1} respectively with an increase in nitrate concentration from 0 to 11.25 me L^{-1} (Table 2.5). Significant increases were obtained with all increases in nitrate concentration treatments for both DM harvest dates. These results clearly demonstrated the dramatic vegetative growth response of canola to increasing nitrogen levels when growth conditions like temperature, water supply and other nutrients are not limiting. Dry matter yields of 23.569 g plant^{-1} obtained at 90 DAP with nitrate concentrations of 9 me L^{-1} which is the basic Steiner (1984) solution were very similar to that found by Hanekom (1999) who used the same nutrient solution.

Table 2.5 Effect of nitrate concentration on dry matter (DM) production (g plant^{-1}) at 54 and 90 days after planting (DAP)

Treatment (me NO_3 L^{-1})	**DM (g plant^{-1}) 54 DAP**	**DM (g plant^{-1}) 90 DAP**
0	0.017*a*	0.050*a*
4.5	1.029*b*	13.225*b*
6.75	1.882*c*	19.996*c*
9	2.773*d*	23.567*d*
11.25	3.138*e*	27.279*e*
$LSD_{(0.05)}$	0.244	1.666

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In spite of a limited number of data points on the x-axis, a good fit with a R^2 value of 0.99 for both 54 DAP (Figure 2.1) and 90 DAP (Figure 2.2) is provided using the following function (eq 2.1):

$$Y = \frac{\beta_0}{(1+\beta_1 e^{(-\beta_2(x-\beta_3))})^{\frac{1}{\beta_1}}} \qquad (2.1)$$

where:

β_0 = Upper limit

β_1 = Point of maximum growth

β_2 = Growth rate

β_3 = Time of maximum growth

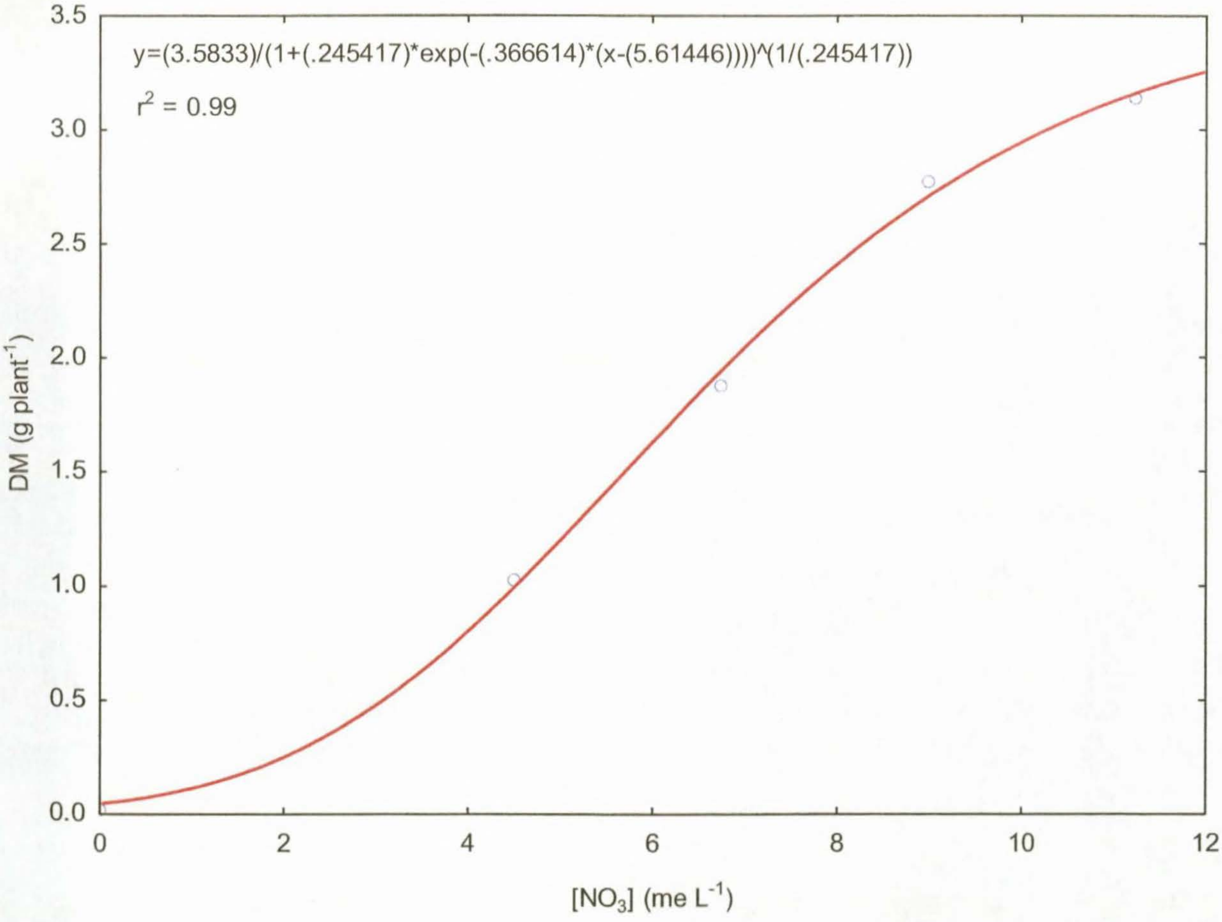

Figure 2.1 Dry matter production (g plant^{-1}) after 54 days for increasing nitrate concentration in nutrient solution fitted with the general growth model.

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Both Figures showed a S- type curve that is very typical for biological responses, indicating that the DM accumulation is small at very low nitrate levels, followed by a high response phase at optimum nitrogen supply and eventually a decreasing response at very high nitrate rates.

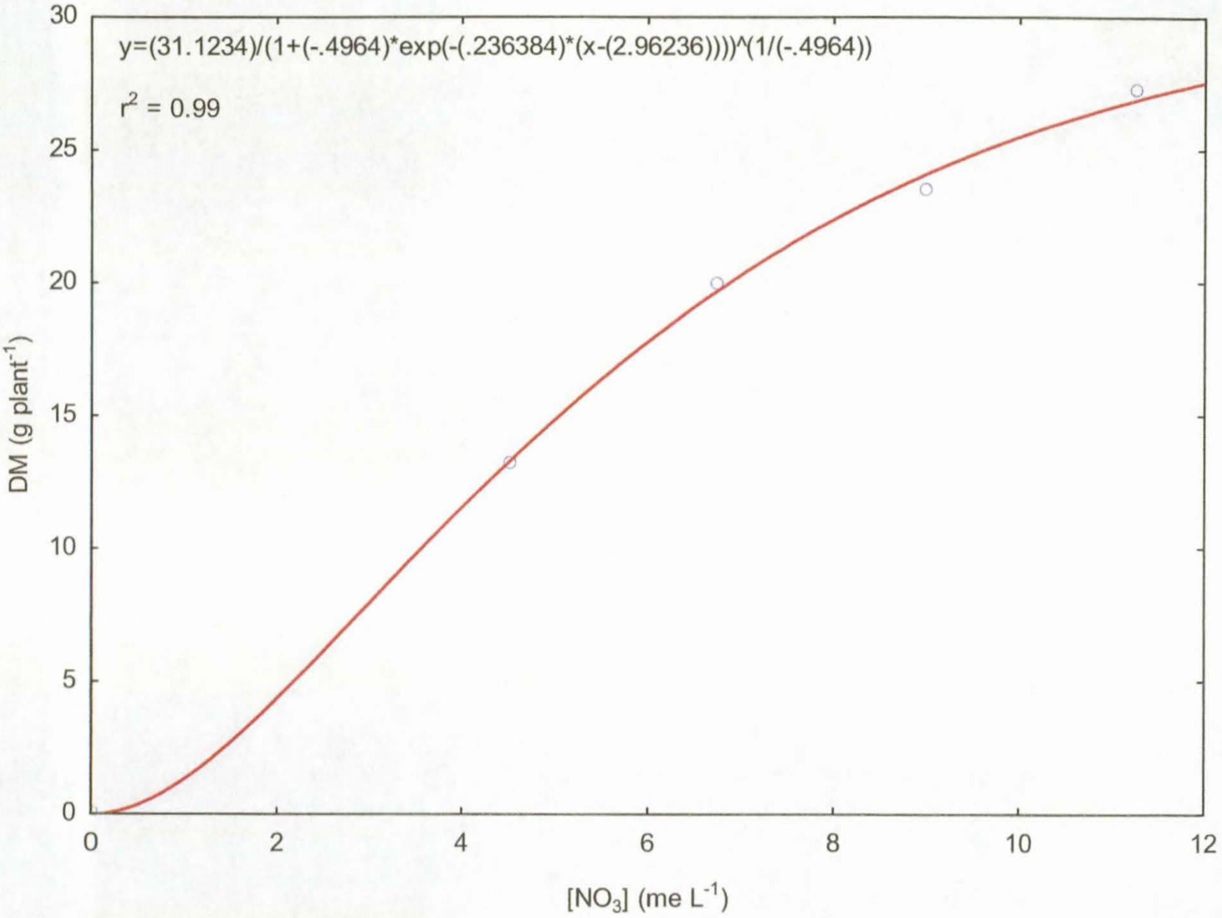

Figure 2.2 Dry matter production (g $plant^{-1}$) after 90 days for increasing nitrate concentration in nutrient solution fitted with the general growth model.

Although the mean response (gradient) clearly differed between the 54 and 90 DAP samplings (0.277 and 2.420 g DM respectively for every 1.0 me L^{-1} increase in nitrate), optimum nitrate concentrations (where the largest response to an increase in nitrate concentration in the nutrient solution were obtained) did not differ that much between growth stages. At 54 DAP the largest response was obtained at approximately three to eight me nitrate L^{-1}, while the largest response at 90 DAP were obtained at approximately two to six me NO_3 L^{-1} in the nutrient solution. Concentrations of less than 2 me L^{-1} clearly inhibited DM production as can be seen by the gradient and deficiency symptoms, manifesting as a purple discoloration of the main stem (Tiaz & Zeiger, 1998), were observed for the treatment that received no nitrate. Although DM production at both growth stages (54 DAP and 90 DAP) were still increased at nitrate concentrations of 12 to 15 me L^{-1} responses were clearly smaller, indicating supra-optimal application levels.

Plant height

Plant height is often used as an indication of growth conditions. In this study, plant height at 90 DAP showed a significant increase with an increase in nitrate concentration in the nutrient solution (Table 2.6).

Table 2.6 Effect of nitrate on plant heights (cm) and number of flower stems at 90 DAP

Treatment (me NO_3 L^{-1})	**Plant height (cm)**	**Flower stems**
0	4.83*a*	0 *a*
4.5	56.37*b*	2.13*b*
6.75	76.71*c*	3.46*b*
9	86.04*cd*	5.88*c*
11.25	97.63*d*	5.92*c*
$LSD_{(0.05)}$	14.94	1.41

From Figure 2.3 it is however clear that the largest response in plant height was obtained with an increase in nitrate concentration from 0 to 4.5 me NO_3 L^{-1} and that the response decreased gradually with an increase in nitrate concentration in the nutrient solution. No significant increases in plant heights were obtained with increases in nitrate concentration from 6.75 to 9 or from 9 to 11.25 me L^{-1}. This hyperbolic response is best described (r^2 = 0.97) using the model $y = b_0 + b_1\log(x)$ which again indicated that nitrate concentrations of 9 to 11.25 me L^{-1} may be supra optimal.

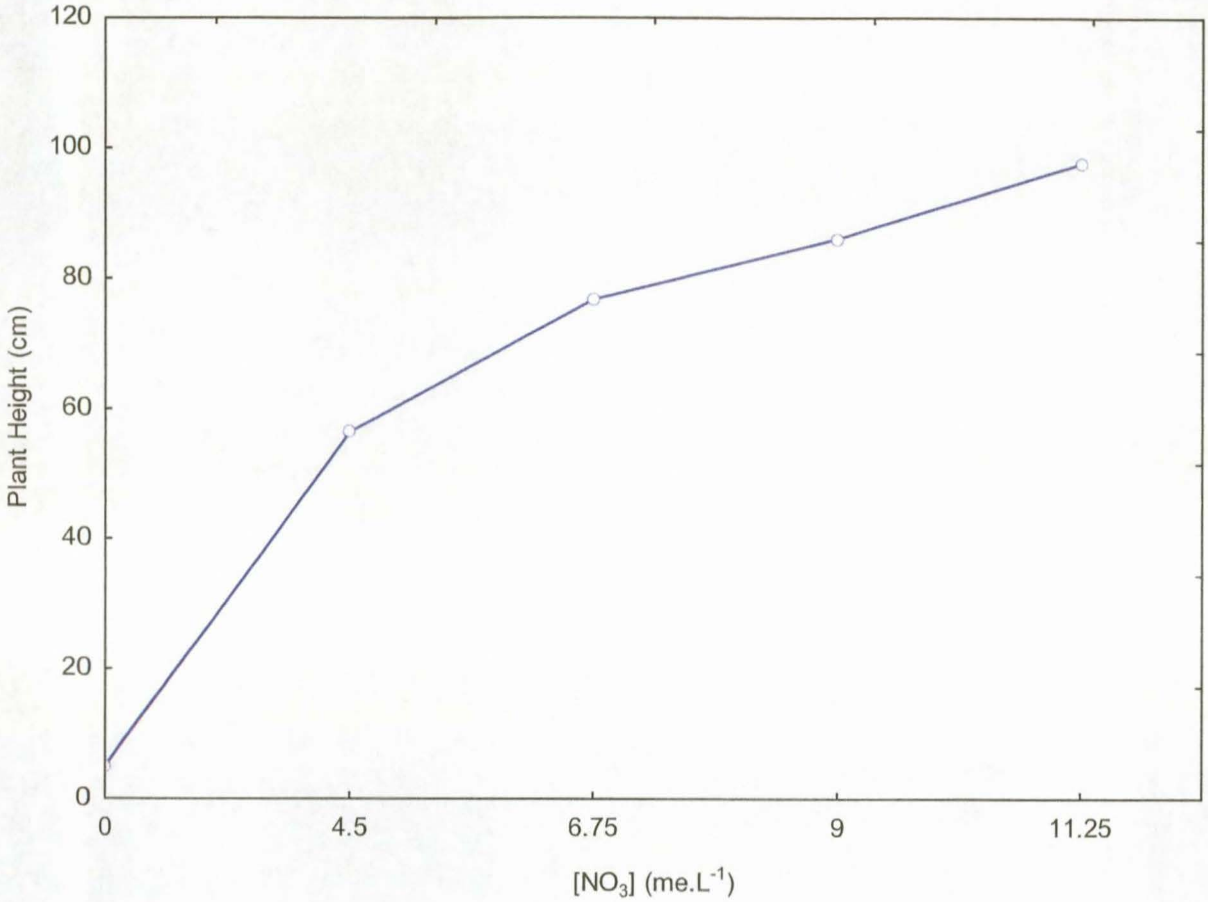

Figure 2.3 Average plant heights (cm) 90 days after planting for increasing amounts of nitrate in the nutrient solution.

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Flowering stems

Because the experiment was terminated at 90 DAP, to prevent inter plant competition becoming the growth determining factor in the confined pot environment, no grain yields could be determined. For this reason the number of flower stems was counted during the final harvest at 90 DAP as an indication of yield potential.

At 90 DAP the control treatment had failed to produce a single flower stem and the fact that differences are apparent between the other treatments suggests that nitrate influences the timing of the different developmental stages of canola. This is in strong contrast to the observations of Kimber & McGregor (1995) where it is stated that nitrogen has no effect on the timing of developmental stages of canola.

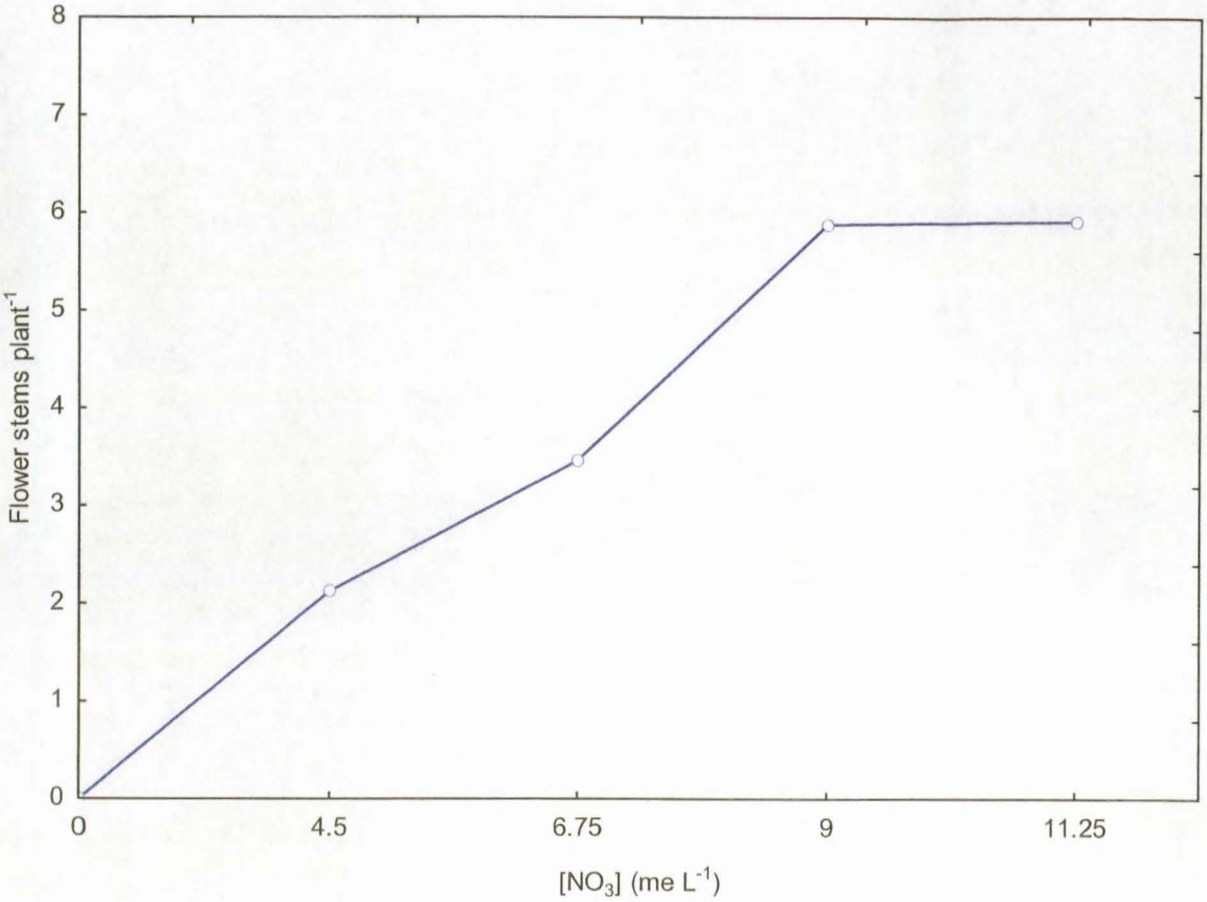

Figure 2.4 Average number of flower stems per plant at 90 days after planting for increasing levels of nitrate in the nutrient solution.

