Refining of Nitrogen Fertilization Guidelines for Irrigated Cotton (*Gossypium hirsutum* L.) in South Africa

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Declaration

I, Eduard Johannes Haumann, declare that the thesis that I herewith submit for the doctoral degree *Doctor of Philosophy* at the University of the Free State, is my independent work, and that I have not previously submitted it for a qualification at another institution of higher education.

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Abstract

Thirteen randomised block nitrogen fertilization field trials were done in five irrigated cotton producing areas of South Africa: Bela Bela, Rustenburg, Vaalharts, Rietriver and Groblersdal, with the aim to refine the existing nitrogen fertilization guideline. At Rustenburg cotton was preceded by harvested oats, harvested soybean, ploughed in soybean and babala in order to create varying soil nitrogen contents.

Soil samples (0–300, 300–600 and 600–900 mm soil depths) were taken at least two weeks after irrigation for land preparation to determine total nitrogen. Leaf petiole samples were collected at two-week intervals, starting one week before first flowering for measurement of total nitrogen. After ripening, seed cotton yield was determined. The yield was subjected to analysis of variance and correlated with the nitrogen application rate to quantify an optimal nitrogen fertilization rate per site for each trial year.

The estimated optimal nitrogen fertilization levels were correlated with the residual soil nitrogen content for each depth resulting in four guidelines for either maximum yield or maximum profit. Therefore, the cotton grower has eight different options for the calculation of an appropriate nitrogen application level based on the residual nitrogen content of the soil.

A randomised block nitrogen fertilization trial on cotton was also done in a glasshouse to evaluate the principles upon which the nitrogen fertilization guidelines of the field study were based. Five residual nitrogen contents were simulated and nitrogen was fertilized at 0, 75, 150, 225 and 300 kg ha^{-1} to each soil. Results of the glasshouse study corresponded well with those of the field study. The glasshouse trial confirmed the nature and validity of the nitrogen fertilization guidelines developed from of the field study.

By adjusting the current nitrogen fertilization guideline to allow for an additional nitrogen extraction of 56 kg ha^{-1} per 1 000 kg seed cotton ha^{-1} yield, a better correlation was found to predict nitrogen fertilization requirement for maximum yield and maximum profit.

Estimated nitrogen use efficiency showed that 32.5 and 54 kg of seed cotton produced kg^{-1} N fertilized can be used as an indicator of best practice until these values are improved by further research.

The total nitrogen content of the cotton leaf petioles was correlated with the applied nitrogen fertilization rate to establish the leaf petiole nitrogen contents that correspond with nitrogen application rates for maximum yield and maximum profit. This data was used to compile in season guidelines for either maximum yield or maximum profit which can be used in combination with the guidelines for residual soil nitrogen. If the guidelines for leaf petiole total nitrogen contents indicate that additional nitrogen fertilization is required, the quantity can be calculated as follows:

$$\text{Nitrogen to apply } = \frac{Model\ Petiole\ N - Petiole\ N}{Model\ Petiole\ N} \times Target\ N$$

where:

Nitrogen to apply	=	the amount of nitrogen to apply as a corrective in season application (kg N ha^{-1})
Petiole N	=	the total nitrogen content of the cotton leaf petiole as sampled at the specific number of days after sowing (%)
Model Petiole N	=	the total nitrogen content of the cotton petiole considered to be sufficient as predicted by the model (%)
Target N	=	target nitrogen fertilization rate as determined by the residual nitrogen content of the soil as elucidated upon in Chapter 4 (kg N ha^{-1})

The suggested cotton leaf petiole guidelines can provide a useful mechanism whereby additional nitrogen applications can be made to compensate for leaching and denitrification that are increasingly affecting cotton production in South Africa, particularly during wet seasons. By implementing these recommendations, the existing guidelines for irrigated cotton in South Africa can be refined.

Keywords: irrigated cotton, nitrogen fertilization guidelines, residual soil nitrogen, leaf petiole nitrogen, maximum yield, maximum profit

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List of Abbreviations and Acronyms

ANOVA	Analysis of variance
BCE	Before Current Era
ERF	Emissions Reduction Fund
Fertasa	Fertilizer Association of Southern Africa
*i*NUE	Internal nitrogen use efficiency
LAN	Limestone ammonium nitrate
LSD	Least significant difference
NFUE	Nitrogen fertilizer use efficiency
NUE	Nitrogen use efficiency
TNUE	Total nitrogen use efficiency

Chapter 1
Motivation, Rationale and Objectives

1.1 Introduction

Cotton has been cultivated for many millennia (since 3 500 BCE) and the art of spinning the fibre and weaving the yarn into cloth has been practiced for more than five and a half thousand years. The use of cotton for the production of clothing by the ancient civilisations of Mesopotamia, Babylon and Egypt has been recorded in detail since 500 BCE. The word cotton was derived from the Arabic word *Kutun* (Brown and Ware 1958), or *Quotn* (Lee 1984).

Portuguese explorers encountered people in Southern Africa that were cultivating cotton and using the fibre to manufacture clothing as early as 1516 (Van Heerden 1988). A wild diploid species of cotton *Gossypium herbaceum var africanum*, can be found growing along the Tropic of Capricorn in Southern Africa. This species is most probably the predecessor of the tetraploid *Gossypium hirsitum*, that currently accounts for about 90% of cotton production in the world (Prentice 1972; Lee 1984).

Cotton is mainly produced for its fibres, but the seed also has economic value. Cotton seed oil can be used for household purposes, such as cooking and the seed-cake serves as a protein-rich feed for cattle. The linters (the short fibres that are removed from the seed before it is pressed for oil) is an important source of industrial cellulose.

In South Africa the first cotton seed was imported in 1846 from North America by an American missionary, Dr Adams. He planted the first fields at Amanzimtoti. The cotton industry flourished between 1860 and 1870 in Natal and the Cape Colony, driven by demand created by the American civil war. After the war the production of cotton in South Africa came to a standstill. Only resuming in 1909 and steadily becoming established as an industry in South Africa as cotton ginneries were built in Rustenburg (1922), Germiston and Barberton (1923) and Upington (1953). In 1946 the first local spinning and weaving plants were built (Van Heerden 1988).

The cotton industry in South Africa has encountered various challenges over time, the latest being the coronavirus pandemic, casting a shadow over the industry concerning the demand and the price of cotton (Botha 2020). The crop estimate for cotton produced by the approximately 450 commercial farmers and 2000 developing farmers in South Africa, is presented in Table 1.1.

Table 1.1 Cotton crop estimate for South Africa for the 2019/20 production year (Botha 2020)

Production region	Hectares irrigation	Hectares dryland	Yield irrigation (kg seed cotton ha^{-1})	Yield dryland (kg seed cotton ha^{-1})	Production (200 kg bales cotton lint ha^{-1})
Limpopo					
Loskop	1 815	0	4 500	0	14 702
North & South flats	817	7 592	4 569	600	15 004
Koedoeskop/Dwaal-boom/Thabazimbi	4 078	450	5 500	750	42 118
Limpopo Other	25	548	3 000	600	727
Weipe	1 000	0	4 500	0	8 325
Northern Cape					
Vaalharts	1 254	0	5 000	0	11 600
Lower Orange River	272	0	5 463	0	2 749
Rest of Northern Cape	989	0	4 776	0	9 807
North West					
Stella/Delareyville/ Schweizer-Reneke	99	4 472	5 000	2 302	19 963
Taung/Skuinsdrif	892	0	5 243	0	8 652
KwaZulu-Natal	69	600	3 500	800	1 400
Mpumalanga	501	1 836	4 000	800	6 425
Free State	490	440	5 000	1 000	5 273
RSA Total	**12 300**	**15 938**	**4 764**	**1 096**	**146 743**

The production of cotton in South Africa has grown annually since the 2014/15 season. The current crop of 29 348,6 tons of seed cotton (146 743 bales × 200 kg $bale^{-1}$), is 30% lower than last year. This can be attributed to unfavourable weather conditions during planting, insufficient seed available at planting, and the higher price of maize on offer at the time of planting (Botha 2020).

The price of cotton is currently subdued by lacklustre demand due to the coronavirus pandemic, trade tensions between the United States and China, and a reduction in demand from China due to economic contraction. Cotton is currently trading at about US$0.64 lb^{-1} (R21.44 kg^{-1}) (Botha 2020).

The average yield recorded during the 2020 growing season from irrigated cotton was 4 764 kg ha^{-1} and cotton produced under dryland conditions, was 1 096 kg ha^{-1}. This represents an income ha^{-1} of R102 140 ha^{-1} for irrigated cotton, and R23 498 ha^{-1} for cotton produced under dryland conditions. Although cotton has a high cost of production (R12 552 ha^{-1} for a mechanised, conventional tilled crop [Washburn 2020]), the income and potential profit ha^{-1} from cotton is substantial (Botha 2020). Apart from being an excellent potential wealth generator, the cotton industry creates a large number of jobs in South Africa. As 75% of the South African cotton crop is picked by hand, it also has the potential to create employment on a large scale, sustain livelihoods and feed families in a time where South Africa faces wide-spread job losses due to the coronavirus pandemic. The cotton industry currently provides employment for 65 000 workers from production to retail sales (Agriculture 2020).

During 2019/20 the global cotton production was 25 826 400 tons, produced from an area of 33 760 000 ha^{-1} (Johnson and Soley 2020). The South African crop accounted for 0.09% of global cotton production. If directly extrapolated from the South African scenario, it is possible that almost 75 million people are employed by the cotton industry worldwide. If each person employed by the cotton industry is involved in providing for a family of five individuals, it is possible that the lives of about 375 million people are affected by the global cotton industry. Therefore, any contribution towards ensuring the stability and sustainability of the cotton industry will have a positive impact on many people.

1.2 Motivation and rationale

In order to ensure the stability and sustainability of the cotton industry, the fertilization of cotton should be done in an economically optimal, profitable and environmentally sustainable manner.

One of the best ways to contribute to the production of cotton in an economically optimal way, is to ensure the correct nitrogen fertilization. Under-fertilization of nitrogen to cotton leads to poor development and weak plants that cannot produce a good crop. Over-fertilization of nitrogen causes luxurious growth of cotton. Such plants use water inefficiently and are prone to pest and disease infestations, use groundwater inefficiently, and develop vegetatively instead of reproductively. Over-fertilization of nitrogen has been proven to reduce cotton yield (Christidis 1955; Linde 1957; Tucker and Tucker 1968; Maples et al. 1977; Arain et al. 1989 and Gordon et al. 1990).

Du Preez and Burger (1986) determined that the residual nitrogen content of soils in the maize producing areas of South Africa can be significant and should be considered when determining the nitrogen fertilization of maize. Residual nitrogen has also been considered to calculate the nitrogen fertilization of cotton for many years (Spencer et al. 1966; Maples et al. 1977; Hearn 1981; Munro 1987; Singh et al. 1987; Constable and Rochester, 1988; Halevy and Bazelet, 1989).

Various approaches are followed by farmers to determine the correct (or optimal) amount of nitrogen to fertilize their cotton with.

All the approaches that are currently in use, rely on an estimation of certain parameters (nitrification and nitrogen utilisation) in order to calculate the “correct” amount of nitrogen that should be applied to cotton on a certain field. This applies to cotton produced under rain fed as well as irrigated conditions. The various approaches that can be used to estimate the “correct” nitrogen fertilization of cotton will be discussed in detail in the literature review.

If nitrogen fertilization of cotton is not done correctly, it will lead to either, yield potential not being achieved (due to over- as well as under-fertilization of nitrogen), or contamination of surface and groundwater with nitrogen due to excessive applications (Maraseni and Kodur 2019).

Additional to the above, the tendency of the clothing market in the developed world is towards natural fibres, such as cotton. The market is driven by well-informed consumers with the desire to support sustainable agriculture producing renewable resources with a low carbon footprint.

Therefore, the decision was made to contribute to the cotton industry by refining existing nitrogen fertilization guidelines in order to reduce the assumptions or “guess-timations” that need to be made by cotton producers. These refined guidelines will contribute to the economically optimal and environmentally sustainable production of cotton.

1.3 Objectives

The objectives of this research were the following:

- To refine and simplify the existing nitrogen fertilization guidelines of cotton that are based on the residual nitrogen content of the soil prior to, or at planting.
- To evaluate the above refined nitrogen fertilization guidelines under controlled glasshouse conditions.
- To develop a cotton leaf petiole guideline for in season use, based on the total nitrogen content of the leaf petiole.

In order to achieve the above objectives, the following actions were planned:

- Nitrogen fertilization trials were planted on typical soils (Hutton and Arcadia) in known cotton producing areas of South Africa namely Rustenburg, Bela Bela, Groblersdal, Vaalharts Irrigation Scheme, and Rietrivier Irrigation Scheme.
- Soil samples were taken from the trial areas at, or after planting, at depths of 0–300 mm, 300–600 mm and 600–900 mm below the soil surface and analysed for total nitrogen content.
- Leaf petiole samples were taken from the cotton plants in each trial plot at regular intervals during the growing season and the total nitrogen content was determined. The results thereof were used to produce a graph of the total nitrogen content of the cotton leaf petiole over time.
- After ripening, the seed cotton was harvested from each plot by hand and the yield for each individual plot was calculated. The seed cotton yield obtained from each plot was correlated with the nitrogen application rate, to determine if the nitrogen fertilization rate had an influence on the yield of seed cotton harvested. The optimal nitrogen fertilization for each individual locality was determined for each individual growing season.
- Once the nitrogen application rate that has led to the highest yield in seed cotton on a specific trial has been determined, this level of nitrogen was correlated with the residual nitrogen content of the soil at planting (together with the amount of nitrogen produced by incubation), for all the different trials performed.

This correlation then provided a guideline between residual nitrogen in the soil and maximal, or optimal nitrogen fertilization of cotton.

- Once the field trials had been completed, a pot-trial was conducted under controlled conditions in a greenhouse. During this trial, different levels of residual nitrogen was simulated, together with different levels of nitrogen fertilization. This was done to evaluate the nitrogen fertilization guidelines compiled from the field data.

Chapter 2

Literature Review

2.1 Introduction

Consensus exists amongst farmers, advisors and researchers, worldwide that nitrogen fertilization of cotton grown under irrigation is essential. The exact amount of nitrogen to be applied however, varies considerably amongst literature sources. For example some researchers (Christidis and Harrison 1955; Berger 1969; Waddle 1984) recommend a nitrogen application of 105 kg ha^{-1}. Others like Constable (1984) recommend that in order to produce a good crop, enough nitrogen must be applied to ensure a plant uptake of 120 kg N ha^{-1}.

De Bruyn et al. (1989) recommend nitrogen applications of 80–160 kg N ha^{-1}, depending on the season, at the South African Vaalharts and Sandvet Irrigation Schemes. Some farmers are of the opinion that nitrogen fertilization of cotton is a futile and expensive practice that does not consistently contribute to the production of good cotton yields. This point of view is also supported by trials done by De Bruyn et al. (1989) where no significant increase in cotton production was achieved by nitrogen fertilization at the Sandvet Irrigation Scheme during a specific growing season, with levels of up to 200 kg N ha^{-1}.

The theoretical maximum yield of cotton has been suggested to be as high as 5 000 kg lint ha^{-1} (Constable and Bange 2015). To achieve such a yield, Rochester (2014) is of the opinion that it would require a nitrogen fertilization rate of 320 to 420 kg N ha^{-1}. According to MacDonald et al. (2018), these yields have not been achieved in practice and care should be taken not to encourage high nitrogen applications on cotton if they are not based on sound scientific evidence.

During the production of cotton under irrigation, it is important to fertilize the correct amount of nitrogen. While under-fertilization of nitrogen can lead to poor yield of cotton, the excessive fertilization of nitrogen can lead to various problems (to be discussed later) as well as nitrogen losses in the form of (among others) nitrous oxide (N_2O). Nitrous oxide is rated as the worst greenhouse gas, with a global warming potential that is 298-fold higher than CO_2 (Grace et al. 2016). Care should be taken therefore to limit the loss of nitrogen in the form of N_2O. All losses of nitrogen from the cropping system, as depicted in the nitrogen cycle (Figure 2.1), can have negative consequences on the environment. It is of the utmost importance that these losses be avoided where possible, or limited to an absolute minimum. Particularly so, as the emissions of nitrous oxide (N_2O), in agriculture account for about 5.6–6.8% of all anthropogenic emissions of N_2O (Maraseni and Kodur 2019).

Australia is actively involved in the control of greenhouse gas emissions from agriculture by the implementation of an AUD2.55 billion Emissions Reduction Fund (ERF). Farmers receive incentives to adopt management practices that reduce greenhouse gas emissions, improve productivity, profitability and sustainability of their farming systems (Maraseni and Kodur 2019).

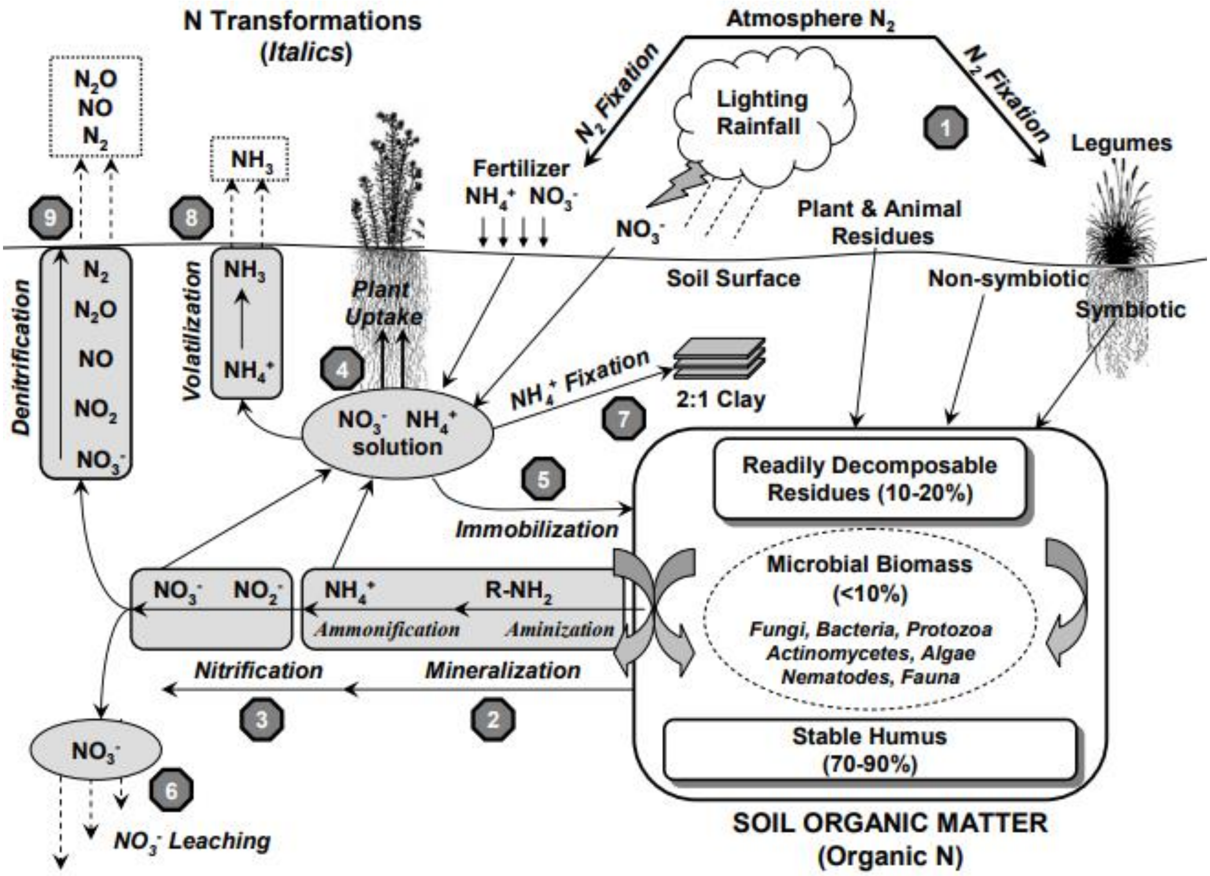


Figure 2.1 The nitrogen cycle (Havlin et al. 2014)

In this literature review the role of nitrogen in cotton growth and development, and nitrogen fertilization effects on cotton will be addressed concisely. More extensively, the current nitrogen fertilization guidelines that are in use for irrigated cotton in South

Africa and internationally will be discussed, including the use of residual nitrogen content in soil for cotton establishment and the use of nitrogen content in leaf petioles during cotton growth. Role of nitrogen in cotton growth and development

As cotton contains more nitrogen than any other mineral nutrient (Hearn 1981), a brief overview of the role of nitrogen may provide insight to the importance thereof in commercial cotton production. Duncan and Raper (2019), have researched the nitrogen uptake of irrigated cotton from planting and have provided a nitrogen uptake curve (Figure 2.2). All nitrogen is taken up by cotton by 100 days after emergence. Therefore nitrogen fertilization should be applied in such a way that it is available to the plant for uptake during this period. Particularly so for the period between 60 and 90 days after emergence, when nitrogen uptake increases logarithmically.

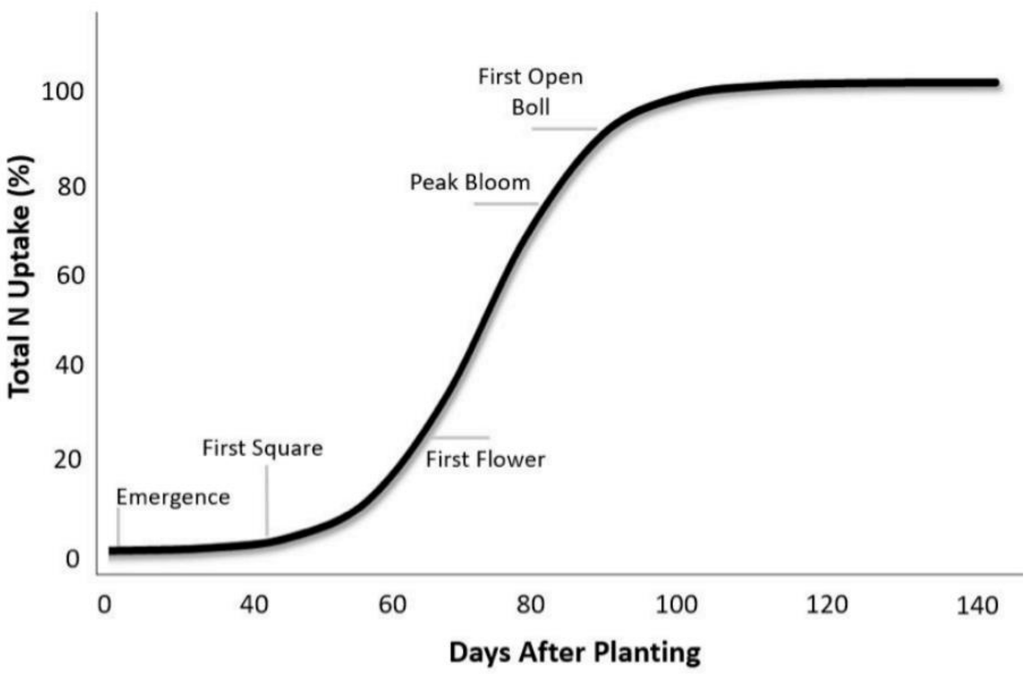


Figure 2.2 Nitrogen uptake of cotton (Duncan and Raper 2019)

It is important to bear in mind that cotton is a perennial plant that will continue to live and grow while conditions are such that the plant can survive (Oosterhuis 1990). Therefore nitrogen fertilization should be applied at an early stage of growth, in order to allow the development of a good framework for the bolls to set on. If nitrogen is applied too late during the growing season, then vegetative growth will continue too long and the crop will not cut-out at a specific stage, to allow a relatively synchronised ripening and bursting of the bolls. This scenario will complicate the harvesting process.

Although nitrogen can be absorbed by cotton in the ammonium form, it is mostly taken up as nitrate. Cotton roots only reduce enough nitrate to cater for their own growth needs and the rest of the nitrate is transported to the leaves, where it is reduced to form amino acids, proteins and other complex molecules required for the functioning of the cotton plant cells (Radin 1990). Excess nitrate can be stored as carboxylase enzymes in the leaf canopy of the plant, which can be mobilised when nitrogen is required by the plant at a later stage. Nitrogen forms part of the chlorophyll molecule. Sufficient nitrogen uptake by the plant can contribute to photosynthesis and carbohydrate production.

As the growth of cotton is morphologically indeterminate, the main stem will produce a new node every 2–3 days while climatic and nutritional conditions are favourable. Branches form from the nodes on the main stem. Lower branches are vegetative and produce leaves only. Reproductive branches form from the 5th to 8th internode on the main stem and higher. These reproductive branches produce leaves and also flower buds at a constant rate. The buds flower 20 to 30 days after appearance. Due to the indeterminate growth form of cotton, flowering can last for several months and the potential yield increases exponentially over time while sufficient nutrients, nitrogen in particular, carbohydrates and water are available to the plant (Hearn 1981).

As the bolls form and develop after flowering, their requirement for nitrogen and carbohydrates increases and vegetative growth slows down and may even stop if nitrogen and carbohydrate demand exceed supply. If more flowers and bolls have formed than are possible to develop, they are shed by the plant. Once bolls have matured and the internal demand for nitrogen and carbohydrate by the plant has reduced and/or inflow and availability in the plant has resumed, the production of nodes on the main stem and flower buds on branches may restart, leading to a second flowering cycle that may benefit yield (Hearn 1981).

2.3 Nitrogen fertilization of cotton

2.3.1 Nitrogen fertilization trials on cotton

Given the role of nitrogen in the growth and development of cotton, fertilization of cotton with nitrogen is essential for sustainable production of the crop. Due to the elusive and dynamic nature of nitrogen, trials have been done on the nitrogen fertilization of cotton for almost 100 years. According to Christidis and Harrison (1955), 170 nitrogen fertilization trials were done on cotton in Alabama between 1923 and 1927. From these trials it was concluded that the best cotton yield was produced by an application of 36 kg N ha^{-1} applied in the form of sodium nitrate. A similar conclusion was reached from trials done between 1921 and 1928 in Georgia, where an application of 36 kg N ha^{-1} together with 36 kg ha^{-1} of phosphoric acid and 36 kg K ha^{-1} gave the best result. Trials done during the same time period in South Carolina indicated that 46 kg N ha^{-1} resulted in the best cotton yield, while higher applications of nitrogen (92 kg N ha^{-1}) resulted in a decrease in cotton yield.

Maples et al. (1977) performed nitrogen fertilization trials on cotton, at the University of Arkansas cotton branch experimental station on Loring and Calloway silt loams. The average residual nitrogen content of the soil was 67 kg N ha^{-1} to a depth of 900 mm. They found that cotton yields increased linearly with increased nitrogen applications from 0 to 168 kg ha^{-1}.

Halevy (1979) found that there was no response to nitrogen fertilization by cotton grown on an alluvial clayey Grumusol at the Volcani Research Centre situated at Bet-Dagan in Israel, where the residual and mineralisable nitrogen in the soil to a depth of 1 500 mm was 250 kg N ha^{-1}. A similar result was obtained from a nitrogen fertilization trial done with cotton on a calcareous silty loam Serozem at Bet She'an in Israel, where the residual and mineralisable nitrogen content of the soil to a depth of 1 500 mm was 264 kg N ha^{-1}.

Nitrogen fertilization trials on cotton grown in a brown clayey Grumusol at Kefar Glickson in Israel with a residual and mineralisable nitrogen content of 130 kg N ha^{-1} to a depth of 1 500 mm, gave the best yield with an application of 120 kg N ha^{-1} (Halevy 1979).

In nitrogen fertilization trials done at the Cotton Research Institute at Gatooma and the university farm at Salisbury in Zimbabwe, Oosterhuis et al. (1983) found significant yield increases with increased nitrogen fertilization. With a residual and mineralisable soil nitrogen content of 140 kg N ha^{-1}, the best yield was obtained at a 120 kg N ha^{-1} application, which was the highest level of nitrogen fertilization used during the trial.

In nitrogen fertilization trials done with cotton on a fine loamy, siliceous thermic Typic Paleudult in the gulf coast of Florida, Lutrick et al. (1986) reported that the best yield was obtained with an application of 100 kg N ha^{-1}. The residual nitrate nitrogen level of the soil prior to planting was 74 kg N ha^{-1} to a depth of 450 mm.

Singh et al. (1987) conducted nitrogen fertilization trials for cotton in rotation with wheat at the Muktsar and Abohar Cotton Research Stations of the Punjab Agricultural University at Ludhiana in India. They measured residual nitrogen levels of 136 kg N ha^{-1} in the loamy soil at Muktsar and 155 kg N ha^{-1} in the sandy loam soil at Abohar. A nitrogen application of 80 kg N ha^{-1} produced statistically the highest seed cotton yields at both trial sites.

In nitrogen fertilization trials done with cotton on a typic Pellustert, which is a grey (60% clay) Vertisol, (with a residual nitrogen content of 10 mg kg^{-1} in the top 300 mm of soil) at the New South Wales Department of Agriculture research farm at Narrabri in Australia, Constable and Rochester (1988) concluded that maximum yield was obtained when crop uptake was about 108 kg N ha^{-1} at 120 days from sowing. To achieve this uptake, 173 kg N ha^{-1} would have to be applied (Constable and Rochester 1988).

In research done on cotton grown on a clayey CalciXerollic Xerochrept in the Hama province, situated in the mid-west of Syria, Janat (2004) observed that a nitrogen application of 120 kg N ha^{-1} produced the highest average cotton lint yield over the trial period. The average soil nitrate content prior to planting, to a soil depth of 1 000 mm was 176 kg N ha^{-1}.

In fertilization and irrigation trials done by Janat (2008) on a clay Chromoxerertic Rhodoxeralf, situated at the Cotton Bureau Research Station in the north of Syria, no significant difference in cotton yield was observed for nitrogen fertilization rates of 50-250 kg N ha^{-1}. The latter being attributed to the high residual nitrogen content of the soil to a depth of 1 000 mm which was 257 kg N ha^{-1}.

In nitrogen fertilization and tillage trials done with cotton, maize, and cotton on a saline, alluvial sandy loam to loamy soil in western Uzbekistan, Devkota et al. (2013) observed a significant increase in seed cotton yield with an increase in nitrogen fertilization. The residual nitrogen content of the soil to a depth of 900 mm, was 135 kg N ha^{-1}. A nitrogen application of 125 kg N ha^{-1} produced 4 168 kg seed cotton ha^{-1}, which was significantly more than the 3 299 kg seed cotton ha^{-1} produced by the control treatment (0 kg N ha^{-1}). Although the 250 kg N ha^{-1} treatment produced 4 301 kg seed cotton ha$^{-1,}$ this was not significantly higher than the 4 168 kg seed cotton ha^{-1} produced by the 125 kg N ha^{-1} treatment (least significant difference [LSD] = 257 kg ha^{-1}).

Chen et al. (2020) found that a nitrogen application of 240 kg N ha^{-1} resulted in a significantly higher seed cotton yield than the other applications of 0, 120 and 480 kg N ha^{-1} on a soil with a residual nitrogen content of 152 kg N ha^{-1} prior to planting. The trials were conducted for two years on a loamy soil situated at the Baoding Agricultural Station of the Hebei Agriculture University, located in the Yellow River valley in Hebei, China.

Human (1982) states that the nitrogen fertilization of cotton in South Africa is based on very broad parameters. This is attributed by Venter (1982) to an absence of measurable parameters on which the nitrogen fertilization of cotton can be based. According to Du Preez and Burger (1986), the nitrogen fertilization of a crop should be based inter alia on the residual nitrogen content of the soil, as well as the amount of nitrogen that is mineralised by the soil during the growing season.

Cackett (1965), as cited by Hearn (1981), found a close correlation between the residual and mineralisable nitrogen content of soils in Zimbabwe and the yields of cotton grown on them. These crops were not fertilized with nitrogen and relied only on the residual and mineralisable nitrogen in the soil.

After research done by Bronson (2008) in the west Texas cotton belt, he concludes that considering the results of preplant soil testing for residual nitrate to a depth of 600 mm can help to improve nitrogen use efficiency in irrigated cotton.

Halevy (1976) reported that two cotton varieties grown under irrigation in a typic loamy Rhodoxeralf, in the centre of the coastal plain, near Rehovot in Israel, removed a total of 235 kg N ha^{-1} to produce an average yield of 3 970 kg seed cotton ha^{-1}. The dry biomass varied between 12 200 and 13 480 kg ha^{-1}. He found that until flower initiation nitrogen uptake was very slow, thereafter, from 57 to 84 days after planting, nitrogen uptake increased 10-fold, with rates of 3.2 to 3.6 kg N ha^{-1} day^{-1}. The highest rate of nitrogen uptake was observed with Acala 1517-C, namely 4.6 kg N ha^{-1} day^{-1} in the period between 84 and 98 days after planting. Thereafter nitrogen uptake dropped fast and by 112 days after planting the uptake of nitrogen was very small. During the period of the highest demand, an uptake rate of 0.077 g N $plant^{-1}$ day^{-1} or 4.62 kg ha^{-1} day^{-1} was measured. The plant population was 60 000 plants ha^{-1}.

Stamatiadis et al. (2016) observed a nitrogen uptake of 235 kg N ha^{-1} for a cotton crop producing 3 900 kg seed cotton ha^{-1} on a typic sandy clay loam Xerocherept in Greece. Rochester (2011) measured an average nitrogen uptake of 247 kg N ha^{-1} from commercial cotton producing an average yield of 2 273 kg lint ha^{-1} on medium to heavy clay soils in Australia. (For the purpose of comparison it should be noted that the weight of harvested seed cotton comprises of approximately one third lint [cotton fibre] and two thirds cotton seeds.)

The fertilization of a full complement of nitrogen will increase the yield of cotton by means of prolonging the active growth period of the crop. This increases the number and size of leaves and bolls that are set, developed and matured during the prolonged period of growth and reproduction (Hearn 1981).

2.3.2 Over-fertilization of cotton with nitrogen

Although the fertilization of a full complement of nitrogen will be advantageous to a cotton crop, the over-fertilization of cotton with nitrogen can be detrimental to the crop in the following ways:

- When nitrogen is applied in excessive quantities, vegetative growth will enjoy priority over reproductive growth and young bolls may be shed, leading to yield reduction (Hearn 1976).
- Excessive vegetative growth may lead to rank and overgrown cotton where fungal and bacterial diseases and insects are difficult to control as spray applications cannot penetrate the dense foliage.
- Overgrown cotton tends to be more succulent and is prone to developing an increased water requirement.

- A reduction in fibre quality can be caused by the over-application of nitrogen to cotton (Rochester et al. 2001).
- Over-application of nitrogen resulting in rank and overgrown cotton that tends to more leafiness. This can lead to defoliation problems resulting in more trash in machine picked cotton. The latter will result in a lower gin out turn, a lower grade of cotton and resultant lower price.
- Over-application of nitrogen may lead to contamination of ground water with unused nitrates that leach through the soil profile, beyond the root zone of cotton.
- Over-application of nitrogen may also lead to denitrification and the formation of N_2O, which is considered as the worst of the greenhouse gasses. Significant denitrification and formation of N_2O may even occur under arid conditions as reported by Scheer et al. (2008), who conducted trials in the Aral sea-basin in Uzbekistan, to determine the effect of nitrogen applications and irrigation practices on nitrous oxide emissions from irrigated cotton.
- Over-application of urea and ammonium containing fertilizers may also contribute to soil acidification (Sainju et al. 2019).

2.3.3 Under-fertilization of cotton with nitrogen

While the over-fertilization of nitrogen may be detrimental to the cotton crop as discussed above, under-fertilization thereof may also be detrimental to the crop in the following ways:

- Cotton that is under fertilized with nitrogen will develop small branches and a smaller framework on which bolls can be produced, leading to a lower yield than cotton that is well fertilized with nitrogen (Hearn 1981).
- The production cost of cotton that is under fertilized with nitrogen is very similar than cotton that are well fertilized with nitrogen. However, an under fertilized crop will produce less cotton, resulting in lower profitability than a crop that is well fertilized with nitrogen.

2.3.4 Nitrogen use efficiency by cotton

The nitrogen use efficiency (NUE) of cotton is often estimated to determine whether the crop is over or under fertilized with nitrogen. For example, in the Australian cotton production manual for 2020 and 2021, the 4R approach to nitrogen fertilization (Right fertilizer, Right rate, Right time and Right place of application) is recommended (Baird and Smith 2019; Baird 2021). The emphasis is on the limitation and possibly prevention of nitrogen losses, and the improvement of NUE by cotton. Their presentation of the potential losses of nitrogen are depicted in the nitrogen cycle for cotton under irrigation (Figure 2.3).

Flis (2019) also recommends the 4R approach to nitrogen fertilization for cotton grown in the United States (5.1 million ha over 20 states during 2017). Hons et al. (2014) emphasizes the importance of this approach in cotton production due to all the potential losses that nitrogen may undergo during the production thereof (Figure 2.3).

Stamatiadis et al. (2016) emphasises the importance of the responsible use of nitrogen whilst fertilizing cotton and defines the NUE of cotton as follows:

NUE = nitrogen removed by the crop (kg ha^{-1}) / nitrogen supplied to the crop (kg ha^{-1}).

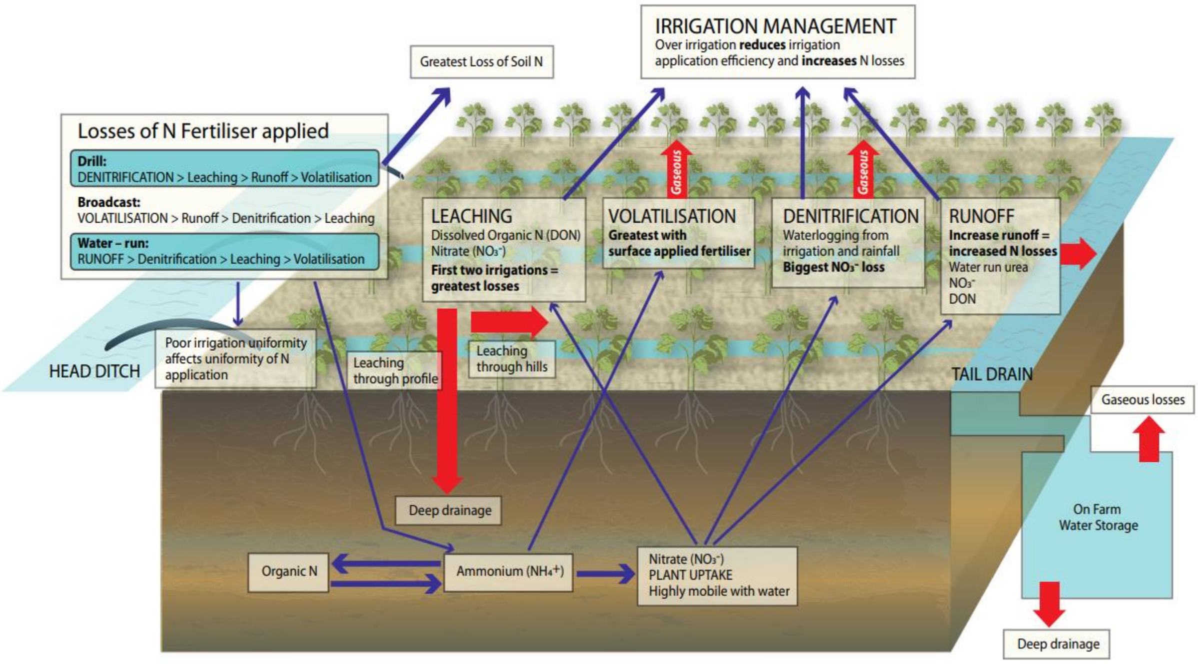


Figure 2.3 The nitrogen cycle, emphasising potential losses of nitrogen during irrigated cotton production under flood irrigation in Australia (Baird and Smith 2019)

The NUE of cotton is not readily used for nitrogen fertilization recommendations, but it is useful to evaluate the long-term efficiency of nitrogen recovery by cotton under steady-state cropping conditions. Values of 1 are ideal because values greater than 1 indicate a depletion of soil reserves, while values less than 1 may be indicative of nitrogen losses due to denitrification, volatilisation, leaching and immobilisation (Stamatiadis et al. 2016).

Nitrogen use efficiency is an important concept to bear in mind when fertilizing a crop like cotton, as nitrogen losses increase rapidly when application levels exceed the crop's nitrogen assimilation capacity. Good weather conditions will favour higher nitrogen uptake, while adverse conditions like heavy rainfall will aggravate volatilization, denitrification, leaching and runoff losses of nitrogen (Stamtiadis et al. 2016). By ensuring that the 4R principles of fertilization (Right source of fertilizer, Right amount of fertilizer, Right time of fertilizer application and Right placement of fertilizer) are adhered to, will contribute to achieving favourable NUE values (Maaz et al. 2021).

In some instances, however, internal nitrogen use efficiency (*i*NUE) is employed as an index to measure the efficiency of cotton lint production relative to the uptake of nitrogen in a cropping system, and can be defined as follows (Stamatiadis et al. 2016): *i*NUE = kg of cotton lint kg^{-1} of nitrogen taken up by the cotton crop.