No flower stems were produced where no nitrogen was applied compared to 5.92 per plant with 11.25 me nitrate L^{-1} in the nutrient solution (Table 2.6). With an application of 9 me nitrate L^{-1} 5.88 stems were produced per plant. Similar productions were obtained by Hanekom (1999) in pot experiments using a comparable nutrient solution. Figure 2.4 clearly show that flower stem production did not increase when nitrate concentration exceeded 9 me L^{-1}. These results support the trends found with dry matter production and plant heights which indicated that concentrations of 9 - 11.25 me nitrate L^{-1} may be supra optimal even when canola is grown under optimal growth conditions.

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Conclusion

From the results obtained it is clear that the influence of nitrate on plant growth (dry matter production, amount of flowering stems and plant length) is uncontested, especially at lower levels of nitrate availability. As the level of availability of nitrate increases the effect of further increases diminish. It was also found that nitrate levels can affect the timing of growth stages as can be seen from the flower stem data. It seems clear that concentrations of between 7 and 9 me nitrate L^{-1} in the soil solution can fall within the optimum range for canola production. Concentrations of less than 3 me nitrate L^{-1} can severely inhibit growth and development while levels higher than 9 me nitrate L^{-1} may be supra optimal. It is however, very difficult to relate the concentrations of nitrate in the nutrient solution to concentrations of nitrate in soil solutions due to amount of available water in the soil which will have a great influence on the concentration of solutes in the soil solution and will vary with changing water levels in the soil.

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Chapter 3

Dry matter response of canola (*Brassica napus* L.) to increasing levels of nitrate nitrogen under two irrigation regimes

Aim

To determine the dry matter production response of canola (*Brassica napus* L. cv. Tornado TT) to different N fertilizer application rates when grown under temperature controlled conditions, but with two irrigation regimes and simultaneously determine the amount of nitrates leached with increasing nitrogen application rates.

Materials and methods

Growth conditions and growth medium

The experiment was conducted in 3 L pots filled with loamy sand (15% clay, silt 12% and 73% sand) in a temperature controlled glasshouse with day/night temperatures of 20/15 °C.

The soil, a loamy sand topsoil on which field trials were conducted in 2005 at Welgevallen Experimental Farm (Chapter 4), was sieved through a 2 mm gauge mesh to remove all

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large particles that might influence drainage in the individual pots and at the same time mixed thoroughly to minimize soil variability. After the pots were filled with 3 kg of dry soil, the bulk density was determined by measuring the volume of the soil in the pots. The bulk density was found to be 1.232 g cm^{-3} indicating a porosity of 54 %. Although the bulk density increased as the soil compacted after irrigation events, it was assumed that the soil in the different pots would compact to the same extent, because all the pots were initially filled with the same mass of soil (3 kg). The final depth of soil in the pots after compaction was approximately 14 cm.

Planting

Five canola (*Brassica napus* L. cv Tornado TT) seeds were sown per pot where after the pots were wetted to the pre-determined field water capacity and covered with shade netting to prevent excessive evaporation and to create a suitable environment for germination. After emergence the shade netting was removed and the pots were arranged according to the experimental layout. After all seedlings have emerged and their first true leaves had unfolded the two most vigorous plants per pot were kept and the others removed.

Irrigation treatments

Two irrigation regimes were applied namely a high (where leaching of nitrates may occur) and a low regime (where no leaching takes place). For the low irrigation regime the soil was kept moist by irrigating the pots when the soil water content dropped to about 70% of field water capacity (FWC), using the weighing method. Because the growing plants with increasing dry mass, causes this method to be increasingly inaccurate, irrigations were applied at approximately 85% FWC during the last 12 days of the experiment to prevent water stress conditions. In spite of this, visible water stress did occur twice during this period and for this reason it was decided to terminate the experiment at 55 days after planting (DAP). The high irrigation regime received the same irrigation than the low regime, but additionally six drainage events were created to cause some nitrogen leaching. At drainage events the irrigation system was left running until the pots started to drain freely before irrigation was stopped. No visible water stress was observed for the high irrigation regime. Irrigation volumes and scheduling for the high and low irrigation treatments are summarized in Figure 3.1. In total 230 mm and 84 mm of water was applied to the high and low irrigation treatments respectively during the experimental period.

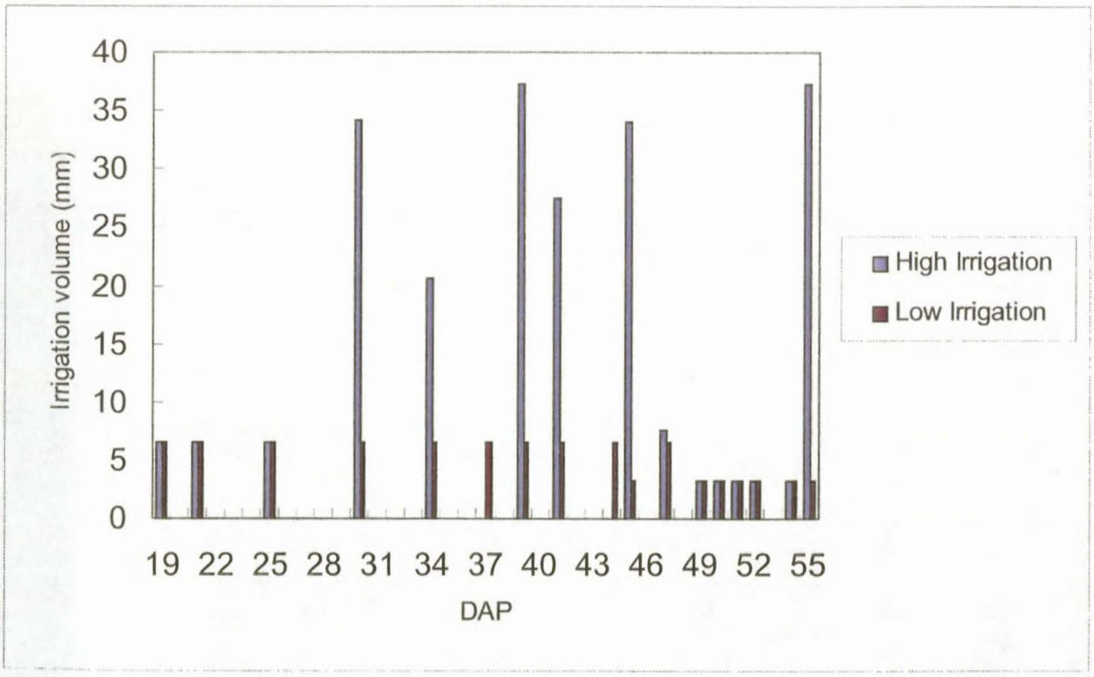

Figure 3.1 Irrigation volumes (mm) applied during the trial period for both high and low irrigation regimes at days after planting (DAP).

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To determine the leaching a slightly adapted method of Mancino & Troll (1990) was used (as described under "measurements") for the following reasons:

The amount of nitrates leached beyond the bottom boundary of the pot would, be more than that lost out of the soil system beyond the same depth under a similar wetting regime. The reason being that under transient rainfall conditions evaporation between rainfall events causes water and solutes to move upwards. This upward movement is not possible once the solutes have moved below the lower boundary of the pot (Logsdon, Keller & Moorman, 2002). Colangelo & Brand (2001) compensated for this problem by placing their nursery containers on the surface of a monolith lysimiter. The monolith lysimeter can also cause downward movement of water and solutes due to the matrix potential of the soil in the lysimeter. Another method of creating matrix potential without the use of a large monolith of soil would be to apply suction in the form of hanging water column (Brandi-Dohrn *et al.*, 1996). This can be achieved through the use of passive capillary wicks and has the advantage that unsaturated pore water can be sampled (Holder *et al.*, 1991) while only saturated pore water can be sampled in a zero tension situation. The methods mentioned above all require a large amount of equipment and skill, and each can be seen as a study field on its own.

Fertilizer treatments

One pot per irrigation treatment were not planted or fertilized to estimate the amount of nitrogen mineralized by the soil and one pot per irrigation treatment were fertilized with 120 kg N ha^{-1} and left unplanted in an attempt to create a nitrate breakthrough curve (Rowell, 1994). Four fertilizer application rates namely 0, 30, 60 and 90 kg N ha^{-1} were applied to the planted pots. A single application of KNO_3 was used. The required mass of dried KNO_3

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(Eq. 3.1, Table 3.1) was weighed into an Erlenmeyer flask and dissolved in 100 ml of distilled water. The solution was then mixed and evenly applied to the surface of the pots.

$$\text{Application}\left(\text{g KNO}_3\ \text{pot}^{-1}\right)=\frac{\text{Application rate}\left(\text{g ha}^{-1}\right)\times\dfrac{100}{13.86}\times\ \text{Area of pot}\left(\text{m}^2\right)}{10000} \qquad (3.1)$$

Table 3.1 Layout of treatments and N application per pot (g), also shown as g KNO$_3$ and equivalent N application per hectare

Treatment	**Irrigation**	**Kg N ha^{-1}**	**Pot application (g KNO$_3$)**	**Pot application (g N)**
1	High unplanted	0	0	0
2	High	0	0	0
3	High	30	0.33	0.046
4	High	60	0.66	0.091
5	High	90	0.99	0.137
6	High unplanted	120	1.32	0.183
7	Low unplanted	0	0	0
8	Low	0	0	0
9	Low	30	0.33	0.046
10	Low	60	0.66	0.091
11	Low	90	0.99	0.137
12	Low unplanted	120	1.32	0.183

After the fertilizers were applied at 19 DAP the irrigation treatments as described were started.

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Measurements

Pots subjected to the high irrigation treatment were placed on a drip tray in order to collect the leachate. After the pots stopped draining the leachate was collected. The volume of leachate was measured and thereafter analyzed for NH_4-N and NO_3-N. The total amount of N lost was calculated using eq 3.2:

$$\text{Total N applied lost (mg)} = \text{Concentration } NO_3\text{ - N (mg L}^{-1}) \times \text{Volume(L)} \qquad (3.2)$$

The percentage of applied N lost was calculated according to eq 3.3:

$$\text{\% N applied lost} = \frac{\text{Total N lost (mg)- Total N lost controlunplanted(mg)}}{\text{N applied(mg)}} \times 100 \qquad (3.3)$$

The plants where harvested before bolting at 55 days after planting (DAP) by cutting them at approximately 2 mm above the soil surface. After the plant samples were dried for 48 hours at 80 °C, the dry matter was determined gravimetrically.

Data analysis

The trial was laid out as a blocked factorial and was replicated five times. Statistical analysis was done using STATISTICA version 7.0 (Statistica, 2004). Factorial analysis of variance was done on dry matter data. Model fitting on the dry matter data was done using non linear estimation. The leaching data was divided in two. The first repeated measures analysis of variance was done on the leachate collected from the planted pots and the

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second on data from both planted and unplanted pots. Means were calculated by the least square means method. Significant differences were determined with the Fisher LSD test and LSD values were calculated using the student's t-LSD (P= 0.05).

Results and discussion

From Table 3.2 it became clear that the nitrate-N concentration in the leachate was significantly affected by the N application rate (N) and time (drainage event), but a significant interaction between N application rate and time indicated that the effect of application rate on nitrate-N in the leachate was not the same for all drainage events.

Table 3.2 Pr>F values for leachate data indicating the significance of nitrogen application rate (N) and time and as calculated using a repeated measures ANOVA

	[NO_3] planted	**[NO_3] unplanted**
N	<0.01	<0.01
Time	<0.01	<0.01
N*Time	<0.01	<0.01

The results also show that dry matter production and nitrogen use efficiency (NUE) were significantly affected by both N application rate (N) and irrigation level (I), but no interaction occurred (Table 3.3).

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Table 3.3 Pr>F values for indicating the significance of nitrogen application rate (N) and irrigation regime on dry matter production using a main effects ANOVA

	Dry matter
N	<0.01
I	<0.01
N*I	0.468

Leaching losses

Leaching losses only occurred from the high irrigation regime. On average 37 % of applied water leached from the pots, which did not differ much from the 46 % leachage reported by Mancino & Troll (1990) under similar experimental conditions. Total nitrate-N lost during the leaching events expressed as a percentage of total nitrate application is shown in Table 3.4.

Table 3.4 Total nitrate-N leaching losses during drainage events of the high irrigation regime, expressed in mg pot^{-1} and expressed as percentage of total nitrate-N applied

Application rate	Total N lost (mg pot^{-1})	N applied lost (%)
0 kg N ha^{-1} unplanted	27.05*ab*	N/A
0 kg N ha^{-1} planted	16.42*a*	N/A
30 kg N ha^{-1} planted	36.73*b*	21.03*a*
60 kg N ha^{-1} planted	58.31*c*	34.35*a*
90 kg N ha^{-1} planted	82.29*d*	40.32*a*
120 kg N ha^{-1} unplanted	252.76*e*	123.34*b*
	$LSD_{(0.05)}$=18.38	$LSD_{(0.05)}$=25.80

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Total amounts of nitrates leached increased in the planted pots from 16.42 mg pot^{-1} to 82.28 mg pot^{-1} as the application rate increased from 0 to 90 kg N ha^{-1} (Table 3.4). In comparison with the planted pots which received no nitrogen, 27.05 mg nitrate-N pot^{-1} leached from the unplanted treatments which received no nitrogen. This amount gave an indication of the residual N in the soil at the start of the experiment and N mineralization during the experimental period. Where 120 kg N ha^{-1} was applied, but pots were not planted, as much as 252.76 mg nitrate-N pot^{-1} leached.

In planted pots the percentage N losses slowly increased from 21.03% with an application of 30 kg N ha^{-1} to 40.32% where 90 kg ha^{-1} was applied (Table 3.4). In a similar study by Mancino & Troll (1990) only 4% of applied nitrogen was lost mostly in the form of nitrate with an application rate of 49 kg N ha^{-1}. This large difference in losses may be explained by the fact that grass crops have a much denser root distribution and a high nitrogen use efficiency compared to canola. In the unplanted 120 kg N ha^{-1} application, 123.34% of applied N was removed by leaching indicating that there may be an overestimation of amount of N leached. The significantly higher losses in the planted treatments versus the unplanted treatments can only be ascribed to the absence of plant uptake in the pots.

Figure 3.2 shows the concentration of nitrates leached during each of the six drainage events created by the high irrigation regime for the planted pots. For the first two drainage events nitrate-N concentration in the leachate increased significantly with an increase in N application rate, while the 60 kg N ha^{-1} treatment was still significantly higher than the 0 and 30 kg N ha^{-1} application rates for the third drainage event, but no significant differences in nitrate concentration in the leachate due to N application rate were found for the last three drainage events. The clear differences between the treatments and relative high concentration of nitrate-N in the drainage water for all planted treatments at drainage

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events one and two which occurred 11 and 15 days after the N application, may be due to the differences in application rates and small plant size (30 and 34 DAP) and therefore low amount of nitrate assimilated at this stage. As the experiment continued (drainage events three to six), plants increased in size and these differences became less pronounced. This may be attributed to the assimilation of nitrates by the plants or because most of the nitrate-N was already leached by earlier drainage events.

Linear regressions fitted to the data showed a high correlation between the N application rate and the amount of nitrate in the leachate from the planted pots for the first two drainage events (R^2 = 0.82 and 0.92 respectively). These correlation values however, decrease sharply with the following drainage events (R^2 = 0.04 at drainage event 6) which supported the suggestion that the decrease in nitrate-N concentration were to a very large extent due to plant assimilation. The fact that the difference between treatments disappear over time suggested that when more nitrate remains in the soil solution more nitrates will be assimilated by plants as long as water supply is sufficient as already shown by Novoa & Loomis (1981) and Van Keulen (1981).