An *i*NUE of around 12 is viewed as being very good and was found by Bronson (2008) to be indicative of high production efficiency for irrigated cotton grown in Texas. Rochester (2011) reported that *i*NUE levels of 12.5 indicating excellent nitrogen fertilizer management in farming systems under cotton production in Australia. In a survey by Rochester (2011) on 82 commercial cotton crops in Australia, the *i*NUE was low in 65 of them. He concluded that *i*NUE can be improved by implementing careful irrigation management, keeping the soil well aerated and by applying the correct quantity of nitrogen as required by the crop. Smith and Welsh (2018) describe the processes that are relevant to achieving good NUE by cotton (Figure 2.4).

Furthermore, Halevy (1979) established that by fertilizing irrigated cotton with the correct amount of nitrogen, water use efficiency increased from 1.06 kg seed cotton mm^{-1} water to between 1.46 and 1.57 kg seed cotton mm^{-1} water. These increases in water use efficiencies are equivalent to 38 and 48%, respectively.

2.4 Nitrogen fertilization guidelines for irrigated cotton

Nitrogen fertilization guidelines for irrigated cotton are primarily based on the nitrogen requirement of the crop. However, internationally, nitrogen fertilization of cotton is frequently based on the nitrogen content of soil samples taken before planting. Some institutions and the farmers advised by them also use the nitrogen content of leaf petiole samples taken from cotton plants in the growing season to manage nitrogen fertilization during growth.

2.4.1 Nitrogen requirements of cotton varieties

The question can be raised if different cotton varieties have different nitrogen requirements. McConnell et al. (2003) found that genetically engineered cotton varieties of *Gossypium hisutum* L. planted in Arkansas had similar nitrogen fertilizer requirements as conventional cotton varieties. Similarly, Bandla et al. (2014) observed no significant difference in the reaction of yields by cotton hybrids of *Gossypium hirsutum* L. to nitrogen fertilization in India.

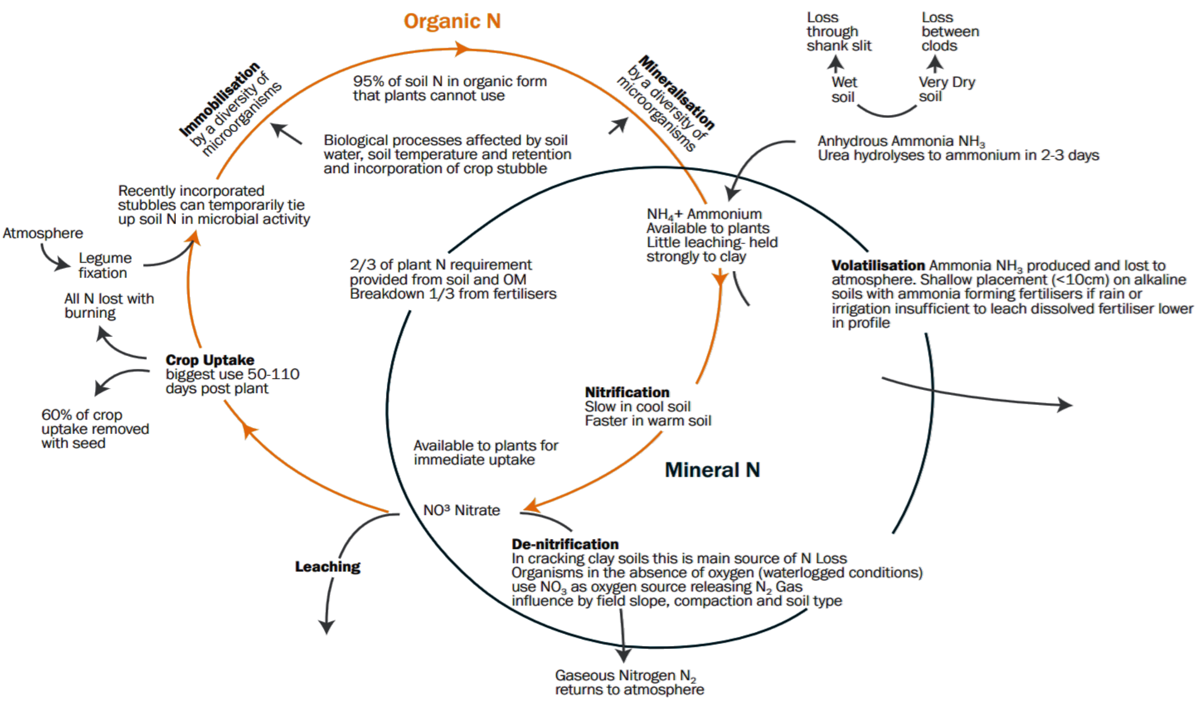


Figure 2.4 The nitrogen cycle emphasising processes of relevance to cotton production (Smith and Welsh 2018)

Constable and Rochester (1988) reported no difference in response to nitrogen fertilization between the cotton cultivars Deltapine 61 and Deltapine 90. The nitrogen uptake of the cotton varieties Deltapine 90, Stoneville 825, Coker 315 and Paymaster 145 also did not differ significantly (Mullins and Burmester 1990).

From the above it seems that the nitrogen requirements of different varieties of *Gossypium hirsutum* L. do not differ significantly. Moreover, Main (2021) found that, provided cotton plants were spaced uniformly and other agronomic practices stayed the same, there was no significant difference in yield with plant populations of between 50 000 and 70 000 plants ha^{-1}.

2.4.2 Nitrogen fertilization guidelines for cotton at establishment

Guidelines used for cotton establishment in Israel, South Africa, Australia and 12 US states will be discussed concisely to serve as an example.

2.4.2.1 Israel

As a result of nitrogen fertilization trials done on cotton from 1955 to 1978 at Gilat, Bet She'an, Kefar Glickson and Bet Dagan in Israel, Halevy (1979) proposed that the prediction of nitrogen fertilization for cotton should be based on the residual nitrogen in the soil, as well as the mineralisable nitrogen present in the soil. He went further to present a nitrogen balance sheet to determine the correct nitrogen application for irrigated cotton. Components that he included in the balance sheet are the following:

- Residual nitrogen (especially nitrate) to a depth of 1 200 mm (even 1 500 mm) in the soil.
- Nitrogen which is mineralisable in the soil (determined by incubation).
- Nitrogen contained in 400 mm of irrigation water.
- Nitrogen fertilizer applied to the cotton crop.
- Applied nitrogen fertilizer is assumed to be 80% effective.

Halevy and Bazelet (1989) found that high yielding cotton may remove nearly 250 kg N ha^{-1}. This figure corresponds well with the 235 kg N ha^{-1} measured by (Stamatiadis et al. 2016) in Greece and the 247 kg N ha^{-1} measured by Rochester (2011) in Australia. He suggested therefore that the amount of nitrogen removed by the target yield that is fertilized for, should be included in the nitrogen balance sheet. Halevy and Bazelet (1989) mentioned that up to 300 kg N ha^{-1} is applied to cotton grown under drip irrigation in Israel. Furthermore to their proposals made in 1979, Halevy and Bazelet (1989) proposes some additions to the nitrogen balance sheet used to determine the correct nitrogen fertilization of cotton:

- The target yield of cotton that is fertilized for.
- The estimated quantity of nitrogen that will be taken up by cotton producing this specific yield. Halevy (1976) found that a good crop of cotton, producing 4 500 kg ha^{-1} or more seed cotton requires 250 kg N ha^{-1}.
- An estimation or measurement of the nitrogen that will be provided by the soil
- The amount of nitrogen to be fertilized will be determined by the difference between the crop requirement and the amount of nitrogen that the soil will provide, adjusted for the efficiency of the fertilizer that is applied.

2.4.2.2 South Africa

Steenkamp and Jansen (1998) used the parameters proposed by Halevy (1976, 1979) and Halevy and Bazelet (1989) in the nitrogen balance sheet to evaluate nitrogen fertilization field trials on cotton, done in South Africa, and found a good correlation between observed and calculated values.

Steenkamp and Jansen (1998) incorporated the above parameters in the nitrogen balance sheet in the form of the following equation:

$$E = A - (B + C + D)$$

where,

E = the nitrogen fertilization required to produce the crop of a selected yield (at an assumed utilisation factor of 80%). Bronson (2008) reported nitrogen utilisation factors of up to 75% depending on the method of fertilizer application in the west Texas cotton belt.

A = the amount of nitrogen removed by the crop for a specific yield (250 kg N ha^{-1} for a seed cotton yield of more than 4 500 kg ha^{-1}).

B = the residual inorganic nitrogen in the soil to a depth of 900 mm prior to planting (of which 66.7% is estimated to be utilised by the cotton crop).

C = the estimated mineralisation of organic nitrogen in the soil over the growing season, namely 60 kg N ha^{-1} for sandy soils, 120 kg N ha for loam soils and 160 kg N ha^{-1} for clay soils (of which 66.7% is estimated to be utilised by the cotton crop).

D = the nitrogen present in 400 mm of the irrigation water used to grow the crop (of which 80% is estimated to be utilised by the cotton crop).

Good results have been obtained by using this South African approach and it has been used by the local cotton industry for the past 22 years. It is currently still in use and is therefore recommended for use by the Fertilizer Association of Southern Africa (Fertasa 2016).

In Figure 2.5, it can be seen that more than 70% of the nitrogen uptake in cotton occurs between 6 and 15 weeks after planting. This is similar to the nitrogen uptake curve in Figure 2.2, as determined by Duncan and Raper (2019). More than 50% of this nitrogen is translocated to the leaves before being translocated to the bolls (Fertasa, 2016). It is essential therefore that all nitrogen fertilization be applied before 13 weeks after planting.

To avoid losses of nitrogen to leaching, particularly on sandy soils, it is recommended that nitrogen fertilization is split over this period and be completed before 13 weeks after planting. If the cotton plant experiences a shortage of nitrogen in this critical period, it may result in lower yields (Fertasa 2016).

If large quantities of undecomposed organic material are incorporated into the soil, shortly before planting cotton, and the C:N ratio in the soil increases significantly, a nitrogen negative period may occur, requiring more nitrogen to be applied earlier on to prevent loss of potential by the cotton crop.

2.4.2.3 Australia

Independent to the above, a nitrogen fertilization guideline was developed over time by researchers in Australia. The emphasis was mainly on NUE and nitrogen trials were designed around this issue, culminating in a nitrogen fertilization guideline based on the nitrate nitrogen content of the soil, taken to a depth of 300 mm, one month before planting. As Australia is situated in the southern hemisphere, soil samples are generally taken in September, one month before planting commences.

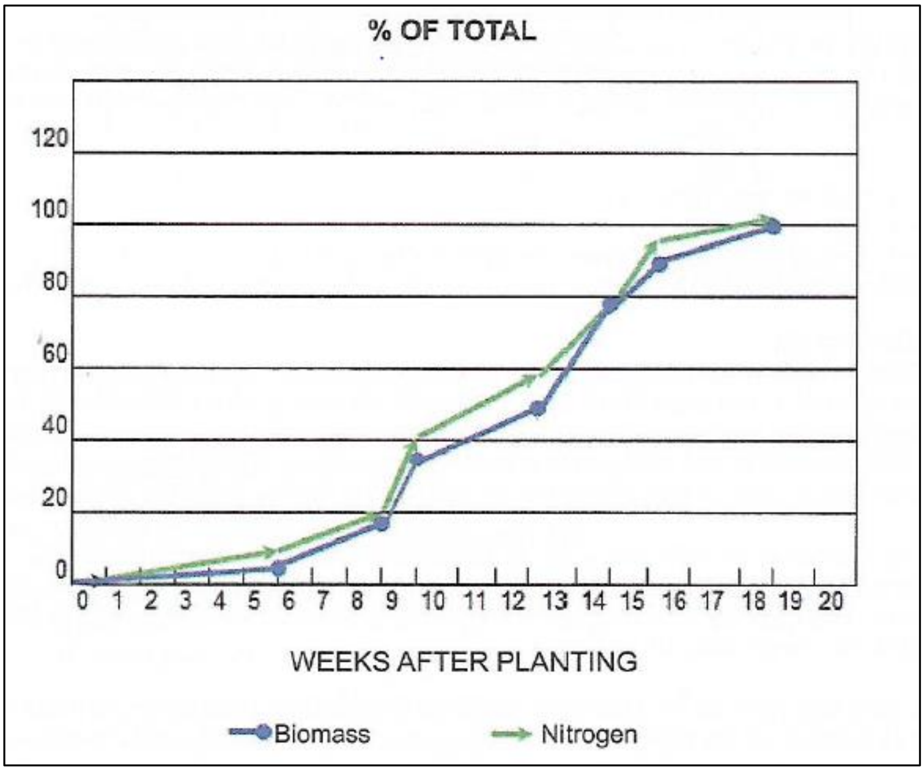


Figure 2.5 Relative increase in biomass production and nitrogen uptake of cotton during the growing season (Fertasa 2016)

Nitrogen fertilization trials were performed by Rochester et al. (2001) to estimate the nitrogen requirement of cotton following a variety of different legume crops. The trials were done on a self-mulching medium grey clay soil, overlying a brown clay in the subsoil. The soil can be classified as a fine, thermic, montmorillonitic typic Haplustert with 53% clay. Twelve different nitrogen regimes were created in the soil by crops preceding cotton. The nitrate nitrogen content of the top 300 mm of soil was recorded prior to planting. Field optimum nitrogen levels were estimated from the yields measured and the following results were obtained (Table 2.1).

Table 2.1 Results of nitrogen fertilization trials done in Australia (Rochester et al. 2001)

Previous crop	Initial soil nitrate (kg N ha^{-1})	Optimum N rate (kg ha^{-1})
Cotton	28.80	186
Soybean	62.55	82
Lablab	108.45	6
Wheat	35.55	184
Faba bean	57.60	133
Field pea	65.25	105
Cotton	26.10	182
Soybean	96.30	43
Lablab	87.30	0
Wheat	42.30	167
Faba bean	95.85	76
Field pea	100.35	78

The results of these studies were used to refine a nitrogen fertilization guideline based on the residual nitrate content of the top 300 mm of soil (sampled prior to sowing) and/or the cotton leaf petiole nitrate content taken at flowering (750 degree-days after sowing). The guidelines are depicted in Figure 2.6. The dotted line in Figure 2.6 (d) is the first guideline that was developed, but it under-estimated the nitrogen fertilization rates and needed to be improved.

The nitrogen fertilization guideline developed by Rochester et al. (2001) is based on a linear correlation found between soil nitrate or petiole nitrate and the optimum nitrogen fertilization of cotton. The constant and slope values for the soil nitrate regression line are 0.123 and 1.001, respectively (r^2 = 0.83) while the constant and slope values for the leaf petiole nitrate content regression line are 0.492 and 0.998, respectively (r^2 = 0,71).

Based on the work done by Rochester et al. (2001), Deutscher et al. (2001) developed a computerised support tool, named NutriLOGIC, to predict the economic optimum nitrogen fertilization rate using soil nitrate and petiole nitrate estimates. Practical implementation of NutriLOGIC led to the conclusion that although it was robust, it needed further calibration to allow it to be useful over a greater range of regions and growing seasons. According to Rochester (2011, 2012), the use of preplanting soil analyses for residual nitrogen, as well as in-crop tissue analysis, is used in Australia to estimate the optimal nitrogen fertilization of cotton.

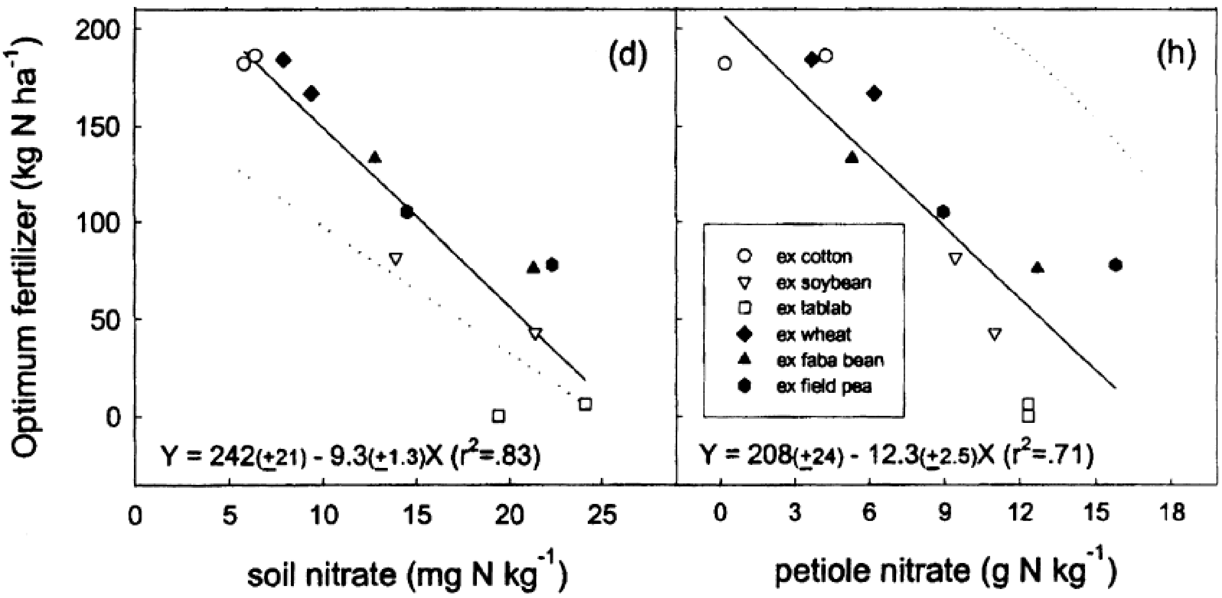


Figure 2.6 Soil nitrate content and nitrate content of the leaf petiole related to the optimum nitrogen fertilization rate for cotton (Rochester et al. 2001)

Subsequently, Smith and Welsh (2018) using data of the late Dr Ian Rochester to incorporate the web based NUTRIpak into NutriLOGIC as a practical nutritional guide for cotton growers in Australia. The resulting regression line from NutriLOGIC to predict the correct nitrogen fertilization of cotton is given in Figure 2.7. The dotted lines represent a lower and higher yield option in the nitrogen fertilization guideline.

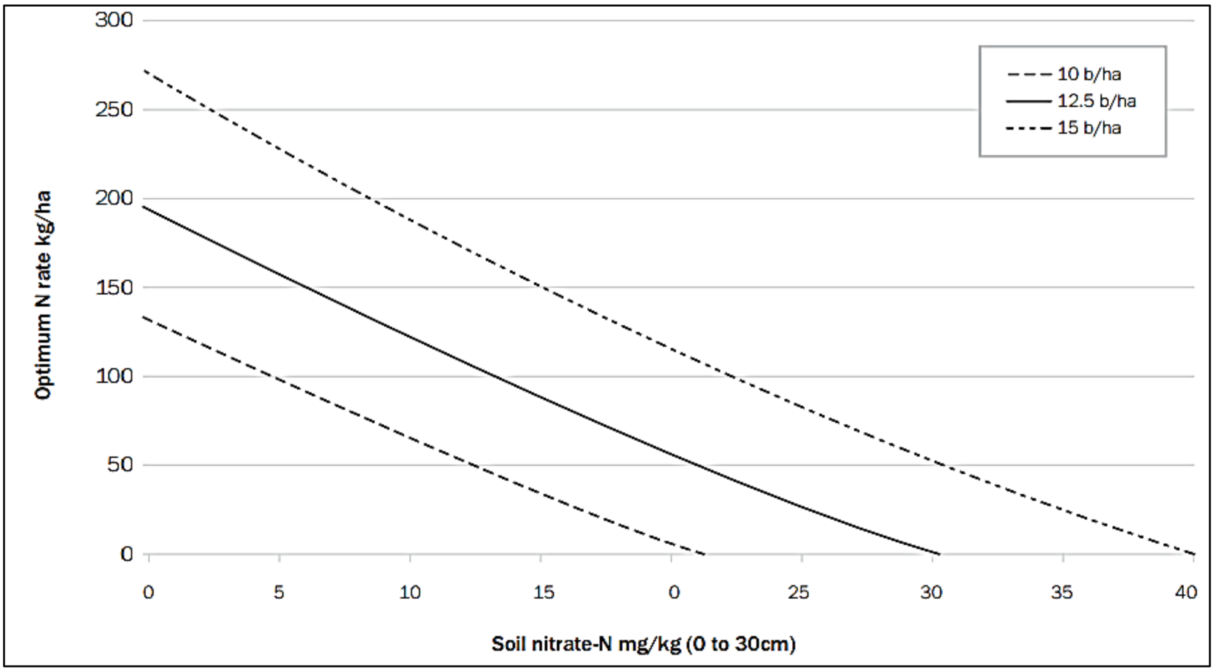


Figure 2.7 The relationship between the optimum nitrogen fertilization requirement for irrigated cotton, based on the residual nitrate nitrogen content of the soil (0–300 mm depth), taken during September, one month before planting cotton (Smith and Welsh 2018)

2.4.2.4 United States

Texas:

The agricultural extension service of Texas A&M University also recommends the use of soil analyses, done to a depth of 600 mm as close as possible to planting time to estimate the amount of residual nitrogen, and the optimal nitrogen fertilization of cotton (Lemon et al. 2009). After conducting research over a seven year period across the major cotton producing areas of Texas, they concluded that in 61% of the 33 sites studied the soils contained more than 112 kg ha^{-1} residual nitrogen to 600 mm depth. This level of nitrogen was sufficient to produce optimum cotton yields without having to fertilize any additional nitrogen.

Based on their findings, Lemon et al. (2009) recommended that 191 kg N ha^{-1} should be fertilized to produce a cotton crop with 1 961 kg lint ha^{-1} that equates to 5 884 kg seed ha^{-1}. They recommend that the amount of nitrogen that is residual in the soil, as well as the amount of nitrogen present in the irrigation water must be subtracted from the estimated amount of nitrogen to be applied on the crop. Additional to this research they conducted nitrogen utilization studies by placing ^{15}N at various depths in the soil and determining the recovery thereof by cotton (Figure 2.8).

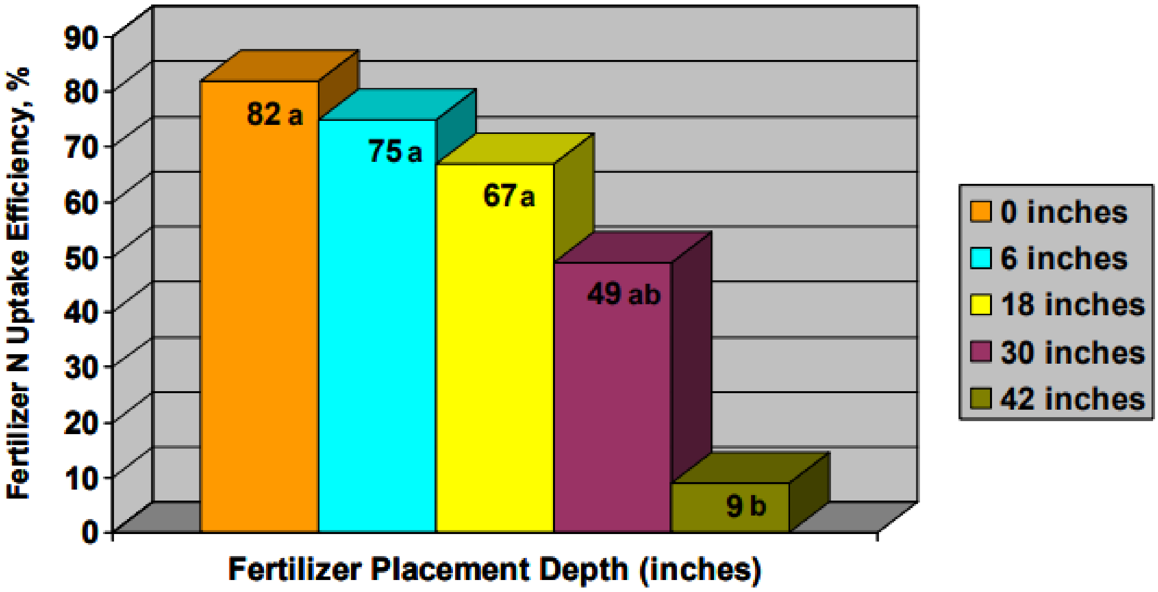


Figure 2.8 Nitrogen uptake efficiency of cotton from ^{15}N-labelled fertilizer placed at various depths Note: Samples were taken at early bloom (Lemon et al. 2009)

Hons et al. (2014) state that current nitrogen recommendations for irrigated cotton in Texas is based on the assumption that 23 kg of nitrogen is required for each 227 kg bale of cotton lint that is produced. For a yield target of 1 400 lint ha^{-1} or 4 200 kg seed cotton ha^{-1}, a nitrogen application of 142 kg N ha^{-1} is recommended. The authors recommend that the residual soil nitrate content, to a depth of 600 mm, as well as the nitrogen content of the irrigation water be deducted from the recommended nitrogen fertilization rate.

In nitrogen fertigation trials on clayey soils (CalciXerollic Xerochrepts), using ^{15}N in the Hama province in the mid-west of Syria, Janat (2004) measured an uptake of 417 kg N ha^{-1} to produce 2 220 kg lint cotton ha^{-1}. This equates to that 43 kg N is required to produce a bale of cotton lint, and this almost twice as high as the nitrogen fertilization rates recommended by Hons et al. (2014). Janat (2004) attributes this high uptake of nitrogen to inter alia the high residual nitrogen content in the clayey soil to a depth of 1 000 mm prior to planting (about 200 kg ha^{-1}), the high level of nitrogen applied during this specific treatment (240 kg N ha^{-1}), and the high release of nitrogen by mineralisation in the clayey soil. A good root development of the cotton resulting in a high efficiency of water and nitrogen uptake also contributed the large amount of nitrogen taken up. This may be an indication that under conditions of low rainfall, high evaporation and high nitrogen supply cotton can take nitrogen up in quantities that are higher than the crop's requirement.

The high nitrogen uptake measured by Janat (2004), of 417 kg N ha^{-1} compares with the previously mentioned theoretical maximum yield of cotton of 5 000 kg lint ha^{-1} suggested by Constable and Bange (2015), where Rochester (2014) is of the opinion that it would require a nitrogen fertilization rate of 320–420 kg N ha^{-1} to achieve such a cotton yield.

Louisiana:

Nitrogen recommendations for cotton in Louisiana are based on more than 40 years' research done by many agronomists (Robinson 1990). Most of the cotton (80%) in Louisiana is grown on alluvial soils of the Mississippi river valley and the upland soils on the Macon ridge. Nitrogen recommendations on the coarse-textured soils varies between 67 and 101 kg N ha^{-1} and on the fine textured soils between 90 and 112 kg N ha^{-1}. The slightly higher nitrogen fertilization rate on the fine textured soils is to cater for nitrogen losses due to denitrification, as these soils are poorly aerated. Nitrogen application rates can be reduced by 11–22 kg N ha^{-1} following a soybean crop and 45–56 kg N ha^{-1} following a winter legume green manure crop.

Alabama:

According to Touchton et al. (1981), the recommended fertilization rates of nitrogen on cotton in Alabama is based on "scores of experiments throughout the state". The results obtained from these experiments have shown the optimum rate of nitrogen fertilization on cotton to be between 67 and 101 kg N ha^{-1}. These nitrogen fertilization rates are used as the basis of the cotton fertilization programme. Additional nitrogen can be applied in season depending on the outcome on cotton leaf petiole analyses that are done during the growing season.

Arkansas:

In Arkansas, nitrogen fertilization recommendations on cotton are based on soil and plant analyses under the stewardship of the University of Arkansas (Maples et al.

1990). The University of Arkansas soil testing service laboratory is capable of analysing between 600 and 800 soil samples for nitrate in an 8-hour day. Nitrogen recommendations are based on results of more than 100 years of research, commenced in 1887 and done by scientists at experimental stations, in cooperation with agricultural advisors and cotton farmers. The nitrogen recommendations (Table 2.2) are primarily based on the nitrogen content of the topsoil, clay content of the soil, calcium content of the soil, area in which the field is situated within Arkansas (North, Central or South), and if excessive stalk growth has been experienced on the particular field before. These nitrogen recommendations are supported by a very well implemented leaf petiole analysing programme during the growing season (Maples et al. 1990).

Table 2.2 Nitrogen fertilization recommendations for cotton by the University of Arkansas (Maples et al. 1990)

Texture: Soil Ca kg ha^{-1}		Clay to clay loam						Silt loam, sandy loam, sand			
		> 5 040		3 361–5 039		< 3 361		> 5 040		< 5 040	
Excessive stalk growth		No	Yes	No	Yes	No	Yes	No	Yes	No	Yes
Nitrate N (kg ha^{-1})	Area	Recommended N (kg ha^{-1})*									
0–25 (or no nitrate)	North	112**	67,2	78,4[$]	56	56[#$]	33,6	78,4	50	56[#$]	44,8
	Central	112**	67,2	89,6[$]	67,2	67,2[$]	44,8	89,6	67,2	67,2[#$@]	56
	South	112**	67,2	100,8[$]	78,4	78,4[$]	56	100,8	78,4	78,4[#$]	67,2
26–40	North	100,8**	67,2	67,2[$]	56	44,8[#$@]	33,6	67,2	56	44,8[#$@]	44,8
	Central	100,8**	67,2	78,4[$]	67,2	56[#$]	44,8	78,4	67,2	56[#$]	56
	South	100,8**	67,2	89,6	78,4	67,2[#$@]	56	89,6	78,4	67,2[#$@]	67,2
41–60	North	89,6**	56	56[$]	44,8	33,6[#$@]	22,4	56	44,8	33,6[#$@]	33,6
	Central	89,6**	56	67,2[$]	56	44,8[#$@]	33,6	67,2	56	44,8[#$@]	44,8
	South	89,6**	56	78,4[$]	67,2	56[#$@]	44,8	78,4	67,2	56[#$@]	56
> 60	North	78,4**	44,8	44,8[$]	33,6	22,4[#$@]	11,2	44,8	33,6	22,4[#$@]	22,4
	Central	78,4**	44,8	56[$]	44,6	33,6[#$@]	22,4	56	44,8	33,6[#$@]	33,6
	South	78,4**	44,8	67,2[$]	56	44,8[#$@]	33,6	67,2	56	44,8[#$@]	44,6

* Statement for N recommendations based on soil nitrates: "The cotton N recommendation based on soil nitrates applies to only the first year of cotton. Retest second year cotton."

** For clay soils with calcium greater than 5 040 kg ha^{-1}: "If denitrification is thought to occur, side-dress an additional 56–67,2 kg N ha^{-1}.

$ If pasture, fallow, or winter legume precedes, subtract 11,2 kg N ha^{-1} from recommendations.

\# If soil organic matter is less than 1% increase N rates by 11,2 kg N ha^{-1}.

@ If calcium level is below 3 361 kg ha^{-1} and organic matter is below 1%: "To decrease risk of salt damage, side-dress 33% to 0% of total N.

General statement for all cotton: "Increase N rate 22,4 to 33,6 kg N ha^{-1} with a high yield potential (irrigation). For best use of high N, split total N between preplant application and side-dressing by early July. For any additional N needs, consider petiole testing. For skip row, adjust total N rate to hectares of cotton."

Georgia:

In the 2021 Georgia cotton guide (Hand et al. 2021), the nitrogen fertilization guideline is based on a nitrogen application rate of 118 kg N ha^{-1} to produce 1 681 kg lint ha^{-1} or approximately 5 043 kg seed cotton ha^{-1}. The nitrogen fertilization can be increased by 25% if it is a deep sandy soil, cotton following cotton or the field has a history of inadequate cotton stalk growth.

North Carolina:

Based on the outcome of many nitrogen fertilization trials, Gatiboni and Hardy (2021) recommend nitrogen fertilization of 35–90 kg N ha^{-1} for rainfed cotton and 20–25% higher for irrigated cotton in the North Carolina cotton growers information guide. Cotton growers in North Carolina are referred to the North Carolina realistic yield expectations and nitrogen fertilizer decision making guide, authored by Osmond et al. (2020), to calculate the correct nitrogen fertilization level for their cotton crops. This guide covers 32 agronomic cropping systems and all of the 465 soil types that are farmed on in North Carolina. It considers various factors such as soil type and texture, the previous crop, soil organic matter, expected rainfall and/or irrigation and the growers experience on the specific field, to determine the amount of nitrogen that should be fertilized.

South Carolina:

In the South Carolina cotton growers' guide produced by the Clemson University (Jones et al. 2019), it is stated that nitrogen and sulphur recommendations for cotton are based on yield goal rather than on soil testing results. For irrigated cotton, the optimal nitrogen fertilization rate is approximately 112 kg N ha^{-1}. If cotton is planted after legumes like soybeans or peanuts, nitrogen application rates may be reduced by 20 to 30 kg N ha^{-1} (Jones et al. 2019).

Missouri:

Nitrogen fertilization recommendations (NR) in Missouri are based on the soil texture as reflected by the cation exchange capacity (CEC) of the soil using the equation NR = CEC × 3 (Tracy 1990). According to Tracy (1990), no adjustments are made for residual nitrate or ammonium, or previous crops grown. Currently the recommended nitrogen fertilization rates for cotton in Missouri is 90–135 kg N ha^{-1} on sandy loam or silt loam soils that have a yield potential of two or more bales of lint cotton ha^{-1} (Missouri Extension 2021b).

Tennessee:

In Tennessee, nitrogen recommendations of cotton are based on research data. Existing nitrogen recommendations are reviewed annually and adapted if new evidence is found to justify any change (Howard and Hoskinson 1990). In the Tennessee cotton production guide for 2021, the recommended nitrogen fertilization rate is 67–90 kg N ha^{-1} on upland soils where excessive growth and late maturity are not a problem (Main 2021). On bottom soils where excessive growth can cause problems, a more conservative application rate of 51–67 kg N ha^{-1} is recommended.

Mississippi:

McCarty and Funderburg (1990) mention that the use of residual nitrogen in soil analyses are not used to determine the nitrogen fertilization of cotton in Mississippi. Preference is given to soil texture and realistic yield goals to determine the nitrogen fertilization of cotton (McCarty and Funderburg 1990). Currently the Mississippi State University extension service states that the factors considered when determining the optimal nitrogen fertilization of cotton in Mississippi are yield potential, weather conditions, sources of nitrogen and timing of application (Mississippi Extension 2021a & b). A general guideline is that approximately 135–157 kg N ha^{-1} would be required to produce four bales of lint cotton ha^{-1} (908 kg lint cotton ha^{-1}).

Arizona:

Guidelines on the nitrogen fertilization of cotton in Arizona are primarily based on the amount of nitrogen that will be removed by the crop. Silvertooth (2015) recommends that 27 kg of nitrogen be applied for each 227 kg bale of cotton lint that is expected to be produced on a particular field. A field that is capable of producing 7.5 cotton bales ha^{-1} (1 702,5 kg lint ha^{-1}), would require a nitrogen fertilization of 202 kg of N ha^{-1}. Silvertooth (2015) recommends that adjustments be made for residual soil nitrogen, fertilizer use efficiency as well as crop condition.

California:

Spencer et al. (1966) researched the relationship between tests done for residual soil nitrogen and the uptake of nitrogen by cotton grown in California on desert soils which are low in organic matter. They concluded that the use of residual nitrogen tests to predict the nitrogen needs of cotton showed promise and that the use of plant analyses for nitrogen during the growing season would add to the accuracy of such predictions.

Building forth on this finding, the University of California cooperative extension service currently bases their nitrogen recommendations for irrigated cotton on preplant soil samples taken at least to a depth of 600 mm, and if possible, to a depth of 900 mm, or even 1 200 mm (Hutmacher 2017). Based on residual nitrate-nitrogen levels in the top 600 mm soil, the following levels of nitrogen fertilization are recommended:

- When the residual nitrate nitrogen in the soil is less than 120 kg N ha^{-1}, a nitrogen fertilization rate of 140–195 kg N ha^{-1} is recommended.
- When the residual nitrate nitrogen in the soil is between 120 and 220 kg N ha^{-1}, a nitrogen fertilization rate of between 85–140 kg N ha^{-1} is recommended.
- When the residual nitrate nitrogen in the soil is more than 220 kg N ha^{-1}, a nitrogen fertilization rate of 85 kg N ha^{-1} or less is recommended (Hutmacher 2017).

Hutmacher (2017) also recommends that leaf petiole samples be taken from cotton in the fields to evaluate the nitrate nitrogen content of the plant to establish if additional nitrogen applications may be required.

Weir et al. (1996) from California State University recommend that preplant soil samples for cotton be taken to a depth of 900 mm, at least three weeks after the application of nitrogen-containing fertilizers such as manure to allow nitrogen mineralisation to take place before the collection of soil samples.

After reviewing many studies on the topic, Breitenbeck (1990) observes that in the United States, the use of soil nitrogen analyses to determine the required nitrogen fertilization of cotton has had more success in the western states that are arid and semi-arid. Less success has been achieved in the eastern, more humid states. He concludes that more research is needed to determine if preplant analyses of soil nitrogen can be used reliably in the more humid states of America.

This is an interesting observation, as many of the studies reporting good results using soil nitrogen analyses to predict optimum nitrogen fertilization of cotton were done in arid or semi-arid areas such as Israel, Syria and Australia.

2.4.3 Use of nitrogen leaf petiole analyses during cotton growth

The evaluation of the nitrogen nutritional status of cotton while it is growing in the field was initiated by Joham (1951) at the Texas agricultural experiment station. He reported that the most reliable plant tissue to sample to determine the nitrogen status of cotton, was the leaf petiole. As the first researcher to sample leaf petioles for this purpose, he found that the best results were achieved by taking samples of the petiole of the first mature leaf on the main stem of the plant, as seen from the top of the plant. He sampled the fourth leaf from the top on the main stem. This leaf is generally accepted as the youngest mature leaf on the main stem (Braud 1987).

The practice is to collect at least 25 to 30 leaf petioles at weekly intervals, beginning at the time when the first square emerges (Munro 1987). Sampling can continue until 8 weeks after the emergence of the first square.

As mentioned previously, Rochester (2012) confirms the necessity of basing the nitrogen fertilization of cotton on the residual nitrogen content of the soil at planting and the use of in season tissue analysis to estimate optimal nitrogen fertilization of cotton in Australia. From literature considered, it seems that leaf petiole analyses during the growing season can be useful to determine the nitrogen status of cotton.

In the same trials referred to earlier, where the residual nitrate nitrogen content of the soil was measured under different cropping systems, Rochester (2012) also measured the nitrate nitrogen of cotton leaf petioles, the results of which are given in Table 2.3.

The graphic representation of the nitrate nitrogen content of cotton leaf petioles, sampled 750 degree-days after sowing, relative to the optimum nitrogen fertilization is given in Figure 2.9 (h).

Table 2.3 Results of nitrogen fertilization trials done by Rochester et al. (2001)

Previous crop	Leaf petiole nitrate content (g kg^{-1})	Optimum N rate observed (kg ha^{-1})
Cotton	4.3	186
Soybean	9.4	82
Lablab	12.3	6
Wheat	3.7	184
Faba bean	5.3	133
Field pea	9.0	105
Cotton	0.2	182
Soybean	11.0	43
Lablab	12.3	0
Wheat	6.2	167
Faba bean	12.7	76
Field pea	15.8	78

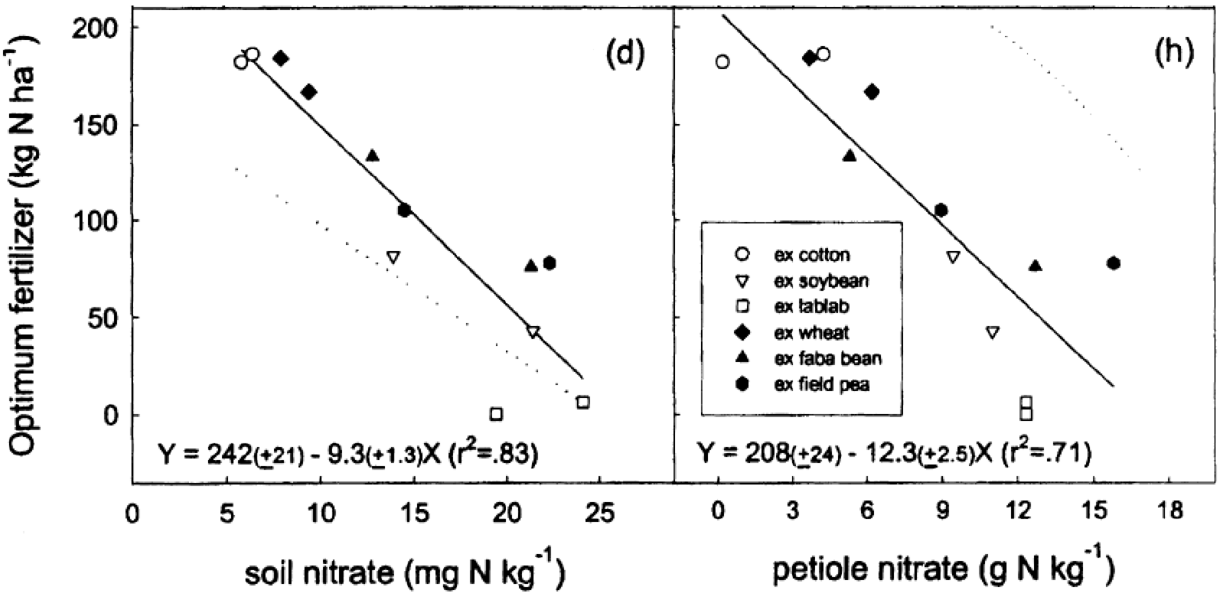


Figure 2.9 Soil nitrate content and nitrate content of the leaf petiole related to the optimum nitrogen fertilization rate for cotton (Rochester et al. 2001)

In order to interpret the results of cotton leaf petiole nitrate nitrogen analyses, they have to be compared with the relevant norms used for the purpose. The sufficiency ranges that have been used since 1985, to identify if the nitrate nitrogen content of cotton leaf petioles is deficient, adequate or excessive are illustrated in Figure 2.10 (Lutrick et al. 1986).