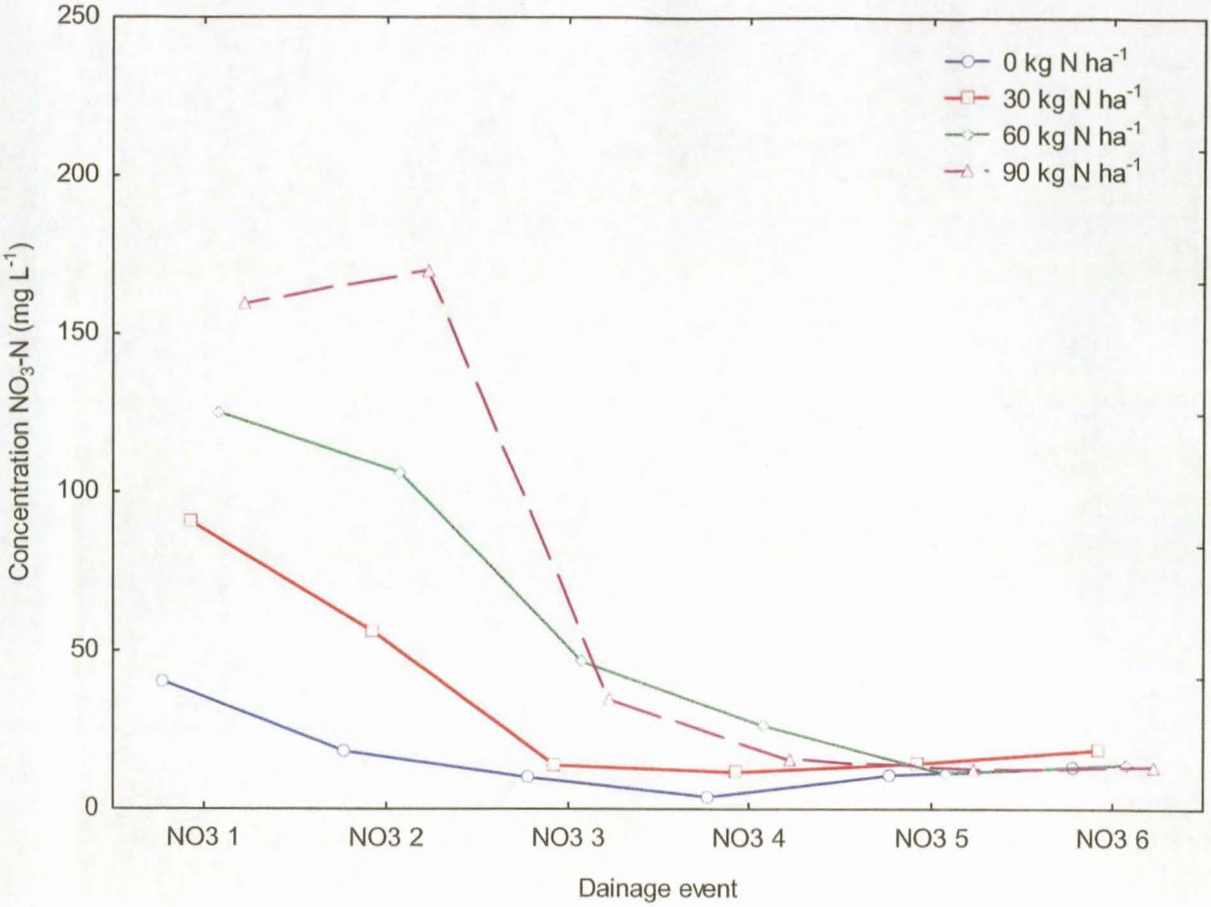

Figure 3.2 Concentration of nitrate (mg L^{-1}) in the leachate for drainage events 1 (NO3 1) to 6 (NO3 6) for the planted pots.

The concentration of nitrate-N in the drainage water stayed relatively constant at a level of approximately 20 mg L^{-1} and did not differ between N-application rates during drainage events four to six suggesting that the uptake of nitrate-N is being inhibited at these concentrations, possibly due to osmotic effects (Van Keulen,1981).

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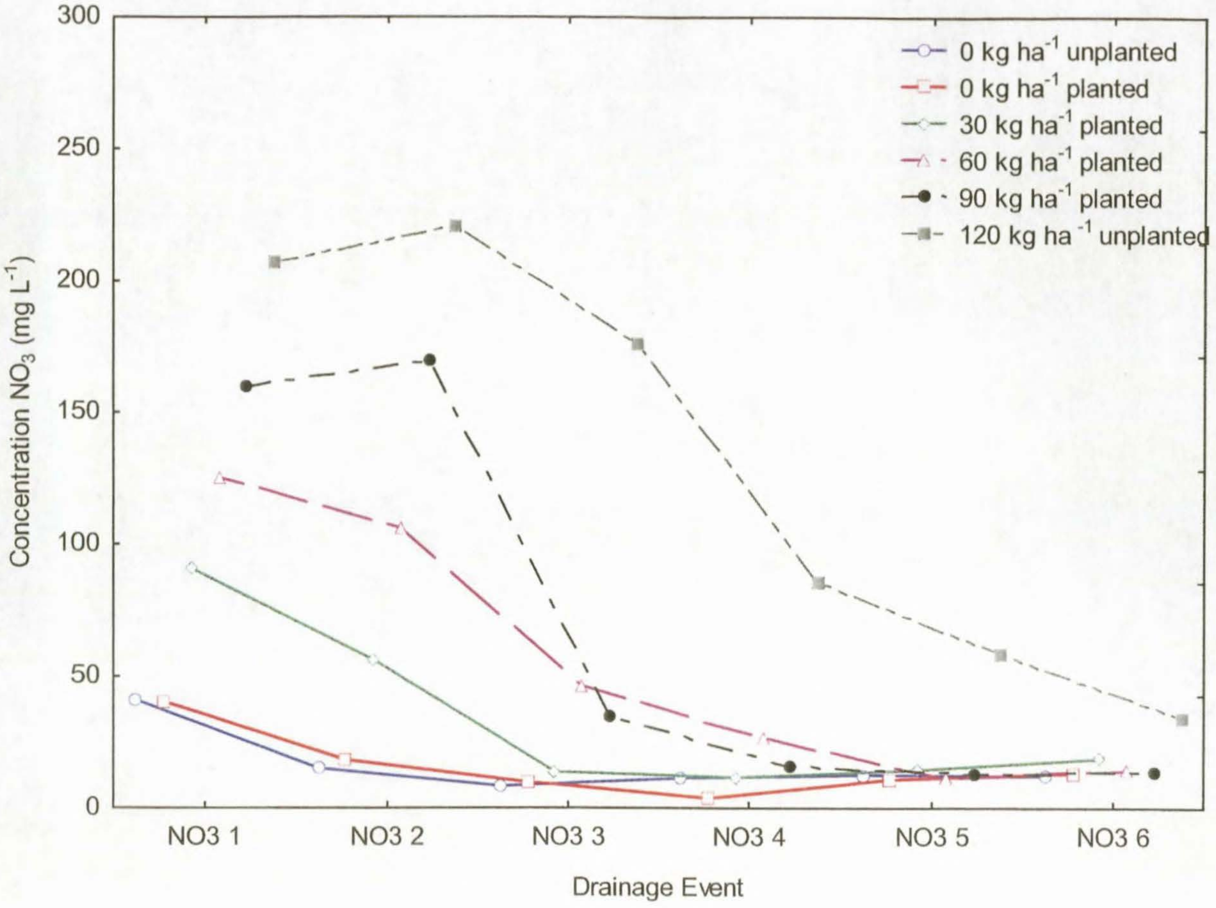

Figure 3.3 Concentration of nitrate (mg L^{-1}) collected in the leachate for drainage event 1 (NO3 1) to 6 (NO3 6) for both the planted and unplanted treatments.

When the nitrate-N concentrations in planted plots were compared to the unplanted plots, no significant differences were found between the two treatments receiving 0 kg N ha^{-1} during any of the drainage events (Figure 3.3). For all treatments which did receive N-fertilizer, nitrate-N concentration in the leachate decreased significantly with decreasing application rates during the first two drainage events. During all drainage events, the 120 kg N ha^{-1} unplanted treatment resulted in a significant higher concentration in comparison with the other treatments, but planted pots did not differ significantly during drainage events four to six, as already discussed. From Figure 3.3 it is however clear that the shape of the nitrate-N concentration curves for the planted pots receiving between 30 and 90 kg N ha^{-1} were very similar to that of the unplanted pots receiving 120 kg N ha^{-1} except for the time needed before the nitrate-N concentration in the leachate of the 120 kg ha^{-1} stabilized at a level similar to that of the planted treatments i.e. when the concentration of nitrate in the soil possibly becomes the limiting factor for uptake. The more rapid decline in nitrate concentration in the leachate for the planted pots must therefore be due to plant uptake.

In contrast to the 120 kg N ha^{-1} treatment, the concentration of nitrate-N in the leachate for the 0 kg N ha^{-1} unplanted treatment stayed more or less at the same low level during drainage events two to six, which suggested that most of the residual N in the soil at the start of the experiment was leached during the first drainage event and that very little N was mineralized during the duration of the experiment. The sharp but steady decline in nitrate concentration in the leachate from the 120 kg N ha^{-1} treatment was similar to that obtained with previous nitrate breakthrough curve studies (Caron *et al.*, 1999; De Vos, Hesterberg & Raats, 2000; Lee, Jayens & Horton, 2000). The nitrate breakthrough curves obtained in this study does not correspond to one pore volume as is expected under continuous flow (Rowell, 1994) because the flow in this trial was transient which gave the solutes the opportunity to redisperse (redistribution due to diffusion) between wetting events, thus effectively removing some of the N while merely diluting the rest of the N present in the soil solution which results in a slower absolute removal of solutes.

Dry matter production

Dry matter (DM) production was significantly (P=0.05) affected by both N-application rate (N) and irrigation regime (I) (Table 3.3). In general DM yield during the final harvest at 55 DAP increased with an increase in N-application rate from 0 to 90 kg N ha^{-1} for both irrigation regimes (Figure 3.4). In contrast to what was expected, the high irrigation regime which aimed at some nitrogen leaching resulted in higher DM production in comparison

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with the low irrigation regime which aimed at well watered but no leaching conditions. Although no significant N x I interaction occurred, the differences between irrigation regimes tended to be larger at high than at low N application rates (Figure 3.4). These results therefore confirmed the visual observations that water stress did occur with the low irrigation regime and that the intensity of stress increased with higher N-rates (larger plants that needed more water).

The absence of a significant N x I interaction indicated that the DM production response to increasing N application rates did not differ significantly between irrigation regimes. DM (g pot^{-1}) increased from 2.42 g to 4.88 g with an increase in N application rate from 0 to 90 kg N ha^{-1} with the high irrigation regime compared to an increase from 2.03 g to 3.80 g with the low irrigation regime. A steeper average growth response curve (b_1=0.78 vs 1.43) was therefore found for the high irrigation treatment compared to the low irrigation regime when a log(x) function was fitted to the data (Figure 3.4). Because only four data points were available on the x-axis, more complex models as described in Chapter 2 could not be used, but values of r^2 = 0.99 and 0.98 for the high and low irrigation regime respectively, indicated that the DM yield of canola cultivar Tornado TT in response to different N-application rates can be predicted using the following equations:

Low irrigation regime: $y = 1.99 + 1.43 \log(x)$

High irrigation regime: $y = 2.37 + 1.78 \log(x)$

Since it is not easy to compare parameters between two different models a comparison between N reactions of this trial and others will not be drawn at this stage.

Although DM yield still increased at the highest N application rate for both irrigation regimes, the response curves clearly showed a smaller response at the 90 kg N ha^{-1} application rate compared to the 30 kg N ha^{-1} rate, suggesting a lower N-use efficiency.

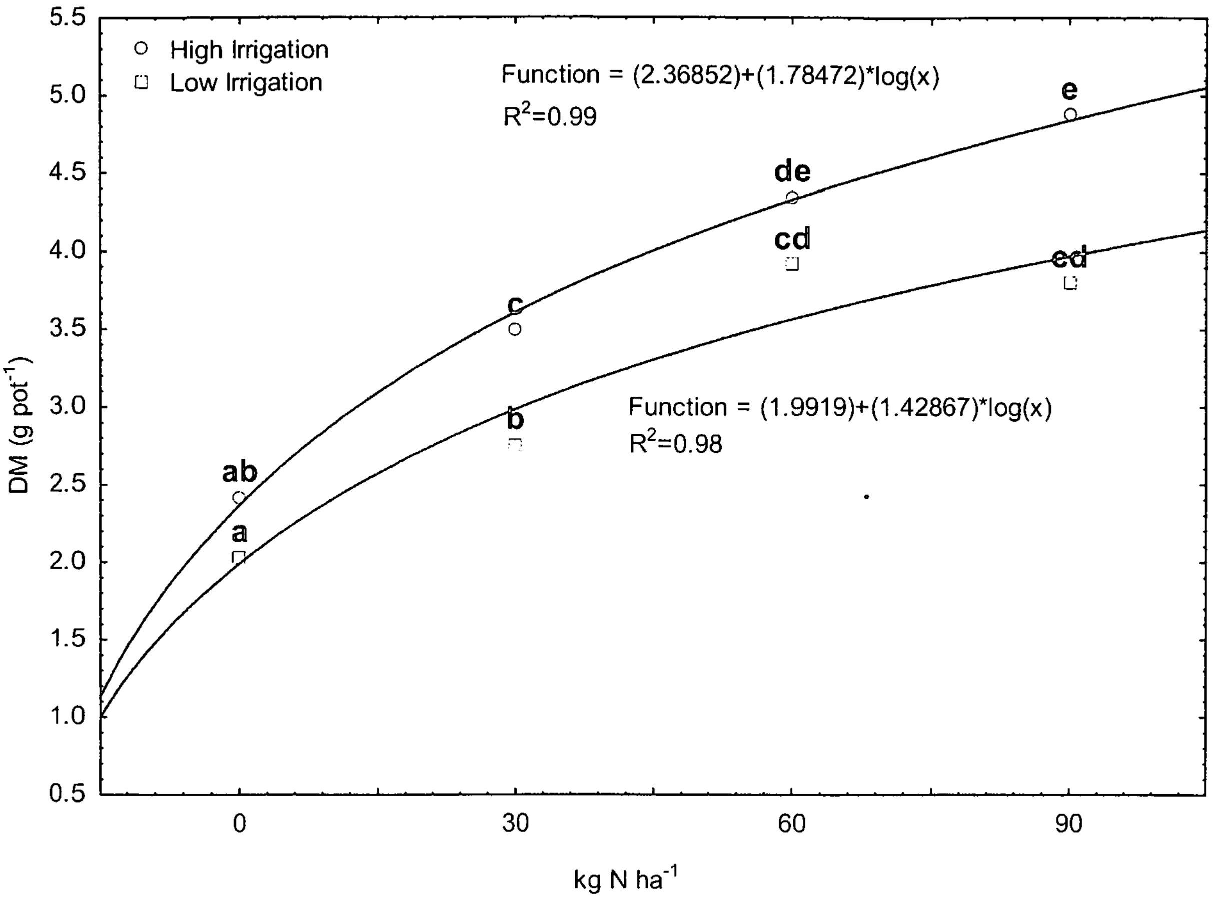

Figure 3.4 Correlation between mean dry matter (DM) production of canola and N application rate fitted with the function $Y=b_0+b_1\log x$.

Conclusion

From the data it is clear that the production of dry matter in canola is affected by the amount of nitrate available to the plant from the soil solution. It is also clear that the nitrogen response curve can be obscured by another limiting factor such as water stress, resulting in a lower efficiency of N use. Although nitrate leaching to below the active root

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zone of the plant can occur under field conditions the data shows that this may have an insignificant effect on dry matter production compared to another limiting factor such as water stress. Another factor for this seemingly insignificance may be that nitrates are taken up rapidly by canola (high nitrogen use efficiency) thus not leaving a lot of nitrates to be leached.

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Chapter 4

Reaction of canola (*Brassica napus* L.) to N fertilizer under field conditions in four contrasting environments

Aim

The objective of the field trials was to test the reaction of canola (*Brassica napus* L., cv Tornado TT and Thunder TT) growth and yield to nitrogen fertilizer rates under different climatic conditions and soil types in field trials. These trials were carried out to determine weather or not different levels of N inputs are required under different environmental conditions.

Materials and methods

Localities

The four experimental sites (Langgewens, Elsenburg, Welgevallen and Roodebloem) used during 2005 and 2006, were situated on experimental farms located throughout the high production potential areas for canola in the western and southern Cape (Canola Working Group of the Western Cape; 2001).

Langgewens (Altitude 217 m; 33°16' S, 18°42' E) is situated in the Swartland approximately 20 km north of Malmesbury. The experiment at Langgewens was planted

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on a medium sandy loam with a high content of coarse fragments and little organic matter (Table 4.1). The soil was classified as a fine non bleached, hard, non calcareous Glenrosa without signs of wetness in the B1 horison that starts at 40 cm.

In 2005 the experiment was planted during the last week of April, on a field that was cultivated, fertilized and planted with canola during 2004, but produced no crop due to the very dry conditions that prevailed during that year. Soil analysis confirmed the hypotheses that there was plenty of carry over nitrogen in the soil (Table 4.1) because of the mentioned conditions during 2004. During the 2006 season the experiment was conducted on fallow land, cultivated with a chisel plough to a depth of 15 cm in August of the fallow year and again about one month before planting at the end of April.

Elsenburg (Altitude 233 m; 33°50' S, 18°50' E) is located in the Boland wine district approximately 12 km north of Stellenbosch. Soils at Elsenburg commonly derived from sandstone overlaying Malmesbury shale. A red loamy sand Oakleaf soil with relict plinthite nodules dominating the matrix from a depth of approximately 30 cm was used during both 2005 and 2006 (Table 4.1). In both 2005 and 2006, the experiment was planted on fallow land, cultivated to a depth of 18 -20 cm during the fallow year. Inspection of the soil profile in both years, showed a clear plough pan as a thin compacted layer at a depth of 20 cm overlain by a thin layer of grey soil, indicating that a shallow water table was formed on the plough pan during wet periods, resulting in a reduction of the iron minerals and the formation of grey colours.