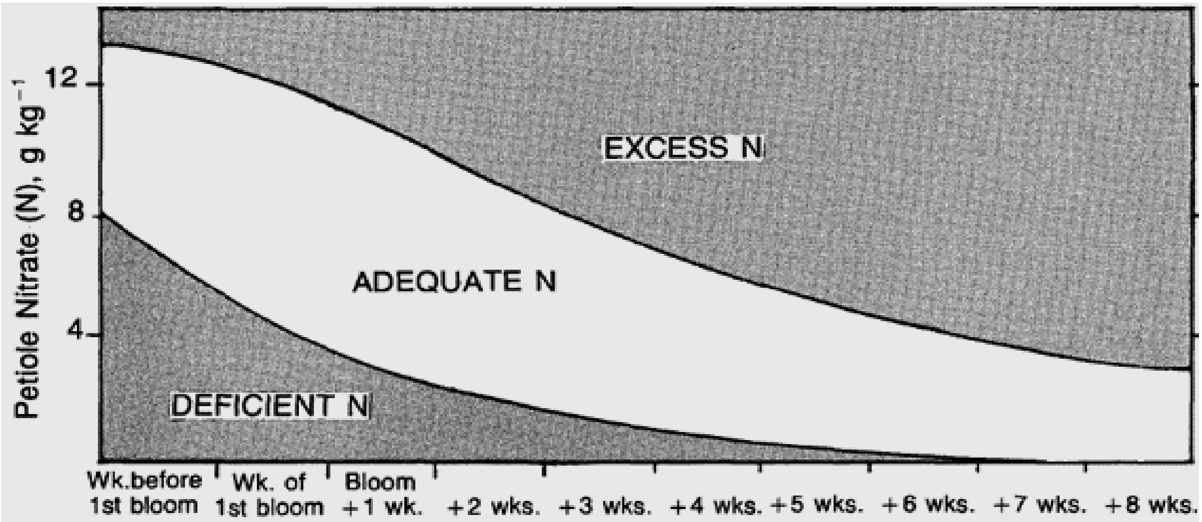
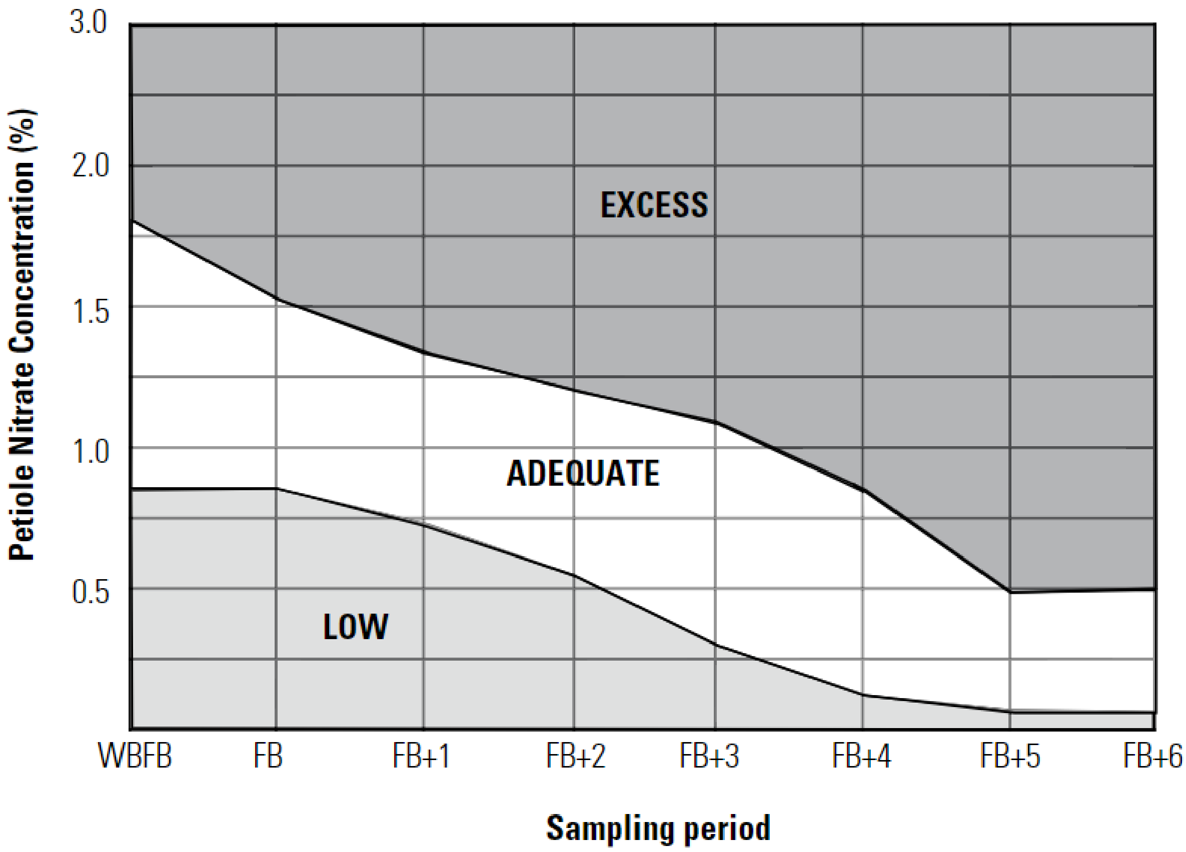


Figure 2.10 Cotton leaf petiole sufficiency ranges at weekly intervals from one week before first bloom (Lutrick et al. 1986)

Care should be taken during the collection of the petiole samples that attention is paid to soil and plant conditions, for example plant maturity, boll load, time of day, air temperature and soil water content, as the nitrate content of the petiole can vary dramatically depending on the mentioned factors (Mitchell and Baker 1997).

In North Carolina the nitrate nitrogen concentration of cotton leaf petioles is used to determine if initial nitrogen applications are sufficient (Figure 2.11) or if additional nitrogen needs to be applied to the crop (Gatiboni and Hardy 2021). The norms for the nitrate nitrogen content of cotton leaf petioles over the various growth stages is given in Table 2.4 (Cleveland 2012). Similar norms that are recommended for use by Georgia State University (Table 2.6) are recommended by Clemson University for use by cotton growers in South Carolina (Jones et al. 2019). Hutmacher (2017) of California State University recommends slightly different values for the nitrate nitrogen levels for cotton leaf petioles, as given in Table 2.5.



Note: WBFB = Week before bloom, FB = First bloom, and the FB number indicates weeks after first bloom

Figure 2.11 Ratings for petiole nitrate concentrations during the bloom period Note: North Carolina (Gatiboni and Hardy 2021)

Table 2.4 Desired range of cotton leaf petiole nitrate nitrogen levels (mg kg^{-1}) for growth stage and week (Cleveland 2012)

Week	Seedling (S) (mg kg^{-1})	Early (E) (mg kg^{-1})	Bloom (B) (mg kg^{-1})	Fruit (F) (mg kg^{-1})	Mature (M) (mg kg^{-1})
1	16 000–30 000	12 000–18 000	6 000–12 000	1 000–6 000	200–2 500
2	15 000–25 000	10 000–16 000	5 000–11 000	500–5 000	150–2 000
3	14 000–22 500	8 000–14 000	3 500–10 000	250–4 000	100–1 500
4	13 000–20 000	7 500–13 000	2 000–8 000	100–3 000	50–1 000

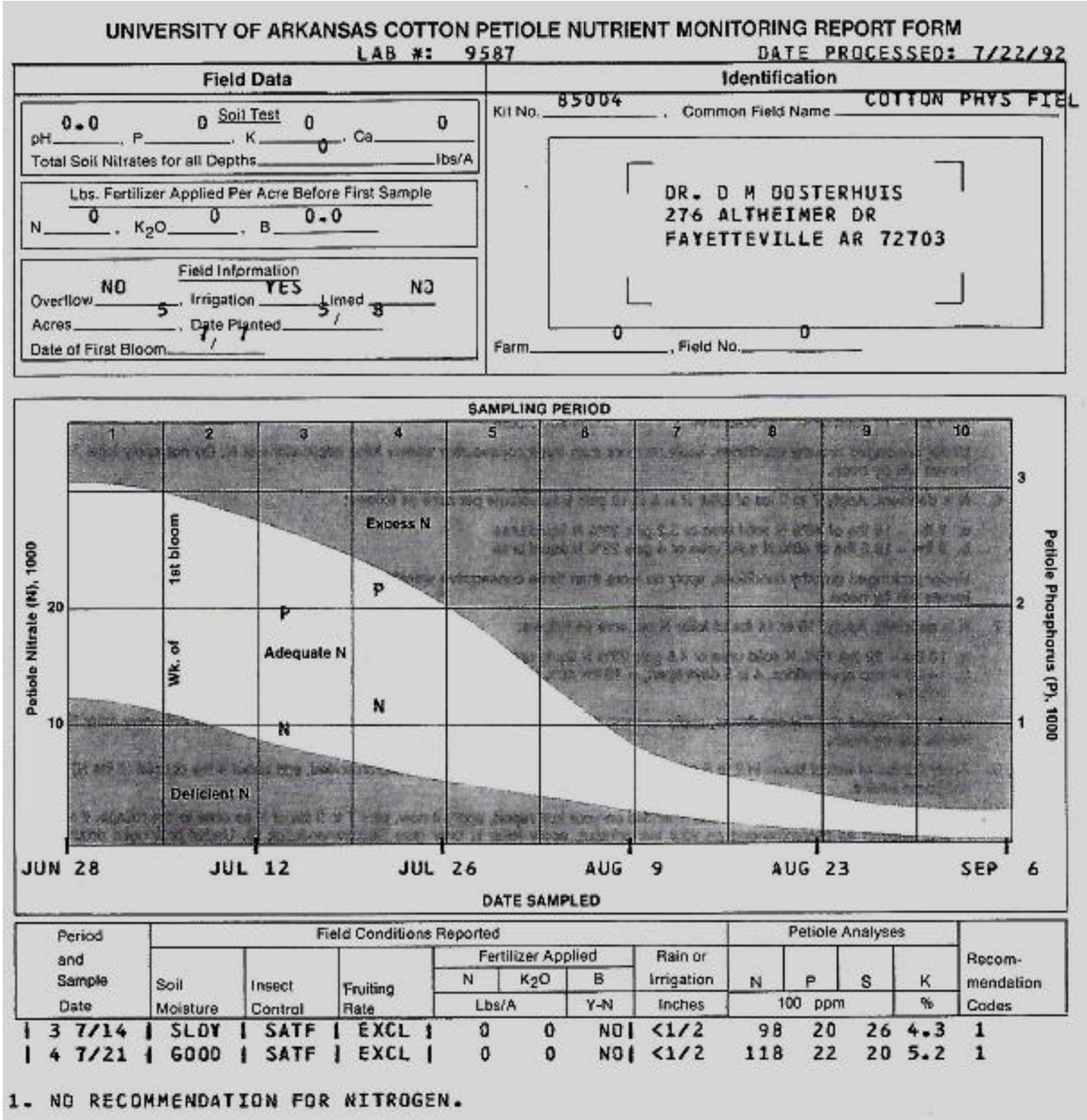
Table 2.5 Cotton leaf petiole nitrate nitrogen levels as recommended by California State University (Hutmacher 2017)

Growth stage	Borderline to deficiency (mg kg^{-1})	Sufficient upper level (mg kg^{-1})
Early square	<14 000	>20 000
First flower	< 11 000–12 000	14 000–18 000
First flower + 10 days	< 8 000–10 000	12 000–14 000
Peak bloom	< 3 500–5 500	> 7 000–9 000
Early open boll	< 1 500–2 000	> 3 500–4 500
10–15 days after cut-out	< 750–1 200	> 1 500–2 000

Table 2.6 Nitrate nitrogen concentration of cotton leaf petioles for the various growth stages as endorsed by Georgia state university and Clemson University of South Carolina (Jones et al. 2019)

Time of sampling	Nitrate nitrogen (mg kg^{-1})
Week before first bloom	7 000–13 000
Week of bloom	4 500–12 500
Bloom + 1 week	3 500–11 000
Bloom + 2 weeks	2 500–9 500
Bloom + 3 weeks	1 500–7 500
Bloom + 4 weeks	1 000–7 000
Bloom + 5 weeks	1 000–6 000
Bloom + 6 weeks	500–4 000
Bloom + 7 weeks	500–4 000
Bloom + 8 weeks	500–4 000

In Arkansas it was found that the leaf petiole nitrate test proved to be a reliable indicator of the nitrogen status of cotton from the third week of squaring, until the eighth week of flowering (Maples et al. 1990). Initially, the programme attracted only 29 farmers, but soon 1 500 fields were being monitored by the system. An example of the leaf petiole monitoring form (Oosterhuis 1992) is given in Figure 2.12.



UNIVERSITY OF ARKANSAS COTTON PETIOLE NUTRIENT MONITORING REPORT FORM

LAB #: 9587 DATE PROCESSED: 7/22/92

Field Data

Soil Test: pH 0.0, P 0, K 0, Ca 0

Total Soil Nitrates for all Depths 0 lbs/A

Lbs. Fertilizer Applied Per Acre Before First Sample: N 0, K_2O 0, B 0.0

Field Information: Overflow NO, Irrigation YES, Limed NO; Acres 5, Date Planted 5/8; Date of First Bloom 7/7

Identification

Kit No. 85004, Common Field Name COTTON PHYS FIEL

DR. D M OOSTERHUIS
276 ALTHEIMER DR
FAYETTEVILLE AR 72703

Farm 0, Field No. 0

Period and Sample Date	Soil Moisture	Insect Control	Fruiting Rate	Fertilizer Applied N (Lbs/A)	K_2O (Lbs/A)	B (Y-N)	Rain or Irrigation (Inches)	N (100 ppm)	P (100 ppm)	S (100 ppm)	K (%)	Recom-mendation Codes
3 7/14	SLDY	SATF	EXCL	0	0	NO	<1/2	98	20	26	4.3	1
4 7/21	GOOD	SATF	EXCL	0	0	NO	<1/2	118	22	20	5.2	1

1. NO RECOMMENDATION FOR NITROGEN.

Figure 2.12 University of Arkansas cotton petiole nutrient monitoring report form (Oosterhuis 1992)

The cotton petiole monitoring report form of the University of Georgia (McMillan 1992) is very similar (Figure 2.13) to the one used by Arkansas, but varies with the levels considered to be sufficient or deficient.

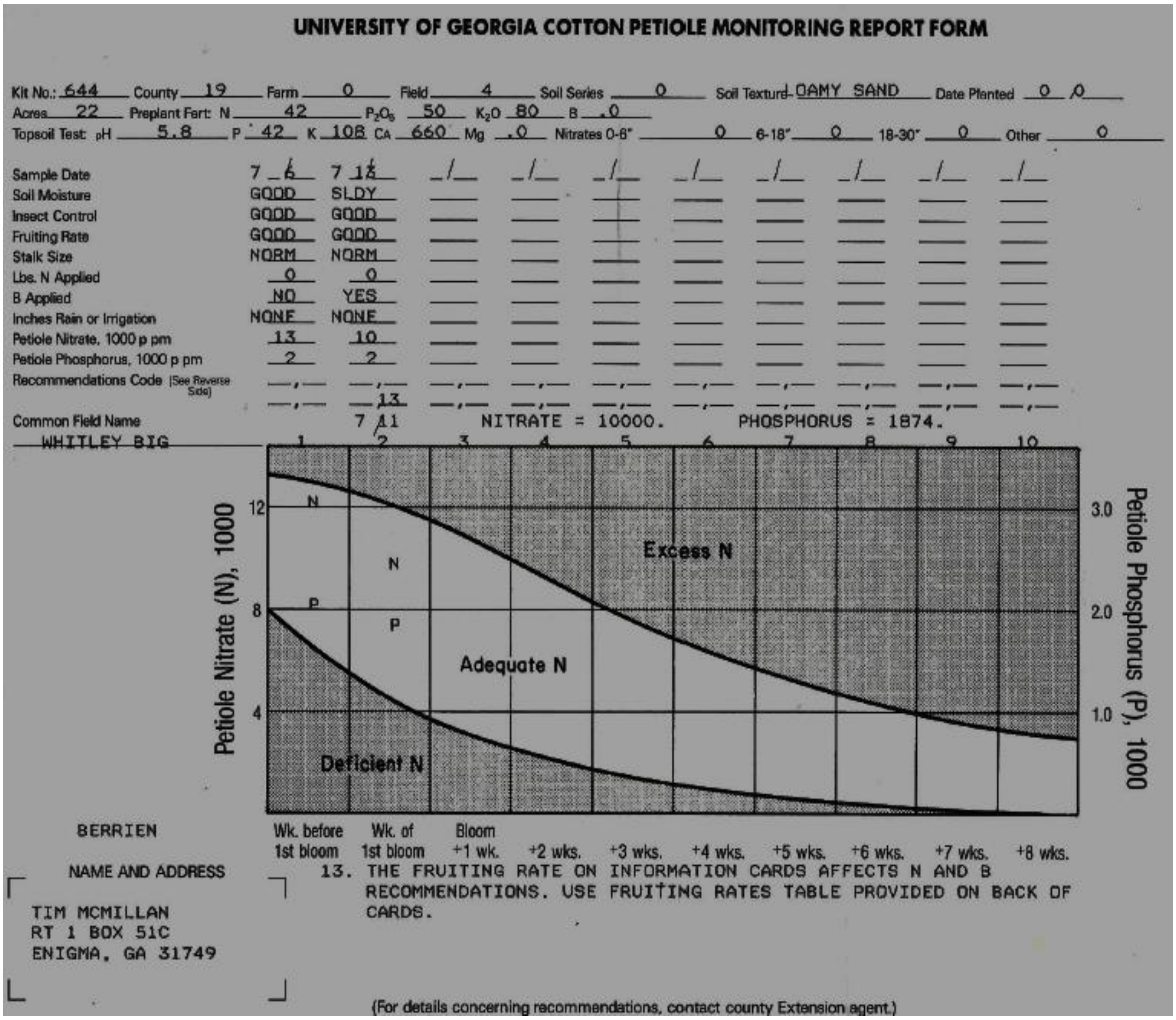


Figure 2.13 University of Georgia cotton petiole monitoring report form (McMillan 1992)

In Missouri no leaf and/or petiole testing are done on a routine basis and nitrogen fertilization recommendations are therefore not based on these tests (Tracy 1990).

2.5 Conclusion

From the literature review it is evident that varying results were found regarding the use of preplant soil nitrogen analyses for the purpose of determining the optimal nitrogen fertilization rate of cotton to be planted on a specific field. It seems that more success is obtained under arid and semi-arid conditions, where nitrogen losses are presumably less (Breitenbeck 1990).

However, for cotton grown on the floodplains of the Mississippi river, the nitrogen content of soil samples taken prior to planting have not been found to have any conclusive benefit in determining the optimum nitrogen fertilization rate for cotton (Mississippi Extension 2021a) preplant. Most probably due to various losses of nitrogen that occur in the soil, as illustrated by Baird and Smith (2019).

Where soil analyses have proven to be useful, the following factors seem to promote the value of these samples, and may be referred to as the 3R approach to nitrogen sampling, namely:

- The right depth of sampling. Although 0–300 mm is a very popular depth to sample (Constable and Rochester 1988), it seems that deeper soil analyses, though being a bit more cumbersome can improve the accuracy of the predicted optimal nitrogen fertilization rate. The preferred depth of sampling seems to be 900 mm (Weir et al. 1996).
- The right time of sampling seems to be at least three (Weir et al. 1996) to four weeks (Laubscher and Du Preez 1989) after land preparation, the incorporation of nitrogenous fertilizer and/or manure, while being as close as possible to planting (Weir et al. 1996). Obviously good soil moisture and temperature (18 °C and above) will be beneficial in promoting as much nitrogen mineralisation as possible.
- The right analysis should be done, and in this instance it seems to be for total plant available inorganic nitrogen, as nitrate is the final product, but ammonium would contribute to the total nitrogen available to the plant.

Although the above approach is applicable for conventional tillage production systems where the soil is aerated by cultivation and mineralisation of nitrogen can take place, there is a move towards agricultural production systems that favour carbon sequestration and thus minimum tillage and even zero tillage production systems. Under these systems, the mineralisation of nitrogen can be much less than in a conventionally tilled soil system, due to less aeration of the soil. Using existing nitrogen fertilization guidelines can lead to an over estimation of the contribution of nitrogen from mineralisation, and result in under-fertilization of the crop with nitrogen, with subsequent lower yields and financial loss.

Due to the above factors, nitrogen fertilization experiments were conducted on irrigated cotton in some of the main cotton producing areas of South Africa, in order to refine existing nitrogen fertilization guidelines for the production of cotton under irrigation. The main objective set in the refinement of the nitrogen fertilization guidelines, is the prerequisite that it must be fundamentally based on both the residual nitrogen content of the soil, as well as the contribution of nitrogen mineralisation in the soil.

The nitrogen fertilization guideline proposed by Fertasa (2016) recommends that the amount of nitrogen to be fertilized on cotton should be based on the crop requirement for the specific yield target, the residual nitrogen content of the soil to a depth of 1.2 m, the expected mineralisation of nitrogen in the soil to a depth of 1.2 m (based on soil texture), as well as the amount of nitrogen added to the soil by 400 mm of irrigation water.

Although the most recent nitrogen fertilization guideline (Fertasa, 2016), incorporates in principle, the recommendations and findings by Du Preez and Burger (1986) practice necessitates a more accurate nitrogen fertilization guideline for irrigated cotton. The reason being that too low an application of nitrogen will result in poor crop growth and development while too much nitrogen will result in a luxurious crop growth and development (even with the use of growth inhibitors), where insect damage and disease can reduce yield.

As the mineralisation of nitrogen can contribute significantly to the amount of nitrogen available in soil for plant uptake, it is essential that the mineralisation process be considered when developing a nitrogen fertilization guideline for crops (Jansson and Persson 1982).

Laubscher and Du Preez (1989) conducted nitrification studies in the soils of the central irrigation areas of South Africa (amongst others, Rietrivier and Vaalharts). Nitrification in these soils was completed in a period of 2.6 to 15.3 days in the topsoil (0–200 mm) and 4.6 to 31.7 days in the subsoil (600-900 mm).

It can be accepted that nitrogen mineralisation and nitrification will be accelerated in soil from the point where the soil is irrigated and tilled during preparation for planting. Similar to the onset of incubation conducted in the research done by Laubscher and Du Preez (1989). Furthermore, it can be assumed that when soil temperatures are suitable for planting of cotton (>20 °C), there should be no limitation on nitrogen mineralisation and nitrification due to temperature.

The research done by Laubscher and Du Preez (1989) practically implies that nitrogen mineralisation and nitrification in the topsoil should be completed within two weeks after irrigation and land preparation, and within four weeks in the subsoil.

By taking soil samples four weeks after irrigation and soil preparation, the samples should provide a relatively dependable measure of the residual and mineralisable nitrogen in the soil that can contribute to nitrogen uptake by the crop.

The use of leaf petioles as an in season guideline for determining whether the nitrogen status of the cotton plant is deficient, adequate or excessive, has proven to be of good use in Australia (Rochester et al. 2001) and some US states, such as Arkansas, Georgia and Texas.

Although the collection of cotton leaf petiole samples in the correct way can be very demanding, and may be affected by many environmental factors such as irrigation, time of day, it is being successfully implemented by many US states, and in other countries under high levels of management.

The use of nitrate nitrogen analysis in cotton leaf petioles to assess the nitrogen status of cotton in season is renowned to be very variable and therefore subject to very wide ranges of acceptability. Hence, the use of nitrate nitrogen determined in cotton leaf petioles requires insight and experience by advisors and farmers.

In an attempt to reduce this variability of nitrate nitrogen content in cotton leaf petioles, total nitrogen content that includes ammonium and nitrate will be determined to reduce variability so that these analysis values can be used with more confidence when evaluating the in season nitrogen status of cotton. This approach may contribute to the refining of nitrogen fertilizer guidelines of irrigated cotton in South Africa.

Chapter 3
Materials and Methods for Field Trials

3.1 Experimental locations and sites

Nitrogen fertilization trials with irrigated cotton were conducted at five cotton producing locations in South Africa. All trials were planted on premises of the Agricultural Research Council (ARC).

- Bela Bela, at the Toowoomba Agriculture Research Station, situated 4 km south-east of Bela Bela (latitude −24.906809°, longitude 28.332058°, altitude 1 135 m).
- Groblersdal, at the Loskop Agriculture Research Station, situated on the southern perimeter of Groblersdal (latitude −25.177125°, longitude 29.392226°, altitude 931 m).
- Rustenburg, located at the Tobacco and Cotton Research Institute (TCRI), situated 6 km south-east of Rustenburg and 1.5 km west of Kroondal, on two sites (Site 1: latitude −25.722447°, longitude 27.291803°, altitude 1 165 m and Site 2: latitude −25.736771°, longitude 27.288422°, altitude 1 162 m).
- Vaalharts, located at the Vaalharts Agriculture Research Station, situated 5 km south of Jan Kempdorp and 86.5 km north of Kimberley (latitude −27.962621°, longitude 24.837023°, altitude 1 175 m).
- Rietriver, located at the Rietriver Agricultural Research Station, situated 46 km south of Kimberley and 19 km west of Jacobsdal (latitude −29.05278°, longitude 24.62778°, altitude 1 117 m).

At Rustenburg two sites and at each of the other four locations only one site was planted. Site 1 and Site 2 at Rustenburg comprised on account of different preceding crops of two and three fields, respectively. Therefore, the trials for the study amounted to nine. Cotton was planted in the 1987/88, 1988/89 and 1989/90 growing seasons. The number of seasons varied amongst the sites as indicated in Table 3.1. A summary of the soil types, cotton cultivars, plant densities and nitrogen rates for each site is also given in Table 3.1.

Table 3.1 Site, season, soil form, soil series, cultivar, plant population, and rates of nitrogen applications that were used at the locations during this study

Site location	Season	Soil form*	Soil series*	Cultivar	Plants ha^{-1}	N rates ($kg\ ha^{-1}$)
Rustenburg 1	1987/88	Arcadia	Arcadia	Letaba	80 000	0, 50, 100, 150
Rustenburg 1	1988/89	Arcadia	Arcadia	Letaba	80 000	0, 50, 100, 150
Rustenburg 2	1989/90	Hutton	Marikana	Acala 1517/70	130 000	0, 50, 100,150, 200
Rietriver 3	1988/89	Hutton	Mangano	Acala 1517/70	80 000	20, 40, 80, 120, 160, 200
Rietriver 3	1989/90	Hutton	Mangano	Acala 1517/70	80 000	20, 40, 80, 120, 160, 200
Vaalharts 4	1988/89	Hutton	Mangano	Acala 1517/70	80 000	20, 40, 80, 120, 160, 200
Vaalharts 4	1989/90	Hutton	Mangano	Acala 1517/70	80 000	20, 40, 80, 120, 160, 200
Groblersdal 5	1989/90	Hutton	Marikana	Acala 1517/70	80 000	0, 40, 80, 120, 160, 200
Bela Bela 6	1988/89	Arcadia	Arcadia	Acala 1517/70	50 000	0, 15, 30, 45

* Macvicar et al. (1988)

3.2 Experimental design and layout

Randomised block designs with six treatments (six levels of nitrogen) in five blocks (five replications) were used at Groblersdal, Vaalharts and Rietriver. The row spacing was 1 m. Trial plots consisted of six rows each, 10 m in length.

A randomized block design with four treatments (four levels of nitrogen) in six blocks (six replications) was used on Site 1 at Rustenburg on both fields. The row spacing was 1 m and each plot consisted of six rows of 12 m in length.

On Site 2 at Rustenburg, a randomized block design was used with five treatments (five levels of nitrogen) in three blocks (three replications). The row spacing was 1 m and each plot consisted of four rows of 10 m in length.

At Bela Bela, a randomised factorial block design of four nitrogen levels × four phosphorus levels in five blocks (five replications) was used. Only results of the highest phosphate level and the four levels of nitrogen associated therewith was used. The row spacing was 1 m. Trial plots consisted of six rows each, 10 m in length.

In order to eliminate side effects, a buffer zone of 3 m was maintained around blocks. This area was not planted with cotton and kept weed free. Only the middle two rows were harvested. Prior to the onset of harvesting, two plants at both ends of a row were removed as an additional measure to eliminate any side effects.

3.3 Agronomic practices

The following agronomic practices were followed at each of the six sites.

3.3.1 Site 1 at Rustenburg

The experimental area was divided into two fields. On the one field, oats were planted during the previous season (Hereinafter referred to as Field 1). After reaching maturity, the oats were cut, above-ground biomass removed and remains ploughed into the soil. On the other field, soya bean was planted and ploughed into the soil at the early-dough stage, to serve as green manure (Hereinafter referred to as Field 2). This procedure resulted in that the soil in Field 1 with oats as preceding crop having a lower, and the soil in Field 2 with soya bean as preceding crop having a higher residual and mineralisable nitrogen content for the following year's cotton crop. The rationale was that the soya bean field will contain organic material with a higher nitrogen content and would produce more nitrogen during mineralisation.

As the Arcadia soil (Table 3.1) has vertic properties and no compaction could be detected, it was not ripped prior to the planting of the trial. A general fertilization of 52.5 kg P ha^{-1} (as single superphosphate) and 140 kg K ha^{-1} (as potassium sulphate) was broadcast over the trial area and incorporated with a disc. The cotton cultivar Letaba was planted during the last week of October of 1987 and 1988, using a mechanical planter set at 1 m spacing between rows.

Four weeks after planting, plants were thinned to achieve a stand of 80 000 plants ha^{-1} (1 m between rows and 125 mm between plants in the row). The four different nitrogen applications (0, 50, 100 and 150 kg ha^{-1} N) were done in the form of limestone ammonium nitrate (LAN = 28% N) as a split application at 8 and 12 weeks after planting.

Nematode control was done by applying Temik (Aldicarb) at a rate of 20 kg ha^{-1} at planting, that also resulted in very good initial pest control. Additional pest control (using Cypermethrin, Acephate and Endosufan) and weed control (using Trifluralin, Metalochlor, mechanical and manual weeding) was performed throughout the trial and no noticeable effects from nematodes, pests or weeds was observed during the execution of the trials. Irrigation was scheduled using tensiometers installed at 300, 600 and 900 mm depths. An overhead sprinkler irrigation system was used to irrigate the cotton. The trial was repeated for two seasons (1987/88 and 1988/89) during which the experimental outlay, preparations and treatments were the same.

3.3.2 Site 2 at Rustenburg

The experimental area was deep ripped, disced and divided into three fields. On Field 1, soya bean was planted and ploughed into the soil at the soft dough stage to induce a high residual inorganic nitrogen content in the soil. Soya bean was planted also on Field 2, but harvested where after the stover was ploughed into the soil to obtain a medium residual inorganic nitrogen content in the soil. On Field 3, babala was planted and allowed to reach maximum biomass, where after the above ground biomass was cut, removed and the stubbles were ploughed into the soil to achieve a low residual inorganic nitrogen content in the soil.

After the preceding crops, the soil was ripped as deep as possible and disced immediately afterwards to break the clods down. Before planting of cotton, a general fertilization of 75 kg P ha^{-1} (as single superphosphate) and 160 kg K ha^{-1} (as potassium sulphate) was broadcast over the trial area and incorporated into the soil with a disc. The cotton cultivar Acala 1517/70 was planted on 1 November 1989, using a mechanical planter at 1 m spacing between rows. Four weeks after planting, plants were thinned to achieve a stand of 130 000 plants ha^{-1} (1 m between rows and 77 mm between plants in the row). Nitrogen applications (0, 50, 100,150 and 200 kg ha^{-1} N) were done in the form of LAN as a split application at four and eight weeks after planting. Nematode, pest and weed control as well as irrigation was done as described in Section 3.3.1.

3.3.3 Site 3 at Rietriver and Site 4 at Vaalharts

The fields at Site 3 (Rietriver) and Site 4 (Vaalharts) were cropped with maize in summer and wheat in winter, respectively before planting of cotton. Subsequently the

Hutton soil (Table 3.1) had low residual inorganic nitrogen levels at the onset of the trials.

Prior to planting the areas designated for the trials were ripped as deep as possible and disced to break down any clods that were formed during the ripping action. The cotton cultivar Acala 1517/70 was planted at Vaalharts on 17 October 1988 and 23 October 1989 and at Rietriver on the 8 November 1988 and 2 November 1989. A mechanical planter was used, set at 1 m spacing between rows. The plant population was thinned to 80 000 plants ha^{-1} after germination, resulting in 125 mm between plants in the row. During planting a 2:3:4(24) + Zn fertilizer mixture was band placed at 375 kg ha^{-1} next to the seed; hence equivalent to 20, 30 and 40 kg N, P and K ha^{-1}, respectively. An additional 45 kg P ha^{-1} (as single superphosphate) and 80 kg K ha^{-1} (as potassium sulphate) was band placed after emergence in bands on both sides of the plant rows.

Subsequently, the control received 20 and not 0 kg ha^{-1} N. The six nitrogen fertilization levels were therefore 20, 40, 80, 120, 160 and 200 kg ha^{-1} N. The rest of the nitrogen fertilization for the five highest levels was applied in two equal applications at five and nine weeks after emergence. During the 1988/89 season, ammonium sulphate (21% N) and during the 1989/90 season, LAN were used as nitrogen sources. Directly after application of nitrogen, 12 mm was irrigated to dissolve the fertilizer and wash it into the soil.

Nematode, pest and weed control, and irrigation was done as described in Section 3.3.1. Fortunately infestation of nematodes, pests and weeds were very low and did not require additional treatment.

Overhead irrigation was used at Rietriver and Vaalharts. Irrigation scheduling was based on tensiometers installed at depths of 300, 600 and 900 mm. At Rietriver a water table fluctuating between 1.0 and 1.2 m below the soil surface was present during both the 1988/89 and 1989/90 seasons. No water table was observed at Vaalharts.

3.3.4 Site 5 at Groblersdal

The trial was conducted on a Hutton soil at Groblersdal (Table 3.1). The preceding crop was maize and subsequently the soil had a low residual inorganic nitrogen content at the onset of the trial.

Prior to planting, the area designated for the trial was ripped as deep as possible, where after 80 kg P ha^{-1} (as single superphosphate) and 120 kg K ha^{-1} (as potassium sulphate) was broadcast and disced into the soil. The cotton cultivar Acala 1517/70 was planted on 1 November 1989 using a mechanical planter set at a row spacing of 1 m. The plant population was thinned to 80 000 plants ha^{-1} after germination, resulting in a 125 mm spacing between plants in the row.

Nitrogen fertilization (0, 40, 80, 120, 160 and 200 kg ha^{-1} N) was applied in the form of LAN, in three equal applications at one, four and eight weeks after emergence.

Nematode, pest and weed control was done as described in Section 3.3.1. This also applies for the irrigation of cotton.

3.3.5 Site 6 at Bela Bela

The trial was conducted on an Arcadia soil at Bela Bela (Table 3.1) which was cropped with wheat during the previous winter season. Subsequently, the soil had a low residual inorganic nitrogen content at the onset of the trial.

No compaction was detected prior to planting of the trial and the vertic soil was therefore not ripped. Before planting, 45 kg P ha^{-1} (as single superphosphate) and 120 kg K ha^{-1} (as potassium sulphate) was broadcast and disced into the soil.

The cotton cultivar Acala 1517/70 was planted on 14 November 1989 using a mechanical planter set at a row spacing of 1 m. The plant population was thinned to 50 000 plants ha^{-1} after germination, resulting in a 200 mm spacing between plants in the row. Nitrogen fertilization (0, 15, 30 and 45 kg ha^{-1} N) was applied four weeks after planting in the form of LAN.

Nematode, pest and weed control was done as described in Section 3.3.1. The infestation of nematodes, pests and weeds were of such a nature that no treatment was justified during the trial.

This trial was not irrigated because it was planted as a dryland trial. However, the rainfall was exceptionally good during the growing season and therefore the trial was included in this study.

3.4 Soil sampling and nitrogen analysis

Representative composite soil samples were taken from all trial fields after land preparation, prior to planting at Site 3 (Rietriver) and Site 4 (Vaalharts). The other sites were sampled two weeks post planting. Sampling depths were 0–300 mm, 300–600 mm and 600–900 mm. These samples were dried, sieved and extracted for inorganic nitrogen using 0.1 N K_2SO_4 (Steenkamp and Boshoff 1987) and analysed for ammonium, nitrite and nitrate, using the colorimetric method of Keeny and Nelson (1982). Sufficient soil was kept from all samples taken for incubation to determine nitrogen mineralisation. Twenty grams of prepared soil was weighed into plastic petri dishes, wet to 90% of field water capacity and incubated for eight weeks at a day temperature of 25 °C (13 hours) and a night temperature of 18 °C (11 hours). Thereafter the samples were analysed for inorganic nitrogen as above.

The rationale behind the above times of sampling was to allow enough time between preparational irrigation and ploughing of the soil, the planting of the cotton and the sampling of the soil, for the bulk of nitrification to take place in-situ in the soil before sampling. Studies done by Laubscher and Du Preez (1989) indicate that in most cases a period of two weeks should be sufficient for this to happen in the topsoil and about 4 weeks in the sub-soil of soils studied by them.

As cotton requires up to 180 days from planting to plant destruction, a farmer cannot afford to let fields remain fallow for four weeks after his previuos crop if he is following a tight crop rotation programme. Therefore soil samples were taken two weeks after planting from sites where no nitrogen was applied at planting.

3.5 Plant sampling and analysis

3.5.1 Leaf petioles nitrogen content

Nitrogen fertilization guidelines based on the residual inorganic nitrogen content of the soil, taken at or soon after planting, do not make provision for the loss of nitrogen through leaching or denitrification. Therefore, it was considered necessary to obtain a further guideline as an aid to the correct nitrogen fertilization of cotton.

Leaf petiole samples were taken from the first mature leaf on the main stem of plants, as seen from the top of the plant (Joham 1951; Braud 1987). Samples were taken at two week intervals, starting one week before first flowering stage from rows 2 and 5 of each six row plot (Rustenburg Site 1, Vaalharts, Rietrivier, Groblersdal and Bela Bela) or rows 1 and 4 of the 4-row plots (Rustenburg Site 2).

Twenty five leaf petioles were collected from each row, to provide 50 leaf petioles per plot for each sample. In order to avoid any potential side effects, leaf petioles were not taken from the first two and last two plants of the two sampling rows. As far as possible, care was taken that during the sampling of the leaf petioles

- samples were taken at the same time of the day before 09:00;
- samples were not taken from any leaves that were visually infected by disease, or eaten by insects;
- samples were not taken shortly after rain or irrigation, and that
- samples were not taken from damaged plants or leaves.

The samples were dried, milled and analysed for total nitrogen content according to the method of Ferrari (1960).

3.5.2 Cotton yield

Once the cotton ripened, and the bolls burst open, the first two and last two plants in the two harvest rows were cut off at soil level using pruning secateurs and discarded. The seed cotton from each plot was harvested from the remaining cotton plants and weighed in order to determine the yield from each plot.

3.6 Data processing and statistical analysis

3.6.1 Seed cotton yield, nitrogen fertilization and soil nitrogen

The following statistical analyses were performed on the obtained data:

- Seed cotton yield data was subjected to an analysis of variance (ANOVA) to determine significant differences ($p < 0.05$ Bonferroni) among nitrogen treatments. The statistical packages R (2021) and Microsoft Excel were used for statistical analyses.
- In order to determine maximum yield for each trial, seed cotton yield was correlated to the rates of nitrogen fertilization applied. In most cases this correlation was best described by a second-order polynomial regression

equation ($y = a + bx + cx^2$). The highest point of the equation would represent the maximum seed cotton yield.

- The nitrogen level associated with maximum profit was also determined for each respective site and growing season, using the principle proposed by Headly (1982) in Figure 3.1.