The Welgevallen (Altitude 104 m; 33°56' S, 18°51' E) experimental farm is in Stellenbosch and the soils are situated on the alluvial plain of the Eersteriver. The soil is a non red fine sandy loam Tukulu with massive structure in the dry condition (Table 4.1). In 2005 the

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experiment was conducted on the outer edges of the alluvial plain on a particularly homogeneous soil (without coarse material and river boulders) that was sown to wheat under irrigation during the summer of 2004/2005 with the result that large quantities of wheat stubble were left on the field at the beginning of the canola planting season. During 2006 a non red non luvic coarse Tukulu soil with better drainage that was also planted with wheat during preceding season was used. Seedbed preparation was done by chisel and disc ploughing in both years.

The Roodebloem (Altitude 262 m; 34°14'S, 19°32'E) experimental farm is situated about 15 km south east of Caledon. Parent material of most of the soils in this area is a mixture of sandstone and Bokkeveld shale. The experiment was in both 2005 and 2006 planted on a fine loamy sand non bleached, not hard, non calcareous Glenrosa with signs of wetness in the B1 starting at 40 cm and an abundance of coarse fragments dominating the topsoil matrix (Table 4.1). The field used in 2005 had a 20% slope and was sown to legume pastures during the preceding years. The site used in 2006 was further from the mountain, with result that the slope was less pronounced and was planted with wheat the year before.

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Table 4.1 Chemical properties of the soil (0-30 cm depth) used for field trials during the 2005 and 2006 seasons at different localities Langgewens, Elsenburg, Welgevallen and Roodebloem

		Langgewens		Elsenburg		Welgevallen		Roodebloem	
	Unit	**2005**	**2006**	**2005**	**2006**	**2005**	**2006**	**2005**	**2006**
pH	KCl	4.9	5	5.8	5.3	5.9	4.8	5.5	5.6
EC	mS cm^{-1}	1.6	1.23	1.1	1.69	0.5	1.23	0.4	1.41
Ca	$cmol_c$ kg^{-1}	4.30	2.03	1.68	3.22	0.74	2.34	2.04	4.74
Mg	$cmol_c$ kg^{-1}	1.56	0.65	0.87	0.65	0.21	0.5	1.15	0.99
K	mg kg^{-1}	118	121	108	112	120	110	50	112
Na	mg kg^{-1}	13	14	25	14	8	13	18	31
P	mg kg^{-1}	25	72	22	39	46	148	25	35
NH_4-N	mg kg^{-1}	22	3.50	3.64	3.84	14	3.67	6.82	0.51
NO_3-N	mg kg^{-1}	19	20	13	33	31	18	3.71	20
Mineral N	mg.kg^{-1}	41	24	17	37	45	22	11	21

Climate

Climatic data (source: ARC Infruitech Nietvoorbij) for 2005 & 2006 are summarized in Figures 4.1 – 4.8 showing the monthly rainfall and daily cumulative class A pan evaporation minus rainfall (cumulative rainfall deficit) for each site as calculated according to the method of Wright, Smith & Woodroofe (1988). As no on site climatic data for Welgevallen and Roodebloem were available, data from nearby weather stations (Nietvoorbij and Boontjieskraal respectively) were used.

Figure 4.1 shows the monthly rainfall for 2005 & 2006 at Langgewens. Although there is not much difference in the total April to October rainfall between 2005 and 2006 (342 vs 347 mm) it seems that the rainfall was more evenly distributed during 2006 compared to 2005. Rainfall before planting (April) during 2006 was less than in 2005 and higher rainfall during July 2005 would ensure more favourable conditions during flowering and early pod set phases during 2006. Total monthly rainfall during September and October were somewhat higher in 2006 compared to 2005, indicating more favourable conditions during grain filling stages. High rainfall during May 2006 would encourage vigorous vegetative growth but also leaching potential of nitrogen.

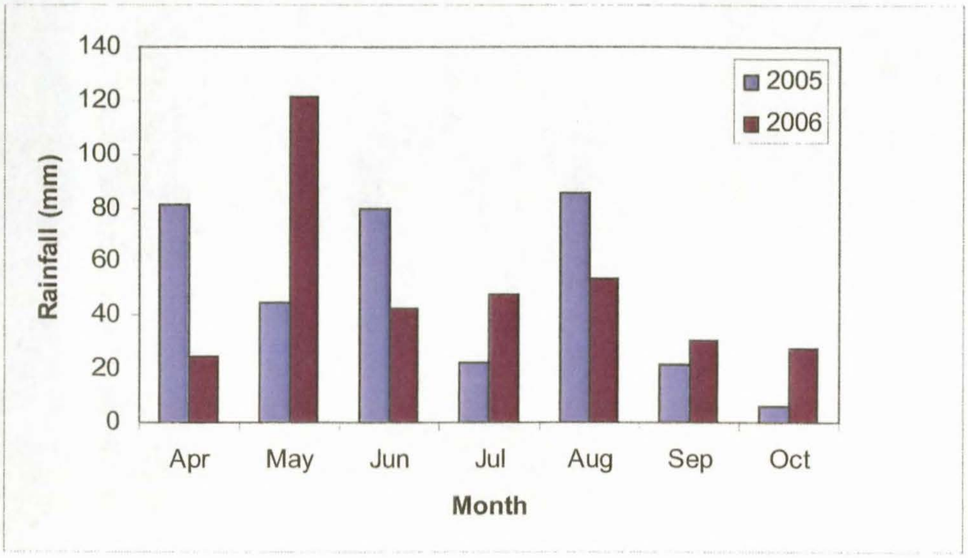

Figure 4.1 Monthly rainfall (mm) at Langgewens during the 2005 & 2006 growth season.

From the cumulative daily rainfall deficit (evaporation minus rainfall) displayed in Figure 4.2 for Langgewens it became clear that differences between seasons were relatively small although deficits were somewhat larger in 2006 compared to 2005 during the 40 to 70 days after planting (DAP) and 110 to 160 DAP periods.

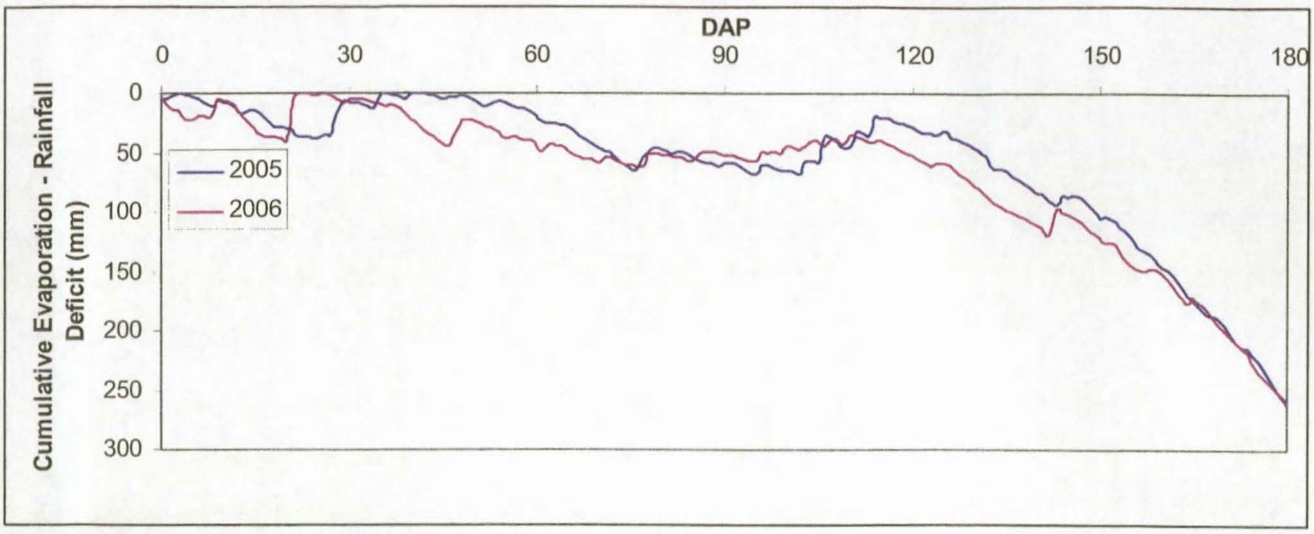

Figure 4.2 Cumulative daily rainfall deficit at days after planting (DAP) for Langgewens during the 2005 and 2006 growing seasons.

The total monthly rainfall at Elsenburg during the 2005 & 2006 growth season is displayed in Figure 4.3 Total April to October rainfall during 2006 was slightly higher than that during 2005 (555 vs 543 mm). Although the rainfall during April 2006 was, as also found at Langgewens, slightly less than 2005, much higher rainfall were experienced during May 2006 and the rainfall during October was almost double that of 2005.

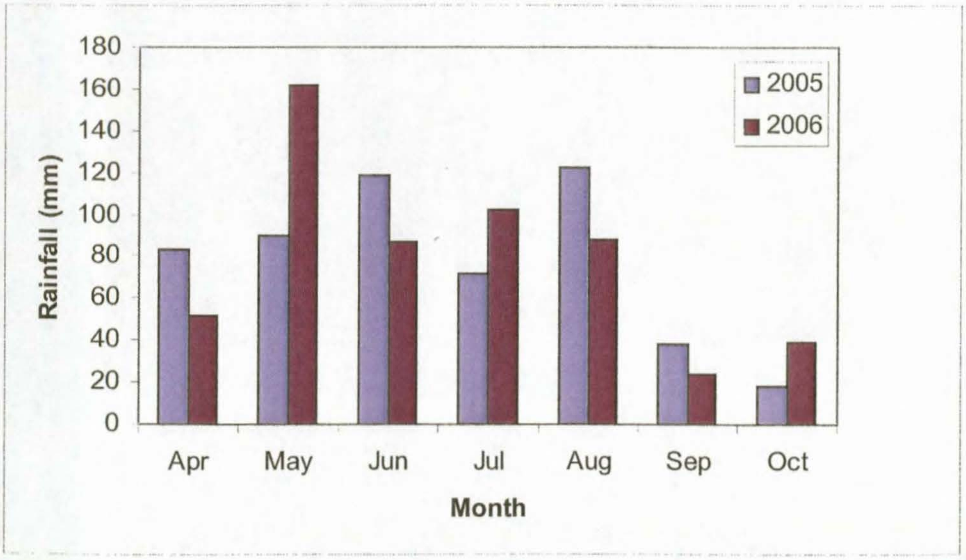

Figure 4.3 Monthly rainfall (mm) at Elsenburg during the 2005 & 2006 growth season.

From the cumulative daily rainfall deficit (Figure 4.4) it can be seen that the period directly after planting was somewhat drier in 2006 compared to 2005, while a higher rainfall deficit was experienced during the period around 70 DAP during the 2005 season compared to the 2006 season. During the latter grain filling and ripening phases from 120 DAP to harvest, larger rainfall deficits were experienced during 2006 compared to 2005.

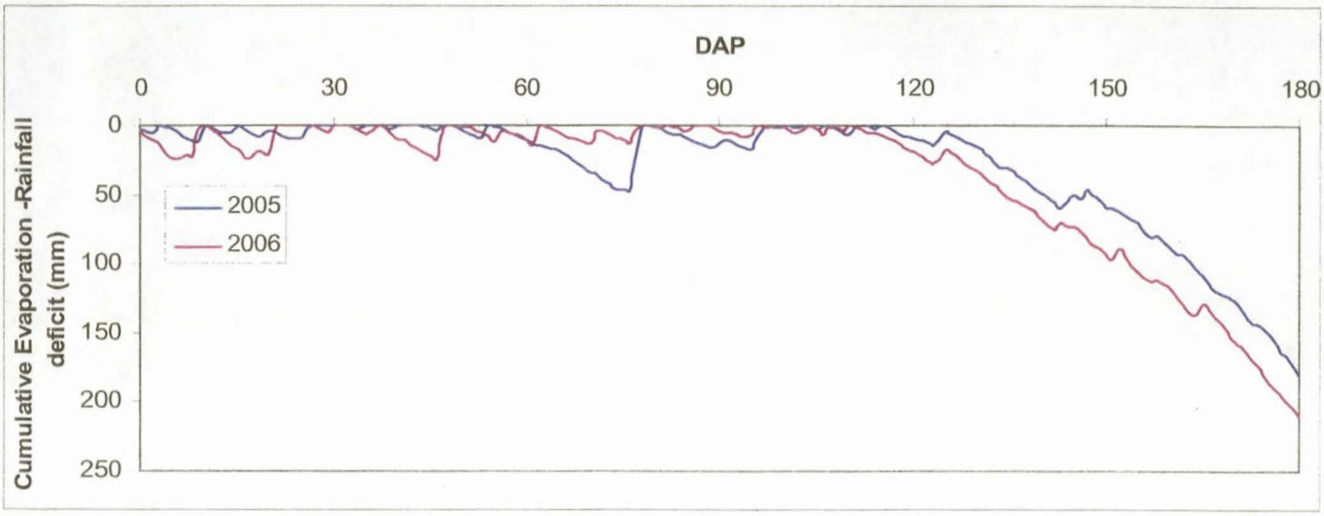

Figure 4.4 Cumulative daily rainfall deficits at days after planting (DAP) for Elsenburg during the 2005 and 2006 growing seasons.

The total April to October rainfall at Welgevallen (Nietvoorbij) during 2006 was 624 mm compared to 644 mm during 2005 (Figure 4.5). Once again May and July received higher rainfall in 2006 than in 2005, while June and August were much wetter during 2005, with little differences during September and October.

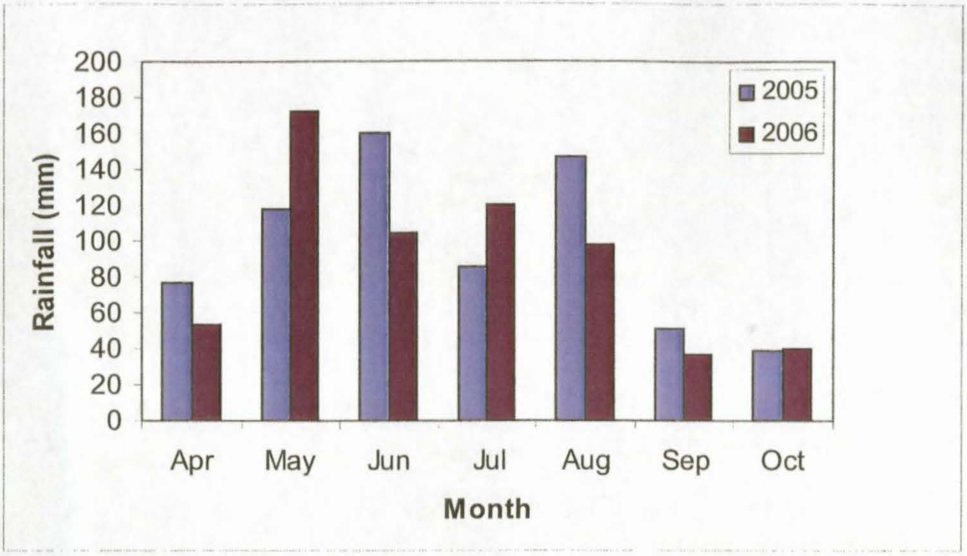

Figure 4.5 Rainfall (mm) at Welgevallen (Nietvoorbij) during the 2005 & 2006 growing season.

From the cumulative rainfall deficit at Welgevallen (Figure 4.6) it can be seen that the two years had very similar rainfall deficits except for the slightly drier period during the first ten days after planting during 2006 and the drier period during 2005 around 70 DAP.

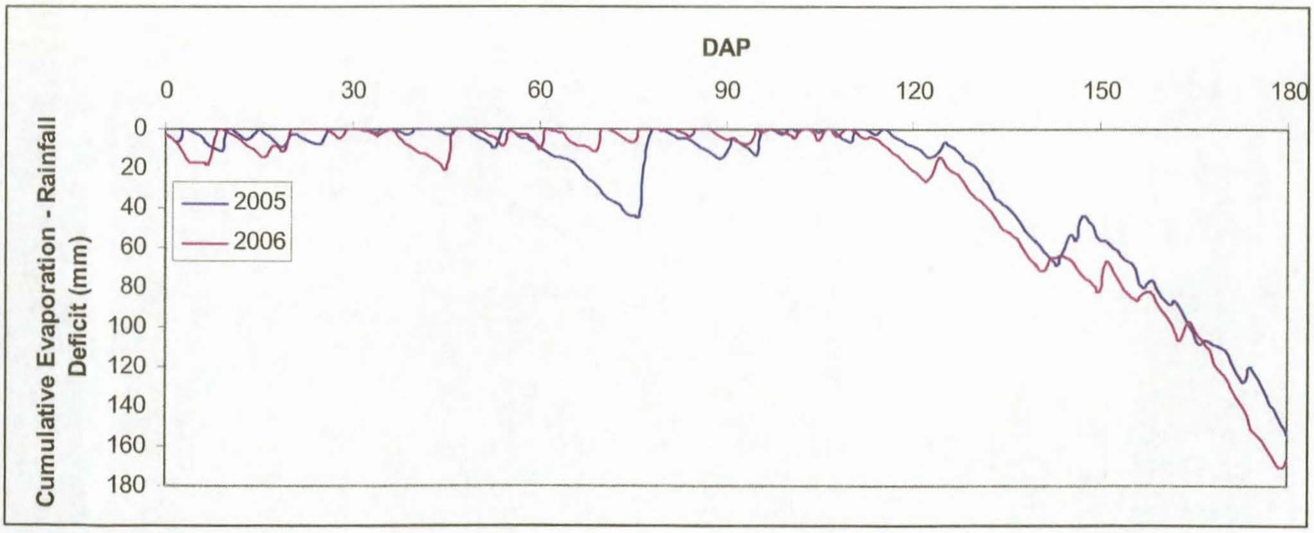

Figure 4.6 Cumulative rainfall deficit at days after planting (DAP) for Welgevallen (Nietvoorbij) during the 2005 and 2006 growing seasons.