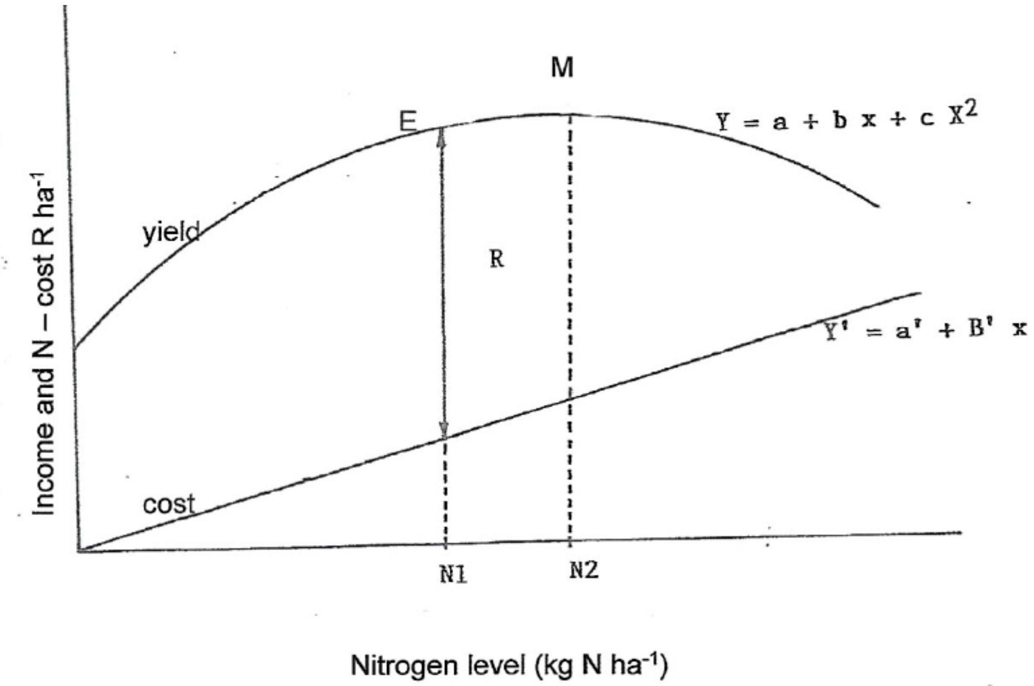


Figure 3.1 Maximum yield and maximum profit as related to nitrogen application level (Headly 1982)

Where:

M = maximum yield associated with nitrogen level N2

E = maximum profit associated with nitrogen level N1

R = greatest difference between input and income

- The statistical program R (2021) was used to determine maximum yield (associated with N2) as well as the largest value of R that would correspond with maximum profit (associated with N1).
- Using Microsoft Excel, the calculated nitrogen application rates required to produce maximum seed cotton yield and maximum profit at each site, were

correlated to the residual inorganic nitrogen content of the soil to depths of 0–300, 0–600 and 0–900 mm, as well as with the residual plus mineralised inorganic nitrogen content of the soil.

3.6.2 Leaf petiole nitrogen content

The following statistical analyses were performed on the leaf petiole nitrogen content data:

- The total nitrogen contents of leaf petioles (% N) sampled at the different times before and after flowering, was correlated to the final seed cotton yield (kg ha^{-1}) of each corresponding experimental plot.
- The total nitrogen content of the leaf petiole corresponding to the maximum cotton yield was calculated using the regression equations (second-order polynomial) obtained from the above mentioned correlations.
- The total nitrogen content (N%) of the leaf petioles corresponding to the maximal seed cotton yield was correlated with the days after planting. The rationale was that the regression equation ($y = a + bx + cx^2$) would be able to serve as a guideline for the required total nitrogen content of the cotton leaf petiole at the specific time of sampling.

The above approach succeeded in providing the desired guideline for the total nitrogen content of cotton leaf petioles (% N) over time (days after planting) in order to pursue the production of maximal seed cotton yield (based on the relationship between total nitrogen content of the cotton leaf petiole and the final yield of the experimental plot).

However, the economically optimum total nitrogen content of the leaf petiole could not be determined by following the above approach, as neither days after planting, nor the total nitrogen content of the leaf petiole, associated with maximum yield can be converted directly to monetary values. As a result, a guideline to predict the total nitrogen content of the cotton leaf petiole over time, required to produce an economically optimum crop, could not be achieved following the above approach.

In order to allow for the refining of guidelines that can be used to predict the total nitrogen content of cotton leaf petioles associated with maximum seed cotton yield and maximum profit, the following statistical approach was followed:

- Using the statistical package R (2021), the total nitrogen content of leaf petioles (% N), at each time of sampling, was correlated to the rate of nitrogen fertilization (kg N ha^{-1}) applied during the trial (R Core Team 2021).
- The regression equation obtained from the above correlation was used to calculate the total nitrogen contents of the leaf petioles corresponding to the nitrogen fertilization levels required to produce maximum profit (N1) and the maximum yield (N2) for each time of sampling. The values for N1 and N2 were obtained for each trial, by following the statistical procedures described in Section 3.6.1.
- Using Microsoft Excel the total nitrogen content of the cotton leaf petioles associated with maximum yield and maximum profit were correlated with the time of sampling (days after planting).
- The regression equations obtained from the above correlations could serve as a guideline of the required total nitrogen content of the cotton leaf petiole to produce maximum seed cotton yield or maximum profit.

The use of the above regression equations may be useful for refining current nitrogen fertilization guidelines of irrigated cotton in South Africa, as they may assist cotton growers to determine the total nitrogen content of cotton leaf petioles required for the production of maximum yield as well as maximum profit during the growing season.

The locally obtained guidelines correspond, to a certain extent, with the guideline compiled by Banton et al. (1979) at the University of Arkansas.

Chapter 4
Influence of Nitrogen Fertilization on Seed Cotton Yields of Irrigated Fields

4.1 Introduction

An objective of this study was to refine and simplify the existing nitrogen fertilization guidelines for irrigated cotton in South Africa, as supported by Fertasa (2016), represented by the following equation:

$$E = A - (B + C + D)$$

where,

E = the nitrogen fertilization required to produce the crop of a selected yield (at an assumed utilisation factor of 80%),

A = the amount of nitrogen removed by the crop for a specific yield (250 kg N ha^{-1} for a seed cotton yield of more than 4 500 kg ha^{-1}),

B = the residual inorganic nitrogen in the soil to a depth of 900 mm prior to planting (of which 66.7% is estimated to be utilised by the cotton crop)

C = the estimated mineralisation of organic nitrogen in the soil over the growing season, namely 60 kg N ha^{-1} for sandy soils, 120 kg N ha^{-1} for loam soils and 160 kg N ha^{-1} for clay soils (of which 66.7% is estimated to be utilised by the cotton crop),

D = the nitrogen present in 400 mm of the irrigation water used to grow the crop (of which 80% is estimated to be utilised by the cotton crop).

Several field trials were done in the irrigated areas of South Africa where cotton is cultivated. In these trials the response of seed cotton yields to nitrogen application levels was quantified. The data was subjected to analyses of variance and presented in the format of either tables or box plots. Moreover, the relationships between nitrogen application rates and seed cotton yields were subjected to polynomial regressions, allowing the deduction at which nitrogen application rate, maximum seed cotton yield is achieved. Polynomial regressions were also done between profits and levels of nitrogen application to establish which rate gave the maximum profit. In a few instances, however, the data did not allow for the establishment of a nitrogen rate at which either the maximum yield or maximum profit realised.

From the data obtained from the trials, the NUE of cotton was determined as follows:

Total nitrogen use efficiency (TNUE) was determined by the following equation:

$$\mathrm{TNUE} = \frac{\mathrm{Yc}}{(\mathrm{Nr} + \mathrm{Nm} + \mathrm{Na})}$$

where,

Y_c = Seed cotton yield (kg ha^{-1})

N_r = Residual nitrogen in the soil (kg ha^{-1})

N_m = Mineralised nitrogen in the soil (kg ha^{-1})

N_a = Applied nitrogen (kg ha^{-1})

The nitrogen fertilization use efficiency (NFUE) as used by MacDonald et al. (2018) in Australia, was determined using the following equation:

$$\mathrm{NFUE} = \frac{\mathrm{Yc}}{\mathrm{Na}}$$

4.2 Procedure

The materials and methods for the irrigated field trials done at Rustenburg, Rietrivier, Vaalharts, Groblersdal and Bela Bela to determine the influence of nitrogen fertilization on seed cotton yield are described in detail in Chapter 3. Hence, materials and methods are not repeated in this chapter.

4.3 Seed cotton yield from Site 1 at Rustenburg

The seed cotton yields that were recorded in the trials performed at Site 1 at Rustenburg during the 1987/88 and 1988/89 growing seasons are given in Appendix 4.1 and Appendix 4.2. A summary of the ANOVAs done is displayed in Table 4.1

Table 4.1 Summary of ANOVA done on seed cotton yields measured at Site 1, Rustenburg (Cotton was preceded by oats on Field 1 and soybean on Field 2, respectively)

Nitrogen application (kg N ha^{-1})	Seed cotton yield (kg ha^{-1}) on oats field Field 1		Seed cotton yield (kg ha^{-1}) on soybean field Field 2	
	1987/88	1988/89	1987/88	1988/89
0	2 018.20	2 561.60	4 879.60	4 451.80
50	2 663.40	2 406.60	4 807.00	4 648.20
100	3 688.40	2 592.20	5 382.60	4 414.00
150	4 053.80	3 458.00	5 379.40	4 504.20
Average	3 105.95	2 754.60	5 112.15	4 504.55
F-value	20.261	2.8743	3.0959	0.4118
t-value	3.008334	3.008334	3.008334	3.008334
R^2	0.7916	0.3502	0.3673	0.07167
p-value	0,00001071	0.06879	0.05659	0.747
Significance*	S	NS	NS	NS
LSD**	882.74	1 194.29	754.05	680.63

*S = Significant, NS = Not Significant
**LSD = Bonferroni at P = 0,05

In the 1987/88 season on the oats field (Field 1), the 50, 100 and 150 kg N ha^{-1} treatments resulted in significantly higher yields of seed cotton than the control treatment. The 100 and 150 kg N ha^{-1} treatments produced significantly higher yields of seed cotton than the 50 kg N ha^{-1} treatment. There was no significant difference in seed cotton yield between the 100 and 150 kg N ha^{-1} treatments (Table 4.1).

In the 1988/89 season on the oats field (Field 1), no significant difference in seed cotton yield was detected between treatments (Table 4.1). This could possibly be explained by higher rainfall during the 1988/89 season, causing denitrification in the Arcadia soil, leading to a loss of nitrogen from the soil profile, which reduced the effect of treatments on seed cotton yield. The lower average seed cotton yield measured in the 1988/89 growing season was 2 755 kg ha^{-1}, compared to 3 106 kg ha^{-1} in the 1987/88 season.

In the 1987/88 and 1988/89 seasons on the soybean field (Field 2), no significant difference in seed cotton yield was observed between treatments (Table 4.1). The reason for the lack of difference between treatments could possibly be explained by a high residual nitrogen content in the soil as well as high levels of nitrogen mineralisation during the growing season, providing sufficient or even more than sufficient nitrogen for the growth of the cotton crop.

4.3.1 Field 1: Oats preceding crop

4.3.1.1 1987/88 growing season

Seed cotton yields obtained from Site 1 at Rustenburg on the oats field in 1987/88 season, are depicted in the box plot (Figure 4.1).

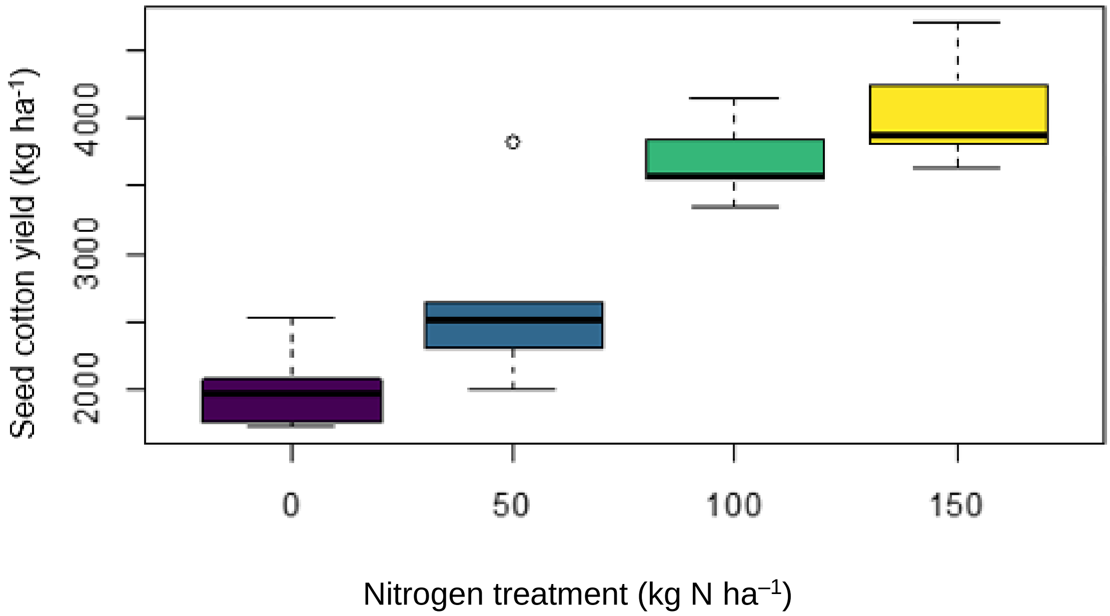
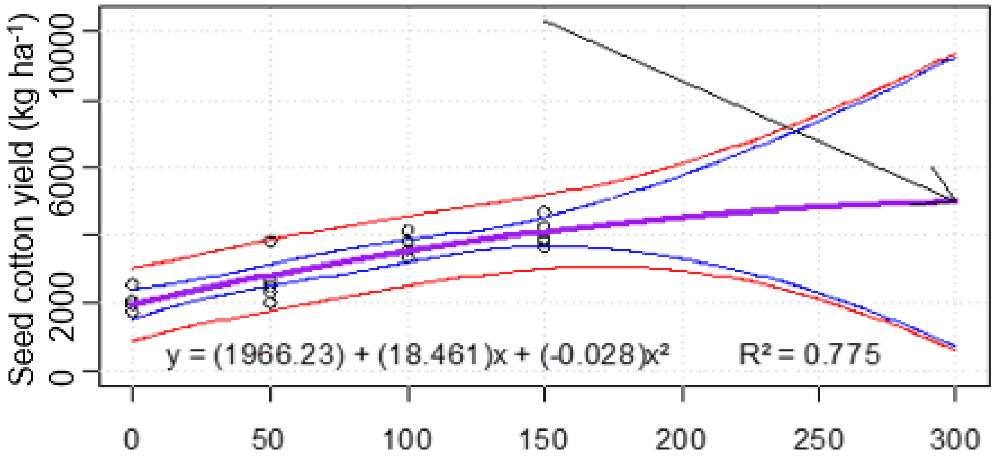


Figure 4.1 Box plot of seed cotton yield (kg ha^{-1}) versus nitrogen treatment at Site 1 (oats field) at Rustenburg, in the 1987/88 growing season

A maximum seed cotton yield of 5 009 kg ha^{-1} was achieved at 330 kg N ha^{-1} (Figure 4.2).

Maximum yield = 5 009 kg ha⁻¹ at N = 330 kg ha⁻¹

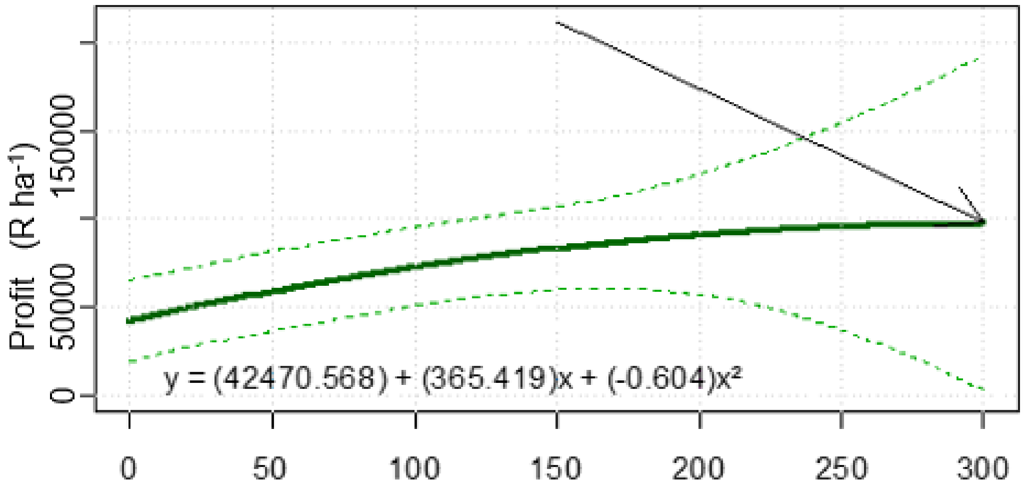


Nitrogen treatment (kg N ha⁻¹)

Figure 4.2 Polynomial regression between seed cotton yield versus nitrogen treatment at Site 1 (oats field) at Rustenburg, in the 1987/88 growing season

The projected nitrogen application rate to achieve maximum profit is at 303 kg N ha^{-1} with a maximum profit of R97 740,04 ha^{-1} at this site (Figure 4.3).

Maximum profit = R97 740.04 ha⁻¹ at N = 302.50 kg ha⁻¹



Nitrogen treatment (kg N ha⁻¹)

Figure 4.3 Polynomial regression between profit versus nitrogen fertilization (kg ha^{-1}) at Site 1 (oats field), Rustenburg, 1987/88 growing season

4.3.1.2 1988/89 growing season

Seed cotton yields obtained from Site 1 (oats field), Rustenburg, in the 1988/89 season are depicted in a box plot in Figure 4.4.

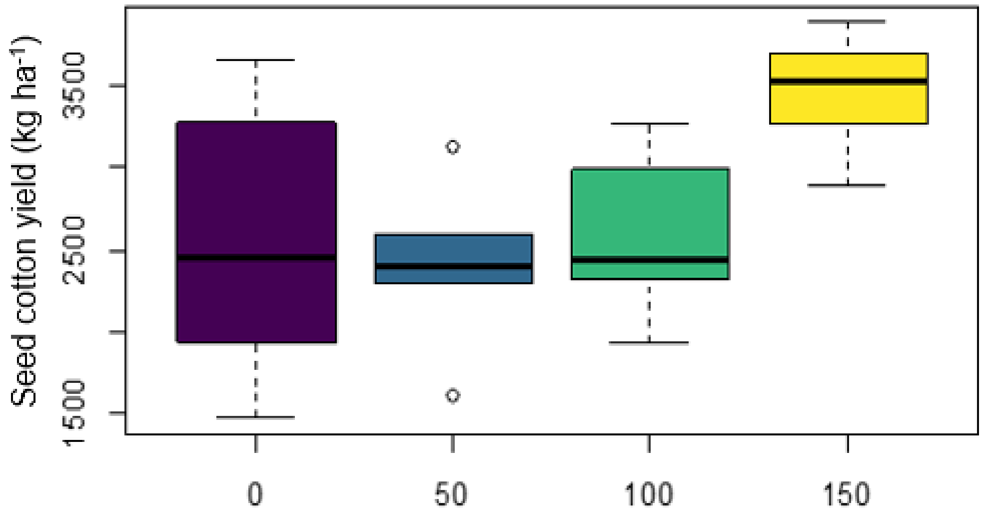


Figure 4.4 Box plot of seed cotton yields versus nitrogen treatment at Site 1 (oats field) Rustenburg, 1988/89 growing season

Maximum seed cotton yield on the oats field of Site 1 at Rustenburg, was not possible to predict, as the polynomial regression has no turning point (Figure 4.5).

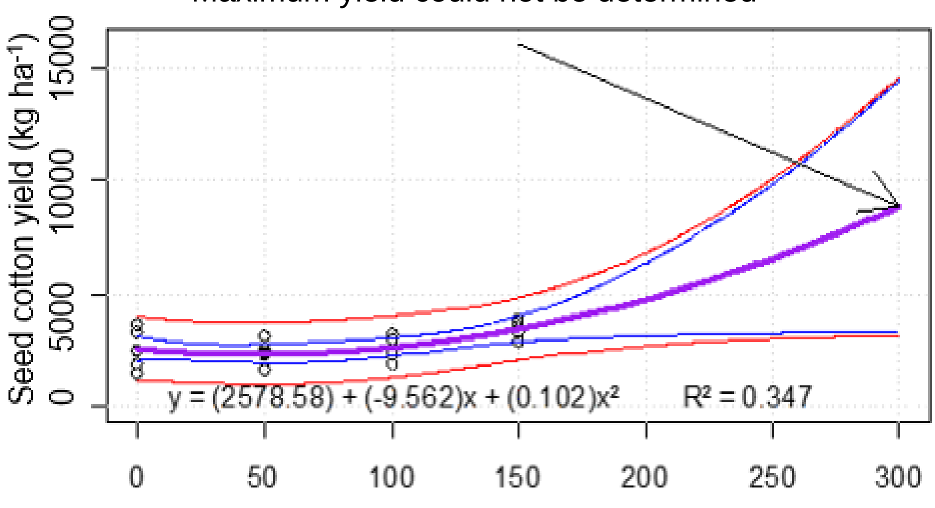


Figure 4.5 Polynomial regression between seed cotton yield versus nitrogen treatment (kg ha^{-1}) at Site 1 (oats field), Rustenburg, 1988/89 growing season

As no turning point resulted from the polynomial regression, it was also not possible to predict the nitrogen application rate required to achieve maximum profit, as depicted in Figure 4.6.

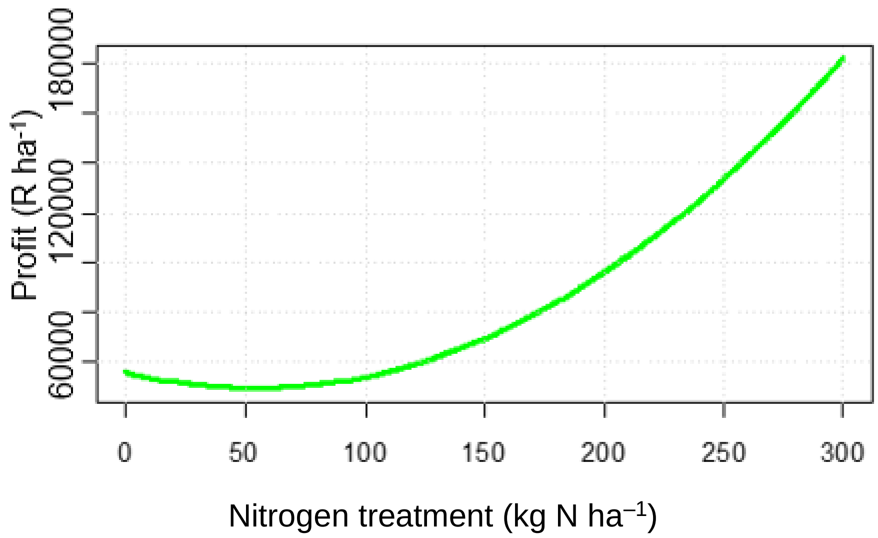


Figure 4.6 Polynomial regression between profit versus nitrogen treatment at Site 1 (oats field), Rustenburg, 1988/89 growing season

4.3.2 Field 2: Soybean preceding crop

4.3.2.1 1987/88 growing season

Seed cotton yields measured on the soybean field of Site 1 at Rustenburg in the 1987/88 season, are shown in a box plot in Figure 4.7.

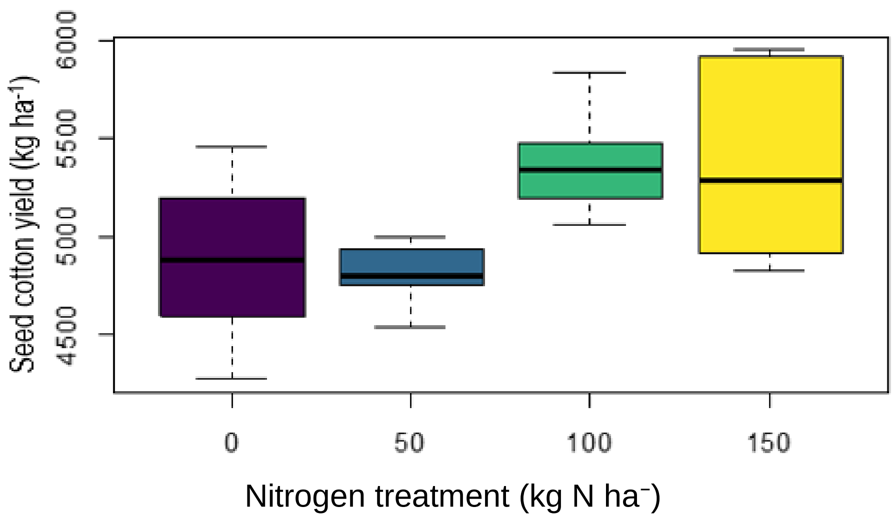


Figure 4.7 Box plot of seed cotton yields versus nitrogen treatment at Site 1 (soybean field) , Rustenburg, 1987/88 growing season

It was not possible to predict the maximum seed cotton yield on the soybean field at Site 1, Rustenburg, from the polynomial regression between seed cotton yield and nitrogen application rate as the polynomial regression showed no turning point (Figure 4.8).

Maximum yield could not be determined

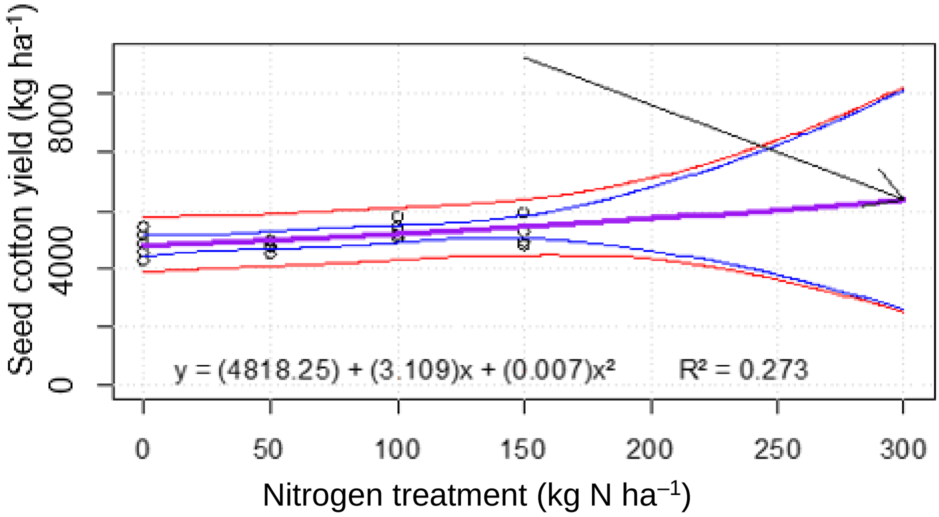


Figure 4.8 Polynomial regression between seed cotton yield versus nitrogen treatment at Site 1 (soybean field), Rustenburg, 1987/88 growing season

The required turning point cannot be established with the polynomial regression. Hence the projected nitrogen application rate to achieve maximum profit on Site 1 (soybean field) at Rustenburg in the 1987/88 growing season is too far beyond the experimental limits to estimate with a significant level of confidence, as seen in Figure 4.9.

Maximum profit cannot be determined

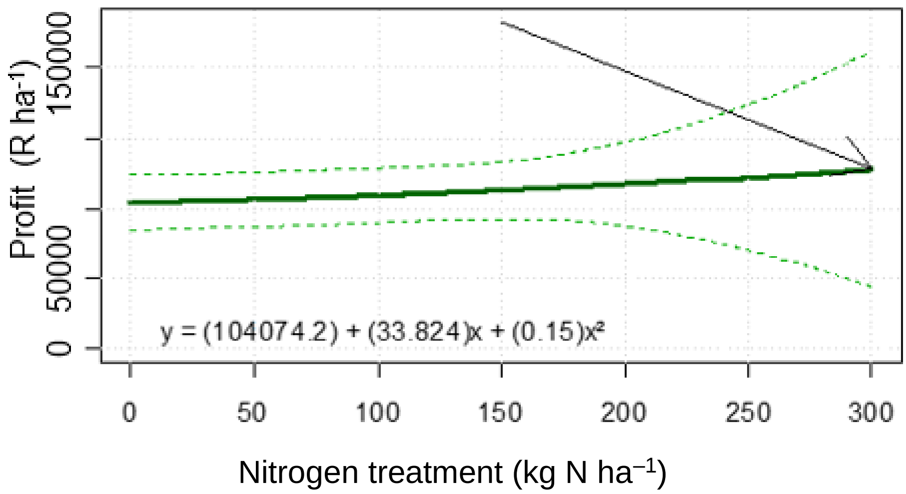


Figure 4.9 Polynomial regression between profit versus nitrogen treatment at Site 1 (soybean field), Rustenburg, 1987/88 growing season

4.3.2.2 1988/89 growing season

Seed cotton yields that realised on the soybean field of Site 1 at Rustenburg in the 1988/89 growing season, are depicted in a box plot in Figure 4.10.

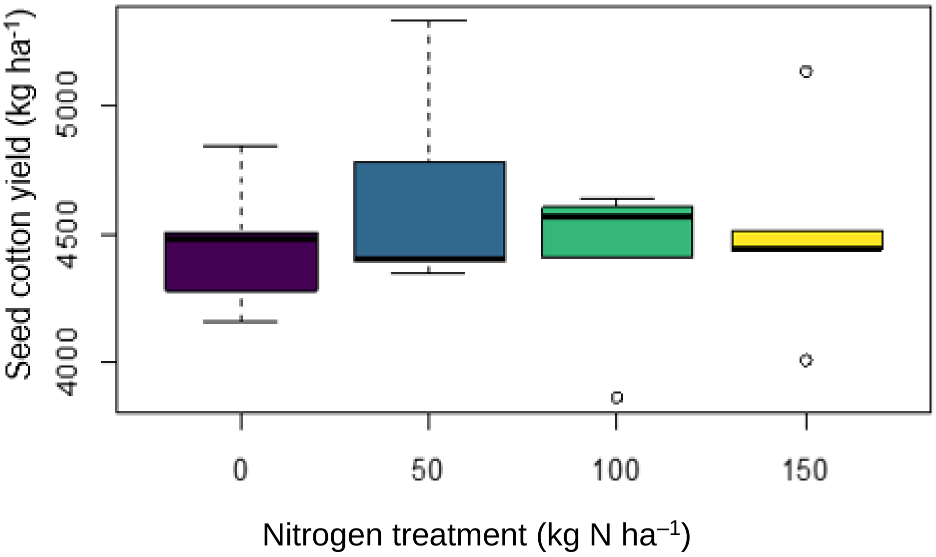


Figure 4.10 Box plot of seed cotton yield versus nitrogen treatment at Site 1 (soybean field), Rustenburg, 1988/89 growing season

Maximum yield was achieved at a nitrogen application of 68 kg ha^{-1} producing a seed cotton yield of 4 538 kg ha^{-1}, as depicted in Figure 4.11.

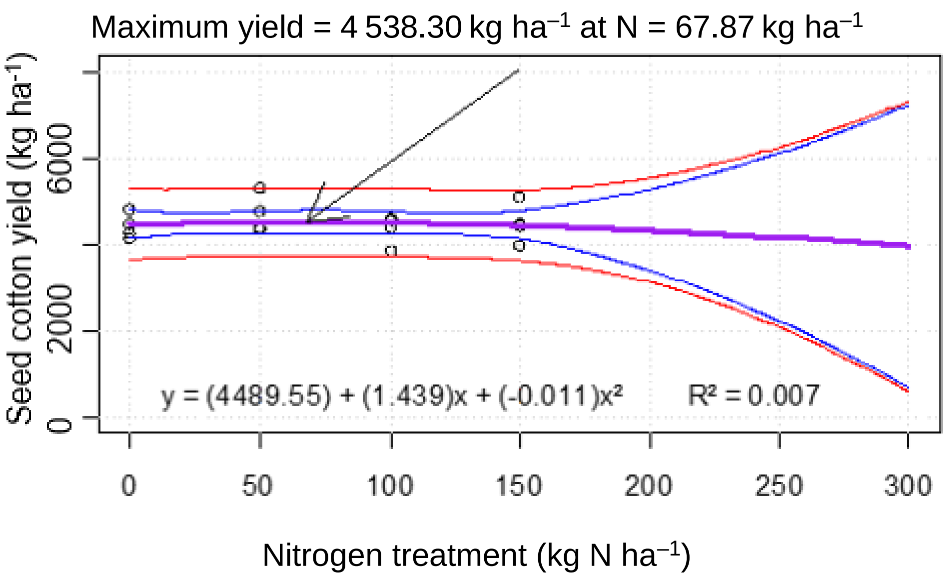


Figure 4.11 Polynomial regression between seed cotton yield versus nitrogen treatment at Site 1 (soybean field), Rustenburg, 1988/89 growing season

The maximum profit realised at a nitrogen application rate of 0 kg ha^{-1} as depicted in Figure 4.12.

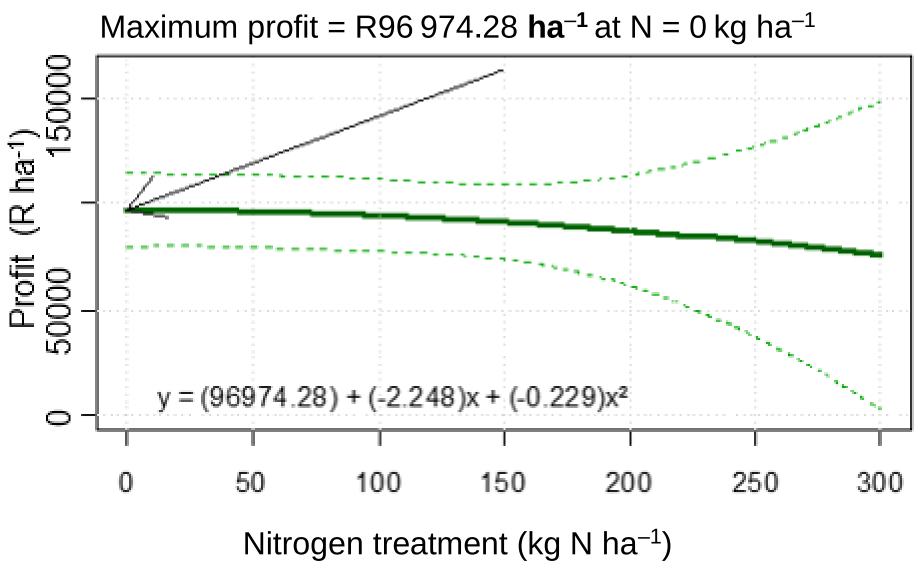


Figure 4.12 Polynomial regression between profit versus nitrogen treatment at Site 1 (soybean field), Rustenburg, 1988/89 growing season

4.4 Seed cotton yield from Site 2 at Rustenburg

The seed cotton yields measured in the 1989/90 growing season at Site 2 of Rustenburg on Field 1 (soybean harvested), Field 2 (soybean ploughed in) and Field 3 (babala), are given in Appendix 4.3. A summary of the ANOVAs performed on the data is given in Table 4.2.

Table 4.2 Summary of ANOVA done on seed cotton yields measured in the 1989/90 growing season on the three fields at Site 2, Rustenburg (Cotton was preceded by harvested soybean on Field 1, ploughed in soybean on Field 2 and babala on Field 3)

Nitrogen application (kg N ha^{-1})	Field 1	Field 2	Field 3
0	3 210.33	4 449.00	3 330.50
50	3 394.33	4 842.67	4 150.33
100	3 876.00	5 293.33	4 829.67
150	3 724.00	5 213.00	4 672.33
200	4 210.67	5 085.33	5 361.67
Average	3 683.07	4 977.07	4 468.90
F-value	4.7684	0.789	4.373
t-value	3.581406	3.581406	3.589662
R^2	0.656	0.2399	0.6603
p-value	0.02061	0.5581	0.03084
Significance*	S	NS	S
LSD**	579.50	1 944.73	571.30

**LSD Bonferonni at P = 0,05
* S = Significant, NS = Not Significant

In Field 1 (harvested soybean) seed cotton yields obtained from the 100 and 200 kg N ha^{-1} treatments were significantly higher than the control treatment. Only the 200 kg N ha^{-1} treatment produced a higher seed cotton yield than the 50 kg N ha^{-1} treatment. Seed cotton yields amongst the 100, 150 and 200 kg N ha^{-1} did not differ significantly (Table 4.2).

In Field 2 (ploughed-in soybean), seed cotton yields amongst the 0, 50, 100, 150 and 200 kg N ha^{-1} treatments did not differ significantly (Table 4.2). The reason for the lack of difference between treatments could probably be explained by a high residual and mineralisable nitrogen content in the soil, caused by ploughing in the preceding soybean crop. Mineralisation of the ploughed-in soybean resulted in the production of sufficient, or possibly even surplus nitrogen for the requirements of the cotton crop.

Contrary to expectations the 0, 50, 100, 150 and 200 kg N ha^{-1} treatments in Field 3 (babala) did not produce significantly different yields of seed cotton (Table 4.2). The average seed cotton yield obtained from Field 3 (babala) was higher than from Field 1 (harvested soybean). During the previous season the babala was planted at a high population, fertilized and irrigated well. It grew to a height of 2 m tall and developed a very strong root system that could improve soil structure. The latter may explain why the average seed cotton yield harvested from the babala field (Field 3) was higher than from Field 1 (harvested soybean).

The strong growth of the babala roots could have contributed to a higher soil organic content, better soil aeration, higher soil water holding capacity, deeper root penetration and possible better soil nitrogen utilisation by the following cotton crop. This possibly improved the availability of nitrogen in the soil and could have resulted in sufficient nitrogen being available to the cotton crop, leading to the absence of significant differences in seed cotton yield between nitrogen treatments in Field 3.

4.4.1 Field 1: Harvested soybean preceding crop

Seed cotton yields obtained on the soybean harvested field at Site 2 of Rustenburg in the 1989/90 growing season, are depicted in a box plot in Figure 4.13.

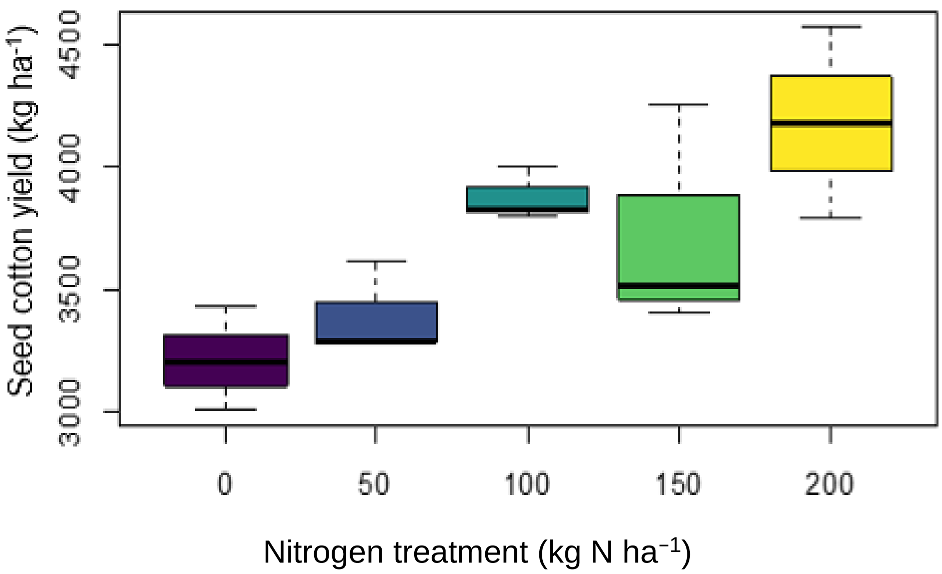


Figure 4.13 Box plot of seed cotton yield versus nitrogen treatment at Site 2 (harvested soybean) Rustenburg, 1989/90 growing season

Maximum yield was achieved at a nitrogen application of 2 412 kg ha^{-1} producing a seed cotton yield of 9 028 kg ha^{-1} (Figure 4.14). Unfortunately, this level of nitrogen application is not realistic, as maximum levels of nitrogen fertilization reported in the literature rarely exceed 300 kg ha^{-1} (Halevy and Bazelet 1989).

Maximum yield = 9 028.28 kg ha^{-1} at N = 2 411.5 kg ha^{-1}

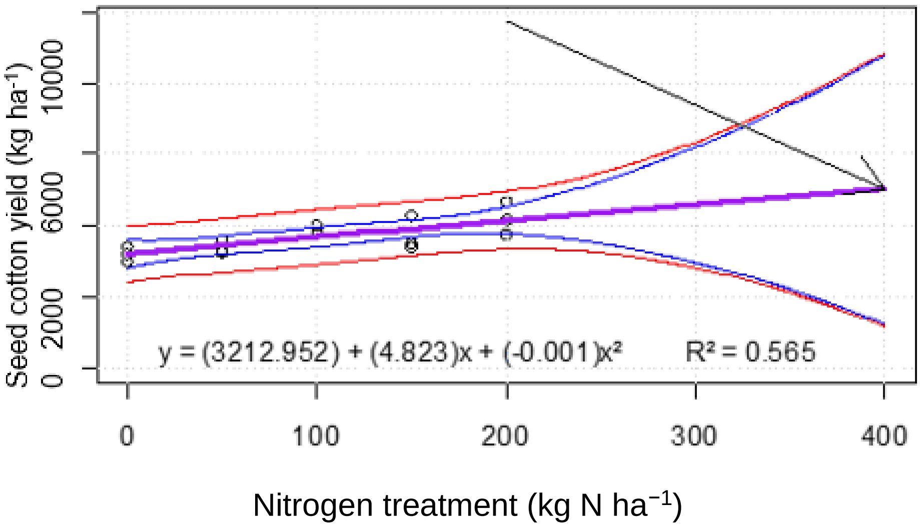


Figure 4.14 Polynomial regression between seed cotton yield versus nitrogen treatment at Site 2 (harvested soybean), Rustenburg, 1989/90 growing season

The projected nitrogen application rate to achieve maximum profit of R143 194.20 ha^{-1} was calculated to be at 2 084 kg ha^{-1} (Figure 4.15), which is not realistic, as maximum levels of nitrogen fertilization reported in the literature rarely exceed 300 kg ha^{-1} (Halevy and Bazelet 1989).

Maximum profit = R143 194.20 ha^{-1} at N = 2 083.47 kg ha^{-1}

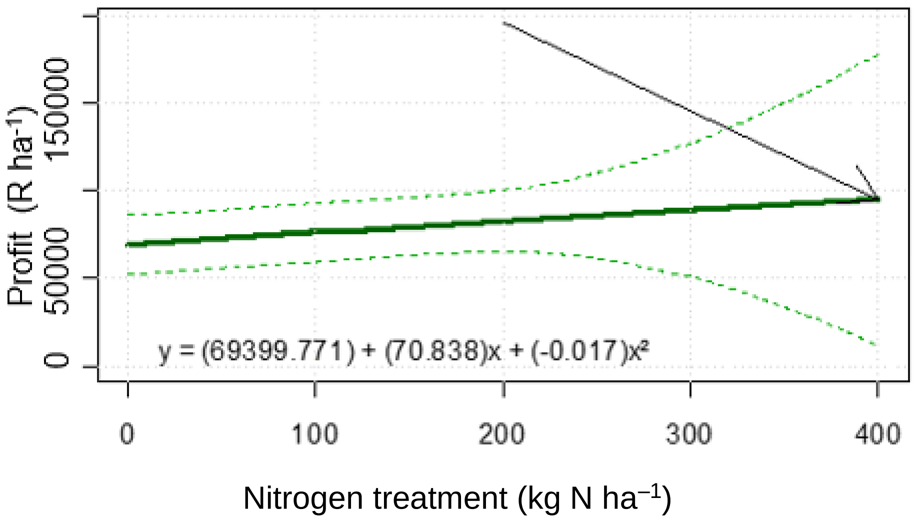


Figure 4.15 Polynomial regression between profit versus nitrogen treatment at Site 2 (ploughed-in soybean), Rustenburg, 1989/90 growing season

The projected nitrogen application rate in order to achieve maximum profit is too far beyond the experimental results, as seen in Figure 4.15.

4.4.2 Field 2: Ploughed-in soybean preceding crop

Seed cotton yields determined on the ploughed-in soybean field at Site 2 of Rustenburg, in the 1989/90 growing season, are depicted in a box plot in Figure 4.16.

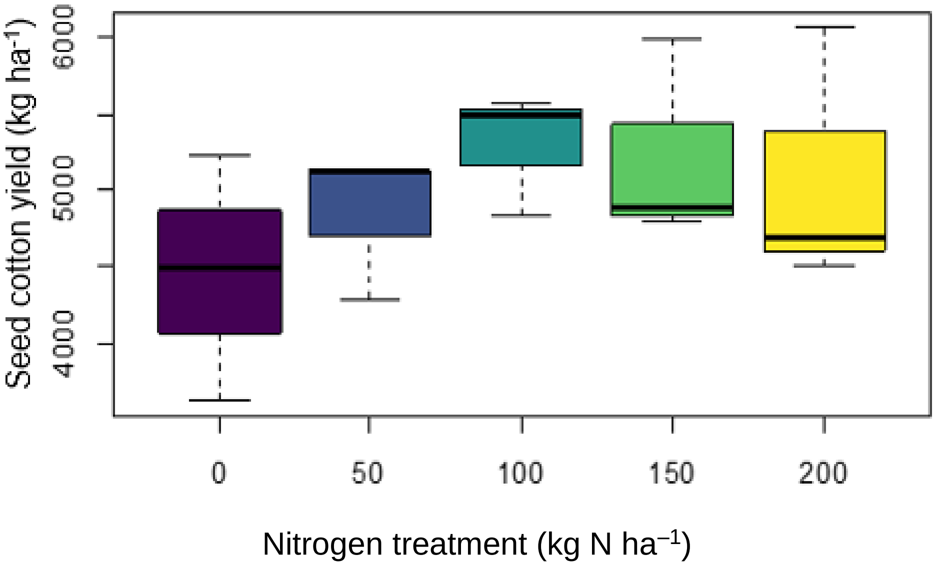


Figure 4.16 Box plot of seed cotton yields versus nitrogen treatment at Site 2 (ploughed-in soybean field), Rustenburg, 1989/90 growing season

Maximum yield realised at a nitrogen application of 137 kg ha^{-1} producing a seed cotton yield of 5 262 kg ha^{1}, as depicted in Figure 4.17.

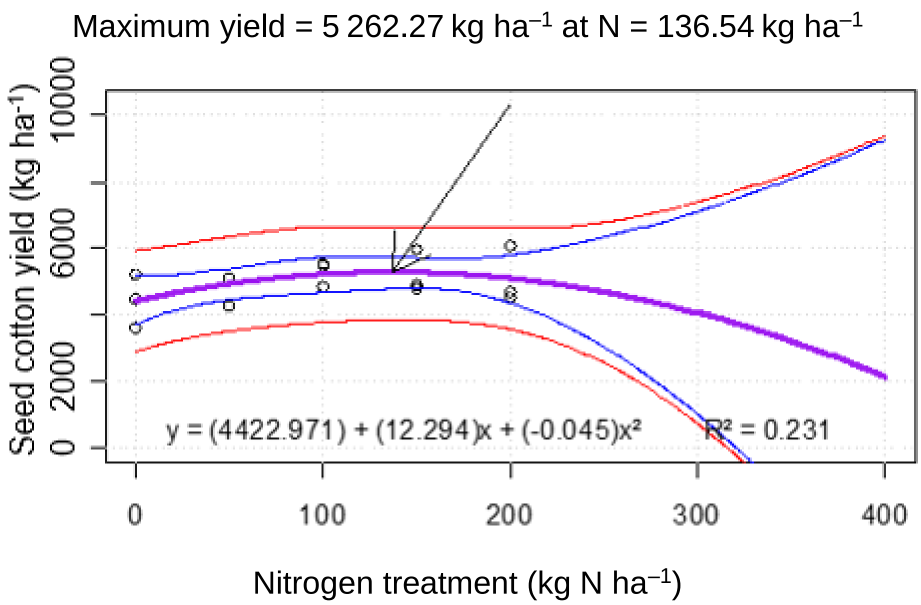


Figure 4.17 Polynomial regression between seed cotton yield versus nitrogen treatment at Site 2 (ploughed-in soybean field), Rustenburg, 1989/90 growing season

Maximum profit was calculated at 119 kg N ha^{-1} as depicted in Figure 4.18.

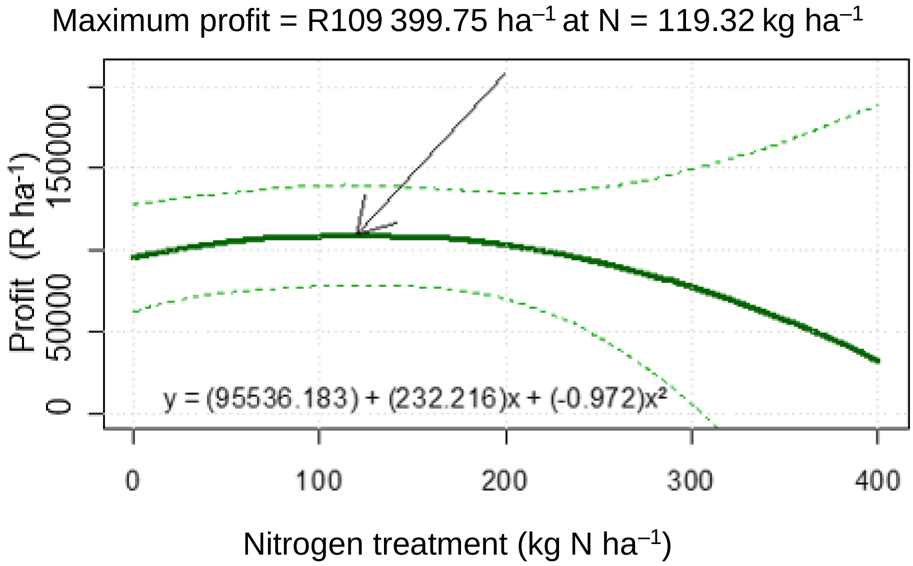


Figure 4.18 Polynomial regression between profit versus nitrogen treatment at Site 2 (ploughed-in soybean field), Rustenburg, 1989/90 growing season

4.4.3 Field 3: Babala preceding crop

4.4.3.1 Outlier included

Seed cotton yields measured on the babala field from Site 2 of Rustenburg in the 1989/90 season, are displayed in a box plot in Figure 4.19.

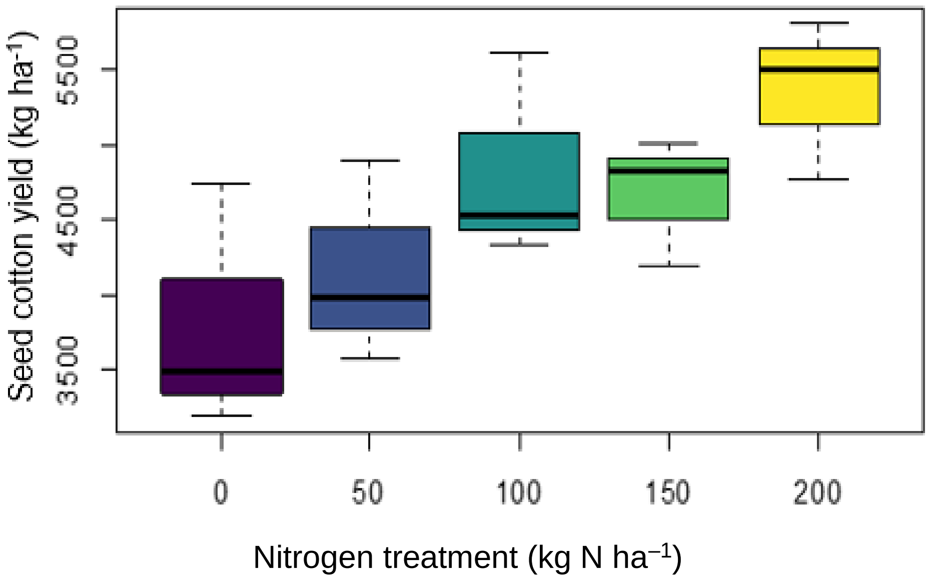


Figure 4.19 Box plot of seed cotton yields versus nitrogen treatment at Site 2 (babala field), Rustenburg, 1989/90 growing season

Maximum yield was estimated at a nitrogen application of 1 023 kg ha^{-1} producing a seed cotton yield of 7 996 kg ha^{-1} (Figure 4.20). Unfortunately the level of nitrogen application is not realistic, as maximum levels of nitrogen fertilization reported in the literature rarely exceed 300 kg ha^{-1} (Halevy and Bazelet 1989).

In an attempt to resolve the above situation, the data used to calculate the polynomial regression in Figure 4.20 was inspected for possible outliers. Using the procedure of Hawkins (1980) to identify statistical outliers, the 4 742 kg ha^{-1} seed cotton yield from the control treatment was identified as being an outlier. In Section 4.4.3.2, this outlier was removed from the data set and the calculations were redone.

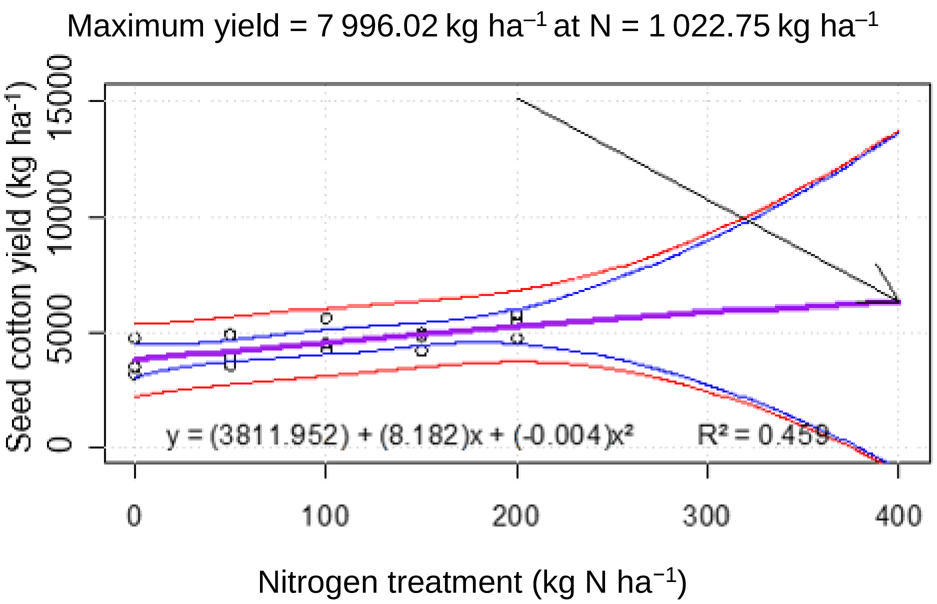
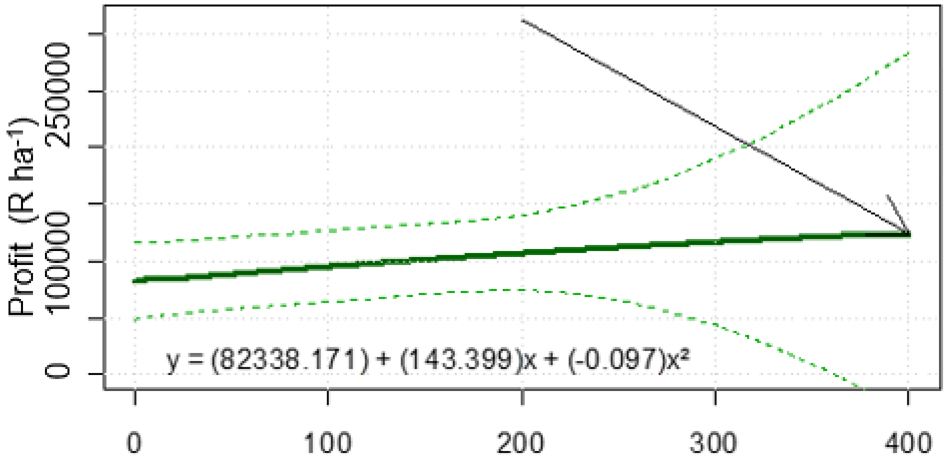


Figure 4.20 Polynomial regression between seed cotton yield versus nitrogen treatment at Site 2 (babala field), Rustenburg, 1989/90 growing season

The turning point of the polynomial regression depicting the maximum profit of R135 336 ha^{-1} is at a nitrogen fertilization level of 739 kg ha^{-1}. This level of nitrogen fertilization is much higher than the fertilization levels used in the field trial and is beyond the range of projection with a significant level of confidence, as depicted Figure 4.21.

Maximum profit = R135 336.30 ha^{-1} at N = 739.17 kg ha^{-1}

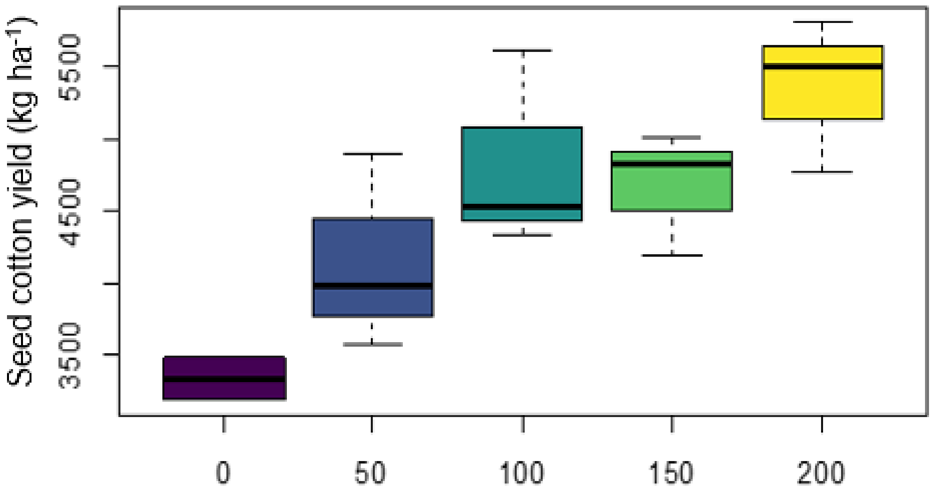


Nitrogen treatment (kg N ha^{-1})

Figure 4.21 Polynomial regression between profit versus nitrogen treatment at Site 2 (babala field), Rustenburg, 1989/90 growing season

4.4.3.2 Outlier excluded

By discarding a data outlier of the babala field (4 742 kg ha^{-1} seed cotton yield from the control treatment, given in Table 3 of the Appendix 4.3) and the statistical analysis redone, the results are depicted in the box plot in Figure 4.22.



Nitrogen treatment (kg N ha^{-1})

Figure 4.22 Box plot of seed cotton yield versus nitrogen treatment without outlier at Site 2 (babala field), Rustenburg, 1989/90 growing season

The maximum yield was estimated at a nitrogen application of 253 kg ha^{-1} producing a seed cotton yield of 5 314 kg ha^{-1} as depicted in Figure 4.23.

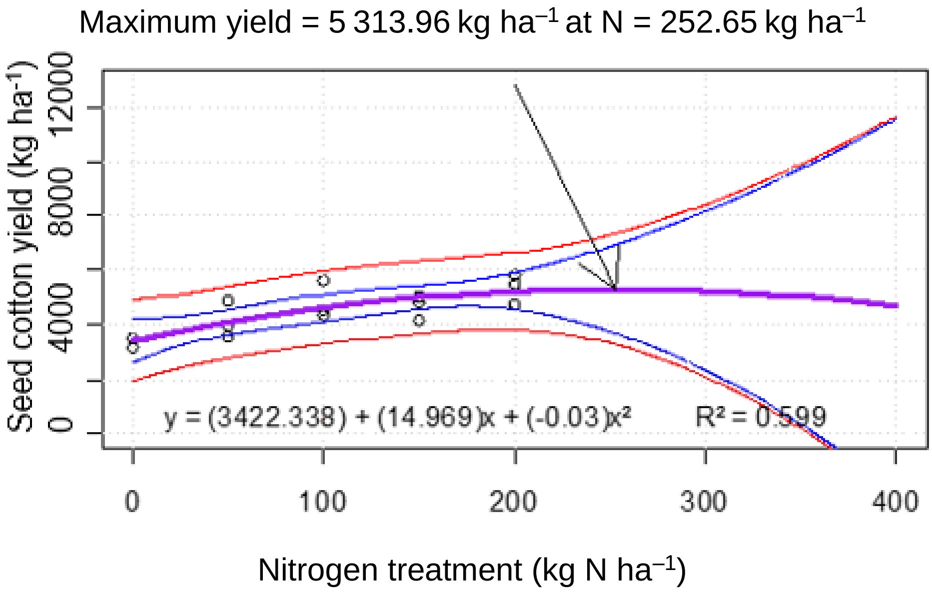


Figure 4.23 Polynomial regression between seed cotton yield and nitrogen treatment without outlier at Site 2 (babala field), Rustenburg, 1989/90 growing season

A maximum profit of R106 791.75 ha^{-1} was estimated at 227 kg N ha^{-1} as displayed in Figure 4.24.

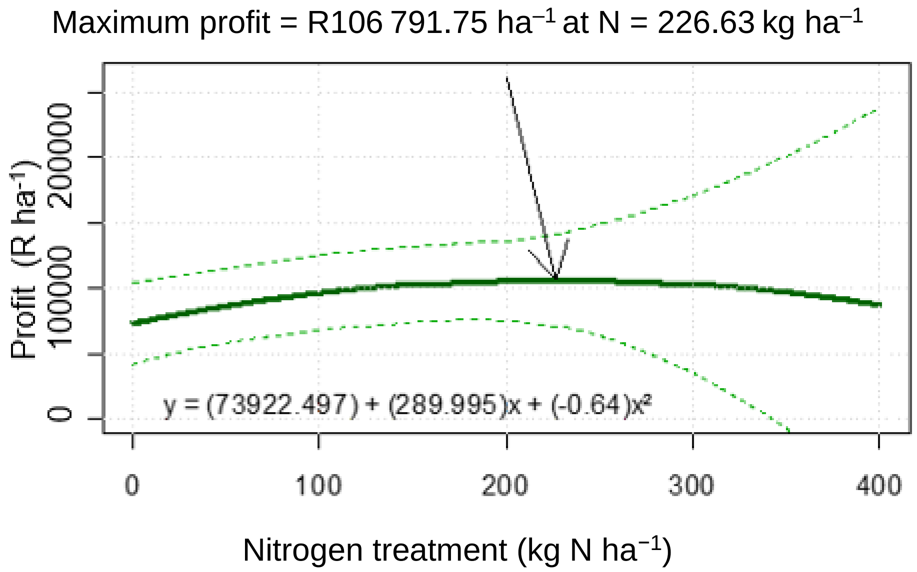


Figure 4.24 Polynomial regression between profit versus nitrogen treatment without outlier at Site 2 (babala field), Rustenburg, 1989/90 growing season

4.5 Seed cotton yields from Rietrivier and Vaalharts

The seed cotton yields realised at Rietrivier and Vaalharts in the 1988/89 and 1989/90 growing seasons, are given in Appendix 4.4. Table 4.3 contains a summary of this data.

Table 4.3 Summary of ANOVAs on seed cotton yields measured at Rietrivier and Vaalharts in the 1988/89 and 1989/90 growing seasons

Nitrogen application (kg N ha^{-1})	Seed cotton yield (kg ha^{-1})			
	Rietrivier		Vaalharts	
	1988/89	1989/90	1988/89	1989/90
20	3 057.29	3 389.80	4 046.61	4 884.40
40	3 465.94	4 375.80	4 409.03	4 706.20
80	3 681.67	5 061.00	4 751.96	4 855.20
120	3 848.03	5 059.60	4 916.07	4 750.60
160	4 112.10	5 392.00	5 122.36	5 404.00
200	4 430.81	5 518.20	5 277.58	4 462.40
Average	3 765.97	4 966.07	4 753.94	5 063.20
F-value	80.028	7.266	9.097	2.719
t-value	3.258382	3.258382	3.258382	3.258382
R^2	0.9434	0.6022	0.6546	0.3616
p-value	0.000000001	0.000287	0.00005881	0.04392
Significance**	S	S	S	S
LSD*	248.9545	1358.277	701.9795	1 204.31

*LSD of Bonferonni at P = 0.05
**S = Significant, NS = Not Significant

In the 1988/89 growing season at Rietrivier, nitrogen applications of 40 kg N ha^{-1} and higher, significantly increased seed cotton yield above that of the control treatment. Nitrogen applications of 80 kg N ha^{-1} and higher, resulted in significantly higher seed cotton yields than the 40 kg N ha^{-1} treatment. In the same growing season 120, 160 and 200 kg N ha^{-1} resulted in a significantly higher seed cotton yield than the 80 kg N ha^{-1} treatment, and the 160 and 200 kg N ha^{-1} treatment led to significantly higher seed cotton yields than the 120 kg N ha^{-1} treatment. The 200 kg N ha^{-1} treatment produced significantly higher seed cotton yields than the 160 kg N ha^{-1} treatments (Table 4.3).

At Rietrivier in the 1989/90 growing season, all treatments of 80 kg N ha^{-1} and higher resulted in significantly higher seed cotton yields than the control treatment (20 kg N ha^{-1}).

In the 1988/89 growing season at Vaalharts, treatments of 80 kg N ha^{-1} and higher resulted in significantly higher seed cotton yields than the control treatment. Treatments of 160 and 200 kg N ha^{-1} gave significantly higher seed cotton yields than the 40 kg N ha^{-1} treatment (Table 4.3).

At Vaalharts in the 1989/90 growing season, none of the nitrogen treatments gave significantly higher seed cotton yields than the control treatment (Table 4.3).

4.5.1 Rietrivier

4.5.1.1 1988/89 growing season

Seed cotton yields obtained from Rietrivier in the 1988/89 season, are shown in the box plot in Figure 4.25.

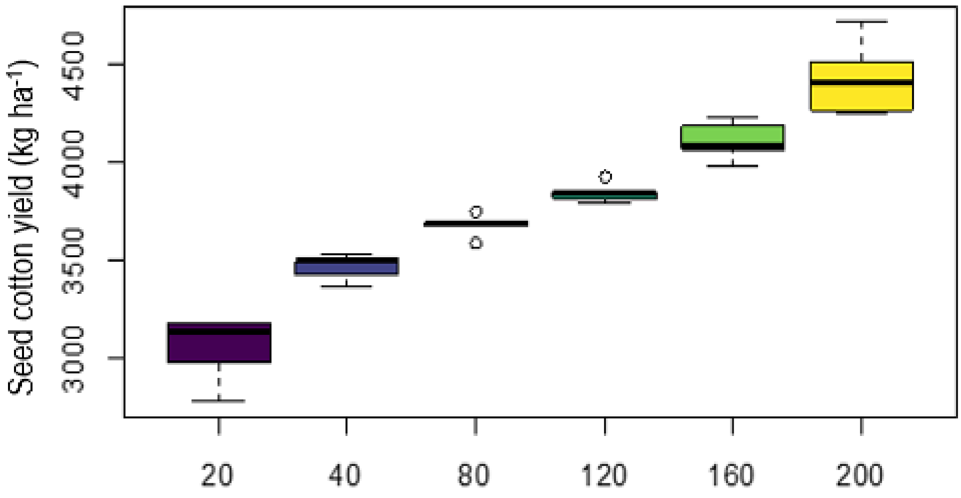


Figure 4.25 Box plot of seed cotton yields versus nitrogen treatment, Rietrivier, 1988/89 growing season

A nitrogen application of 532 kg ha^{-1} produced the maximum seed cotton yield of 5 265 kg ha^{-1}, as depicted in Figure 4.26.

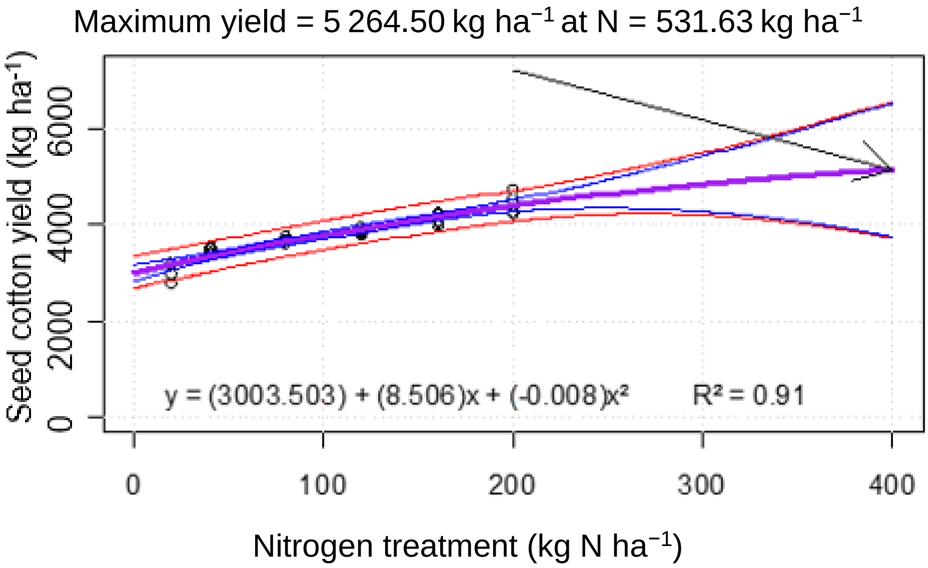


Figure 4.26 Polynomial regression between seed cotton yield versus nitrogen treatment, Rietrivier, 1988/89 growing season

Maximum profit of R97 942.99 ha^{-1} was estimated at a nitrogen treatment of 440 kg ha^{-1} (Figure 4.27).

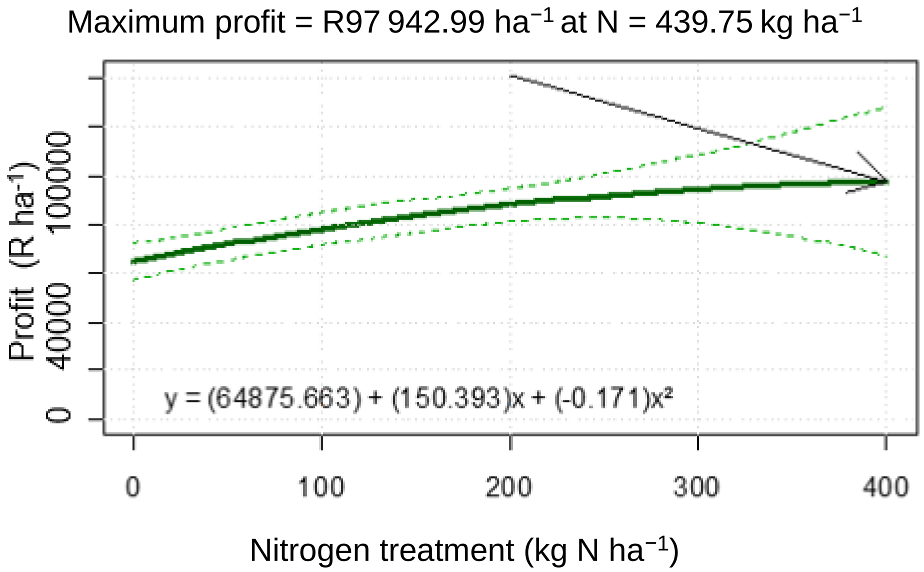


Figure 4.27 Polynomial regression between profit versus nitrogen treatment, Rietrivier, 1988/89 growing season

4.5.1.2 1989/90 growing season

Seed cotton yields measured at Rietrivier in the 1989/90 season are depicted in the box plot in Figure 4.28.

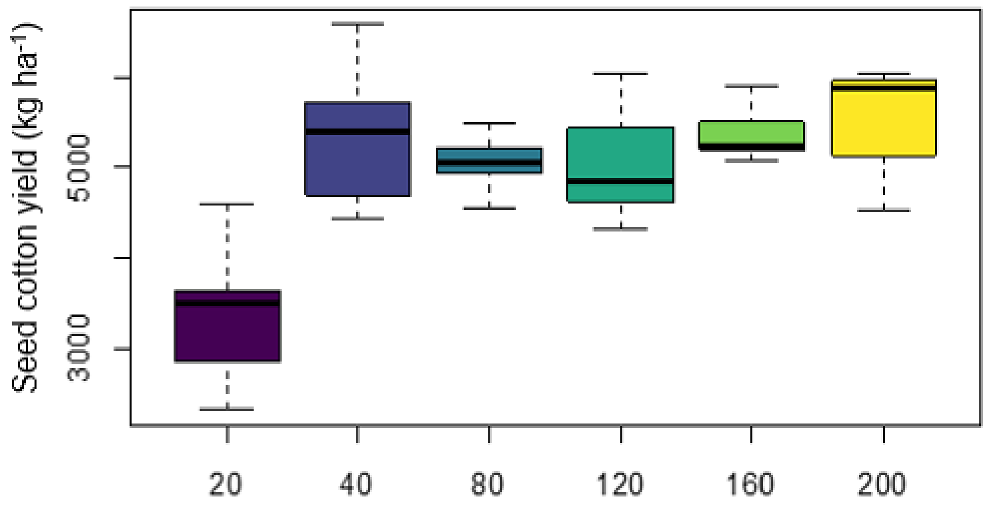


Figure 4.28 Box plot of seed cotton yield versus nitrogen treatment, Rietrivier, 1989/90 growing season

At Rietrivier in the 1989/90 growing season a maximum yield of 5 495 kg ha^{-1} was achieved from a nitrogen treatment of 159 kg ha^{-1}, as displayed in Figure 4.29.

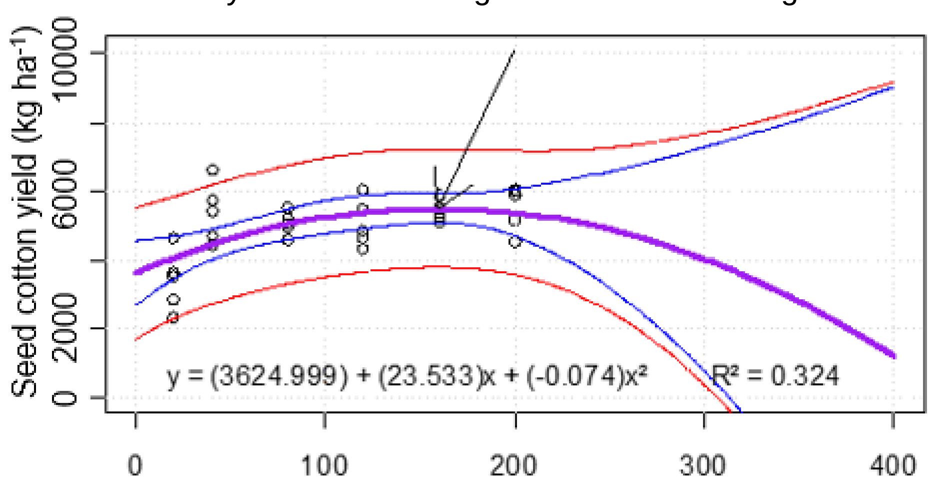


Figure 4.29 Polynomial regression between seed cotton yield versus nitrogen treatment, Rietrivier. 1989/90 growing season

A maximum profit of R113 573.34 ha^{-1} was calculated at 149 kg N ha^{-1} as depicted in Figure 4.30.

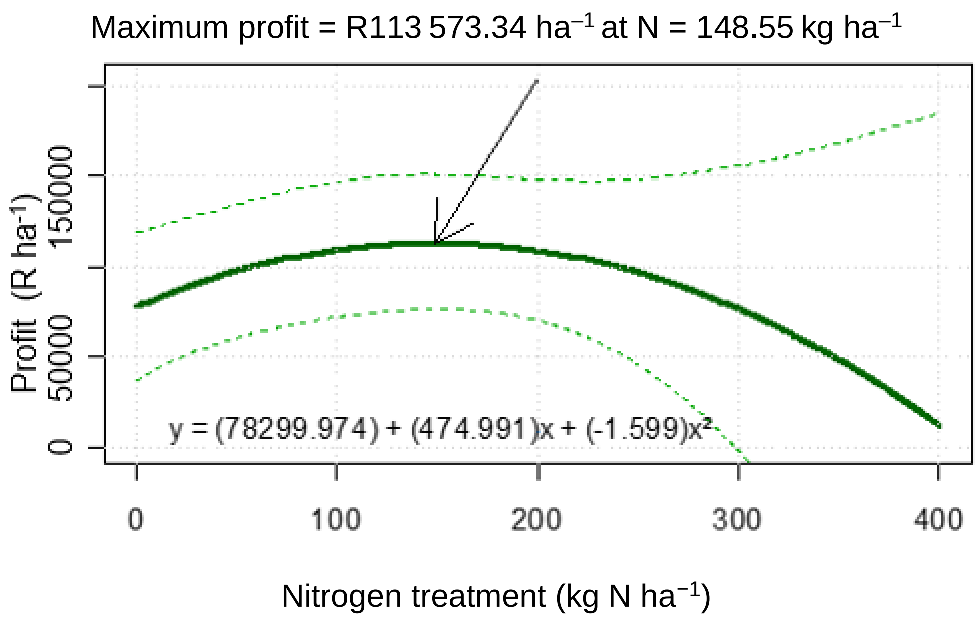


Figure 4.30 Polynomial regression between profit versus nitrogen treatment, Rietrivier, 1989/90 growing season

4.5.2 Vaalharts

4.5.2.1 1988/89 growing season

The seed cotton yields determined at Vaalharts in the 1988/89 growing season are depicted in the box plot in Figure 4.31.

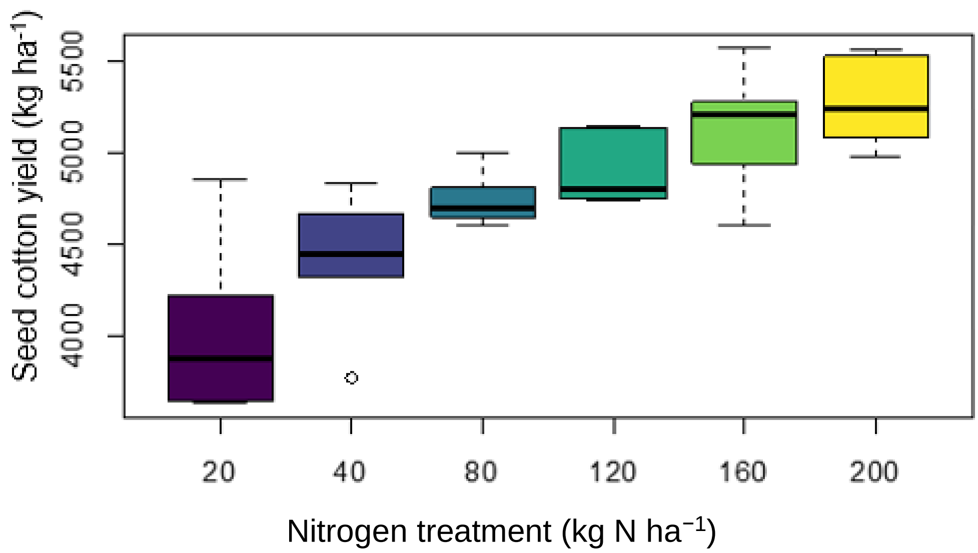


Figure 4.31 Box plot of seed cotton yields versus nitrogen treatment, Vaalharts, 1988/89 growing season

Maximum yield of 5 260 kg ha^{-1} was achieved at a nitrogen treatment of 221 kg ha^{-1} as shown in Figure 4.32.

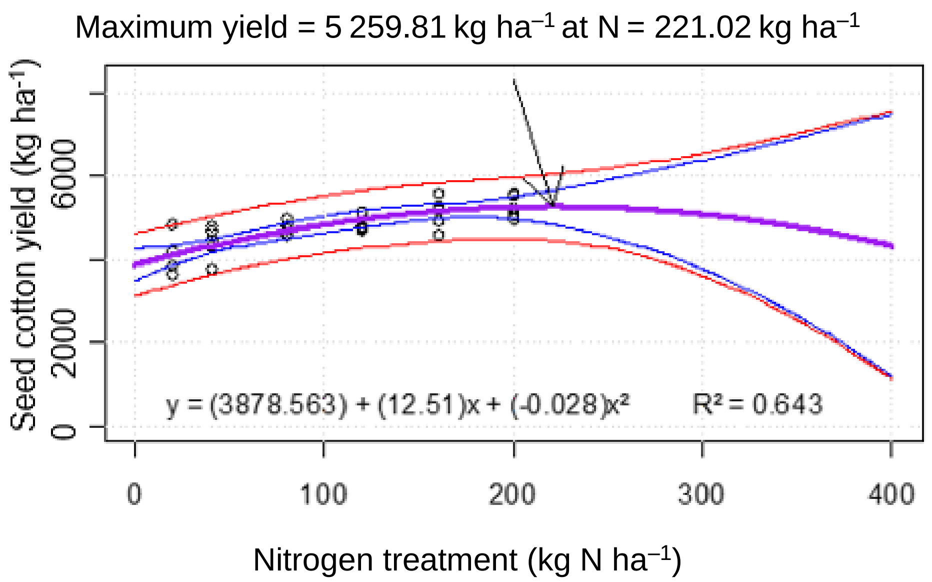


Figure 4.32 Polynomial regression between seed cotton yield versus nitrogen treatment, Vaalharts, 1988/89 growing season

A maximum profit of R106 705.72 was calculated at a nitrogen treatment of 193 kg N ha^{-1} as depicted in Figure 4.33.

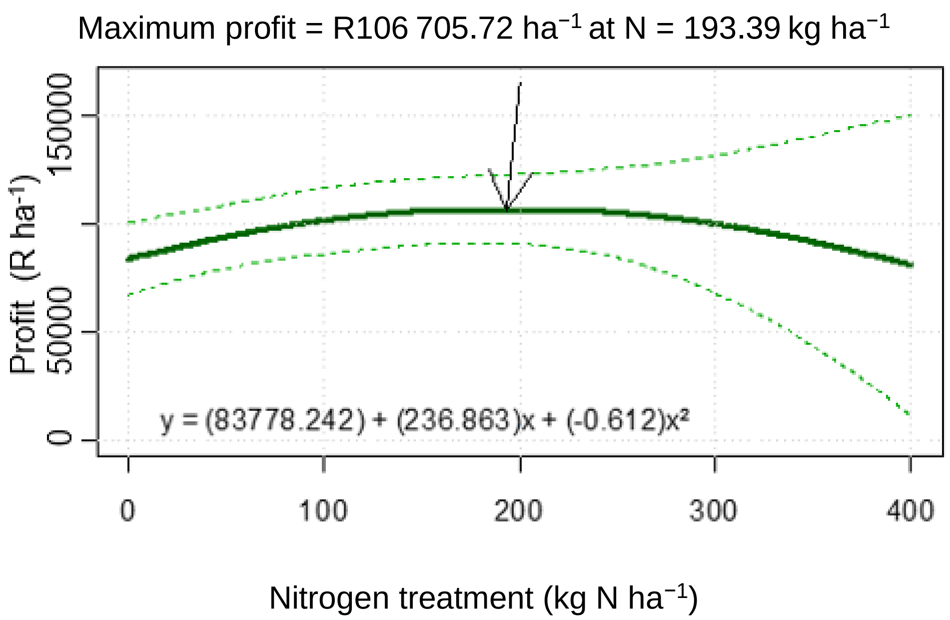


Figure 4.33 Polynomial regression between profit versus nitrogen treatment, Vaalharts, 1988/89 growing season

4.5.2.2 1989/90 growing season

The seed cotton yields determined at Vaalharts in the 1989/90 growing season, are shown in the box plot in Figure 4.34.