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The total April to October rainfall at Roodebloem (Boontjieskraal) during 2005 was only 20 mm less (313 vs 332 mm) than the rainfall received during 2006 (Figure 4.7), but the distribution differed substantially. April 2005 for instance, was an extremely wet month for this area with a rainfall of more than 120 mm, which suggested that the total rainfall for the rest of the season was less than 200 mm, with very dry conditions during July. During 2006 the highest monthly rainfall was received during July and August.

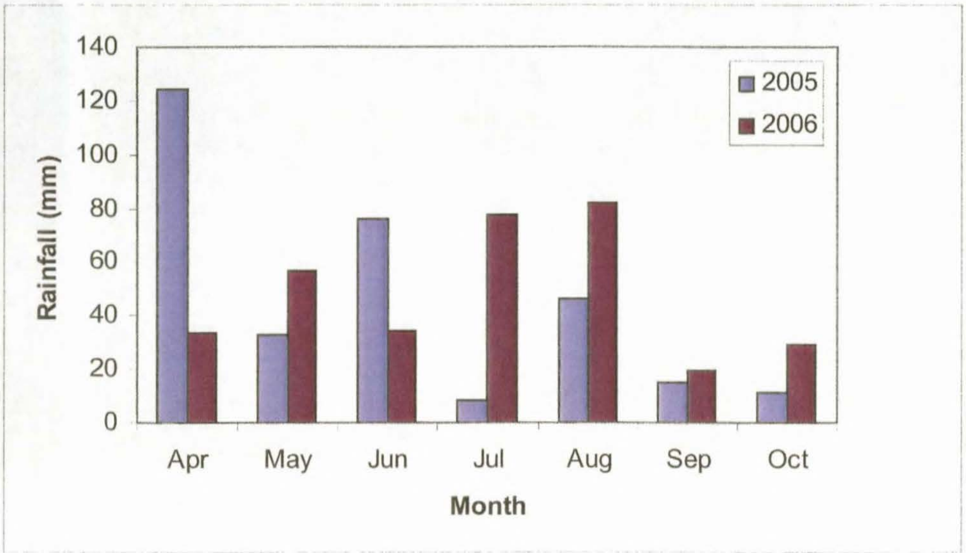

Figure 4.7 Rainfall (mm) at Roodebloem (Boontjieskraal) during the 2005 & 2006 growing season.

From Figure 4.8 it is clear that 2005 was much drier after 80 DAP largely due to higher rainfall during July and August 2006 resulting in a final deficit of 190 mm in 2006 compared to a final deficit of 351 mm at 180 DAP during 2005.

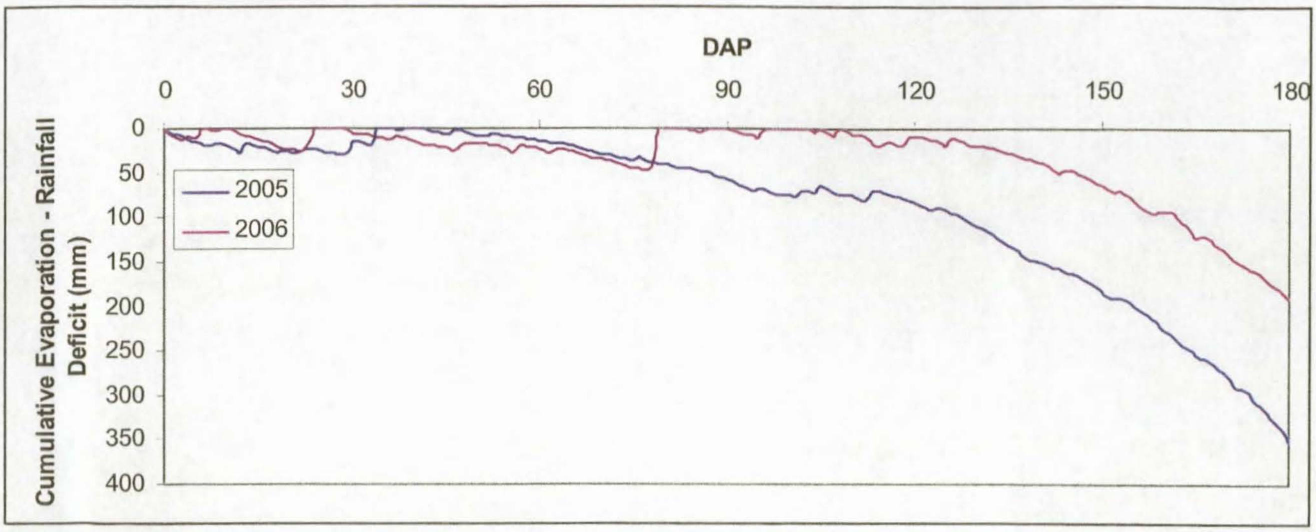

Figure 4.8 Cumulative rainfall deficit at days after planting (DAP) for Roodebloem (Boontjieskraal) during the 2005 and 2006 growing seasons.

Rainfall data therefore showed that both the total April to October as well as the distribution there-of differed substantially between localities, with Welgevallen and Elsenburg receiving significantly more rain compared to Langgewens and Roodebloem. Total April to October rainfall did not differ much between years, but did differ with regard to distribution.

Agronomic practices

Because canola is a fine seeded crop, a well prepared and weed free seedbed is required. For this reason final seedbed preparation was done by either disc or tine harrows, while herbicides with active ingredients like simazine or glyphosate were applied as needed. Planting were done with a plot-planter fitted with tine openers 17 cm apart and presswheels. As already mentioned, all experiments were planted during the last week in April or the first week in May at a seeding rate of 4 kg ha^{-1}. Canola cultivars Tornado TT and Thunder TT were used during 2005 and 2006 respectively.

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Fertilization (with the exception of N) was done according to the soil analyses (Table 4.1). The pH and EC for al the sites were well within the limits for the production of canola in both 2005 and 2006. The phosphate contents for Elsenburg, Langgewens and Roodebloem were low and corrections were made by adding 18, 18 and 30 kg P ha^{-1} respectively as single superphosphate before planting commenced. In 2006, 12 and 14 kg P ha^{-1} were applied as superphosphate before planting at Elsenburg and Roodebloem respectively. Additionally 30 kg S ha^{-1} were given to all sites as $CaSO_4$ in 2006.

Weed, disease and insect control were done if necessary. To prevent bird damage, experiments at Welgevallen and Elsenburg were covered by netting during the grain filling stage.

Nitrogen treatments & experimental design

Eleven treatments, consisting of a control (0 kg N ha^{-1}) and five nitrogen treatments (30, 60, 90, 60+60 and 120 kg N ha^{-1}) in combination with two application methods, each replicated four times in a randomized block design were used (Table 4.2). At the time of planting N was either broadcast (B) as LAN or placed below the seed (P) as liquid ammoniumnitrate. The balances of the nitrogen to be received by treatments were broadcast as LAN at 30 day intervals as shown in Table 4.2 Plots sizes of 1.38 m × 5 m x 2 were used, from which one 1.38 m × 5 m area was used for plant samplings and the other 1.38 m × 5 m area to determine the grain yield.

Table 4.2 Nitrogen application rates (kg ha^{-1}) for different treatments and time of application in days after planting (DAP)

Treatment	DAP 0	DAP 30	DAP 60	DAP 90	Total
Control	0				**0**
30 B	30 Broadcast				**30**
60 B	30 Broadcast	30			**60**
90 B	30 Broadcast	30	30		**90**
60+60 B	30 Broadcast	30	60		**120**
120 B	30 Broadcast	30	30	30	**120**
30 P	30 Banded				**30**
60 P	30 Banded	30			**60**
90 P	30 Banded	30	30		**90**
60 +60 P	30 Banded	30	60		**120**
120 P	30 Banded	30	30	30	**120**

Data collected

Plant density

In 2005 the number of plants per plot was determined (eq. 4.1) by counting the number of plants in one meter in one row. The count was then multiplied by five (5 m row length) and then by eight (eight rows per plot).

$$\text{Plants per plot} = \text{count} \times 5 \times 8 \qquad [4.1]$$

From this the number of plants m^{-2} was calculated using the equation 4.2:

$$\text{Plants per square metre} = \frac{\text{Plants per plot}}{(1.38\,\text{m} \times 5\,\text{m})} \qquad [4.2]$$

During 2006 the plant density was determined by counting the plants in 0.5 m^{-2} and then calculated the plants m^{-2}.

Dry matter production (DM), N concentration and N accumulation in the plant material

Plant samples were collected three times during the 2005 season to calculate the production of biomass for each treatment. The samples were taken by randomly selecting 10 plants from each treatment and cutting the plants off as close to the soil surface as possible. The samples were then put into a blower oven at 68°C until dry. The samples were then weighed and milled. Samples were taken at 60, 90 and 120 days after planting.

Total N content (Kjeldahl) of the milled samples were done at the Elsenburg analytical laboratory. From the N concentration found in the plant material N accumulation was calculated by using DM and multiplying this figure by the percentage N in the plant material.

Due to the absence of any treatment effects during 2005, no DM samplings were conducted at 60 and 90 DAP during 2006, but only at 120 days after planting and the biomass sampling method was revised to incorporate a larger number of plants per sampling unit. Half a square metre of plants per treatment were cut at the soil surface. The plants were put into a bag and taken to the laboratory where the plants where weighed. From the total amount of plants collected per treatment 5 plants were taken out, weighed, cut into pieces and put into a blower oven to dry. After the plants were dried they were

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weighed again to calculate the ratio between the wet and dry mass. This ratio was then used to calculate the dry mass of the total number of plants collected and dry mass per square metre.

Nitrogen fertilizer use efficiency

Nitrogen fertilizer use efficiency was expressed in four different ways:

i) Nitrogen use efficiency at 120 DAP (NUE120) was expressed as g dry matter produced per g N added according to Novoa and Loomis (1981):

$$\text{NUE120}(\text{g DM g N}^{-1}) = \frac{\text{DM}(\text{g m}^{2}) - \text{DM control}(\text{g m}^{2})}{\text{N added}(\text{g m}^{2})} \qquad [4.3]$$

ii) Apparent N recovery (ANR) in the plant material (plant and seed) was calculated according to Novoa and Loomis (1981):

$$\text{ANR}(\%) = \frac{\text{N accumulated}(\text{kg ha}^{-1}) - \text{N accumulated control}(\text{kg ha}^{-1})}{\text{N fertilizer applied}(\text{kg ha}^{-1})} \times 100 \qquad [4.4]$$

iii) Nitrogen use efficiency (NUE) was calculated according to Stapper and Fischer (1990):

$$\text{NUE}(\text{kg seed kg N accumulated}^{-1}) = \frac{\text{Grain yield}(\text{kg ha}^{-1})}{\text{N accumulated}(\text{kg ha}^{-1})} \qquad [4.5]$$

iv) Agronomic efficiency (AE) was calculated according to Smith *et al.* (1988):

$$\text{AE (kg seed kg N applied}^{-1}\text{)} = \frac{\text{Grain yield (kg ha}^{-1}\text{)} - \text{Grain yield control (kg ha}^{-1}\text{)}}{\text{N fertilizer applied (kg ha}^{-1}\text{)}} \qquad [4.6]$$

Yield and quality

At the end of the season the grain was harvested with a small combine harvester, designed for the harvesting of the plots. The grain was cleaned and then weighed to calculate the grain yield per hectare. Thousand seed weight was calculated by measuring the weight of 500 kernels and multiplying this figure by two. Due to excessive bird damage at Elsenburg during 2005 this site was harvested by cutting out 0.75 m^2 of plants. The grain was then thrashed from of the pods and weighed to calculate grain yield per hectare. Oil and protein content of the seed were again determined at the Elsenburg analytical laboratory, using an infralyzer.

Data analysis

The data were analysed as a factorial design with nitrogen application rates and application method combinations (N) and localities (L) as factors, using STATISTICA version 7.0 (Statistica, 2004). Student's t-LSD (P= 0.05) test was used to compare treatment means.

Results and discussion

Table 4.3 shows the Pr>F values for different measurements and their interactions during the 2005 season. The number of plants m^{-2}, were significantly affected by different localities only. Dry matter (DM) production was significantly affected by localities during the first two sampling times and by localities and N treatments during the third sampling. Nitrogen use efficiency in DM at 120 days after planting (NUE 120), N content (%N) and apparent N recovery (ANR) showed significant interactions between locality and N treatments, while the mass of N accumulated in the biomass (N acc) was only significantly affected by different localities and N treatments. Yield, NUE in seed and agronomic efficiency (AE) were significantly affected by different localities, but AE was also affected by different N treatments. Quality parameters such as thousand seed weight (TSW), % protein and % oil in the seed were significantly affected by locality, while % protein and % oil were also affected by N treatments.

Table 4.3 Pr>F Values for nitrogen treatments (N), localities (L) and the interaction N x L of measurements taken during the 2005 season

	Plant density	DM 60	DM 90	DM 120	NUE120	%N	N acc	ANR	Yield	NUE	AE	TSW	Protein	Oil
N	0.871	0.153	0.077	0.018	<0.01	0.266	0.010	<0.01	0.371	0.054	<0.01	0.560	<0.01	0.019
L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
N x L	0.713	0.468	0.133	0.270	<0.01	<0.01	0.311	<0.01	0.252	0.298	0.095	0.669	0.684	0.925

The Pr>F values for different measurements and their interactions during 2006 are summarized in Table 4.4 As also found in 2005, all properties measured showed significant differences due to locality, which clearly illustrated the dominant effect of the environment (climatic and soil conditions) on the growth, yield, quality and efficiency of canola. Several properties such as DM 120, %N, N acc, yield, protein and oil were however also significantly affected by N treatments. As found in 2005, very few properties showed any interaction between locality and N treatment. The response to N treatments therefore did not differ between localities for most properties tested except %N, ANR, yield, TSW and protein.

Table 4.4 Pr>F Values for nitrogen treatments (N), localities(L) and the interaction N x L of measurements taken during the 2006 season

	Plant density	DM 120	NUE120	%N	N acc	ANR	Yield	NUE	AE	TSW	Protein	Oil
N	0.355	<0.01	0.676	<0.01	<0.01	0.077	<0.01	0.404	0.382	0.061	<0.01	0.015
L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
N x L	0.299	0.422	0.636	0.046	0.325	0.005	<0.01	0.224	0.551	<0.01	0.019	0.101

Plant density

Plant density was affected by locality in both 2005 and 2006, but not as a result of N treatments (Table 4.5) which indicated that the application of 30 kg N ha^{-1} (broadcasted as LAN or bandplaced as liquid ammonium nitrate) did not have any harmful effect on the germinating seed. In 2005 the plant density at all locations varied between a mean of 68 plants m^{-2} at Welgevallen and 89 plants m^{-2} at Roodebloem, while in 2006 the plant densities varied between a mean of 46 plants m^{-2} at Langgewens and 113 plants m^{-2} at Elsenburg. With the exception of Langgewens 2006, plant densities were therefore within or higher than the recommended (Canola working group, 2001) range of 50-80 plants m^{-2} needed for maximum yields. High densities found at Elsenburg during 2006 and to a lesser extent at Roodebloem during 2005, might enhance inter-plant competition and thereby reduced possible DM responses to N-treatments. Using the same argument, slightly less than optimum plant densities at Langgewens during 2006 might on the other hand favour possible responses to N treatments.

Table 4.5 Plant densities (plants m^{-2}) in the 2005 and 2006 seasons for various nitrogen application combinations at Langgewens (L), Elsenburg (E), Welgevallen (W) and Roodebloem (R)

N treatment	Season									
	2005					2006				
	L	E	W	R	Mean	L	E	W	R	Mean
0	78	73	59	82	**73**	48	131	90	74	**86**
30 B	68	76	73	111	**82**	54	120	83	73	**82**
30 P	84	63	79	83	**77**	32	106	80	98	**79**
60 B	63	74	66	89	**73**	53	111	82	79	**81**
60 P	71	77	63	87	**75**	38	106	85	80	**77**
90 B	71	65	66	81	**71**	68	109	77	74	**82**
90 P	67	75	69	84	**74**	38	100	71	79	**72**
60+60 B	71	85	59	83	**75**	50	112	95	73	**82**
60+60 P	67	75	79	91	**78**	45	115	72	101	**83**
120 B	63	72	75	83	**73**	46	122	95	71	**83**
120 P	63	82	64	102	**78**	37	108	72	65	**70**
Mean	**70*a***	**74*a***	**68*a***	**89*b***	**75**	**46*a***	**113*c***	**82*b***	**79*b***	**80**

Dry matter production

During 2005, dry matter (DM) production differed significantly due to locality at all sampling dates with the lowest DM production obtained from Roodebloem (Table 4.6). Even at 120 days after planting (Table 4.7), a mean DM production of only 4.61 t ha^{-1} was obtained at this locality. Highest DM production was obtained from Welgevallen with a mean of 11.43 t ha^{-1} at 120 days after planting. At this stage Langgewens and Elsenburg recorded mean DM productions of 5.51 and 10.20 t ha^{-1} respectively. These productions were generally in the same order of magnitude than what have been reported by Hocking *et al.* (1997) and Wright *et al.* (1988). Although the control treatments (0 kg N ha^{-1}) tended to produce less

DM on average during all sampling dates, differences were significant at 120 days after planting only. At this sampling date the control plots yielded on average only 5.72 t ha^{-1} compared to average DM productions of 9.21 t ha^{-1} where 90 kg N ha^{-1} was applied. Although DM production tended to reach a maximum where 90 kg N ha^{-1} was applied, differences between different N treatments were not significant.

Table 4.6 Dry matter (DM) production (g m^{-2}) at 60 and 90 DAP in the 2005 season for various nitrogen application combinations at Langgewens (L), Elsenburg (E), Welgevallen (W) and Roodebloem (R)

N treatment	**60 DAP**					**90 DAP**				
	L	**E**	**W**	**R**	**Mean**	**L**	**E**	**W**	**R**	**Mean**
0	88.4	61.1	73.2	38.1	**65.2**	446.8	200.1	292.3	159.3	**274.6**
30 B	82.2	72.4	102.4	53.2	**77.6**	743.7	177.1	348.4	279.9	**387.3**
30 P	66.6	58.2	84.4	53.0	**65.6**	620.4	212.0	400.3	195.8	**357.1**
60 B	73.8	87.4	127.8	60.2	**87.3**	641.8	275.1	342.2	259.0	**379.5**
60 P	85.7	93.4	96.8	49.1	**81.3**	980.9	322.0	391.0	279.2	**493.3**
90 B	90.1	74.5	98.1	41.3	**76.0**	649.8	256.7	312.2	302.3	**380.3**
90 P	67.2	70.7	112.9	47.3	**74.5**	669.0	309.1	356.1	262.2	**399.1**
60+60 B	79.4	86	79.6	48.5	**73.4**	627.4	394.6	329.4	280.0	**407.9**
60+60 P	89.0	63.8	152.8	59.4	**91.3**	650.8	258.7	452.1	331.1	**423.2**
120 B	95.9	78.9	120.5	49.0	**86.1**	551.3	307.9	404.4	283.2	**386.7**
120 P	65.1	85.6	83.3	56.3	**72.6**	471.7	405.7	284.8	451.6	**403.5**
Mean	**80.3*b***	**75.6*b***	**102.9*c***	**50.5*a***	**77.3**	**641.2*c***	**283.5*a***	**355.7*b***	**280.3*a***	**390.2**

During the sampling at 120 days after planting (Table 4.7) DM production was significantly affected by both localities and N-treatments in 2006. Langgewens produced on average the most DM (9.59 t ha^{-1}) and Welgevallen the least (5.96 t ha^{-1}). Low DM production at Welgevallen in spite of the more favourable rainfall conditions during 2006, may be

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ascribed to the more sandy soil and high coarse material content in the subsoil of the experimental site used in 2006, which might have resulted in lower soil fertility, soil water retention and more N leaching during the growth season.

In general DM again tended to increase with increasing N application rates from 0 kg N ha^{-1}, but level off at rates of 60 to 90 kg N ha^{-1} and in some cases even showed a decrease at rates of 120 kg N ha^{-1}. Differences due to increasing N rates were however very inconsistent and with the exception of the 90 kg N ha^{-1} rate, no significant difference due to application method (banded v. broadcasted) were found. Treatments which received between 60 kg N ha^{-1} and 120 kg N ha^{-1} (except the 90 P treatment) therefore produced significantly more DM than the control, while the 60+60 P and the 90 B treatments produced significantly more DM than treatments which received 30 kg N ha^{-1} and less.

Table 4.7 Dry matter (DM) production (g m^{-2}) at 120 DAP in the 2005 and 2006 seasons for various nitrogen application combinations at Langgewens (L), Elsenburg (E), Welgevallen (W) and Roodebloem (R)

N treatment	**Season**									
	2005					**2006**				
	L	**E**	**W**	**R**	**Mean**	**L**	**E**	**W**	**R**	**Mean**
0	9.36	2.95	5.57	3.72	**5.40**	8.26	5.01	4.07	5.53	**5.72*a***
30 B	9.62	4.90	11.79	5.22	**7.88**	8.78	8.01	4.20	7.09	**7.02*abc***
30 P	10.39	3.41	11.78	3.79	**7.34**	8.13	8.18	3.85	7.14	**6.82*ab***
60 B	9.40	6.50	10.16	5.72	**7.95**	9.62	9.06	6.71	9.60	**8.75*cde***
60 P	12.26	4.56	11.25	4.58	**8.16**	7.95	7.07	8.14	9.48	**8.16*bcde***
90 B	10.59	5.77	11.13	5.01	**8.12**	14.06	9.66	5.91	8.12	**9.44*e***
90 P	10.40	5.39	12.65	4.16	**8.15**	7.07	8.27	5.65	8.65	**7.41*abcd***
60+60 B	11.27	7.05	10.91	4.20	**8.36**	10.62	7.32	6.60	8.93	**8.37*bcde***
60+60 P	10.10	6.45	14.84	5.46	**9.21**	10.33	9.12	7.05	13.55	**10.01*e***
120 B	9.91	7.50	15.69	3.59	**9.17**	12.04	9.36	7.48	8.23	**9.28*de***
120 P	8.94	6.23	10.04	5.31	**7.63**	8.68	9.15	5.96	8.83	**8.15*bcde***
Mean	**10.20*b***	**5.52*a***	**11.44*c***	**4.61*a***	**7.94**	**9.59*c***	**8.20*b***	**5.96*a***	**8.65*cb***	**8.10**

Because no difference in DM production was found due to the method of N application, the DM data of 2005 and 2006 was compounded to show only the data for the different N application rates before a model was fit to the data. When the DM data of 2005 and 2006 was fitted with the function $y = b_0 + b_1x + b_2x^2$ good R^2 values were obtained (eq. 4.7 – 4.14). This indicates that a good correlation between DM (y) and N application rate (x) exists across locations even though the response was very small as can be seen from the small b_2 values and the insignificant differences between treatments in Table 4.7. Regression equations and values of R^2 for 2005 for different localities are given in eq. 4.7 – 4.10 and equations and R^2 values for 2006 are given in eq. 4.11 – 4.14:

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Langgewens: $y = 9.3 + 0.038x - 0.00026x^2$ $R^2 = 0.93$ [4.7]

Elsenburg: $y = 3.0 + 0.043x - 0.00010x^2$ $R^2 = 0.96$ [4.8]

Welgevallen: $y = 6.5 + 0.127x - 0.00065x^2$ $R^2 = 0.79$ [4.9]

Roodebloem: $y = 3.8 + 0.032x - 0.00021x^2$ $R^2 = 0.83$ [4.10]

Langgewens: $y = 8.1 + 0.014x + 0.00006x^2$ $R^2 = 0.85$ [4.11]

Elsenburg: $y = 5.3 + 0.082x - 0.00045x^2$ $R^2 = 0.91$ [4.12]

Welgevallen: $y = 3.8 + 0.052x - 0.00024x^2$ $R^2 = 0.60$ [4.13]

Roodebloem: $y = 5.6 + 0.069x - 0.0003x^2$ $R^2 = 0.85$ [4.14]

It was possible to create a single equation to accommodate the rate of change between different localities and between both seasons as can be seen from the small differences of b_1 and b_2 values across locality and season. These equations for both seasons separately and together are given in eq. 4.15 – 4.17 and displayed in Figure 4.9. The problem in creating an equation for the response of canola to N fertilizer rates is the large differences in b_0 i.e. the DM production when no N is applied (production potential). This value of b_0 which varied between 3.0 at Elsenburg and 9.3 at Langgewens in 2005 and between 3.8 at Welgevallen and 8.1 at Langgewens in 2006, will always differ between localities due to differences in climate and soil from one season to the next. The challenge is thus to create a model to predict b_0 using different soil and climatic parameters.

2005: $y = 5.62 + 0.0599x + 0.000307x^2$ $R^2 = 0.97$ [4.15]

2006: $y = 5.68 + 0.0543x + 0.000231x^2$ $R^2 = 0.93$ [4.16]

Both seasons: $y = 5.65 + 0.0571x + 0.000269x^2$ $R^2 = 0.97$ [4.17]

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Y = DM; x = N application rate

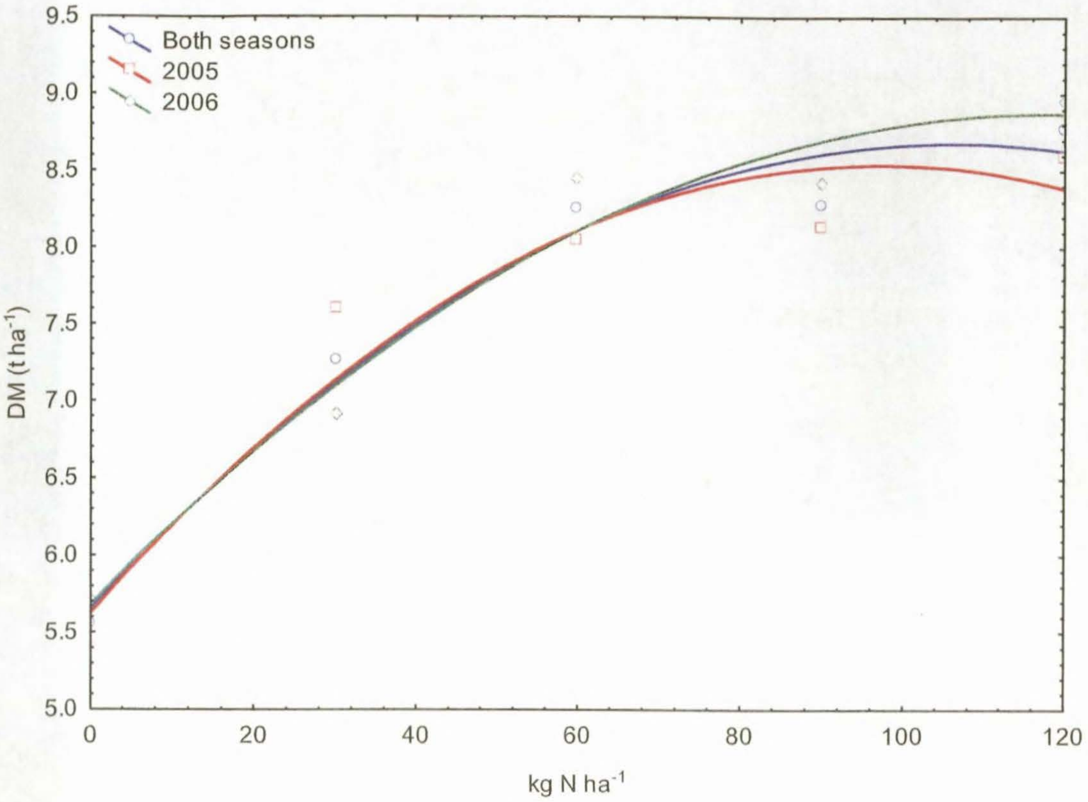

Figure 4.9 Scatterplot of DM (t ha^{-1}) for different N application rates (kg N ha^{-1}) during 2005, 2006 and during both seasons fitted with the function $y = b_0 + b_1x + b_2x^2$.

As can be seen from Figure 4.9 the difference in average response of DM to increasing N application rates between 2005 and 2006 is very small. From Figure 4.9 the response curve seem to flatten at around the 90 kg N ha^{-1} mark. It is also clear that the difference in DM production between the control and the 90 kg N ha^{-1} is about 3 tonnes which would make the response approximately 1 t of DM for every 30 kg N applied. Similar responses were reported by Hocking *et al.* (1997) and Wright *et al.* (1988). More data of similar experiments across seasons and different regions are however needed to verify and refine this trend.

Nitrogen use efficiency at 120 DAP (NUE120)

Although significant differences in N use efficiency (g DM produced per g N applied) were found at all localities in both years, no clear trends emerged (Table 4.8). In some cases negative values were even found because the control (0 kg N applied) yielded more DM that the plots where N was applied. These results clearly indicated that although DM production showed very good correlations with N application rate (Eq 4.7 – 4.17), responses were small and variable. Mean values however did indicate a decrease in N use efficiency at 120 DAP with increasing N application rates in both years.

Table 4.8 Nitrogen use efficiency at 120 DAP (NUE120, g DM g N^{-1}) in the 2005 and 2006 seasons for various nitrogen application combinations at Langgewens (L), Elsenburg (E), Welgevallen (W) and Roodebloem (R)

N treatment	**Season**									
	2005					**2006**				
	L	**E**	**W**	**R**	**Mean**	**L**	**E**	**W**	**R**	**Mean**
0	N/A	N/A	N/A	N/A	**N/A**	N/A	N/A	N/A	N/A	**N/A**
30 B	8.7_{ab}	$65.2_{b\text{-}f}$	207.2_{g}	$50.5_{a\text{-}f}$	**82.9*c***	17.3	100.2	4.1	52.0	**43.4**
30 P	$34.4_{a\text{-}f}$	15.3_{abc}	206.9_{g}	2.8_{ab}	**64.8*bc***	-4.2	105.7	-7.4	53.8	**37.0**
60 B	0.7_{ab}	$59.1_{a\text{-}f}$	$76.4_{c\text{-}f}$	$33.6_{a\text{-}f}$	**42.5*ab***	22.8	67.5	44.0	67.9	**50.5**
60 P	$48.3_{a\text{-}f}$	$26.8_{a\text{-}d}$	94.5_{f}	14.5_{abc}	**46.1*ab***	-5.1	34.3	67.7	65.8	**40.7**
90 B	13.7_{abc}	$31.4_{a\text{-}f}$	$61.7_{a\text{-}f}$	14.4_{abc}	**30.3*a***	64.5	51.7	20.4	28.7	**41.3**
90 P	11.6_{abc}	$27.1_{a\text{-}d}$	$78.6_{c\text{-}f}$	5.0_{ab}	**30.6*a***	-13.2	36.2	17.5	34.8	**18.8**
60+60 B	15.9_{abc}	$34.2_{a\text{-}f}$	$44.5_{a\text{-}f}$	4.0_{ab}	**24.7*a***	19.7	19.3	21.0	28.4	**22.1**
60+60 P	6.2_{abc}	$29.2_{a\text{-}f}$	$77.2_{c\text{-}f}$	14.6_{abc}	**31.8*ab***	17.3	34.3	24.8	66.8	**35.8**
120 B	4.6_{ab}	$37.9_{a\text{-}f}$	84.3_{def}	-1.0_{ab}	**31.5*ab***	31.5	36.2	28.4	22.5	**29.7**
120 P	-3.5_{a}	$27.4_{a\text{-}f}$	$37.2_{a\text{-}f}$	13.4_{abc}	**18.6*a***	3.5	34.5	15.7	27.5	**20.3**
Mean	**14.1*a***	**35.3*b***	**96.9c**	**15.2*ab***	**40.4**	**15.4*a***	**52.0*c***	**23.6*ab***	**44.8*bc***	**34.0**

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Nitrogen concentration in plant material (%N)

Due to the fact that there were no significant differences between nitrogen application method for DM, samples were compounded and analysis for percentage N in the plant material were only conducted for different locations and application rates (Table 4.9).

Although significant N application rate x locality interactions were found in both years and even mean values did differ significant, no clear trends with regard to N application rate were shown for individual localities. On average %N in plant material at 120 DAP seem to decrease with an increase in N rate from 0 to 30 kg N ha^{-1}, but increased with further increases in N application rates in both years. All values were comparable with these obtained by Hocking *et al.* (1997) and Smith, Wright & Woodroofe (1988) and mean values of N concentration in the plant material varied between 2.51% and 2.84% in 2005 and 1.82% and 2.16% in 2006.

Table 4.9 Concentration of N in the plant material (N%) at 120 DAP in the 2005 and 2006 season for various nitrogen application rates at Langgewens (L), Elsenburg (E), Welgevallen (W) and Roodebloem (R)

N treatment	**Season**									
	2005					**2006**				
	L	**E**	**W**	**R**	**Mean**	**L**	**E**	**W**	**R**	**Mean**
0	$2.74_{b\text{-}h}$	$2.84_{c\text{-}h}$	$2.36_{a\text{-}d}$	$2.44_{a\text{-}d}$	**2.59*ab***	1.99_{def}	$2.19_{e\text{-}h}$	1.60_{abc}	1.61_{abc}	**1.85*a***
30	$2.60_{b\text{-}g}$	$2.75_{b\text{-}h}$	$2.40_{a\text{-}d}$	$2.34_{a\text{-}d}$	**2.51*a***	1.89_{cde}	$2.31_{f\text{-}i}$	1.56_{abc}	1.53_{ab}	**1.82*a***
60	$3.05_{e\text{-}i}$	$2.57_{b\text{-}f}$	1.88_{a}	$3.14_{f\text{-}i}$	**2.66*ab***	2.39_{ghi}	2.09_{efg}	1.38_{ab}	1.65_{abc}	**1.88*a***
90	$2.90_{d\text{-}i}$	$2.46_{a\text{-}e}$	2.23_{ab}	3.27_{hi}	**2.72*ab***	2.50_{hi}	2.14_{efg}	1.42_{ab}	1.71_{bcd}	**1.94*a***
60+60	3.31_{hi}	2.28_{abc}	$2.33_{a\text{-}d}$	3.45_{i}	**2.84*b***	2.37_{ghi}	2.34_{ghi}	1.36_{a}	1.88_{cde}	**1.99*a***
120	$3.18_{g\text{-}i}$	$2.66_{b\text{-}g}$	$2.50_{b\text{-}e}$	$2.90_{d\text{-}i}$	**2.81*ab***	2.61_{i}	2.44_{ghi}	1.60_{abc}	1.99_{def}	**2.16*b***
Mean	**2.98*c***	**2.57*b***	**2.27*a***	**2.96*c***	**2.69**	**2.32*c***	**2.26*c***	**1.48*a***	**1.74*b***	**1.95**

Nitrogen accumulation in the plant material

In 2005 the control plants accumulated 14.04 g N m^{-2} or 140.4 kg ha^{-1} on average, despite the fact that no N was applied (Table 4.10). This was however significant less than all treatments receiving more than 30 kg N ha^{-1}. N accumulation increased with increasing N application rates and the highest accumulation of 25.39 g N m^{-2} or 253.9 kg N ha^{-1} was obtained with the 60+60 P treatment. Accumulated N for this treatment was therefore more than double the application of 120 kg N ha^{-1}. Method of application did not have any effect on N accumulation. On average canola grown at Langgewens accumulated the most N (30.13 g N m^{-2}) and canola grown at Roodebloem accumulated the least (13.79 g N m^{-2}) despite having the highest concentration of N in the plant material.