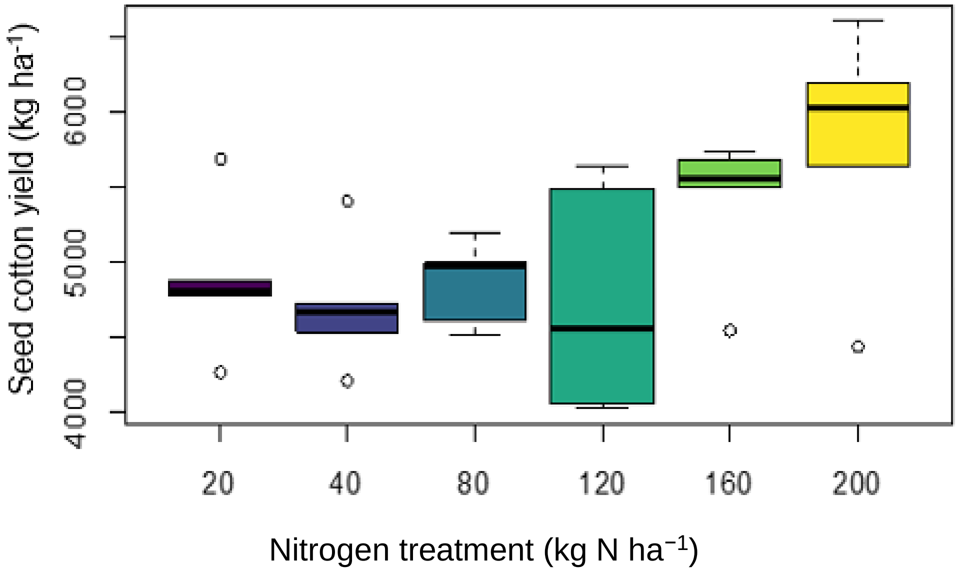


Figure 4.34 Box plot of seed cotton yield versus nitrogen treatment, Vaalharts, 1989/90 growing season

It is not possible to predict the maximum seed cotton yield at Vaalharts in the 1989/90 growing season from the polynomial regression between seed cotton yield and nitrogen treatment as the polynomial regression showed no turning point (Figure 4.35).

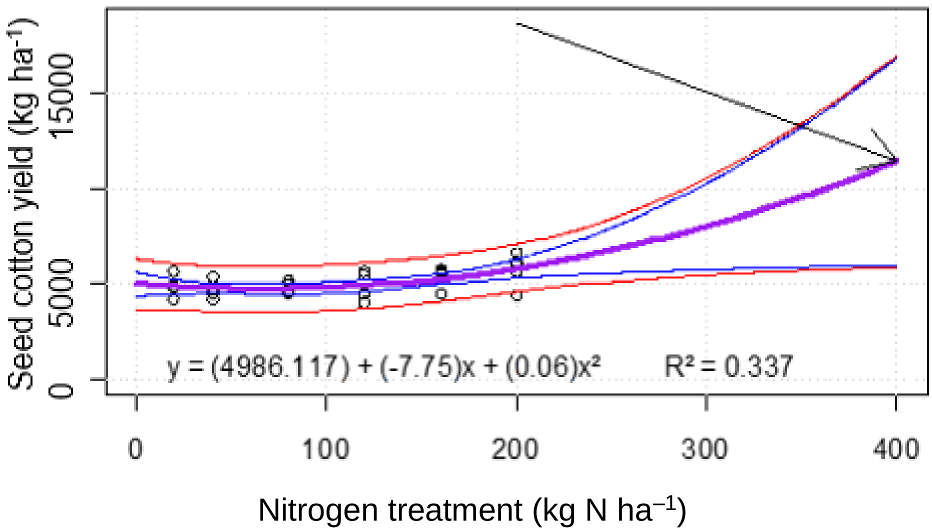


Figure 4.35 Polynomial regression between seed cotton yield versus nitrogen treatment, Vaalharts, 1989/90 growing season

The polynomial regression between profit and nitrogen treatment had no turning point (Figure 4.36), hence maximum profit cannot be estimated.

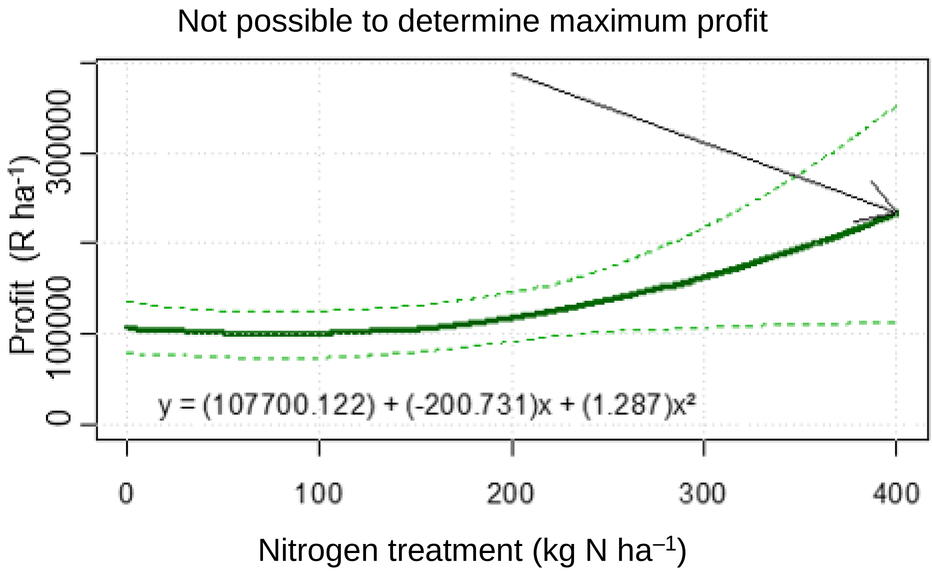


Figure 4.36 Polynomial regression between profit versus nitrogen treatment depicting nitrogen application, Vaalharts, 1989/90 growing season

4.6 Seed cotton yield at Groblersdal

The seed cotton yields that realised from the nitrogen treatments at Groblersdal in the 1988/89 growing season, are given in Appendix 4.5. A summary of the ANOVA done on the data is presented in Table 4.4.

Table 4.4 Summary of ANOVA done on seed cotton yields measured, Groblersdal, 1988/89 growing season

Nitrogen application (kg N ha^{-1})	Seed cotton yield (kg ha^{-1})
0	2 833.20
40	3 868.20
80	4 299.00
120	4 330.20
160	4 524.60
200	4 462.40
Average	4 061.27
F-value	16.840
t-value	3.258382
R^2	0.7782
p-value	0.0000003649
Significance**	S
LSD*	697.5726

*LSD Bonferonni at P = 0,05; **S = Significant, NS = Not Significant

Nitrogen fertilization rates of 40 kg N ha^{-1} and higher resulted in significant increases in seed cotton yield as compared to seed cotton yields measured from the control treatment (Table 4.4). The 200 kg N ha^{-1} treatment gave higher yields of seed cotton than the 40 kg N ha^{-1} treatment. Seed cotton yields obtained from the 80, 120, 160 and 200 kg N ha^{-1} treatments did not differ significantly from each other.

The seed cotton yields obtained from Groblersdal in the 1988/89 growing season, are depicted in the box plot in Figure 4.37.

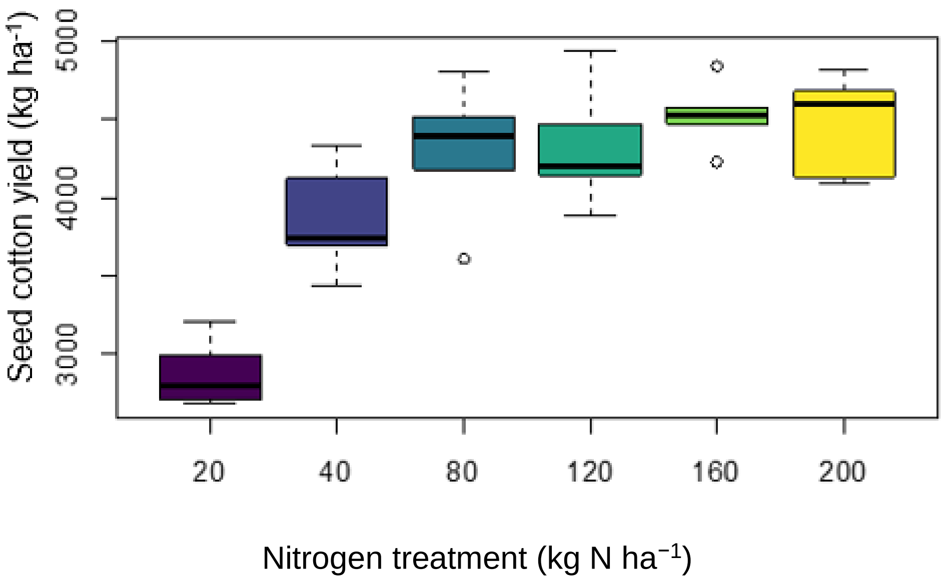
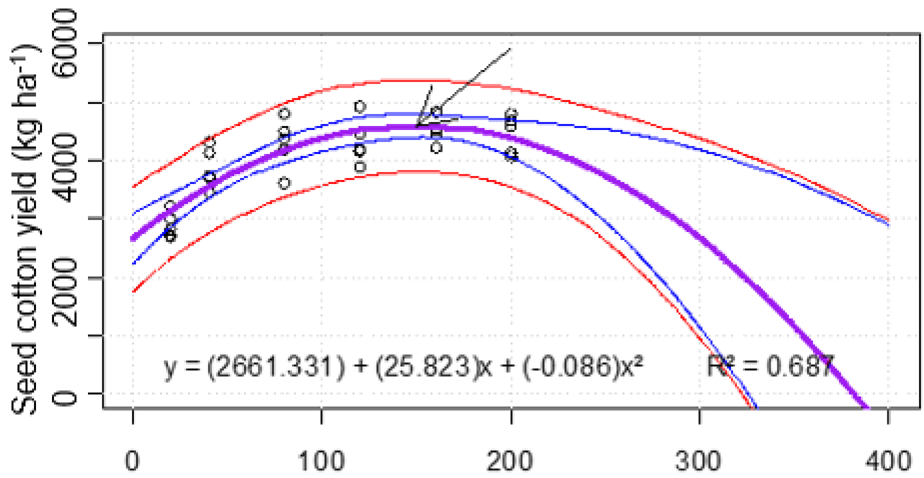


Figure 4.37 Box plot of seed cotton yield versus nitrogen treatment Groblersdal, 1988/89 growing season

A maximum yield of 4 598 kg ha^{-1} was achieved at Groblersdal in the 1988/89 growing season with a nitrogen treatment of 150 kg ha^{-1} (Figure 4.38).

Maximum yield = 4 597.68 kg ha^{-1} at N = 150.15 kg ha^{-1}

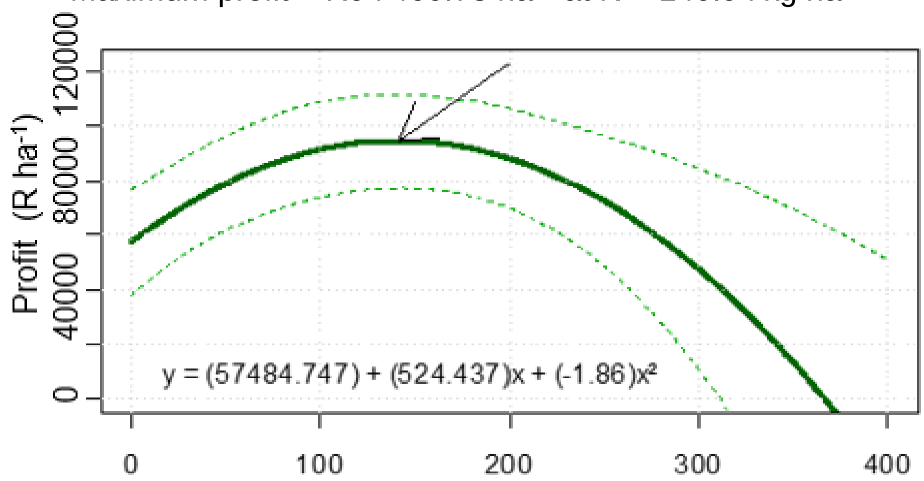


Nitrogen treatment (kg N ha^{-1})

Figure 4.38 Polynomial regression obtained between seed cotton yield versus nitrogen treatment, Groblersdal, 1988/89 growing season

Maximum profit of R94 460.72 was calculated at an application of 141 kg N ha^{-1} as depicted in Figure 4.39.

Maximum profit = R94 460.73 ha^{-1} at N = 140.94 kg ha^{-1}



Nitrogen treatment (kg N ha^{-1})

Figure 4.39 Polynomal regression obtained between profit and nitrogen treatment, Groblersdal, 1988/89 growing season

4.7 Seed cotton yield at Bela Bela

The seed cotton yields of the nitrogen fertilization trial at Bela Bela in the 1988/89 growing season, is given in Appendix 4.6. A summary of the ANOVA done on the data is given in Table 4.5.

Table 4.5 Summary of the ANOVA done on seed cotton yields, Bela Bela, 1988/89 growing season

Nitrogen application (kg N ha^{-1})	Seed cotton yield (kg ha^{-1})
0	2 456.83
15	2 426.14
30	2 406.52
45	2 424.29
Average	2 453.45
F-value	1.128
t-value	3.008334
R^2	0.1746
p-value	0.3673
Significance**	NS
LSD*	414.3055

*LSD Bonferonni at P = 0,05
** S = Significant, NS = Not Significant

There was no significant difference in the seed cotton yields between the nitrogen treatments at Bela Bela (Table 4.5). It is possible that the residual and mineralisable nitrogen content of the soil was sufficient for crop requirements and that the applied nitrogen fertilizer had no significant effect on seed cotton yield, or that the increments between fertilizer applications were too small.

Seed cotton yields measured at Bela Bela in the 1988/89 growing season, are depicted in the box plot in Figure 4.40.

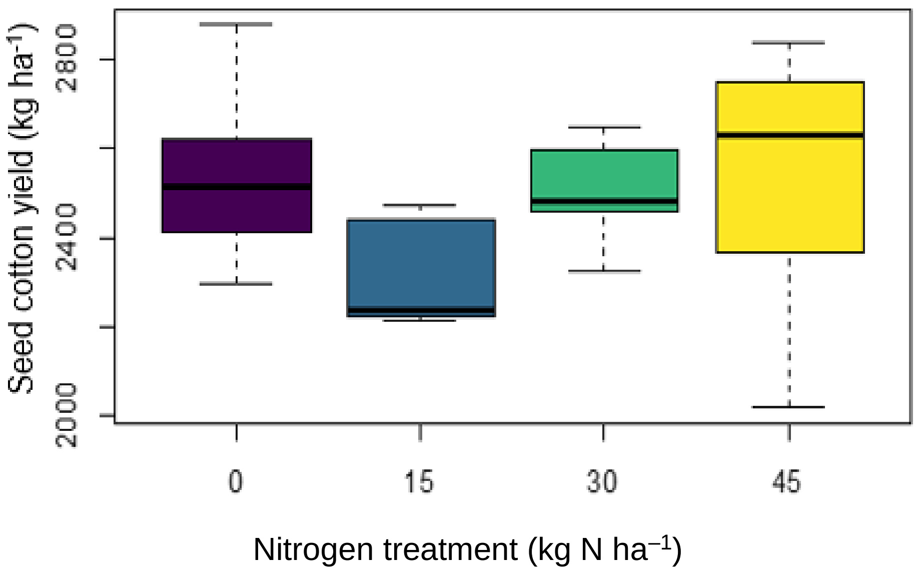


Figure 4.40 Box plot of seed cotton yield versus nitrogen treatment, Bela Bela, 1988/89 growing season

The relationship between nitrogen application and seed cotton yield at Bela Bela in the 1988/89 growing season is displayed in Figure 4.41. It was impossible to establish at which nitrogen application maximum seed cotton yield realised due to the absence of a turning point in the polynomial regression.

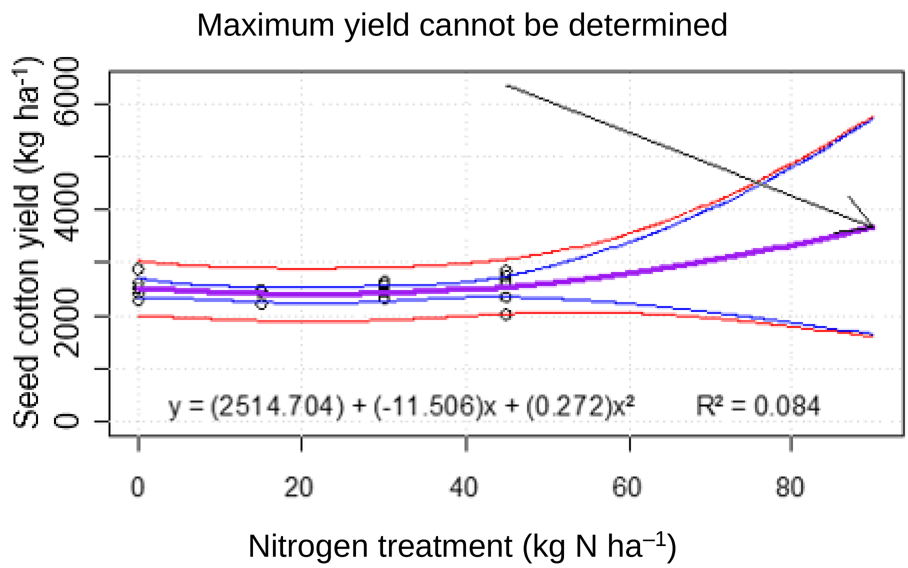


Figure 4.41 Polynomial regression between seed cotton yield versus nitrogen treatment, Bela Bela, 1988/89 growing season

A maximum profit cannot be calculated from the data obtained at Bela Bela in 1988/89, as the polynomial regression depicted in Figure 4.42 below, does not have a turning point.

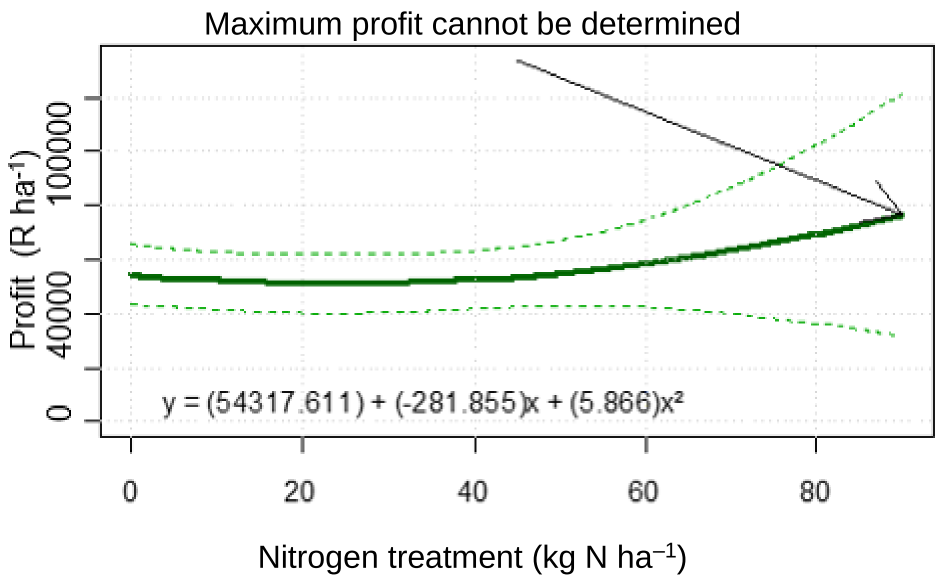


Figure 4.42 Polynomial regression between profit and nitrogen treatment, Bela Bela, 1988/89 growing season, depicting nitrogen application in kg ha^{-1} for maximum profit in R. ha^{-1}

4.8 Synthesis

The above-mentioned results are summarised in Table 4.6 for a synthesis of the data in order to obtain a better perspective thereof. The procedure to determine the nitrogen requirement of cotton according to the Fertasa and adjusted guidelines, with examples of calculations is given in Appendix 4.7. A summary of the calculations of both the Fertasa and adjusted guidelines for each experimental site is given in Appendix 4.8.

Table 4.6 Nitrogen fertilization rates associated with maximum seed cotton yield and maximum profit established for irrigated cotton with field trials and nitrogen use efficiencies

Site and season	Fertilization rate (kg N ha^{-1})		900 mm soil depth			Fertasa guideline (kg N ha^{-1})	Adjusted guideline (kg N ha^{-1})	Nitrogen use efficiencies using total and applied nitrogen[d]							
								Total nitrogen use efficiency				Applied nitrogen use efficiency			
	Maximum yield (kg ha^{-1})	Maximum profit (R ha^{-1})	Residual N (kg ha^{-1})	Mineralised N (kg ha^{-1})	Total N (kg ha^{-1})			Calculated	Fertasa	Adjusted	MaxPro-fit	Calculated	Fertasa	Adjusted	MaxPro-fit
Rustenburg Site 1 (oats): 1987/88	330 5 009	303 97 740 (4 990)[f]	38	131	169	147	183	10.0	15.9	14.2	10.6	15.2	34.1	27.4	16.5
Rustenburg Site 1 (oats): 1988/89	Not calculated[c] 2 755[e]	Not calculated[c]	31	131	162	153	134	[c]	8.7[c]	9.3c	[c]	[c]	18.0	20.6	[c]
Rustenburg Site 1 (soy beans): 1987/88	Not calculated[c] 5 112[e]	Not calculated[c]	145	144	289	58	101	[c]	14.7 [c]	13.1 [c]	[c]	[c]	88.1	50.6	[c]
Rustenburg Site 1 (soy beans): 1988/89	68 4 538	0 96 974 (4 490)[f]	95	144	239	100	103	14.8	13.6	13.3	18.8	66.7	45.38	44.1	[c]
Rustenburg Site 2 (soy beans harvest): 1989/9	2 412[a,b] 9 028 3 683[e]	2 084[a,b] 143 194	46	73	119	174	137	[b]	12.6[b]	14.4[b]	[b]	[b]	21.2	26.9	[b]
Rustenburg Site 2 (soy beans plough): 1989/90	137 5 262	119 109 400 (5 249)[f]	71	243	314	153	207	11.7	11.3	10.1	12.1	38.4	34.4	25.4	44.1
Rustenburg Site 2 (babala): 1989/90	253 5 314	227 106 792 (5 274)[f]	34	110	144	184	241	13.4	16.2	13.8	14.2	21.0	28.9	22.1	23.2
Rietrivier 1988/89	532[a,b] 5 265	440[a,b] 97 943 (5 197)[f]	69	108	177	205	258	7.4[a]	13.8 [a]	12.1 [a]	8.4	9.9[a]	25.7	20.4	11.8
Rietrivier 1989/90	159 5 495	149 113 573 (5 489)[f]	74	108	182	202	270	16.1	14.3	12.2	16.6	34.6	27.2	20.4	36.8

Site and season	Fertilization rate (kg N ha⁻¹)		900 mm soil depth			Fertasa guideline (kg N ha⁻¹)	Adjusted guideline (kg N ha⁻¹)	Nitrogen use efficiencies using total and applied nitrogen[d]							
								Total nitrogen use efficiency				Applied nitrogen use efficiency			
	Maximum yield (kg ha⁻¹)	Maximum profit (R ha⁻¹)	Residual N (kg ha⁻¹)	Mineralised N (kg ha⁻¹)	Total N (kg ha⁻¹)			Calculated	Fertasa	Adjusted	MaxPro-fit	Calculated	Fertasa	Adjusted	MaxPro-fit
Vaalharts 1988/89	221 5 260	193 106 706 (5 250)	50	147	197	221	274	12.6	12.6	11.2	13.5	23.8	23.8	19.2	27.2
Vaalharts 1989/90	Not calculated[c] 5 063[e]	Not calculated[c]	47	147	194	223	263	[c]	12.1[c]	11.1[c]	[c]	[c]	22.7	19.3	.[c]
Groblersdal 1988/89	150 4 598	141 94 461 (4 593)[f]	83	64	147	143	150	15.5	15.9	15.5	16.0	30.7	32.2	30.7	32.6
Bela Bela 1988/89	Not calculated[c] 2 454[e]	Not calculated[c]	125	143	268	37	32	[c]	8.0[c]	8.2[c]	[c]	[c]	66.32	76.7	[c]
Average								12.7	13.1	12.2	13.8	30	36	31.1	27.5

[a]Level is higher than usually applied in practice
[b]Level is too far beyond the range of confident prediction
[c]Polynomial regression has an inverse nature and the turning point cannot be calculated
[d]Total nitrogen use efficiency and applied (fertilized) nitrogen use efficiency as described in the introduction
[e]Average yield (kg ha⁻¹) of the trial, used where the turning point of the polynomial regression cannot be calculated
[f]Seed cotton yield (kg ha⁻¹) at maximum profit

4.8.1 Nitrogen requirements

In the 1987/88 growing season, 330 kg N ha^{-1} gave maximum seed cotton yield of 5 009 kg ha^{-1} on Field 1 (oats) at Rustenburg. This N level is slightly beyond the rate at which statistical predictions can be made with confidence, as it is more than twice the maximum nitrogen fertilization rate (150 kg N ha^{-1}) applied. The calculated nitrogen fertilization rate required to produce a maximum profit of R97 740.04 ha^{-1} was 303 kg ha^{-1}. The residual nitrogen content of the soil to a depth of 900 mm at planting was 38 kg ha^{-1}. Using the nitrogen fertilization estimation procedure currently recommended by Fertasa (2016), the required nitrogen fertilization rate for the soil on which the trial was done, is 147 kg N ha^{-1}, which is less than half the nitrogen fertilization level found in the trial.

The nitrogen fertilization guideline assumes a nitrogen removal of 250 kg N ha^{-1} for a crop producing 4 500 kg seed cotton and above (55.55 kg N ha^{-1} for every ton of seed cotton produced). If a correction is done for the yield exceeding 4 500 kg ha^{-1} to allow for the additional nitrogen uptake, the required nitrogen uptake for the maximum seed cotton yield of 5 009 kg ha^{1} produced in this trial, is 278 kg ha$^{-\mathbf{1}}$. Using this amount of nitrogen instead of the standard 250 kg N ha^{-1}, the required nitrogen fertilization rate for the soil is 183 kg N ha^{-1}. Although this level is still substantially lower than experienced in practice, it is closer to the level observed in practice.

Although it was not possible to calculate the nitrogen fertilization rate required to produce the maximum amount of seed cotton on the oats field of Site 1 at Rustenburg in the 1988/89 growing season, the required nitrogen fertilization rate was calculated from the soil data. For a seed cotton yield of 4 500 kg ha^{-1}, a nitrogen fertilization rate of 153 kg ha^{-1} would be applied according to the Fertasa (2016) guideline. The average seed cotton yield of the field trial was 2 755 kg ha^{-1}. According to the Fertasa (2016) guideline, the crop would remove 242 kg N ha^{-1}. Adjusting the nitrogen requirement for the average yield obtained over the trial, a nitrogen fertilization of 134 kg ha^{-1} would be required. The maximum profit for this trial could not be calculated due to the absence of a turning point in the polynomial regression.

Although it was not possible to estimate the nitrogen fertilization rate required to produce the maximum amount of seed cotton on the soybean field of Site 1 at

Rustenburg, in the 1988/89 growing season, a required nitrogen fertilization rate was calculated from the soil data. The residual nitrogen content of the soil to a depth of 900 mm was 145 kg ha^{-1}. According to the Fertasa (2016) guideline, the required nitrogen fertilization rate to produce a seed cotton yield of 4 500 kg ha^{-1} with the above soil parameters is 58 kg ha^{-1}. The average seed cotton yield of the trial was 5 112 kg ha^{-1}. Adjusting the nitrogen requirement for the average yield obtained over the trial, a nitrogen extraction of 284 kg ha^{-1} would occur while a nitrogen fertilization of 101 kg ha^{-1} would be required. The maximum profit for this trial could not be calculated due to the absence of a turning point in the polynomial regression.

In the soybean field of Site 1 at Rustenburg (1988/89 season) the correlation between nitrogen fertilization and seed cotton yield was not significant (R^2 = 0.07; p = 0.75). Although the correlation was not significant, the polynomial regression estimated a maximum seed cotton yield of 4 538 kg ha^{-1} at a nitrogen fertilization rate of 68 kg ha^{-1} and maximum profit of R96 974.28 ha^{-1} at a nitrogen fertilization rate of 0 kg ha^{-1}. The residual nitrogen content of the soil to 900 mm depth was 95 kg ha^{-1}. Calculated according to the Fertasa (2016) guidelines, the required fertilization rate for these parameters is 100 kg N ha^{-1}. Adjusting the nitrogen requirement for the maximum yield obtained over the trial, a nitrogen extraction of 252 kg ha^{-1} would take place and a nitrogen fertilization of 103 kg ha^{-1} would be required, which is higher than the nitrogen fertilization level found in the trial.

In the soybean harvested field of Site 2 at Rustenburg, in the 1989/90 growing season, the estimated nitrogen fertilization required to produce a maximum seed cotton yield of 9 028 kg ha^{-1} is 2 412 kg ha^{-1}. This level is far beyond the rate at which statistical predictions can be made with confidence, and hence impractical. The calculated nitrogen fertilization rate required to produce a maximum profit of R143 194.21 ha^{-1} was 2 084 kg ha^{-1} and is not feasible. The residual nitrogen content of the soil to a depth of 900 mm at planting was 46 kg ha^{-1}. Using the nitrogen fertilization method as currently recommended by Fertasa (2016), the required nitrogen fertilization rate for a seed cotton yield of 4 500 kg ha^{-1} using the soil parameters on which the trial was done, is 174 kg ha^{-1}. If a correction is done for the average seed cotton yield of 3 683 kg ha^{-1} for the trial, the nitrogen removal by the crop would be about 240 kg ha^{-1}, resulting in a required nitrogen fertilization rate of 137 kg ha^{-1}.

In the ploughed soybean field of Site 2 at Rustenburg, in the 1989/90 growing season, the estimated nitrogen fertilization required to produce a maximum seed cotton yield of 5 262 kg ha^{-1} is 137 kg ha^{-1}. The calculated nitrogen fertilization rate required to produce a maximum profit of R109 399.75 ha^{-1} is 119 kg ha^{-1}. The residual nitrogen content of the soil to 900 mm depth at planting was 71 kg ha^{-1}. Using the nitrogen fertilization procedure recommended by Fertasa (2016), the required nitrogen fertilization rate for a seed cotton yield of 4 500 kg ha^{-1} using the soil parameters of the trial is 153 kg N ha^{-1}. After correcting for the calculated maximum seed cotton yield of 5 262 kg ha^{-1}, the nitrogen removal by the crop would be 292 kg ha^{-1}, resulting in a required nitrogen fertilization rate of 207 kg ha^{-1}, which is higher than the nitrogen fertilization level found in the trial. The over prediction of nitrogen fertilization rate by both the Fertasa (2016) and adjusted approaches can most probably be explained by the high rate of nitrogen mineralisation found in the soil (243 kg N ha^{-1}). This was purposefully brought about by the ploughing in of soybeans at late soft dough stage to create a high nitrogen environment in the soil. This high nitrogen mineralisation is substantially higher than the 120 kg N ha^{-1} that is allowed for in the Fertasa (2016) procedure.

In the babala field of Site 2 at Rustenburg, for the 1989/90 growing season, the calculated nitrogen fertilization required to produce a maximum seed cotton yield of 5 314 kg ha^{-1} is 253 kg ha^{-1}. The estimated nitrogen fertilization rate required to produce a maximum profit of R106 791.75 ha^{-1} is 227 kg ha^{-1}. The residual nitrogen content of the soil to a depth of 900 mm at planting was 34 kg ha^{-1}. Using the nitrogen fertilization procedure recommended by Fertasa (2016), the required nitrogen fertilization rate for a seed cotton yield of 4 500 kg ha^{-1} using the soil parameters on which the trial was done, is 184 kg N ha^{-1}. For correction of the maximum seed cotton yield to 5 314 kg ha^{-1}, the nitrogen removal by the crop would be 295 kg ha^{-1}, resulting in a required nitrogen fertilization rate of 241 kg ha^{-1}, which is almost the same as the nitrogen fertilization level found in the trial.

In the trial at Rietriver for the 1988/89 season, the calculated nitrogen fertilization required to produce a maximum seed cotton yield of 5 265 kg ha^{-1} was 532 kg ha^{-1} which is impractical and beyond the range of confident prediction. The calculated nitrogen fertilization rate required to produce a maximum profit of R97 942.99 was 440 kg ha^{-1} and is much higher than what is applied in practice. The residual nitrogen content of the soil to a depth of 900 mm at planting was 69 kg ha^{-1}. Using the prescribed method of nitrogen fertilization procedure of Fertasa (2016), the required nitrogen fertilization rate for a seed cotton yield of 4 500 kg ha^{-1} using the trial's soil parameters, is 205 kg N ha^{-1}. After a correction for the calculated maximum seed cotton yield of 5 265 kg ha^{-1}, the nitrogen removal by the crop would be 292 kg ha^{-1}, resulting in a required nitrogen fertilization rate of 258 kg ha^{-1}.

For the 1989/90 growing season at Rietriver, the calculated nitrogen fertilization required to produce a maximum seed cotton yield of 5 495 kg ha^{-1} is 159 kg ha^{-1}. An estimated nitrogen fertilization rate required to produce a maximum profit of R113 573.34 ha^{-1} is 149 kg ha^{-1}. The residual nitrogen content to 900 mm soil depth at planting was 74 kg ha^{-1}. By using the procedure recommended by Fertasa (2016), the required nitrogen fertilization rate to produce a seed cotton yield of 4 500 kg ha^{-1} based on the trial's soil parameters was estimated at 202 kg N ha^{-1}. Correcting for the calculated maximum seed cotton yield of 5 495 kg ha^{-1}, the nitrogen removal by the crop would be 305 kg ha^{-1}, resulting in a required nitrogen fertilization rate of 270 kg ha^{-1}, which is higher than the nitrogen fertilization level found in the trial. This can most probably be explained by the high mineralisation of nitrogen in the sandy soil (108 kg N ha^{-1}), much higher than the 60 kg N ha^{-1} that is allowed for in the Fertasa (2016) procedure.

At Vaalharts in the 1988/89 growing season, the estimated nitrogen fertilization required to produce a maximum seed cotton yield of 5 260 kg ha^{-1} was 221 kg ha^{-1}. The calculated nitrogen fertilization rate required to produce a maximum profit of R106 705.72 ha^{-1} was 193 kg ha^{-1}. The residual nitrogen content of the soil to a depth of 900 mm at planting was 50 kg ha^{-1}. Using the nitrogen fertilization procedure recommended by Fertasa (2016), the required nitrogen fertilization rate for a seed cotton yield of 4 500 kg ha^{-1}, based on the soil parameters of the trial was 221 kg N ha^{-1}, which is exactly the same as the field trial. After correction for a calculated maximum seed cotton yield of 5 260 kg ha^{-1}, the nitrogen removal by the crop would be 292 kg ha^{-1}, giving a required nitrogen fertilization rate of 274 kg ha^{-1}, which is higher than the nitrogen fertilization level found in the trial. This can also most probably be explained by the high mineralisation of nitrogen in the sandy soil (147 kg N ha^{-1}), much higher than the 60 kg N ha^{-1} that is allowed for in the Fertasa (2016) procedure. If the measured nitrogen mineralisation (147 kg N ha^{-1}) is used instead of the assumed nitrogen mineralisation (60 kg N ha^{-1}), then the predicted nitrogen fertilization by the adjusted procedure is 201 kg N ha^{-1}, which is much closer to the nitrogen level found in the trial.

In the 1989/90 growing season at Vaalharts, it is not possible to calculate the nitrogen fertilization required to produce a maximum seed cotton yield, or the nitrogen fertilization required to produce maximum profit, due to that the polynomial regressions had no turning point. The residual nitrogen content of the soil to a depth of 900 mm at planting was 47 kg ha^{-1}. The average seed cotton yield of all plots in the trial was 5 063 kg ha^{-1}. Using the guideline recommended by Fertasa (2016), as well as the available soil parameters, the required nitrogen fertilization rate for a seed cotton yield of 4 500 kg ha^{-1} was estimated to be 223 kg N ha^{-1}. For a corrected seed cotton yield of 5 063 kg ha^{-1}, the nitrogen removal by the crop would be 281 kg ha^{-1}, resulting in a required nitrogen fertilization rate of 263 kg ha^{-1}.

At Groblersdal in the 1988/89 growing season, the calculated nitrogen fertilization required to produce a maximum seed cotton yield of 4 598 kg ha^{-1} was 150 kg ha^{-1}. The calculated nitrogen fertilization rate required to produce a maximum profit of R94 460.72 ha^{-1} was 141 kg ha^{-1}. The soil's residual nitrogen content to 900 mm depth was 126 kg ha^{-1}. Using the guideline recommended by Fertasa (2016), the required nitrogen fertilization rate for a seed cotton yield of 4 500 kg ha^{-1} as estimated from the trial's soil parameters was 143 kg N ha^{-1}. After correction for the calculated maximum seed cotton yield of 4 598 kg ha^{-1}, the nitrogen removal by the crop would be 255 kg ha^{-1}, resulting in a required nitrogen fertilization rate of 150 kg ha^{-1}. This amount is exactly the same as the nitrogen fertilization level found in the trial.

For the trial at Bela Bela in the 1988/89 growing season, it is not possible to calculate the nitrogen fertilization required to produce a maximum seed cotton yield, or the nitrogen fertilization required to produce a maximum profit, due to the absence of turning points in the polynomial regressions. The residual nitrogen content of the soil to 900 mm depth at planting was 125 kg ha^{-1}. The average seed cotton yield of all plots in the trial was 2 454 kg ha^{-1}. Using the procedure recommended by Fertasa (2016), the required nitrogen fertilization rate for a seed cotton yield of 2 500 kg ha^{-1} was estimated as 37 kg N ha^{-1} based on the trial's soil parameters. For a corrected average seed cotton yield of 2 453 kg ha^{-1}, nitrogen removal by the crop would be

216 kg ha^{-1}, giving a required nitrogen fertilization rate of 32 kg ha^{-1}. Apparently the residual plus mineralised nitrogen content of the soil was sufficient for the seed cotton yields obtained and therefore no significant correlation could be found between nitrogen fertilization and seed cotton yield at Bela Bela.

4.8.2 Nitrogen use efficiencies

As far as NUE is concerned, the TNUE and the applied NFUE is given in Table 4.6.

The TNUE and NFUE were determined as described in the introduction, where

- the calculated nitrogen level associated with maximum yield;
- the nitrogen application rate proposed by Fertasa (2016);
- the adjusted nitrogen fertilization level for maximum yield; as well as
- the nitrogen application level associated with maximum profit,

were respectively used as the input for applied nitrogen (N_a).

4.8.2.1 Total nitrogen use efficiency

Using the calculated nitrogen level associated with maximum yield as N_a, TNUE varied from 7.4 kg seed cotton produced ha^{-1} for every 1 kg N ha^{-1} available to the cotton plant (Rietriver 1988/89 season) to 16.1 kg seed cotton produced ha^{-1} for every 1 kg N ha^{-1} available to the cotton plant (Rietriver 1989/90 season). The low TNUE obtained from the Rietriver 1988/89 trial can be explained due to the calculated nitrogen content associated with maximum yield being 532 kg N ha^{-1} which is far beyond the range of confident prediction of the trial. The level of nitrogen is also substantially higher than levels applied routinely in practice.

Using the nitrogen application rate proposed by Fertasa (2016) as N_a, TNUE varied from 8.0 kg seed cotton produced ha^{-1} for every 1 kg N ha^{-1} available to the cotton plant (Bela Bela 1988/89 season) to 16.2 kg seed cotton produced ha^{-1} for every 1 kg N ha^{-1} available to the cotton plant (Rietriver 1989/90 season). The low TNUE obtained from the Bela Bela 1988/89 season can be explained due to high soil nitrogen, poor correlation of nitrogen treatments with seed cotton yield, as well as relatively low yield, as the experiment was essentially carried out under dryland conditions.

Using the adjusted nitrogen fertilization level for maximum yield as N_a, TNUE varied from 8.2 kg seed cotton produced ha^{-1} for every 1 kg N h^{-1} available to the cotton plant (Bela Bela 1988/89 season) to 15.5 kg seed cotton produced ha^{-1} for every 1 kg N ha^{-1} available to the cotton plant (Groblersdal 1988/89) in the 1989/89). As mentioned above, the low TNUE obtained from Bela Bela in the 1988/89 season can be explained due to high soil nitrogen, poor correlation of nitrogen treatments with seed cotton yield, as well as relatively low yield, as the experiment was essentially carried out under dryland conditions.

Using the adjusted nitrogen fertilization level for maximum profit as N_a, TNUE varied from 8.4 kg seed cotton produced ha^{-1} for every 1 kg N ha^{-1} available to the cotton plant (Rietrivier 1988/89 season) to 18.8 kg seed cotton produced ha^{-1} for every 1 kg N ha^{-1} available to the cotton plant (Soybean field at Rustenburg Site 1 in the 1988/89 season). As mentioned previously, the low TNUE obtained from the Rietrivier 1988/89 trial can be explained due to the calculated nitrogen content associated with maximum yield being 532 kg N ha^{-1} which is far beyond the range of confident prediction of the trial, and that the level of nitrogen is also substantially higher than levels applied routinely in practice. The relatively high TNUE of 18.8 measured for the soybean field at Rustenburg Site 1 in the 1988/89 season, can be explained by the fact that $N_a = 0$ for this trial.

4.8.2.2 Nitrogen use efficiency

Although TNUE is a unique calculation to this study, with average values that vary between 12.2 and 13.8, there are no existing references to TNUE in literature. However, Rochester (2014) and MacDonald et al. (2018), have done extensive work on nitrogen fertilizer use efficiency (NFUE), the calculation of which has been elucidated on in the introduction. According to their findings, long term nitrogen fertilization trials in Australia have shown that the optimum NFUE range for irrigated cotton grown under nitrogen fertilization rates of between 100 and 300 kg ha^{-1}, varies between 13 and 18 kg cotton lint ha^{-1} for every kilogram of nitrogen applied as fertilizer. As seed cotton contains between 33% and 40% lint, the optimum range (for yield measured as seed cotton) would equate to between 32.5 and 39.0 and 45 and 54, respectively. For the purpose of this study NFUE levels of between 32.5 and 54 will be viewed as optimal. Lower than optimal levels indicate potential nitrogen losses and higher than optimum levels indicate potentially excessive extraction of soil nitrogen (MacDonald et al. 2018).

Using the calculated nitrogen level associated with maximum yield as N_a, NFUE varied from 9.9 (Rietriver 1988/89 season), which is below optimum, to 66.7 (Soybean field at Rustenburg Site 1 in the 1988/89 season), which is above optimum. The low TNUE obtained from the Rietriver trial in 1988/89 trial can be explained due to the calculated nitrogen content associated with maximum yield being 532 kg N ha^{-1} which is far beyond the range of confident prediction of the trial. The level of nitrogen is also substantially higher than levels applied routinely in practice. The above optimum NFUE measured at Rustenburg Site 1 (Soybean field in 1988/89 season), can be explained by the high soil nitrogen contribution to seed cotton yield from this soil, presenting as exceptionally good utilization of applied nitrogen fertilizer.

The NFUE for the oats field at Rustenburg Site 1 in 1987/88 is below the optimum, namely 15.2. This can be explained by low soil nitrogen contribution due to the previous crop being oats that extracted a lot of nitrogen from the soil, leaving it with low residual nitrogen and low potential mineralisation due to low nitrogen containing matter left behind after the oats.

The NFUE of 21.0 for the babala field at Rustenburg Site 2 in 1989/90 is also below the optimum. Similar to the above this can be explained by the previous crop (babala) growing vigorously and resulting in a lower contribution of nitrogen from the soil.

The NFUE of 23.8 for Vaalharts in the 1988/89 season is also below the optimum. This can possibly be explained by a lower contribution of nitrogen from the soil, as can be seen in the low level of residual nitrogen.

The NFUE for Groblersdal at 30.7 is acceptable, while the levels for Rietriver in 1989/90 (34.6) and ploughed-in soybean field at Rustenburg Site 2 (38.4) are good.

Using the nitrogen application level associated with maximum profit as N_a, NFUE varied between 11.8 at Rietriver in 1988/89 and 44.1 at Rustenburg Site 2 (soybean ploughed-in) in 1989/90. The NFUE of the trial at Rustenburg Site 1 (oats) in 1987/88 was also low at 16.5. The rest of the NFUEs varied from slightly below optimum at Rustenburg Site 2 (babala) in 1989/90 (23.2), and Vaalharts 1988/89 (27.2), to optimal at Groblersdal in 1988/89 (32.6) and Rietriver 1989/90 (36.8).

Using the nitrogen application rate proposed by Fertasa (2016) as N_a, NFUE values varied greatly between 18.0 and 88.1, indicating that the Fertasa (2016) procedure does not cater well for varying conditions that may influence NFUE. Apart from the large variation, NFUE values were mostly optimal (Table 4.6) with the exceptions of the Rustenburg Site 1 (oats) in 1988/89 (NFUE = 18.0), and Rustenburg Site 1 (soybean) in 1988/89 (NFUE = 88.1), explained by poor correlation of obtained data during the trials and the inverse nature of the polynomial regression, not allowing for the determination of a turning point.

Also at Rustenburg Site 2 (soybean harvested) in 1989/90 the measured NFUE value is 21.2. This can also be explained by poor correlation of data and prediction beyond the level of confidence.

At Rustenburg Site 2 (soybeans ploughed-in) in 1989/90 the NFUE = 34.4, which is optimal. This can be explained by a high level of nitrogen mineralisation brought about by the ploughing in of the preceding soybean crop at late soft dough stage.

Using the adjusted nitrogen fertilization level for maximum yield as N_a, NFUE variation was lower (between 19.2 and 76.7) than previous methods of determination. The NFUE for Rustenburg Site 1 (oats) 1988/89 is 20.6, due to poor data correlation and the absence of a turning point in the polynomial regression. The NFUE for Vaalharts 1988/89 is 19.2 and Vaalharts 1989/90 is 19.3, possibly due to nitrogen losses to leaching and/or volatilisation and/or denitrification, as well as the absence of a turning point at Vaalharts 1989/90. The NFUE for Bela Bela is 76.7 due to data prediction beyond the point of confidence. The rest of the NFUE values vary between 20.4 and 50.6 (Table 4.6) and make sense when evaluated on an individual basis, considering the conditions under which each of the field trials were performed.

For example the NFUE at Groblersdal 1088/89 is 30.7 which indicates a slightly low utilisation of applied nitrogen due to possible losses such as leaching, volatilization and denitrification. As the maximum seed cotton yield at this site was 4 598 kg ha^{-1} this indicates that there might indeed be room for improving the seed cotton yield by implementing crop production practices to improve the NFUE, such as:

- correct source of nitrogen (nitrate/ammonium ratio);
- applying the correct quantity of nitrogen fertilizer;

- applying the nitrogen fertilizer at the right time/times considering the nitrogen uptake curve of cotton;
- the use of multiple nitrogen applications – possible throughout the growing season to provide nitrogen for subsequent growth flushes;
- correct placement of the nitrogen fertilizer; and
- correct irrigation techniques and scheduling to promote efficient nitrogen uptake and utilisation by the plant.

It seems that the use of nitrogen use efficiency (NUE) measurements and calculations may prove to be useful during the planning and determination of nitrogen fertilization on cotton and can be beneficial to the production of cotton in South Africa.

4.8.3 Relationships

Relationships were sought between the residual soil nitrogen in kg N ha^{-1} to three soil depths (0–300 mm, 0–600 mm and 0–900 mm, given in Appendix 4.9) and the nitrogen fertilization rate required to produce maximum yield and maximum profit respectively in kg N ha^{-1} (Table 4.6).

Relationships were also sought between the total of residual soil nitrogen plus mineralised soil nitrogen in kg N ha^{-1} versus the nitrogen fertilization required to produce maximum yield and maximum profit respectively in kg N ha^{-1} (Table 4.6).

Furthermore, the relationships between the predicted nitrogen fertilization levels for maximum yield as well as maximum profit in kg N ha^{-1} as determined by the Fertasa (2016) procedure versus the measured nitrogen levels in kg N ha^{-1} that produced maximum yield and maximum profit was investigated (data available in Table 4.6).

4.8.3.1 Residual soil nitrogen at planting versus measured nitrogen levels needed for maximum yield

The relationship between the residual soil nitrogen content of the soil (0–300 mm) in kg N ha^{-1} at planting time versus the nitrogen fertilization level in kg N ha^{-1} that produced the maximum seed cotton yield measured in the field trials is given in Figure 4.43.

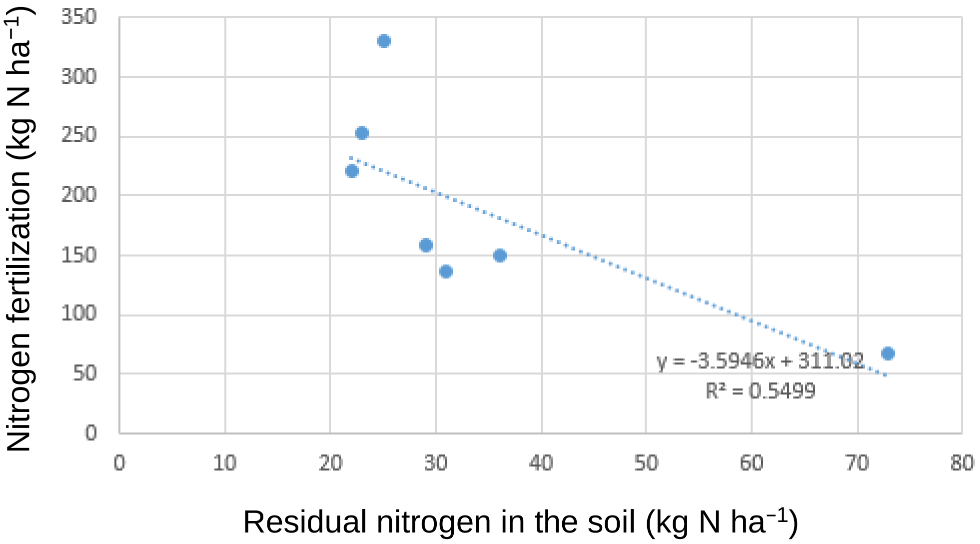


Figure 4.43 Linear regression between residual soil nitrogen (0–300 mm) in kg N ha^{-1} at planting time and nitrogen fertilization for maximum yield in kg N ha^{-1}

The correlation coefficient for the above linear regression is significant ($R^2 = 0.55$) which indicates that there is a significant relationship between the residual nitrogen content of the soil at planting time and the nitrogen fertilization level required to produce maximum seed cotton yield. A summary of the statistical analysis of data used in Figure 4.43 is given in Appendix 4.10. Figure 4.43 confirms similar findings in Australia by Smith and Welsh (2018) as depicted in Figure 2.7 in Chapter 2. For ease of reference, Figure 2.7 will be given here again as Figure 4.44.

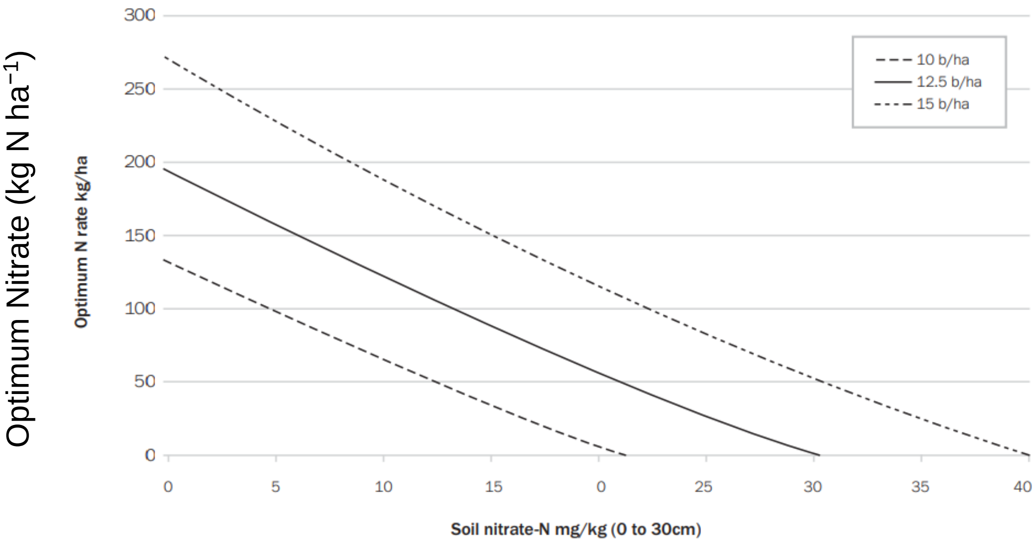


Figure 4.44 The relationship between the optimum nitrogen fertilization requirement for irrigated cotton, based on the residual nitrate content of the soil (0–300 mm depth taken in Australia during September, one month before planting cotton (Smith and Welsh 2018)

It is interesting to note that the linear regression in Figure 4.43 intersects the Y-axis at 311 kg N ha^{-1}, slightly higher than the 275 kg N ha^{-1} of Smith and Welsh (2018) for the higher yield. The intersection of the regression line with the X-axis in Figure 4.43 is at a residual nitrogen content of 86.5 kg N ha^{-1} in the soil, which is close to the 21 mg N kg^{-1} (94.5 kg N ha^{-1}) residual soil nitrate-N, X-axis intersection for lower yield in Figure 4.44 (Smith and Welsh 2018). Although the regression line obtained in Figure 4.43 is not exactly the same as in Figure 4.44, it is within the same range, considering that the soil analyses for Figure 4.44 were taken one month before planting and those for Figure 4.43 were taken at planting.

The relationship between the residual soil nitrogen content of the soil (0–600 mm) in kg N ha^{-1} at planting versus the nitrogen fertilization level in kg N ha^{-1} that produced the maximum seed cotton yield measured in the field trials is given in Figure 4.45.

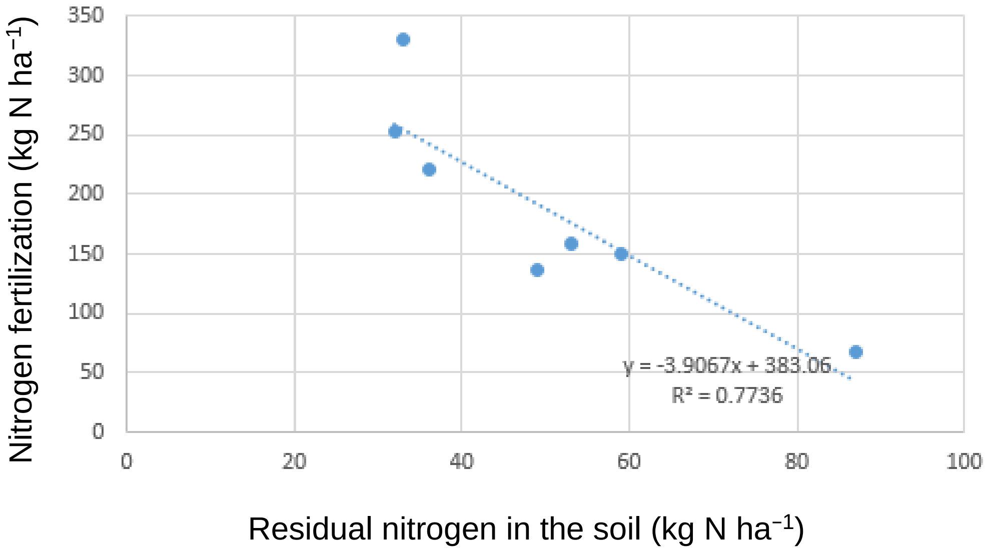


Figure 4.45 Linear regression between residual soil nitrogen (0–600 mm) in kg N ha^{-1} at planting time and nitrogen fertilization for maximum yield in kg N ha^{-1}

The correlation coefficient for the above linear regression is highly significant (R^2 = 0.77) which indicates that there is a highly significant relationship between the residual nitrogen content of the soil to a depth of 0–600 mm at planting time and the nitrogen fertilization level required to produce maximum seed cotton yield. A summary of the statistical analysis of data used in Figure 4.45 is given in Appendix 4.11. The Y-axis intercept of the regression in Figure 4.45 is at nitrogen fertilization rate of 383 kg N ha^{-1} and the X-axis intercept is at 98 kg N ha^{-1} residual in the soil at planting time.

The relationship between the residual soil nitrogen content of the soil (0–900 mm) in kg N ha^{-1} at planting time versus the nitrogen fertilization level in kg N ha^{-1} that produced the maximum seed cotton yield measured in the field trials is given in Figure 4.46.

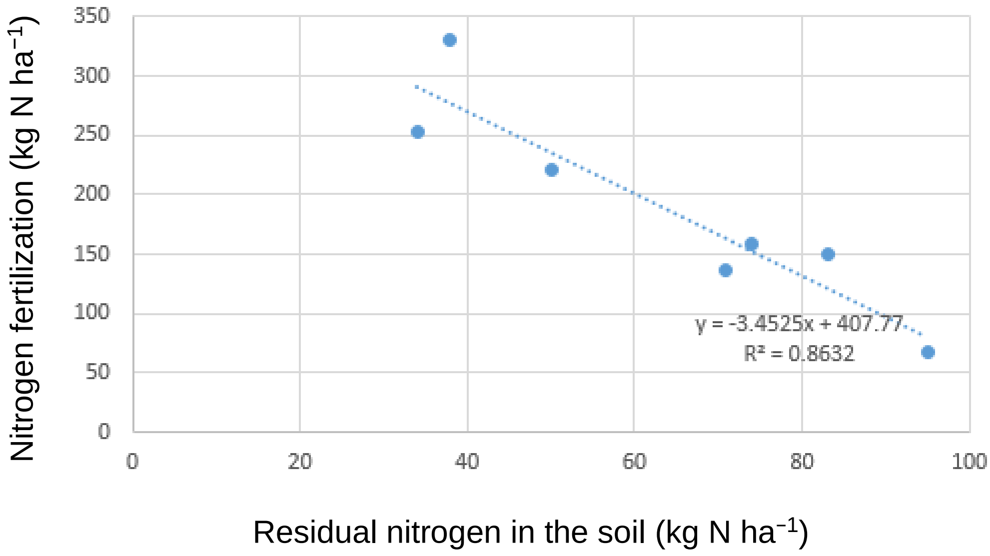


Figure 4.46 Linear regression between residual soil nitrogen (0–900 mm) in kg N ha^{-1} at planting time and nitrogen fertilization for maximum yield in kg N ha^{-1}

The correlation coefficient for the above linear regression is highly significant (R^2 = 0.86) which indicates that there is a highly significant relationship between the residual nitrogen content of the soil to a depth of 0–900 mm at planting time and the nitrogen fertilization level required to produce maximum seed cotton yield. A summary of the statistical analysis of data used in Figure 4.46 is given in Appendix 4.12. The Y–axis intercept of the regression in Figure 4.46 is at nitrogen fertilization rate of 407.8 kg N ha^{-1} and the X–axis intercept is at 118.1 kg N ha^{-1} residual in the soil at planting time.

Because of the high level of significance of the above linear correlation it is suggested that this regression equation can be used as an additional aid in the calculation of the nitrogen fertilization of cotton to achieve maximum yield in South Africa and thereby contribute to the refining of nitrogen fertilization guidelines for irrigated cotton in South Africa. The correlations and regression equations obtained from the 0–300 mm (Figure 4.43), as well as the 0–600 mm (Figure 4.45) soil depths may also prove to be useful for this purpose where residual soil nitrogen data is not available to a depth of 0–900 mm.

4.8.3.2 Residual soil nitrogen at planting versus measured nitrogen levels needed for maximum profit

The relationship between the residual soil nitrogen content of the soil (0–300 mm) in kg N ha^{-1} at planting time versus the nitrogen fertilization level in kg N ha^{-1} that produced the maximum profit measured in the field trials is given in Figure 4.47.

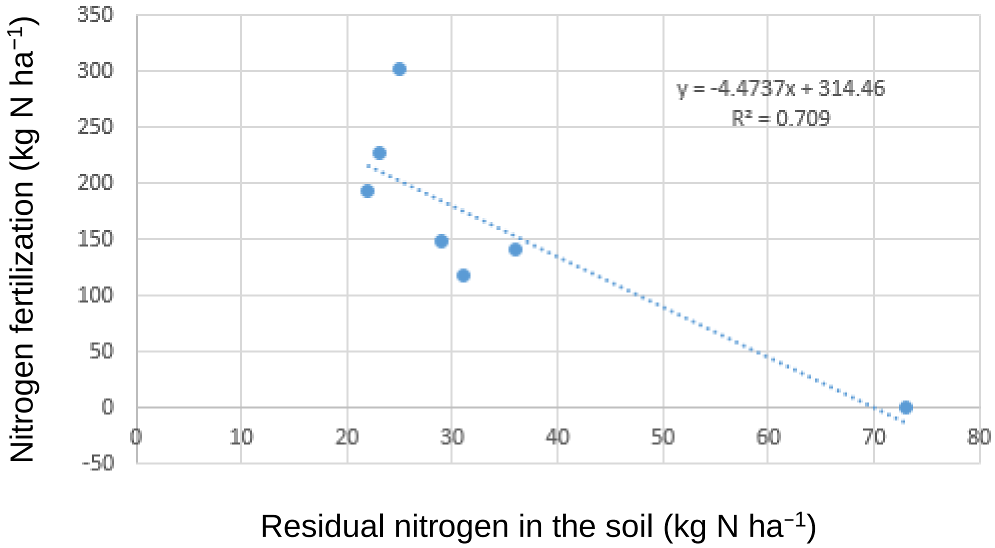


Figure 4.47 Linear regression between residual soil nitrogen (0–300 mm) in kg N ha^{-1} at planting time and nitrogen fertilization for maximum profit in kg N ha^{-1}

The correlation coefficient for the above linear regression is significant ($R^2 = 0.71$) which indicates that there is a significant relationship between the residual nitrogen content of the soil at planting time and the nitrogen fertilization level required to produce maximum profit. A summary of the statistical analysis of data used in Figure 4.47 is given in Appendix 4.13.

As observed with the correlation between residual soil nitrogen (0–300 mm) at planting time and maximum yield, depicted in Figure 4.43, Figure 4.47 affirms similar findings in Australia by Smith and Welsh (2018) as depicted in Figure 4.44. Where Smith and Welsh (2018) presented a correlation between residual soil nitrate (samples taken one month before planting) and optimal nitrogen fertilization for cotton. It is interesting to note that the linear regression in Figure 4.47 intersects the Y-axis at 314.5 kg N ha^{-1}, slightly higher than the 275 kg N ha^{-1} of Smith and Welsh (2018) for the higher yield. The intersection of the regression line with the X-axis in Figure 4.47 is at a residual nitrogen content of 70.3 kg N ha^{-1} in the soil, which is comparable to the 21 mg N kg^{-1}

(94.5 kg N ha^{-1}) residual soil nitrate-N X-axis intersection for lower yield in Figure 4.44 (Smith and Welsh 2018).

Although the regression line obtained in Figure 4.47 is not exactly the same as in Figure 4.44, it is within the same range, similar to Figure 4.43, considering that the soil analyses for Figure 4.44 were taken one month before planting and those for Figure 4.47 were taken at planting.

The relationship between the residual soil nitrogen content of the soil (0–600 mm) in kg N ha^{-1} at planting time versus the nitrogen fertilization level in kg N ha^{-1} that produced the maximum profit measured in the field trials is given in Figure 4.48.

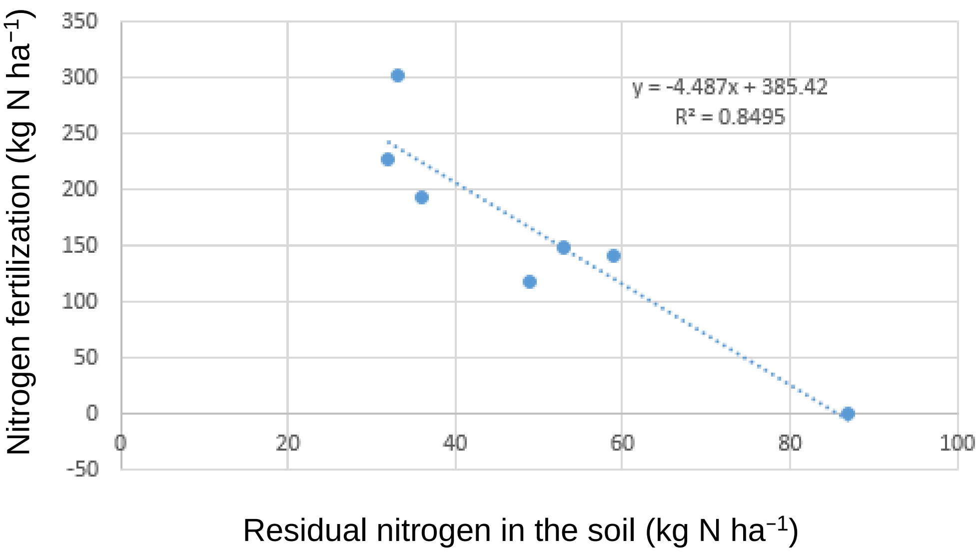


Figure 4.48 Linear regression between residual soil nitrogen (0–600 mm) in kg N ha^{-1} at planting time and nitrogen fertilization for maximum profit in kg N ha^{-1}

The correlation coefficient for the above linear regression is highly significant (R^2 = 0.85) which indicates that there is a highly significant relationship between the residual nitrogen content of the soil to a depth of 0–600 mm at planting time and the nitrogen fertilization level required to produce maximum seed cotton yield. A summary of the statistical analysis of data used in Figure 4.48 is given in Appendix 4.14. The Y-axis intercept of the regression in Figure 4.48 is at nitrogen fertilization rate of 385.4 kg N ha^{-1} and the X-axis intercept is at 85.9 kg N ha^{-1} residual in the soil at planting time.

The relationship between the residual soil nitrogen content (0–900 mm) in kg N ha^{-1} at planting time versus the nitrogen fertilization level in kg N ha^{-1} that produced the maximum profit measured in the field trials is given in Figure 4.49.

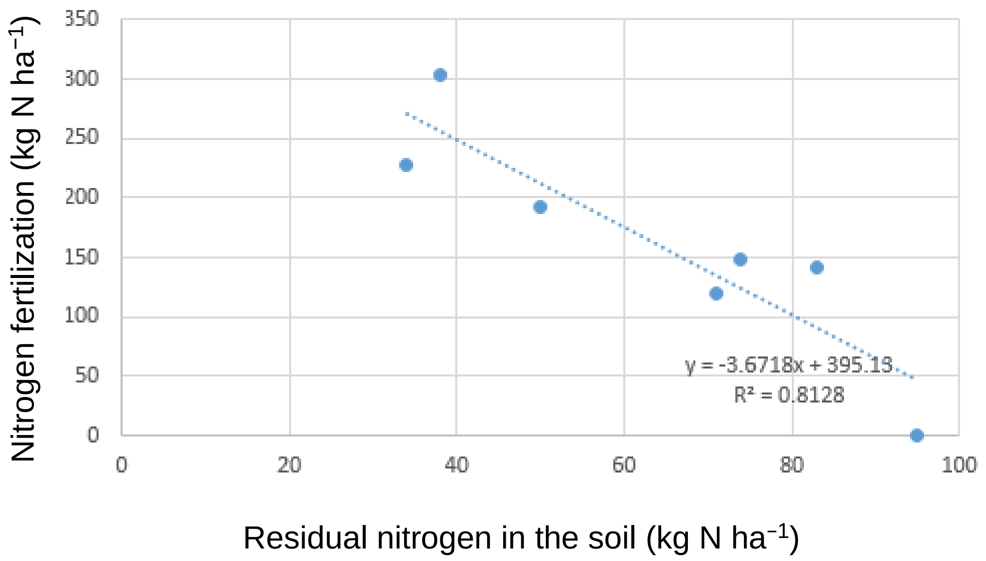


Figure 4.49 Linear regression between residual soil nitrogen (0–900 mm) in kg N ha^{-1} at planting time and nitrogen fertilization for maximum profit in kg N ha^{-1}

The correlation coefficient for the above linear regression is highly significant (R^2 = 0.81) which indicates that there is a highly significant relationship between the residual nitrogen content of the soil to a depth of 0–900 mm at planting time and the nitrogen fertilization level required to produce maximum seed cotton yield. A summary of the statistical analysis of data used in Figure 4.49 is given in Appendix 4.15. The Y-axis intercept of the regression in Figure 4.49 is at nitrogen fertilization rate of 395.1 kg N ha^{-1} and the X-axis intercept is at 107.6 kg N ha^{-1} residual in the soil at planting time.

Due to the high level of significance of the above linear correlation it is suggested that this regression equation be used as an additional aid in the calculation of the nitrogen fertilization of cotton to achieve maximum profit in cotton production in South Africa. The correlations and regression equations obtained from the 0–300 mm (Figure 4. 47), as well as the 0–600 mm (Figure 4.48) soil depths may also prove to be useful for this purpose where residual soil nitrogen data is not available to a depth of 0–900 mm. These findings can contribute to the refining of nitrogen fertilization guidelines for irrigated cotton in South Africa.

4.8.3.3 Residual soil nitrogen at planting plus mineralised soil nitrogen versus measured nitrogen levels for maximum yield and maximum profit

The relationship between the residual soil nitrogen content of the soil (0–900 mm) in kg N ha^{-1} at planting time plus mineralised soil nitrogen versus the nitrogen fertilization level in kg N ha^{-1} that produced the maximum yield measured in the field trials is given in Figure 4.50.

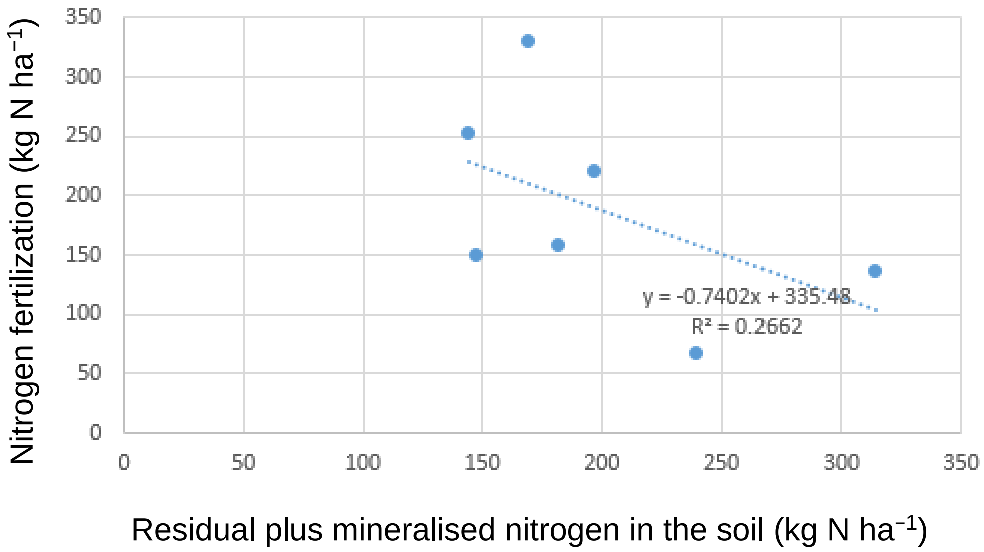


Figure 4.50 Linear regression between residual nitrogen at planting time plus mineralised soil nitrogen (0–900 mm) in kg N ha^{-1} versus nitrogen fertilization for maximum yield in kg N ha^{-1}

The correlation coefficient for the above linear regression is significant (R^2 = 0.27) which indicates that there is a significant relationship between the residual nitrogen content of the soil at planting time to a depth of 0–900 mm plus the nitrogen mineralisation in the soil versus the nitrogen fertilisation level required to produce maximum seed cotton yield. The significance of the regression is significant with F = 0.24 and F-critical = 1.8. This finding indicates that there is a significant correlation between the residual plus mineralised nitrogen content of the soil and the nitrogen fertilization rate needed to produce maximum yield. A summary of the statistical analysis of data used in Figure 4.50 is given in Appendix 4.16.

The relationship between the residual soil nitrogen content of the soil (0–900 mm) in kg N ha^{-1} at planting time plus mineralised soil nitrogen versus the nitrogen fertilization level in kg N ha^{-1} that produced the maximum profit measured in the field trials is given in Figure 4.51.

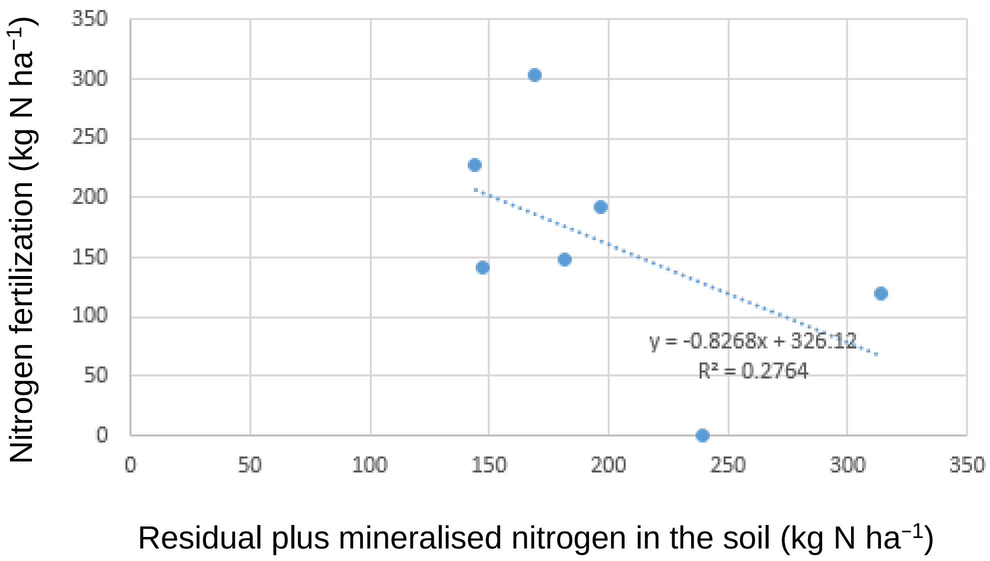


Figure 4.51 Linear regression between residual nitrogen at planting time plus mineralised soil nitrogen (0–900 mm) in kg N ha^{-1} versus nitrogen fertilization for maximum profit in kg N ha^{-1}

The correlation coefficient for the above linear regression is significant (R^2 = 0.28) which indicates that there is a significant relationship between the residual nitrogen content of the soil at planting time to a depth of 0–900 mm plus the nitrogen mineralisation in the soil versus the nitrogen fertilization level required to produce maximum seed cotton yield. The significance of the regression is significant with F = 0.23 and F-critical = 1.9. As above, this finding indicates that there is a significant correlation between the residual plus mineralised nitrogen content of the soil and the nitrogen fertilization rate needed to produce maximum profit. A summary of the statistical analysis of data used in Figure 4.51 is given in Appendix 4.17.

4.8.3.4 Estimated nitrogen rates with Fertasa (2016) procedure versus measured nitrogen levels for maximum yield and maximum profit

The relationship between the nitrogen fertilization level as determined with the Fertasa (2016) procedure versus the measured nitrogen fertilization rate associated with maximum yield in the field trials is given in Figure 4.52.

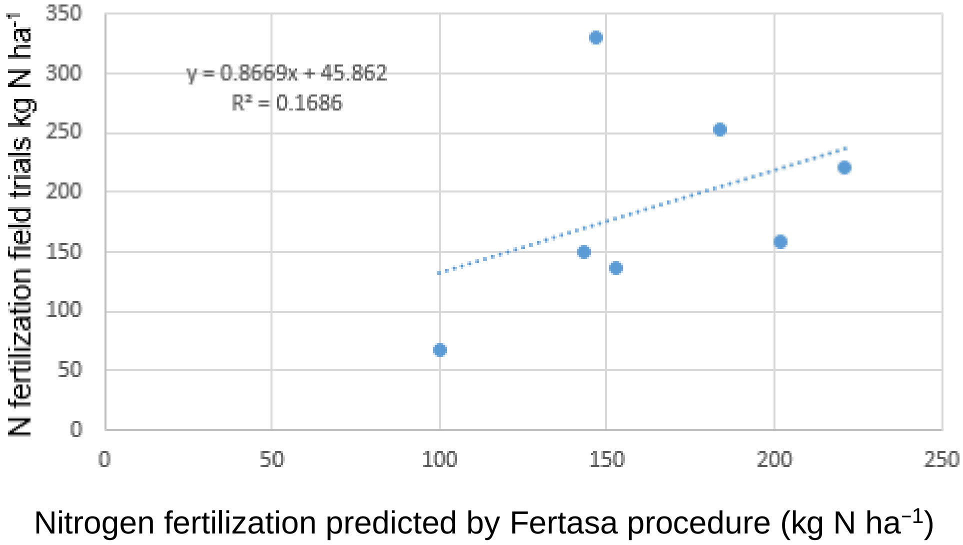


Figure 4.52 Linear regression between nitrogen fertilization levels predicted by the Fertasa (2016) procedure in kg N ha^{-1} versus nitrogen fertilization levels for maximum yield measured in the field trials in kg N ha^{-1}

The correlation coefficient for the above linear regression is significant ($R^2 = 0.1686$) which indicates that there is a low significance in the relationship between nitrogen fertilization levels predicted by the Fertasa (2016) procedure and nitrogen fertilization levels for maximum yield measured in the field trials yield. A summary of the statistical analysis of data used in Figure 4.52 is given in Appendix 4.18.

The relationship between the nitrogen fertilization level as determined with the Fertasa (2016) procedure versus the measured nitrogen fertilization rate associated with maximum profit in the field trials is given in Figure 4.53.

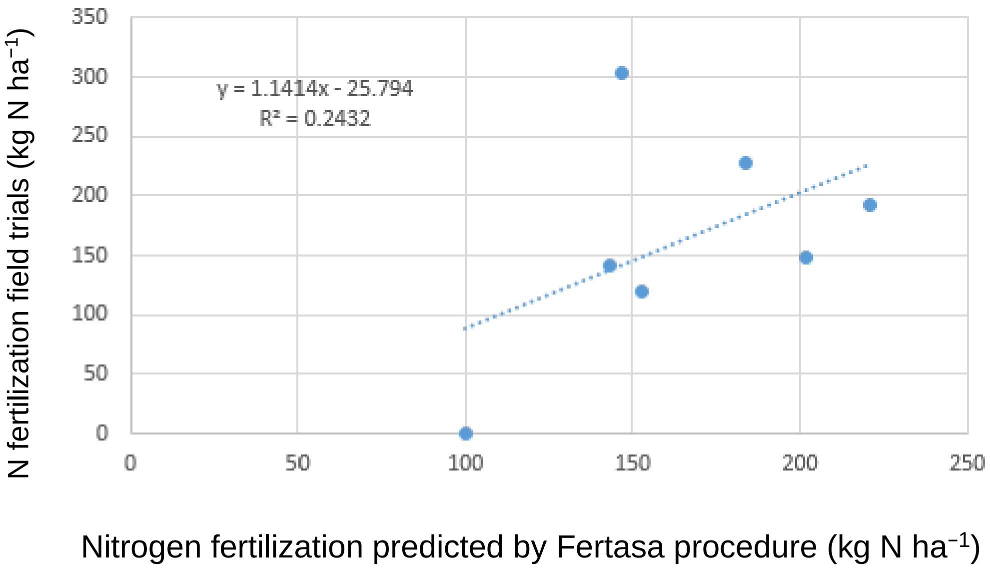


Figure 4.53 Linear regression between nitrogen fertilization levels predicted by the Fertasa (2016) procedure in kg N ha^{-1} versus nitrogen fertilization levels for maximum profit measured in the field trials in kg N ha^{-1}

The correlation coefficient for the above linear regression is significant at a very low level of confidence (R^2 = 0.24), which indicates that there is a poor relationship between nitrogen fertilization levels predicted by the Fertasa (2016) procedure and nitrogen fertilization levels for maximum yield measured in the field trials yield. A summary of the statistical analysis of data used in Figure 4.53 is given in Appendix 4.19.

4.8.3.5 Nitrogen fertilization adjusted procedure versus measured nitrogen levels for maximum yield and maximum profit

The relationship between the nitrogen fertilization level as determined with the adjusted procedure versus the measured nitrogen fertilization rate associated with maximum yield in the field trials is given in Figure 4.54.

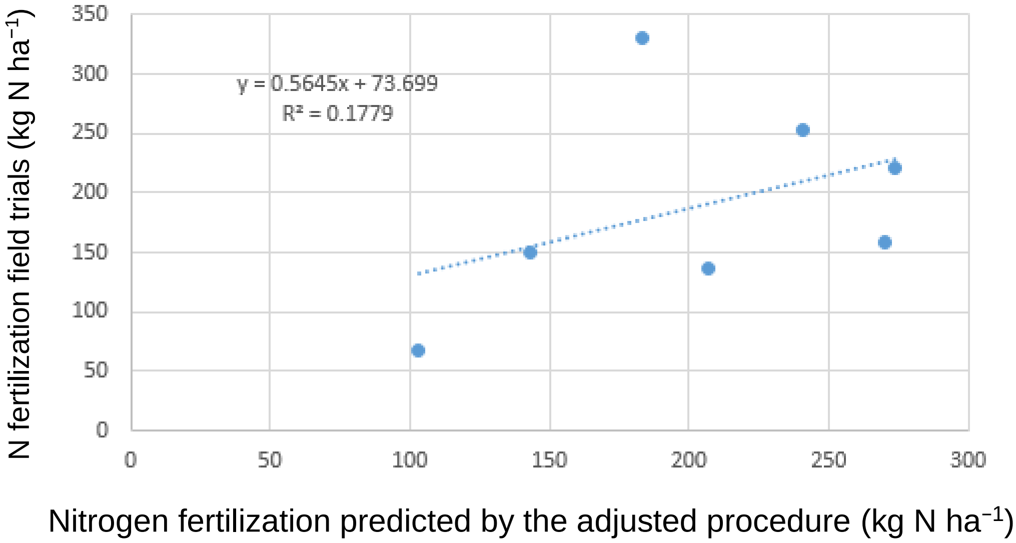


Figure 4.54 Linear regression between nitrogen fertilization levels predicted by the adjusted procedure in kg N ha^{-1} versus nitrogen fertilization levels for maximum yield measured in the field trials in kg N ha^{-1}

Although the correlation coefficient for the above linear regression is low, it is significant ($R^2 = 0.1779$) which is better than the relationship found with the Fertasa (2016) procedure. This indicates that the adjusted procedure is indeed an improvement on the Fertasa (2016) procedure and can contribute to the refinement of nitrogen fertilization guidelines for irrigated cotton in South Africa. A summary of the statistical analysis of data used in Figure 4.54 is given in Appendix 4.20.