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Table 4.10 N accumulated in the plant material (g N m^{-2}) at 120 DAP in the 2005 season for various nitrogen application combinations at Langgewens (L), Elsenburg (E), Welgevallen (W) and Roodebloem (R)

N treatment	**Season**									
	2005					**2006**				
	L	**E**	**W**	**R**	**Mean**	**L**	**E**	**W**	**R**	**Mean**
0	25.45	8.52	13.11	9.07	**14.04*a***	16.86	10.61	6.45	9.04	**10.74*a***
30 B	24.37	13.70	27.80	12.19	**19.52*abc***	16.91	18.51	6.38	10.82	**13.15*bc***
30 P	26.91	9.40	29.20	8.86	**18.59*ab***	16.20	19.27	6.04	10.86	**13.09*bc***
60 B	28.39	16.83	19.03	17.89	**20.54*bcd***	22.50	19.44	9.31	15.78	**16.76*bcd***
60 P	36.68	11.88	21.04	16.35	**20.49bcd**	19.20	14.75	11.18	15.67	**15.20*bc***
90 B	30.60	14.25	25.16	17.45	**21.87bcd**	35.01	20.63	8.31	14.14	**19.52*d***
90 P	29.99	13.28	27.46	13.71	**21.11bcd**	17.70	17.64	8.19	14.63	**14.54*abc***
60+60 B	37.16	16.72	24.71	14.58	**23.29bcd**	25.39	17.25	8.93	16.90	**17.12*bcd***
60+60 P	32.85	14.37	35.43	18.90	**25.39*d***	24.49	21.55	9.69	25.19	**20.23*d***
120 B	30.90	19.34	37.81	9.66	**24.43cd**	30.83	22.96	12.16	16.43	**20.60*d***
120 P	28.10	16.68	23.43	15.05	**20.82*bcd***	22.67	21.71	9.50	17.76	**17.91*cd***
Mean	**30.13*c***	**14.09*a***	**25.83*b***	**13.79*a***	**21.00**	**22.52*d***	**18.58*c***	**8.74*a***	**15.20*b***	**16.26**

On average N accumulation in the plant material at 120 DAP during 2006 were less than that of 2005 and varied between 10.74 g m^{-2} where no nitrogen was applied and about 20 g m^{-2} or 200 kg ha^{-1} where 120 kg N was applied, but this was due to a much lower accumulation at Welgevallen due to soil and climatic factors already discussed. Accumulation at Langgewens were again the highest namely 22.52 g N m^{-2} or 225.2 kg N ha^{-1}, but all values of N accumulated in plant material at 120 DAP in this study were much higher than that reported by Smith *et al.* (1988).

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Apparent N recovery (ANR)

As also found with regard to N use efficiency in the plant material at 120 DAP, apparent N recovery (ANR) also showed large variations and despite significant differences, no clear trends when individual localities are considered (Table 4.11).

On average Welgevallen showed the highest apparent N recovery (ANR) of 212.6% in 2005 and Langgewens (58.3%) the lowest. Across all localities mean apparent recovery rates of more than 100% were obtained from all treatments receiving 30 and 60 kg N ha^{-1} during 2005. On average ANR decreased to less than 100% when application rates were increased from 60 to 90 and 120 kg N ha^{-1} and a mean ANR of only 56.5% was obtained where 120 kg N ha^{-1} was applied with 30 kg N liquid ammonia-nitrate band placed at planting. This data suggested that application rates of more than 60 kg N ha^{-1} is supra optimal as further increases in application rate results in an efficiency of less than 100% and consequent wasting of resources. Smith *et al.* (1988) also recorded ANR values of 60 to 80% for irrigated canola, but much lower values for rainfed crops.

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Table 4.11 Apparent N recovery (ANR) at 120 DAP (%) in the 2005 season for various nitrogen application combinations at Langgewens (L), Elsenburg (E), Welgevallen (W) and Roodebloem (R)

N treatment	Season									
	2005					2006				
	L	E	W	R	Mean	L	E	W	R	Mean
0	N/A	N/A	N/A	N/A	**N/A**	N/A	N/A	N/A	N/A	**N/A**
30 B	-36.0$_{a}$	172.5$_{bcd}$	489.7$_{e}$	103.8$_{a-d}$	**182.5**	0.0	333.0	0.0	64.5	**99.4*bc***
30 P	48.6$_{a-d}$	29.4$_{a-d}$	536.6$_{e}$	-7.3$_{ab}$	**151.8**	80.8	358.2	0.0	78.5	**129.4*c***
60 B	49.0$_{a-d}$	138.5$_{a-d}$	98.8$_{a-d}$	146.9$_{a-d}$	**108.3**	0.0	182.0	3.4	111.8	**74.3*abc***
60 P	187.2$_{cd}$	56.0$_{a-d}$	132.2$_{a-d}$	88.0$_{a-d}$	**115.9**	1.9	103.8	15.8	116.5	**59.5*ab***
90 B	57.2$_{a-d}$	63.7$_{a-d}$	134.0$_{a-d}$	93.1$_{a-d}$	**87.0**	106.2	134.6	0.0	57.5	**74.6*abc***
90 P	50.5$_{a-d}$	52.9$_{a-d}$	159.6$_{a-d}$	51.5$_{a-d}$	**78.6**	0.6	101.3	2.5	61.7	**41.5*a***
60+60 B	97.6$_{a-d}$	68.3$_{a-d}$	96.7$_{a-d}$	45.9$_{a-d}$	**77.1**	40.1	72.8	0.0	65.2	**44.5*ab***
60+60 P	61.6$_{a-d}$	48.8$_{a-d}$	186.0$_{cd}$	81.9$_{a-d}$	**94.6**	30.9	108.6	4.0	134.3	**69.4*ab***
120 B	45.4$_{a-d}$	94.3$_{a-d}$	205.9$_{d}$	4.9$_{bcd}$	**87.6**	62.7	120.4	8.5	61.3	**63.2*ab***
120 P	22.1$_{a-d}$	68.0$_{a-d}$	86.1$_{a-d}$	49.8$_{a-d}$	**56.5**	24.9	110.0	0.0	72.3	**51.8*ab***
Mean	**58.3*a***	**79.2*a***	**212.6*b***	**65.9*a***	**104.0**	**34.8*a***	**162.5*c***	**3.4*a***	**82.4*b***	**70.8**

During 2006 the highest mean ANR of 162.5% was obtained at Elsenburg and the lowest mean value of only 3.4% at Welgevallen. Very low ANR values at Welgevallen were due to the combined effect of small DM production responses to N application and the decrease in %N in the DM with increasing N application rates. Apparent nitrogen recovery (ANR) rates of more than 100% were again obtained at low (30 kg N ha^{-1}) nitrogen application rates indicating that the uptake of both applied and residual soil N were enhanced by these applications. As found in 2005, ANR decreased with increasing N application rates reaching values of even less than 50%.

Seemingly impossibly high ANR of more than 100% may be ascribed to the deep rooting depth of canola which can enable the plant to take up nitrogen present in the subsoil that is beyond the reach of many other plants. It has been reported by Ward, Dunin & Micin (2002) that canola roots can exceed 1 m. Especially following a deep rooted crop such as lucerne. Merrill, Tanaka & Hanson (2002) also reported rooting depths past 1 metre in a haplustol on the great plains. Merill *et al.* (2004) reports the active extraction of water by canola up to 1.8 m, once more in a haplustol while Kristenson & Thorup-Kristenson (2004) found a good correlation between root frequency and nitrate uptake ($r^2 = 0.95$) in fodder radish, where root intensity was measured with a minirhizotron.

In a non quantitative investigation on the rooting depth of canola planted at all four localities during 2006, it was found that canola roots are very persistent and reaching depths of up to one metre and possibly beyond (Plate 4.1 & 4.2). Even dense shale in Glenrosa soil forms did not seem to give much resistance (Plate 4.3) however, wetness identified by grey matrix colours and mottling seemed to be a limiting factor on the rooting depth (Plate 4.4).

Plate 4.1 Soil profile at Welgevallen showing roots, insert indicating maximum visible rooting depth.

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Plate 4.2 Soil profile at Elsenburg showing roots, insert indicating maximum visible rooting depth.

Plate 4.3 Soil profile at Langgewens showing roots, insert indicating maximum visible rooting depth.

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Plate 4.4 Soil profile at Roodebloem showing roots, insert indicating maximum visible rooting depth.

Grain yield

Mean grain yields of 1.87 and 1.92 t ha^{-1} were obtained in 2005 and 2006 respectively, but yields for different localities varied largely (Table 4.12). In 2005 the highest yields of 2.26 t ha^{-1} were produced at Welgevallen which showed the smallest cumulative rainfall deficit. On average, Langgewens yielded 1.87 t ha^{-1} and Roodebloem 1.71 t ha^{-1}. Although situated in an area with high rainfall Elsenburg only yielded 1.64 t ha^{-1}. Although no significant differences were found between nitrogen application rates, the control tended to yield less on average compared to treatments which did receive nitrogen fertiliser. No differences were again obtained with different methods of application and on average yields tended to increase with increasing nitrogen application rates, to reach a maximum at rates of 90 kg N ha^{-1}. Trends for individual localities were however very inconclusive.

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Table 4.12 Grain yield (t ha^{-1}) in the 2005 and 2006 seasons for various nitrogen application combinations at Langgewens (L), Elsenburg (E), Welgevallen (W) and Roodebloem (R)

N treatment	Season									
	2005					2006				
	L	E	W	R	Mean	L	E	W	R	Mean
0	1.98	1.23	2.15	1.41	**1.69**	1.70_{c-g}	2.51_{h-n}	0.96_{a}	1.50_{b-e}	**1.67*ab***
30 B	2.06	1.82	2.12	1.65	**1.91**	1.45_{a-d}	2.71_{j-n}	1.20_{abc}	1.41_{a-d}	**1.69*abc***
30 P	1.97	1.57	2.20	1.44	**1.80**	1.65_{c-f}	2.21_{g-j}	1.08_{ab}	1.55_{b-e}	**1.62*a***
60 B	1.87	1.57	2.21	1.81	**1.87**	1.43_{a-d}	2.92_{n}	2.10_{f-i}	1.32_{a-d}	**1.94*cd***
60 P	1.97	1.81	2.17	1.68	**1.91**	1.46_{a-d}	2.75_{k-n}	2.00_{e-h}	1.41_{a-d}	**1.91*bcd***
90 B	1.97	1.59	2.18	1.85	**1.90**	1.41_{a-d}	2.89_{mn}	2.31_{h-k}	1.46_{a-d}	**2.02*d***
90 P	1.96	1.84	2.54	1.70	**2.01**	1.41_{a-d}	2.84_{lmn}	2.20_{g-j}	1.68_{c-f}	**2.03*d***
60+60 B	1.75	1.79	2.26	1.82	**1.91**	1.38_{a-d}	2.71_{j-n}	2.38_{h-m}	1.50_{b-e}	**1.99*d***
60+60 P	1.97	1.58	2.14	1.92	**1.90**	1.42_{a-d}	2.71_{j-n}	2.58_{i-n}	1.71_{c-f}	**2.11*d***
120 B	1.55	1.69	2.46	1.75	**1.86**	1.45_{a-d}	2.77_{k-n}	2.34_{h-l}	1.58_{b-e}	**2.03*d***
120 P	1.56	1.57	2.44	1.78	**1.84**	1.44_{a-d}	2.54_{i-n}	2.51_{h-n}	1.74_{d-f}	**2.06*d***
Mean	**1.87*b***	**1.64*a***	**2.26*c***	**1.71*a***	**1.87**	**1.47*a***	**2.69*d***	**1.97*c***	**1.53*b***	**1.92**

In 2006, highest yields were obtained at Elsenburg (mean of 2.69 t ha^{-1}), followed by Welgevallen with a yield of 1.96 t ha^{-1} while Roodebloem yielded 1.53 t ha^{-1} and Langgewens despite its high biomass (959.3 g m^{-2}) only 1.47 t ha^{-1}. At Langgewens and Elsenburg N application did not have any effect on yield, but on all other localities tested yields were significantly increased by N applications. Optimal N rates were however different for different localities and trends were again very inconclusive, but maximum yields were once again obtained with an application of 90 -120 kg N ha^{-1}.

In an effort to get clearer trends, grain yield data of 2005 and 2006 were, as was done with DM data, compounded to show only the data for the different N application rates and then subjected to different regression analysis models.

When the function $y = b_0 + b_1x + b_2x^2$ where X = N application rate and Y = grain yield, was fit to the data strong correlations ($R^2 > 0.80$) between N application rate and grain yield were obtained for most localities in both 2005 (eq. 4.18-4.21) and 2006 (eq. 4.22-4.25). The only exceptions were Welgevallen 2005 and Elsenburg and Roodebloem 2006:

Langgewens: $y = 1.97 + 0.002x - 0.36 \times 10^{-4}x^2$ $R^2 = 0.83$ [4.18]
Elsenburg: $y = 1.28 + 0.013x - 0.80 \times 10^{-4}x^2$ $R^2 = 0.89$ [4.19]
Welgevallen: $y = 2.14 + 0.001x + 0.45 \times 10^{-5}x^2$ $R^2 = 0.78$ [4.20]
Roodebloem: $y = 1.40 + 0.007x - 0.27 \times 10^{-4}x^2$ $R^2 = 0.98$ [4.21]

Langgewens: $y = 1.58 - 0.006x + 0.30 \times 10^{-4}x^2$ $R^2 = 0.99$ [4.22]
Elsenburg: $y = 2.25 + 0.008x - 0.45 \times 10^{-4}x^2$ $R^2 = 0.61$ [4.23]
Welgevallen: $y = 0.79 + 0.019x - 0.49 \times 10^{-4}x^2$ $R^2 = 0.93$ [4.24]
Roodebloem: $y = 1.39 + 0.003x + 0.35 \times 10^{-4}x^2$ $R^2 = 0.72$ [4.25]

As can also be seen in Table 4.12, grain yields where no N was applied (b_0), as was the case for DM, varied largely between different localities, illustrating differences in soil fertility levels and climatic conditions. Although b_1 and b_2 values for grain yield varied largely, these values are generally small, illustrating small yield responses to N applications at all localities. The larger variation compared to DM may be due to the fact that greater differences in cumulative rainfall deficit exists between sites toward the end of the season than at 120 DAP when DM was measured.

When data from different localities and even different years are pooled the following models (eq. 4.26-4.28) explained 88 and 95% of the yield responses to nitrogen applications obtained during 2005 and 2006 in areas which yielded less than 2.0 ton ha^{-1}.

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2005: $y = 1.70 + 0.0057x - 0.35 \times 10^{-4}x^2$ $R^2 = 0.95$ [4.26]

2006: $y = 1.50 + 0.0044x - 0.74 \times 10^{-5}x^2$ $R^2 = 0.88$ [4.27]

Both seasons: $y = 1.60 + 0.0050x - 0.21 \times 10^{-4}x^2$ $R^2 = 0.95$ [4.28]

More data and especially for areas with higher yield potentials are however needed to verify the model.

Nitrogen use efficiency (NUE)

Nitrogen use efficiency (kg grain produced per kg N accumulated in DM at 120 DAP) did vary between localities in both years, but were not affected by N application rate or application method (Table 4.13). During 2005 highest NUE was obtained at Roodebloem (mean of 14.2) and Elsenburg (mean of 14.0) and the lowest at Langgewens (6.9 kg grain produced per kg N accumulated).

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Table 4.13 Nitrogen use efficiency (NUE, kg grain produced per kg N accumulated) in the 2005 season for various nitrogen application combinations at Langgewens (L), Elsenburg (E), Welgevallen (W) and Roodebloem (R)

N treatment	**Season**									
	2005					**2006**				
	L	E	W	R	**Mean**	L	E	W	R	**Mean**
0	8.4	16.7	20.6	15.7	**15.4**	10.7	24.9	19.0	18.8	**18.36**
30 B	8.7	16.1	8.0	14.8	**11.9**	8.7	15.2	33.9	13.5	**17.8**
30 P	9.0	19.0	8.8	16.3	**13.3**	18.3	12.4	20.2	15.3	**16.6**
60 B	6.8	9.5	12.0	10.3	**9.7**	6.4	17.9	26.4	9.2	**15.0**
60 P	5.5	16.3	12.0	12.1	**11.5**	8.2	18.8	18.4	11.4	**14.2**
90 B	7.7	14.6	9.6	14.4	**11.6**	4.2	14.1	28.4	11.5	**14.6**
90 P	6.8	16.2	9.3	13.9	**11.6**	9.1	16.2	33.3	11.7	**17.6**
60+60 B	5.1	15.2	10.5	14.4	**11.3**	6.5	16.3	27.1	9.5	**14.9**
60+60 P	6.6	11.2	7.2	11.1	**9.0**	6.7	13.2	28.7	7.3	**14.0**
120 B	5.6	8.8	6.6	20.0	**10.2**	5.2	12.5	20.1	10.2	**12.0**
120 P	6.0	9.9	11.0	13.1	**10.0**	6.9	12.3	27.0	10.2	**14.1**
Mean	**6.9*a***	**14.0*c***	**10.5*b***	**14.2*c***	**11.4**	**8.3*a***	**15.8*c***	**25.7*d***	**11.7*b***	**15.4**

During 2006 the highest NUE of 25.7 kg grain produced per kg N accumulated was obtained at Welgevallen, while Langgewens again showed the lowest NUE of 8.3 kg grain produced per kg N accumulated. This shows that despite the fact that Langgewens accumulated significantly more N during the growing period because of high DM productions, higher grain yields were produced at Welgevallen. This tendency clearly indicated that climate – and especially rainfall deficit towards the end of the season, has a larger effect on grain production than the amount of N accumulated by the plant at 120 DAP. In general NUE decreases with increasing N application rates and were less than that reported by Hocking *et al.* (1997). This may be an indication that the accumulation of nitrogen and DM production was generally not the limiting factors for grain production in this study. Low grain yields and poor growth responses to N fertilizer obtained in this study may therefore most possibly be ascribed to conditions during the grain filling phase which limited NUE's.

Agronomic efficiency (AE)

The agronomic efficiency (AE) illustrated the use of applied N for grain production. On average very low values of 2.9 and 2.8 kg grain per kg N applied were obtained during 2005 and 2006 respectively (Table 4.14). On average AE tended to decrease with increasing N application rates in 2005, but not in 2006. During 2005 the highest mean AE was obtained at Elsenburg (7.1 kg grain per kg N), while the highest mean AE during 2006 was obtained at Wegevallen (12.7 kg grain per kg N). The seemingly large reaction of canola to applied N at Welgevallen may be due to the fact that applications were split over 90 days which meant that treatments receiving lower application rates were fertilized fewer times during the season which may have resulted in a large portion of N being leached. Nitrogen supply was therefore spread over a longer period with treatments receiving higher N application rates. In both years mean AE for Langgewens were negative, indicating that grain yield on average decreased with an increase in N application rate.

Table 4.14 Agronomic efficiency (AE, kg grain yield per kg N applied) in the 2006 season for various nitrogen application combinations at Langgewens (L), Elsenburg (E), Welgevallen (W) and Roodebloem (R)

N treatment	**Season**									
	2005					**2006**				
	L	**E**	**W**	**R**	**Mean**	**L**	**E**	**W**	**R**	**Mean**
0	N/A	N/A	N/A	N/A	**N/A**	N/A	N/A	N/A	N/A	**N/A**
30 B	2.7	19.5	-0.9	8.1	**7.3**	-8.4	6.6	7.9	-3.0	**0.8**
30 P	-0.5	11.3	1.7	0.9	**3.4**	-1.6	-10.0	4.1	1.7	**-1.4**
60 B	-1.8	5.6	0.9	6.6	**2.9**	-4.6	6.9	19.0	-3.0	**4.6**
60 P	-0.1	9.7	0.3	4.5	**3.6**	-4.0	4.1	17.3	-1.4	**4.0**
90 B	-0.1	4.0	0.4	4.9	**2.3**	-3.3	4.2	15.0	-0.4	**3.9**
90 P	-0.2	6.8	4.4	3.2	**3.6**	-3.2	3.6	13.8	2.0	**4.1**
60+60 B	-1.9	4.7	0.9	3.4	**1.8**	-2.7	1.7	11.8	0.0	**2.7**
60+60 P	-0.1	2.9	-0.1	4.3	**1.8**	-2.3	1.7	13.5	1.7	**3.6**
120 B	-3.6	3.8	2.6	2.9	**1.4**	-2.1	2.1	11.5	0.7	**3.1**
120 P	-3.5	2.8	2.4	3.1	**1.2**	-2.2	0.2	12.9	2.0	**3.2**
Mean	**-0.9*a***	**7.1*c***	**1.3*a***	**4.2*b***	**2.9**	**-3.4*a***	**2.1*b***	**12.7*c***	**0.0*b***	**2.8**

In general values for AE in this study were with the exception of Langgewens, similar to values of AE calculated by Smith *et al.* (1988) when very high N rates were applied, but much lower than values calculated by Hocking *et al.* (1997).

Thousand seed weight (TSW)

Thousand seed weight did not show any response to N application in 2005, but a significant N treatment X locality interaction was found during 2006 (Table 4.15). In 2005 the highest TSW of 3.27 g on average was obtained at Elsenburg and the lowest (1.71 g

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on average) at Welgevallen. During 2006, TSW tend to decrease with an increase in N rates at Langgewens and Roodebloem, while Elsenburg and Welgevallen showed a positive response to N application, but optimum rates varied between localities. The highest TSW in 2006 of 3.29 g was obtained at Roodebloem and the lowest of 2.55 g at Langgewens. It is therefore clear that high TSW values did not necessarily correspond with high yields. Because seed size (TSW) is largely affected by growth conditions during the grain filling stage, the observed trends did not support the argument that differences in grain yield are primarily the result of differences in climatic conditions and especially rainfall during the grain filling phase. It seems rather that high DM production corresponds to low TSW, but not necessarily to low yields.

Table 4.15 Thousand seed weight (TSW, g) in the 2005 and 2006 seasons for various nitrogen application combinations at Langgewens (L), Elsenburg (E), Welgevallen (W) and Roodebloem (R)

N treatment	Season									
	2005					2006				
	L	E	W	R	Mean	L	E	W	R	Mean
0	2.39	3.21	1.74	2.95	**2.57**	2.61_{a-e}	2.54_{abc}	2.76_{c-f}	3.45_{lm}	**2.84**
30 B	2.11	3.46	1.84	2.90	**2.58**	2.61_{a-e}	2.80_{c-f}	2.91_{f-i}	3.39_{klm}	**2.93**
30 P	2.13	3.37	1.63	2.97	**2.53**	2.46_{ab}	2.60_{a-d}	2.72_{b-f}	3.50_{m}	**2.82**
60 B	2.20	3.05	1.63	2.75	**2.41**	2.64_{a-f}	2.85_{d-g}	3.27_{j-m}	3.36_{j-m}	**3.03**
60 P	2.22	3.23	1.69	2.98	**2.53**	2.66_{b-f}	2.65_{b-f}	3.20_{jkl}	3.33_{j-m}	**2.96**
90 B	2.07	3.21	1.75	2.94	**2.49**	2.56_{b-f}	2.73_{b-f}	3.35_{j-m}	3.25_{j-m}	**2.97**
90 P	2.04	3.17	1.62	2.83	**2.42**	2.55_{abc}	2.88_{e-h}	3.23_{j-m}	3.33_{jkl}	**3.00**
60+60 B	2.10	3.41	1.76	2.74	**2.50**	2.37_{a}	2.78_{c-f}	3.19_{jkl}	3.10_{jkl}	**2.86**
60+60 P	2.19	3.25	1.76	2.55	**2.44**	2.57_{abc}	2.80_{c-f}	3.17_{ijk}	3.20_{jkl}	**2.93**
120 B	1.98	3.24	1.68	2.97	**2.47**	2.56_{abc}	2.84_{d-g}	3.18_{i-l}	3.18_{i-l}	**2.94**
120 P	2.14	3.40	1.72	2.69	**2.49**	2.46_{ab}	2.86_{d-g}	3.17_{ijk}	3.15_{h-k}	**2.91**
Mean	**2.14*b***	**3.27*d***	**1.71*a***	**2.84*c***	**2.49**	**2.55*a***	**2.75*b***	**3.10*c***	**3.29*d***	**2.92**

Oil

Because of the absence of large yield responses to N application rates, grain from different N application methods were compounded before oil and protein contents were determined. In 2005 oil content of the grain decreased significantly with an increase in N application rate from 41.11% for the control to 39.43% where 120 kg N ha^{-1} was applied (Table 4.16), while the highest oil content, namely 42.3% was obtained at Welgevallen and the lowest 36.8% at Langgewens.

Table 4.16 Concentration of oil in the seed (%) in the 2005 season for various nitrogen application combinations at Langgewens (L), Elsenburg (E), Welgevallen (W) and Roodebloem (R)

N treatment	**Season**									
	2005					**2006**				
	L	**E**	**W**	**R**	**Mean**	**L**	**E**	**W**	**R**	**Mean**
0	37.55	40.09	43.15	43.67	**41.11*c***	33.98	35.67	36.70	39.58	**36.48*ab***
30	37.24	38.99	42.98	41.41	**40.15*ab***	33.81	36.68	38.56	39.01	**37.02*b***
60	37.37	39.38	42.53	42.11	**40.34*bc***	34.30	37.06	40.07	38.29	**37.43*b***
90	37.38	39.22	42.20	41.10	**39.97*ab***	32.23	37.17	40.13	37.29	**36.71*ab***
60+60	36.40	39.56	41.45	41.44	**39.71*ab***	31.75	34.93	39.59	35.50	**35.44*a***
120	35.33	38.66	41.90	41.82	**39.43*a***	32.10	35.15	38.69	36.49	**35.61*a***
Mean	**36.82*a***	**39.24*b***	**42.30*c***	**41.76*c***	**40.12**	**33.03*a***	**36.11*b***	**38.96*d***	**37.69*c***	**36.45**

In 2006 the treatments receiving 30 and 60 kg N ha^{-1} had the highest concentration of oil in the seed (Table 4.16) with 37.02 and 37.43% respectively. Nitrogen applications of 120 kg N ha^{-1} again tend to have lower oil contents in the seed. On average Welgevallen had the highest concentration of oil (38.96%) and Langgewens had the lowest concentration of oil in the seed (33.03%).

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In both seasons Welgevallen had the highest concentration of oil in the seed while also having the lowest concentration of N in the plant material at 120 DAP, similarly Langewens had the lowest concentration of oil in the seed while having the highest concentration of N in the plant material. This clearly shows that an inverse relationship exists between oil concentration in the seed and N concentrations in the plant material at 120 DAP.

Protein

Protein content of the grain showed a negative correlation with oil content. Control plots where no N fertiliser was applied therefore resulted in a significant lower protein content compared to the fertilised plots in 2005 (Table 4.17). Although not significant, protein content tended to increase with increasing N rates from 30 to 120 kg N ha^{-1}. Significant differences were also found between localities with the highest content at Langgewens (42.3%) and the lowest at Welgevallen (19.9%).

Table 4.17 Concentration of protein in the seed (%) in the 2005 season for various nitrogen application combinations at Langgewens (L), Elsenburg (E), Welgevallen (W) and Roodebloem (R)

N treatment	**Season**									
	2005					**2006**				
	L	**E**	**W**	**R**	**Mean**	**L**	**E**	**W**	**R**	**Mean**
0	23.46	21.29	18.60	18.79	**20.54*a***	24.24_{g}	23.49_{efg}	21.19_{bcd}	19.77_{a}	**22.17*a***
30	23.52	22.09	19.30	21.04	**21.49*b***	24.29_{g}	23.83_{g}	20.28_{ab}	20.11_{ab}	**22.13*a***
60	23.66	22.29	19.75	20.46	**21.54*b***	24.41_{gh}	23.80_{g}	19.68_{a}	20.96_{abc}	**22.21*a***
90	23.34	22.24	20.06	21.42	**21.76*b***	25.63_{hi}	23.58_{efg}	19.80_{a}	21.69_{cd}	**22.68*ab***
60+60	24.01	22.03	19.87	20.59	**21.63*b***	25.89_{i}	23.77_{fg}	20.26_{ab}	22.40_{de}	**23.08*b***
120	24.96	22.10	21.16	20.61	**22.21*b***	25.83_{i}	23.96_{g}	20.89_{abc}	22.48_{def}	**23.29*b***
Mean	**23.86*d***	**22.07*c***	**19.90*a***	**20.64*b***	**21.52**	**25.05*d***	**23.74*c***	**20.35*a***	**21.24*b***	**22.59**

During 2006 the protein concentration at Langgewens and Roodebloem increased from 24.24 to 25.83% and 19.77 to 22.48% between the control and where 120 kg N ha^{-1} was applied respectively (Table 4.17). On average protein concentration increased significantly from 22.17% where no N was applied to 23.29% where 120 kg N ha^{-1} was applied. Langgewens showed the highest concentration of protein in the seed (25.05%) and Welgevallen had the lowest (20.35%). In both 2005 and 2006 protein showed a positive correlation with the N concentration in the plant material at 120 DAP.

Conclusion

From the data the dominant effect of the environment (soil and climate) is clearly shown by the significant differences between localities for all parameters. Further it is shown that applied N can positively influence parameters such as DM production at 120 DAP, N concentration in the plant material, N accumulation in the plant material and protein in the seed. An increase in DM of 1 t for every 30 kg N applied can be expected up to an application rate of 90 kg N ha^{-1}. Increasing N application rates can also negatively influence parameters like NUE 120, ANR and oil concentration in the seed. The deep rooting of canola when compared to other crops can result in a very efficient recovery of N as shown by high ANR values and consequently lower leaching possibility. The effect of applied N on grain yield, although not significant may be positive (Elsenburg, Welgevallen and Roodebloem) or negative (Langgewens) possibly due to the undefined growth of canola which results in the absence of a correlation between DM and grain yield.

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Chapter 5

Summary and final conclusions

In the Western Cape Province it is often perceived that canola shows no response to increasing applications of N fertilizers. From this study it became clear that a response exists but that this response can be influenced by other factors.

From plant counts taken after germination it is clear that no adverse effects are shown when N (as liquid ammonia-nitrate) is placed below the seed at a rate of 30 kg N ha^{-1} compared to where 30 kg N ha^{-1} (as LAN) is broadcast above the seed at the time of planting.

Glasshouse studies showed a good correlation ($R^2 = 0.99$) between the concentration of N in the root zone and the amount of dry matter (DM) produced during the early vegetative and flower initiation stages. At DM harvests at both 54 and 90 days after planting (DAP) DM production showed a typical S-type response to the concentration of N in the root zone which indicate that concentrations of between 7 and 9 me nitrate L^{-1} in the soil solution may be within the optimum range for canola production. Concentrations of less than 3 me nitrate L^{-1} may severely inhibit growth and development, while levels higher than 9 me nitrate L^{-1} may be supra optimal. These data indicate that canola, as expected shows a typical crop reaction to increasing N supply in the absence of other adverse factors that may limit growth.

In a further glasshouse experiment it however became clear that the response of canola to increasing N applications could be adversely affected by moisture stress and results in

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lower N use efficiency (g DM g N^{-1}). It was also shown that despite losses which may occur due to leaching, soil water may play a larger role in DM production than the availability of N. However, a good correlation between DM and N application rate could still be attained for both the stressed (R^2= 0.98) and unstressed (R^2=0.99) plants.

From the field trials done at four different localities for two years the complex interaction between soil, climate and crop response to N applications became clear, because responses differs between localities and years. In spite of these differences which resulted in correlation coefficients (R^2) of between 0.60 and 0.96, good correlations between DM at 120 DAP (y) and N application rate (x) was still found when all data for different localities and years were pooled namely:

$$DM = 5.65 + 0.0571x + 0.000269x^2 \qquad R^2 = 0.97$$

Results from this study showed that although the DM production where no nitrogen was applied varied largely between localities and years, an increase of approximately 1 t of DM ha^{-1} can be expected for every 30 kg N ha^{-1} to a maximum of 90 kg N ha^{-1}. DM production values for 0 kg N ha^{-1} however need to be known.

The relationship between yield and N application rate was found to be much less pronounced than the relationship with DM. This is most probably due to increased levels of soil water stress experienced toward the end of the season, which differs between localities and years. No positive correlation between DM produced (120 DAP) and grain yield across all localities could be found, because high DM yields at 120 DAP may be yield limiting factor when soil moisture becomes limiting toward the end of the season. For this reason more research to establish optimum levels of DM production for different soil and climatic conditions is needed.

Grain yield obtained with no N application varied between 1.28 t ha^{-1} and 2.14 t ha^{-1} in 2005 and 0.79 t ha^{-1} and 2.25 t ha^{-1} in 2006. For this reason more research to establish yield potentials for different soil/climatic conditions when no N is applied is needed in spite of the good correlation ($R^2 = 0.95$) between N application rate (x) and yield that have been found is this study when all data were pooled and the following equation was used:

$$\text{Yield (t ha}^{-1}) = 1.60 + 0.0050x - 0.21 \times 10^{-4}x^2$$

Efficiency ratios for grain yield (N use efficiency and agronomic efficiency) varied between localities, but were generally low as can be expected from the yield response equation. On average only 2.9 and 2.8 kg grain were produced for every kg of N applied per hectare.

As also found by a number of earlier studies, the percentage protein in the grain also increased with increasing N application rates in this study, but oil content decreased.

Finally it should be noted that in this study canola showed responses to N supply in controlled conditions, but poor responses under field conditions. These poor responses can be attributed to climatic conditions which limited the grain yields and because of relatively high DM and grain yields obtained without any N application. Studies to measure/predict the mineral N in the soil at the time of planting and N-mineralization during the growth period will thus be of utmost importance to streamline N application rates.

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