The relationship between the nitrogen fertilization level as determined with the adjusted procedure versus the measured nitrogen fertilization rate associated with maximum profit in the field trials is given in Figure 4.55.

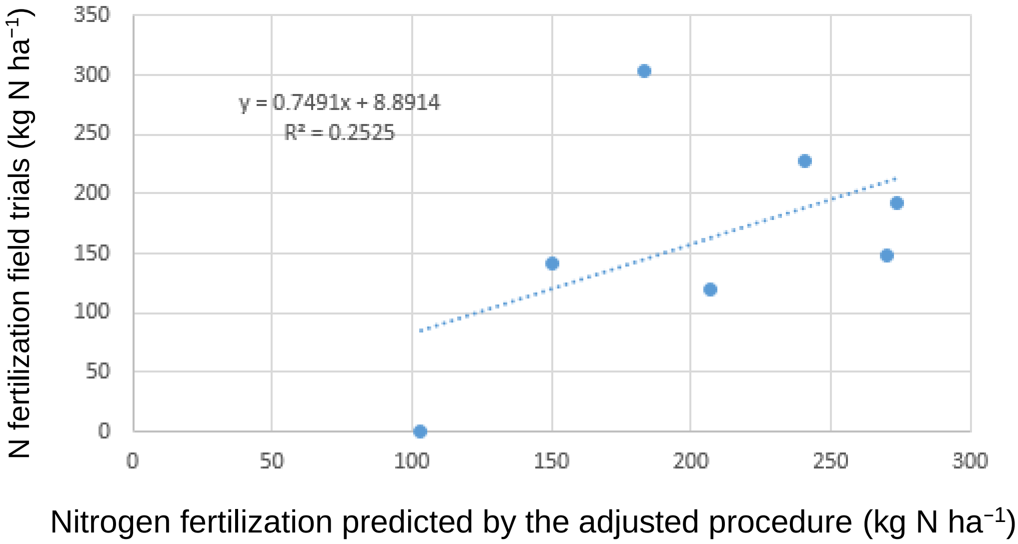


Figure 4.55 Linear regression between nitrogen fertilization levels predicted by the adjusted procedure in kg N ha^{-1} versus nitrogen fertilization levels for maximum profit measured in the field trials in kg N ha^{-1}

As seen with the previous correlation, although the correlation coefficient for the above linear regression is low, it is significant (R^2 = 0.2525), which is better than the relationship found with the Fertasa (2016) procedure for maximum yield as well as maximum profit. This confirms that the adjusted procedure is indeed an improvement on the Fertasa (2016) procedure and can contribute to the refining of nitrogen fertilization guidelines for irrigated cotton in South Africa. A summary of the statistical analysis of data used in Figure 4.55 is given in Appendix 4.21.

4.9 Conclusion

From this study it is evident that the South African nitrogen fertilization guidelines for cotton as supported by Fertasa (2016), correlate well with data obtained with the field trials done at various locations. However, once seed cotton yields exceed 4 500 kg ha^{-1}, the existing nitrogen fertilization recommendations are apparently not as accurate as below 4 500 kg ha^{-1}. A nitrogen extraction of 250 kg N ha^{-1} is not sufficient under conditions where seed cotton yields in excess of 4 500 kg ha^{-1} are produced. Therefore, it is recommended that the existing nitrogen fertilization guidelines for cotton should be refined by amending it to provide for an additional nitrogen extraction of 56 kg ha^{-1} for every 1 000 kg of seed cotton produced or fertilized for a yield in excess of 4 500 kg ha^{-1}. The amount of 56 kg N ha^{-1} is suggested until further research has been conducted under South African conditions to provide accurate, scientifically based data regarding nitrogen extraction data for seed cotton yields exceeding 4 500 kg ha^{-1}.

It is also suggested that actual determined nitrogen mineralisation levels (using soil incubation methods) are used when calculating the nitrogen requirement of irrigated cotton where they are available. This is in preference to the nitrogen mineralisation levels provided by the Fertasa (2016) procedure, which rely on generalised nitrogen mineralisation values based on soil texture. Actual soil nitrogen mineralisation measurements will obviously be more accurate and will reduce variations in the calculation of nitrogen use efficiencies, as seen above.

Information on soil nitrogen mineralisation could also be obtained by sampling the actual field in situ at a set time (four weeks after planting), or at set intervals after planting (every two weeks after planting).

Furthermore, it is suggested that the use of NUE measurements such as TNUE and NFUE be introduced into the nitrogen fertilization recommendation programme in South Africa. This can contribute to the refinement of nitrogen fertilization guidelines for irrigated cotton in South Africa. It is suggested that the initial parameters for NFUE be between 32.5 and 54.0 for seed cotton production. The use of TNUE and NFUE measurements as a management tool to assist farmers to ensure the best possible utilisation of applied nitrogen during the growing of a cotton crop, will not only be financially rewarding to the farmer, but also be environmentally responsible, by limiting losses of nitrogen into the atmosphere and ground water.

Significant relationships were found between the residual nitrogen content of the soil at planting and fertilization levels of nitrogen required to produce maximum yield, as well as maximum profit as measured in the field trials. These relationships were found for soil depths of 0–300 mm, 0–600 mm and 0–900 mm allowing for a wide range of application depending on available residual soil nitrogen data at planting. The relationship found for the 0–300 mm soil depth corresponded to a large degree with broad based research done by Smith and Welsh (2018) on the correlation of residual soil nitrogen with the optimum nitrogen fertilization of cotton in Australia. Although these findings need to be expanded by future studies they can initiate and contribute to the refining of nitrogen fertilization guidelines for irrigated cotton in South Africa with South African data.

Chapter 5
Total Nitrogen Content of Cotton Leaf Petioles Under Irrigation

5.1 Introduction

Joham (1951) was the first researcher to report that the cotton leaf petiole is the most reliable plant tissue to sample for the purpose of determining the nitrogen status of cotton in-field. During research done at the Texas Agricultural Experiment Station he established that the best results were obtained by sampling the petioles of the first mature leaf on the main stem, as seen from the top of the plant. This leaf is generally accepted to be the fourth leaf from the top on the main stem (Braud 1987). The practice is to collect at least 25 to 30 leaf petioles at weekly intervals starting from when the first squares (flower buds) emerge (Munro 1987).

In many of the eastern USA states that experience high rainfall (Texas, Georgia, Arkansas, North Carolina and South Carolina) preference is given to the use of in-season cotton leaf petiole analyses of nitrate nitrogen to estimate the nitrogen fertilization of cotton above the use of preplant soil analyses of residual nitrogen (Oosterhuis 1992, Cleveland 2012, Jones et al. 2019, Gatiboni and Hardy 2021). This is most probably due to various losses of nitrogen, such as leaching and denitrification that occur in the soil under these conditions and can lead to changes in the amount of plant available soil nitrogen between the time of sampling and plant uptake (Baird and Smith 2019).

However, because leaf petiole nitrate is prone to large fluctuations, caused by factors such as soil water content, air temperature, time of day and boll load, many of the other USA states do not use leaf petiole nitrate analyses to evaluate the nitrogen status of cotton in field (Mitchell and Baker 1997) and preference is given to soil analyses for residual nitrogen.

As soil nitrogen losses are presumably less under arid and semi-arid conditions, such as encountered in the western USA states, Israel, Australia and South Africa, it seems that more success is obtained using residual soil nitrogen measured pre-plant to predict the optimal nitrogen fertilization of cotton under these conditions (Breitenbeck 1990). Under these conditions, it can be expected that residual nitrogen soil tests would be preferred above leaf petiole tests for nitrate nitrogen, as residual nitrogen soil tests are potentially more stable.

However, this is not necessarily the case, as nitrate nitrogen analyses on cotton leaf petioles are used successfully to predict the optimal nitrogen fertilization of cotton in California (Hutmacher 2017). It is interesting to note that the critical values used in nitrogen fertilization guidelines in California (Table 2.4) are more than twice as high as the values used in South Carolina, depicted in Table 2.5 (Jones et al. 2019). This could possibly be due to higher uptake of nitrogen in the generally drier climate of California and a more diluted uptake of nitrogen in the generally wetter climate of South Carolina.

Rochester (2012) confirms the complementary use of both residual soil nitrogen analyses as well as cotton leaf petiole nitrate nitrogen analyses for the determination of optimal nitrogen fertilization of cotton in Australia. Soil analyses for residual soil nitrogen taken before planting provide cotton growers with a target nitrogen application that can be commenced with before and during planting. Final topdressings of nitrogen are then made pending the results of the nitrate nitrogen analyses of cotton leaf petioles taken in-season, commencing at 750 degree-days after sowing.

5.2 Rationale

Considering the above, the fact that in South Africa, no guidelines for the optimal nitrogen fertilization of cotton based on the in-season sampling and nitrogen analysis of cotton leaf petioles, currently exist, needs to be addressed. If such guidelines were to be introduced, they could contribute to refining the guidelines that are currently available for the nitrogen fertilization of irrigated cotton in South Africa.

Due to the dynamic character of nitrate nitrogen in leaf petioles and the many factors that contribute to the variation thereof, cotton leaf petioles taken from field trials were analysed for total nitrogen (which is less exposed to large fluctuations) using the determination procedure as described by Ferrari (1960).

From the results of the field trials discussed in Chapter 4, the nitrogen fertilization rates associated with maximum yield and maximum profit are given in Table 4.6. Only the field trials that resulted in calculable and realistic nitrogen fertilization rates associated with maximum yield as well as maximum profit will be used in statistical analyses in this chapter. Therefore, only data pertaining to the following field trials will be used:

- Rustenburg Site 1 in 1987/88 season with harvested oats as preceding crop.
- Rustenburg Site 1 in 1988/89 season with harvested soybean as preceding crop.
- Rustenburg Site 2 in 1989/90 season with ploughed-in soybean as preceding crop.
- Rustenburg Site 2 in 1989/90 season with harvested babala as preceding crop.
- Rietriver in 1989/90 season.
- Vaalharts in 1988/89 season.
- Groblersdal in 1988/89 season.

5.3 Procedure

The results of total nitrogen analyses done on the cotton leaf petioles taken from the above field trials at various times from first flower will be discussed in this chapter. The methodology for each of these field trials are described in detail in Chapter 3. Hence the materials and methods are not repeated in this chapter.

The total nitrogen content of the cotton leaf petioles taken from each trial plot, at each time of sampling will be correlated with the applied nitrogen fertilization rate. Regression equations obtained from this correlation will be used to calculate the total nitrogen content of the cotton leaf petioles that corresponds with the nitrogen fertilization rate associated with maximum yield, as well as maximum profit for the specific trial.

Once the total nitrogen content of the cotton leaf petioles associated with maximum yield as well as maximum profit have been determined for each time of sampling, on all field trials, this data will be used to compile a guideline for evaluating the total nitrogen content of cotton leaf petioles in-season.

5.4 Results and discussion

The results of the cotton leaf petiole analyses will be discussed per trial location.

5.4.1 Rustenburg Site 1 in 1987/88: Harvested oats as preceding crop

Leaf petioles of cotton were sampled at 77 and 91 days after sowing. The results of total nitrogen analyses on cotton leaf petioles taken from the trial done at Rustenburg

Site 1 during the 1987/88 growing season are given in Table 5.1. Harvested oats was the preceding crop. Samples were taken at 77 days (first flowering) and 91 days after sowing.

Table 5.1 Total nitrogen content of cotton leaf petioles sampled at 77 days (first flowering) and 91 days after sowing, with harvested oats as preceding crop, Rustenburg Site 1, 1987/88 growing season

N rate (kg ha^{-1})	Repetition	Total nitrogen content of leaf petiole (%)	
		77 days	91 days
0	1	2.78	0.92
0	2	1.41	1.08
0	3	1.91	1.10
0	4	1.90	1.09
0	5	1.42	1.09
50	1	1.59	1.01
50	2	1.69	0.98
50	3	2.74	1.00
50	4	1.53	1.08
50	5	1.40	0.90
100	1	2.20	1.25
100	2	2.17	1.29
100	3	2.51	1.23
100	4	2.51	1.50
100	5	2.69	1.69
150	1	2.92	1.72
150	2	2.58	1.51
150	3	2.73	1.71
150	4	2.74	1.47
150	5	2.27	1.35

5.4.1.1 Leaf petiole total nitrogen content at 77 days

The best relationship between total nitrogen content of cotton leaf petioles at 77 days after sowing and nitrogen fertilization rate are given by the linear regression depicted in Figure 5.1. The summary of the regression statistics and ANOVA are given in Appendix 5.1.

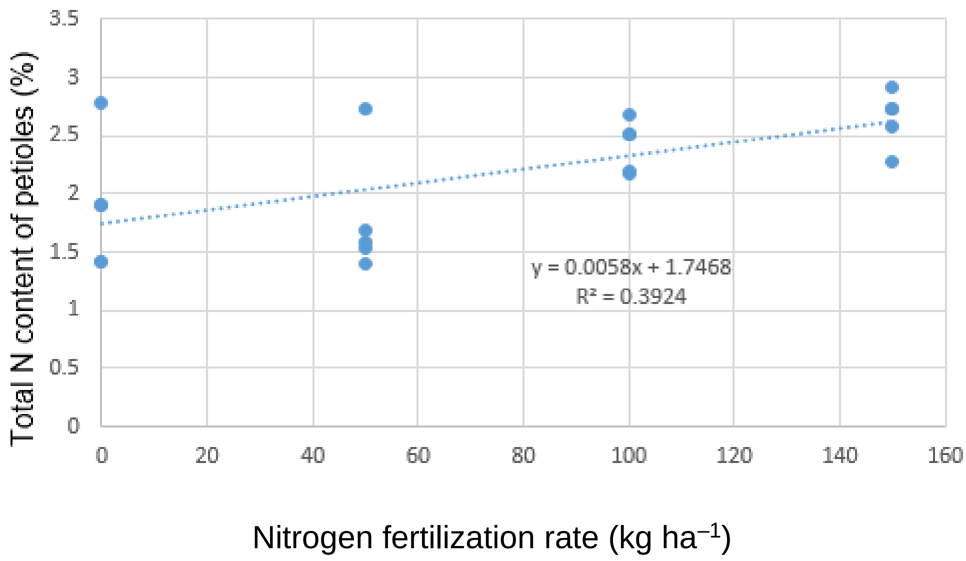


Figure 5.1 Linear relationship between nitrogen fertilization rate and total nitrogen content of cotton leaf petioles 77 days after sowing at Rustenburg Site 1 in 1987/88, preceded by harvested oats

5.4.1.2 Leaf petiole total nitrogen content at 91 days

The best relationship found between total nitrogen content of cotton leaf petioles at 91 days after sowing and nitrogen fertilization rate are given by the linear regression depicted in Figure 5.2. The summary of the regression statistics and ANOVA are given in Appendix 5.2.

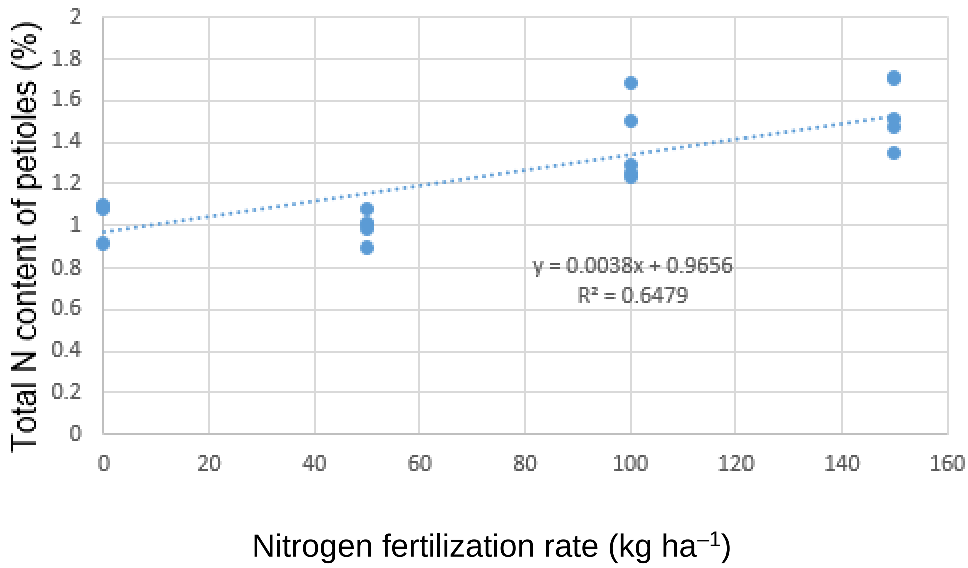


Figure 5.2 Linear relationship between nitrogen fertilization rate and total nitrogen content of cotton leaf petioles 91 days after sowing at Rustenburg Site 1 (oats) in 1987/88, preceded by harvested oats

5.4.1.3 Leaf petiole total nitrogen content at maximum yield and maximum profit

The yields for the trial done at Rustenburg Site 1 in 1987/88 (harvested oats preceding crop) were used to calculate fertilization rates for maximum yield (330 kg N ha^{-1}) and maximum profit (303 kg N ha^{-1}) (See Section 4.3.1.1). Concerning these fertilization rates, the leaf petiole total nitrogen content at 77 and 91 days after sowing were calculated with the equations given in Figures 5.1 and 5.2, respectively. The estimated leaf petiole total nitrogen contents are given in Table 5.2.

Table 5.2 Estimated leaf petiole total nitrogen contents for maximum yield and maximum profit 77 and 91 days after sowing

Parameter	N rate (kg ha^{-1})	Equation	Days	Petiole N (%)
Maximum yield	330	$Y = 0.008X + 1.7468$[a]	77	3.66
Maximum profit	303		77	3.50
Maximum yield	330	$Y = 0.0038X + 0.9658$[b]	91	2.22
Maximum profit	303		91	2.12

[a]Figure 5.1, [b]Figure 5.2

5.4.2 Rustenburg Site 1 in 1988/89: Harvested soybean preceding crop

The results of total nitrogen analyses on cotton leaf petioles taken from the trial done at Rustenburg Site 1 (soybean) in 1988/89 are given in Table 5.3. Harvested soybean was the preceding crop. Samples were taken at 77 days (first flowering) and 91 days after sowing.

Table 5.3 Total nitrogen content of cotton leaf petioles sampled at 77 days (first flowering) and 91 days after sowing, during the 1988/89 growing season at Rustenburg Site 1 with harvested soybean as preceding crop

N rate (kg ha^{-1})	Repetition	Total nitrogen content of leaf petiole (%)	
		77 days	91 days
0	1	1.49	1.30
0	2	1.56	1.19
0	3	1.30	1.32
0	4	1.59	1.44
0	5	1.35	1.39
50	1	1.61	1.29
50	2	1.52	1.35
50	3	1.63	1.66
50	4	1.70	1.70
50	5	1.29	1.60
100	1	1.69	1.41
100	2	1.58	1.79
100	3	1.75	1.90
100	4	1.49	1.63
100	5	2.02	1.78
150	1	1.65	1.71
150	2	1.66	1.83
150	3	2.05	1.94
150	4	1.72	1.70
150	5	1.43	1.67

5.4.2.1 Leaf petiole total nitrogen content at 77 days

The best relationship found between the total nitrogen content of cotton leaf petioles sampled 77 days after sowing and nitrogen fertilization rate are given by the second-order polynomial regression depicted in Figure 5.3. The summary of the regression statistics and ANOVA are given in Appendix 5.3.

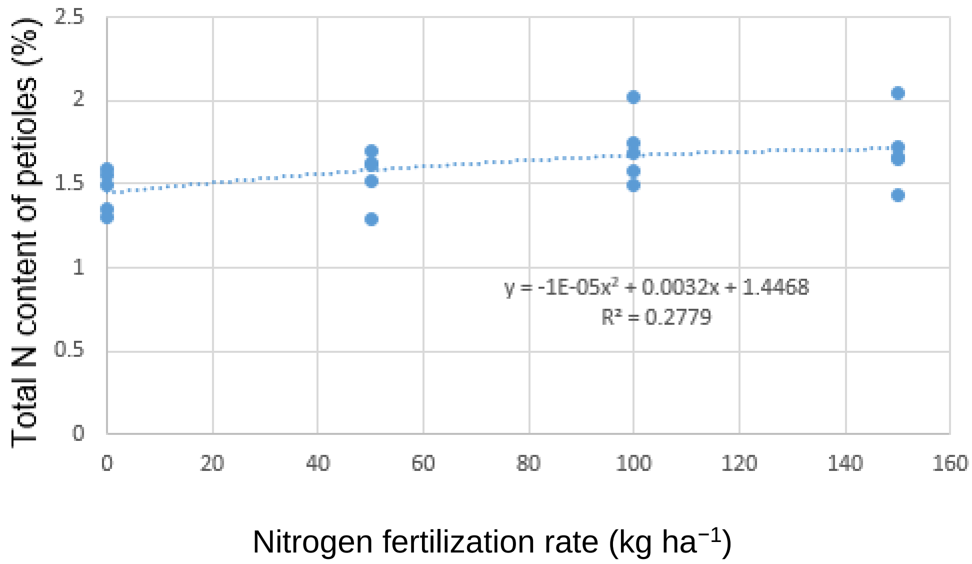


Figure 5.3 Second-order polynomial relationship between nitrogen fertilization rate and total nitrogen content of cotton leaf petioles 77 days after sowing at Rustenburg Site 1 in 1988/89, preceded by harvested soybean

5.4.2.2 Leaf petiole total nitrogen content at 91 days

The best relationship between total nitrogen content of cotton leaf petioles at 91 days and nitrogen fertilization rate are given by a second-order polynomial regression depicted in Figure 5.4. A summary of the regression statistics and ANOVA are given in Appendix 5.4.

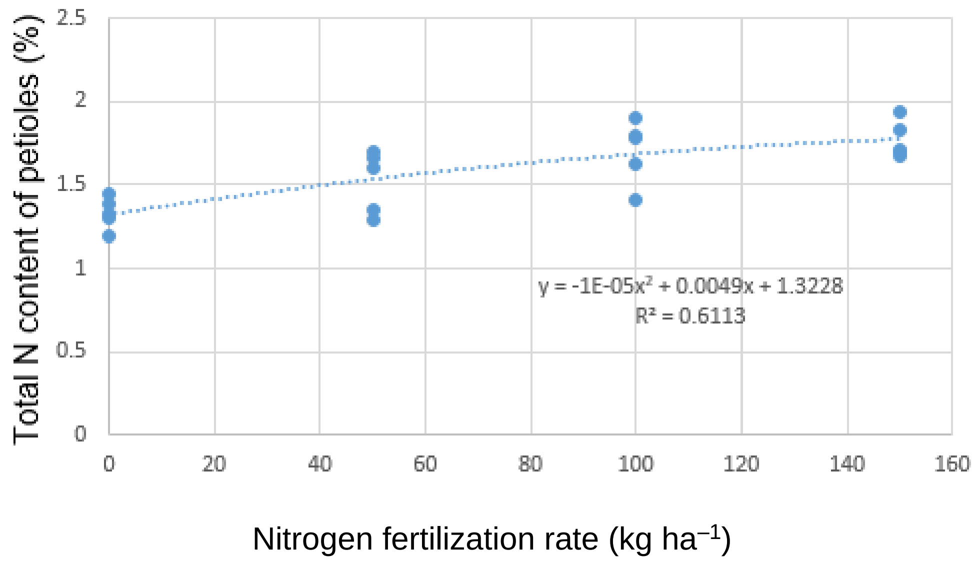


Figure 5.4 Second-order polynomial relationship between nitrogen fertilization rate and total nitrogen content of cotton leaf petioles 91 days after sowing at Rustenburg Site 1 in 1988/89, preceded by harvested soybean

5.4.2.3 Leaf petiole total nitrogen content at maximum yield and maximum profit

The yields for the trial done at Rustenburg Site 1 in 1987/88 (harvested soybean preceding crop) were used to calculate fertilization rates for maximum yield (68 kg N ha^{-1}) and maximum profit (0 kg N ha^{-1}) (See Section 4.3.2.2). The same procedure described in Section 5.4.1.3 was used to estimate leaf petiole total nitrogen contents for maximum yield and maximum profit 77 and 91 days after sowing. The results are presented in Table 5.4.

Table 5.4 Estimated leaf petiole total nitrogen contents for maximum yield and maximum profit 77 and 91 days after sowing

Parameter	N rate (kg ha^{-1})	Equation	Days	Petiole N (%)
Maximum yield	68	$Y = -1E-05X^2 + 0.0032X + 1.4468$[a]	77	3.66
Maximum profit	0		77	3.50
Maximum yield	68	$Y = -1E-05X^2 + 0.0049X + 1.3228$[b]	91	2.22
Maximum profit	0		91	2.12

[a]Figure 5.3; [b]Figure 5.4

5.4.3 Rustenburg Site 2 in 1989/90: Ploughed-in soybean preceding crop

The results of total nitrogen analyses on cotton leaf petioles taken from the trial done at Rustenburg Site 2 in 1989/90 with ploughed-in soybean as preceding crop, are given in Table 5.5. Samples were taken every two weeks, starting from first flowering at 70 days after sowing until 147 days after sowing.

Table 5.5 Total nitrogen content of cotton leaf petioles 70, 91, 112 and 147 days after sowing, during the 1989/90 growing season at Rustenburg Site 2 with ploughed in soybean as preceding crop

N rate (kg ha^{-1})	Repetition	Total nitrogen content of leaf petiole (%)			
		70 days	91 days	112 days	147 days
0	1	2.99	2.94	2.32	1.21
0	2	2.79	2.79	2.10	1.21
0	3	2.82	2.53	1.94	1.10
50	1	3.01	3.05	2.45	1.41
50	2	3.01	3.15	2.27	1.32
50	3	2.98	3.03	2.11	1.29
100	1	3.11	3.17	2.53	1.30
100	2	2.90	2.79	2.26	1.31
100	3	3.10	2.94	2.00	1.30
150	1	3.03	3.23	2.28	1.55
150	2	3.07	2.93	2.45	1.51
150	3	3.08	2.90	2.31	1.30
200	1	3.00	3.36	2.56	1.45
200	2	3.08	2.93	2.22	1.39
200	3	2.75	3.01	2.20	1.51

5.4.3.1 Leaf petiole total nitrogen content at 70 days

The best relationship found between the nitrogen content of cotton leaf petioles at 70 days after sowing and nitrogen fertilization rate are given by a second-order polynomial regression depicted in Figure 5.5. The summary of the regression statistics and ANOVA are given in Appendix 5.5.

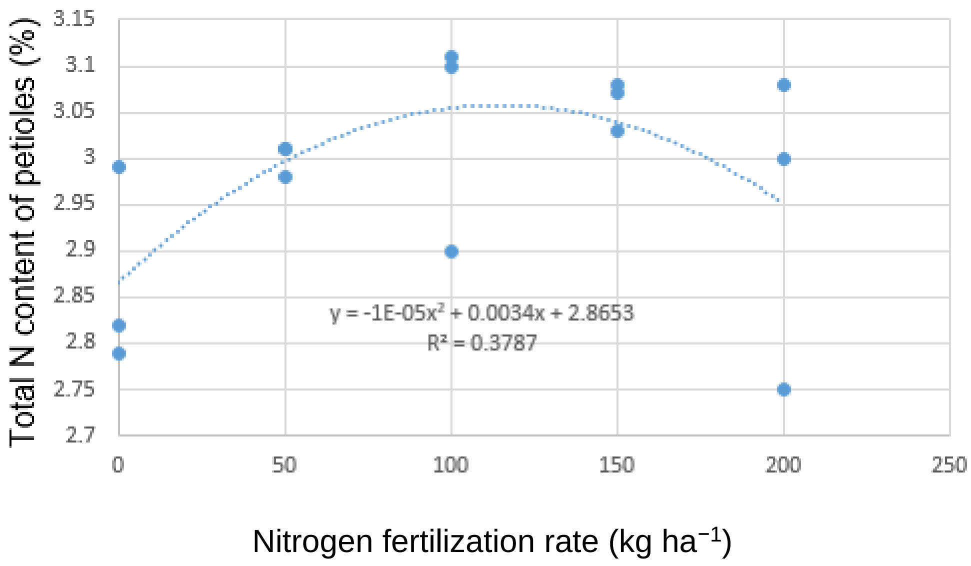


Figure 5.5 Second-order polynomial relationship between nitrogen fertilization rate and total nitrogen content of cotton leaf petioles 70 days after sowing at Rustenburg Site 2 in 1989/90, preceded by ploughed-in soybean

5.4.3.2 Leaf petiole total nitrogen content at 91 days

The best relationship between total nitrogen content of cotton leaf petioles at 91 days after sowing and nitrogen fertilization rate are given by the linear regression depicted in Figure 5.6. A summary of the regression statistics and ANOVA are given in Appendix 5.6.

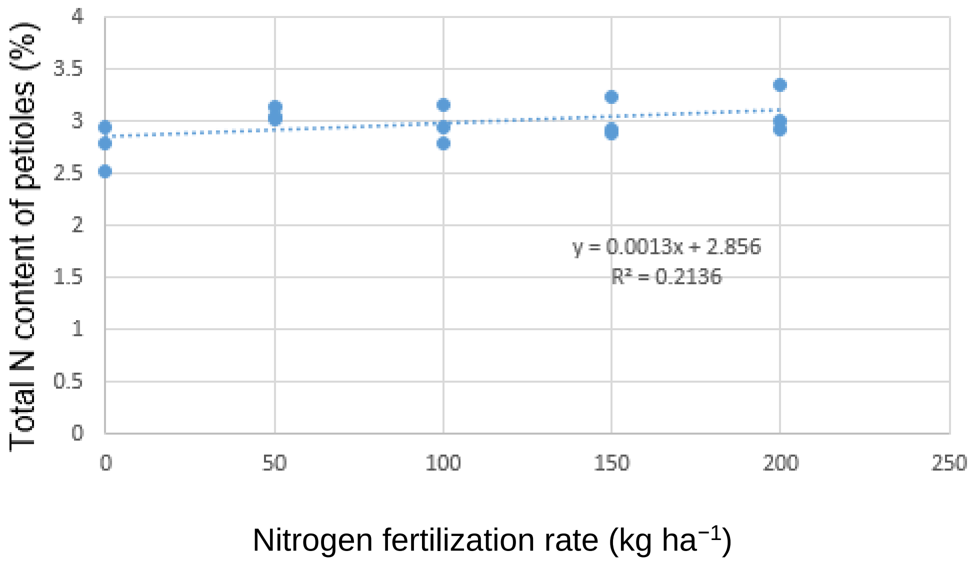


Figure 5.6 Linear relationship between nitrogen fertilization rate and total nitrogen content of cotton leaf petioles 91 days after sowing at Rustenburg Site 2 in 1989/90, preceded by ploughed-in soybean

5.4.3.3 Leaf petiole total nitrogen content at 112 days

The best relationship found between the total nitrogen content of cotton leaf petioles at 112 days and nitrogen fertilization rate are given by a second-order polynomial regression depicted in Figure 5.7. The summary of the regression statistics and ANOVA are given in Appendix 5.7.

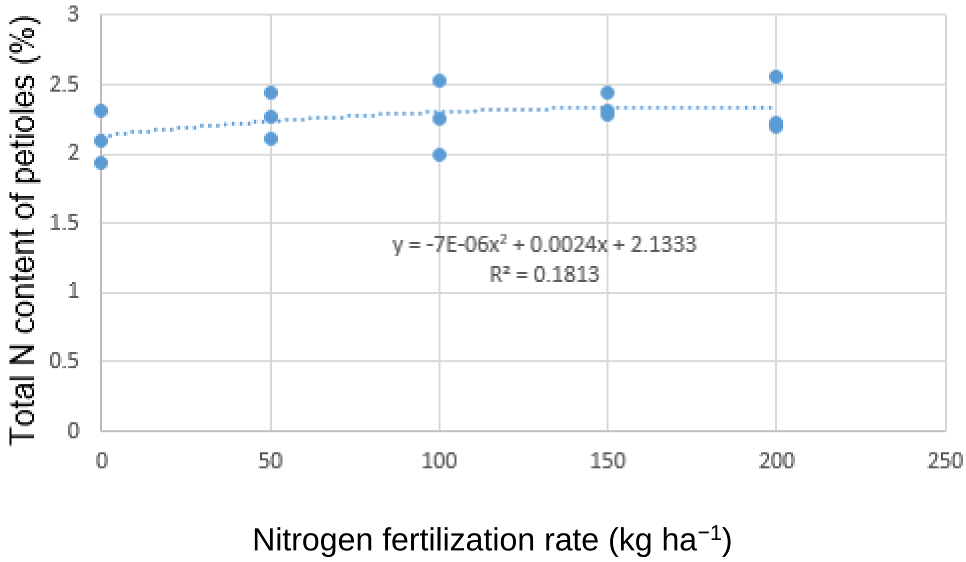
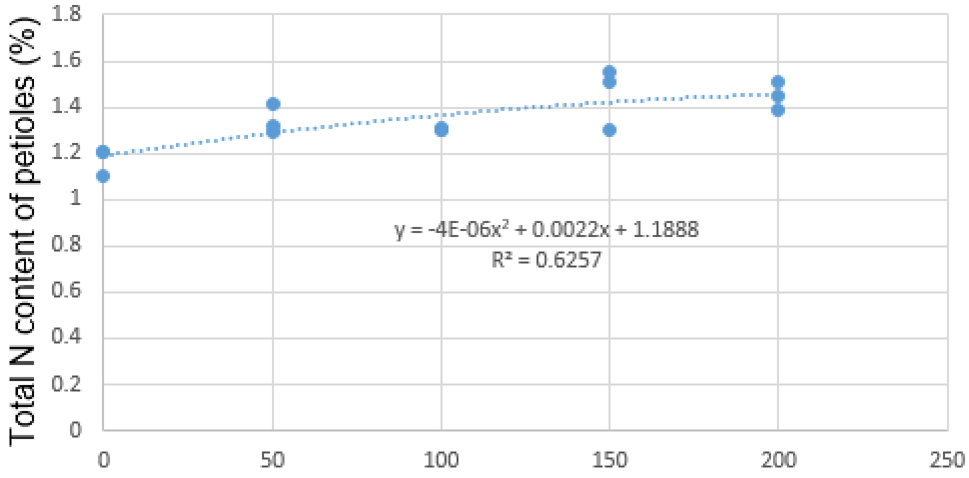


Figure 5.7 Second-order polynomial relationship between nitrogen fertilization rate and total nitrogen content of cotton leaf petioles 112 days after sowing at Rustenburg Site 2 in 1989/90, preceded by ploughed-in soybean

5.4.3.4 Leaf petiole total nitrogen content at 147 days

The best relationship found between total nitrogen content of cotton leaf petioles 147 days after sowing and nitrogen fertilization rate are given by a second-order polynomial regression depicted in Figure 5.8. The summary of the regression statistics and ANOVA are given in Appendix 5.8.



Nitrogen fertilization rate (kg ha^{-1})

Figure 5.8 Second-order polynomial relationship between nitrogen fertilization rate and total nitrogen content of cotton leaf petioles 147 days after sowing at Rustenburg Site 2 in 1989/90, preceded by ploughed-in soybean

5.4.3.5 Leaf petiole total nitrogen content at maximum yield and maximum profit

The yields for the trial done at Rustenburg Site 2 in 1989/90 (ploughed-in soybean preceding crop) were used to calculate fertilization rates for maximum yield (137 kg N ha^{-1}) and maximum profit (119 kg N ha^{-1}) (see Section 4.4.2). Concerning these fertilization rates, the leaf petiole total nitrogen content at 70, 91, 112 and 147 days after sowing was calculated using the equations given in Figures 5.5, 5.6, 5.7 and 5.8 respectively.

The calculated leaf petiole total nitrogen contents are given in Table 5.6.

Table 5.6 Estimated leaf petiole total nitrogen contents for maximum yield and maximum profit 77, 91, 112 and 147 days after sowing

Parameter	N rate (kg ha^{-1})	Equation	Days	Petiole N (%)
Maximum yield	137	$Y = -1E\text{-}05X^2 + 0.0034X + 2.8653$[a]	70	3.14
Maximum profit	119		70	3.13
Maximum yield	137	$Y = 0.0013X + 256$[b]	91	3.03
Maximum profit	119		91	3.01
Maximum yield	137	$Y = -7E\text{-}06X^2 + 0.0024X + 2.1333$[c]	112	2.33
Maximum profit	119		112	2.32
Maximum yield	137	$Y = -4E\text{-}06X^2 + 0.0022X + 1.1888$[d]	147	1.42
Maximum profit	119		148	1.39

[a]Figure 5.5, [b]Figure 5.6, [c]Figure 5.7, [d]Figure 5.8

5.4.4 Rustenburg Site 2 in 1989/90: Harvested babala preceding crop

The results of total nitrogen analyses on cotton leaf petioles taken from the trial done at Rustenburg Site 2 (babala was the preceding crop) in 1989/90 are given in Table 5.7. Samples were taken every two weeks, starting from first flowering until 147 days after sowing.

Table 5.7 Total nitrogen content of cotton leaf petioles sampled from at 70, 91, 112 and 147 days after sowing, during the 1989/90 growing season at Rustenburg Site 2, with babala as preceding crop

N rate (kg ha^{-1})	Repetition	Total nitrogen content of leaf petiole (%)			
		70 days	91 days	112 days	147 days
0	1	2.85	2.90	2.20	1.45
0	2	2.90	2.57	2.19	1.50
0	3	2.88	2.13	1.89	1.30
50	1	3.02	3.20	2.40	1.37
50	2	3.01	2.78	2.28	1.30
50	3	2.93	2.65	2.12	1.31
100	1	3.16	3.17	2.42	1.65
100	2	3.12	3.22	2.31	1.57
100	3	3.00	2.99	2.35	1.63
150	1	2.99	3.34	2.30	1.50
150	2	3.09	3.15	2.59	1.65
150	3	3.00	2.89	2.24	1.39
200	1	3.29	3.30	2.47	1.53
200	2	3.07	3.40	2.41	1.50
200	3	3.16	3.05	2.41	1.50

5.4.4.1 Leaf petiole total nitrogen content at 70 days

The best relationship found between total nitrogen content of cotton leaf petioles at 70 days and nitrogen fertilization rate are given by a second-order polynomial regression depicted in Figure 5.9. The summary of the regression statistics and ANOVA are given in Appendix 5.9.

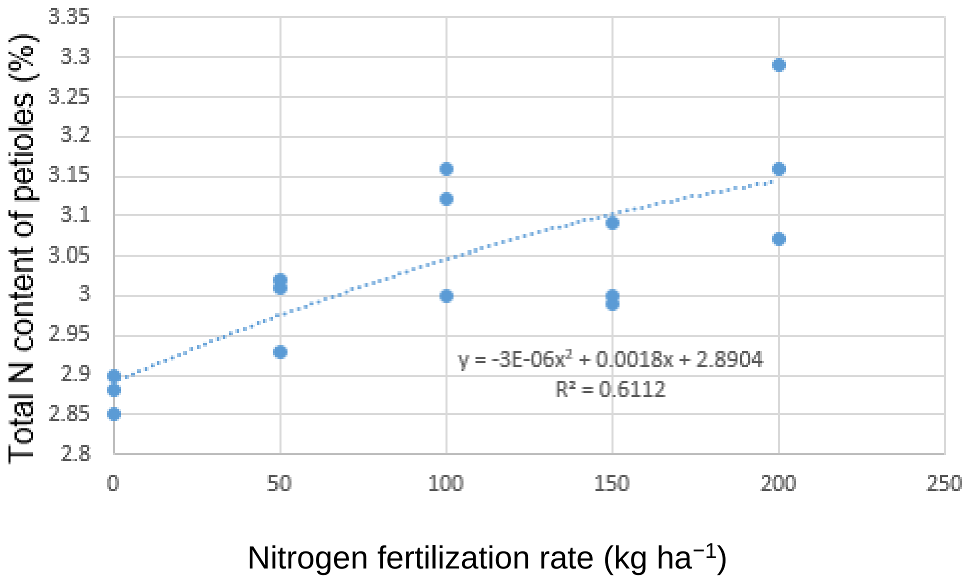


Figure 5.9 Second-order polynomial relationship between nitrogen fertilization rate and total nitrogen content of cotton leaf petioles 70 days after sowing at Rustenburg Site 2 in 1989/90, preceded by babala

5.4.4.2 Leaf petiole total nitrogen content at 91 days

The best relationship between total nitrogen content of cotton leaf petioles at 91 days after sowing and nitrogen fertilization rate are given by a second-order polynomial regression depicted in Figure 5.10. A summary of the regression statistics and ANOVA are given in Appendix 5.10.

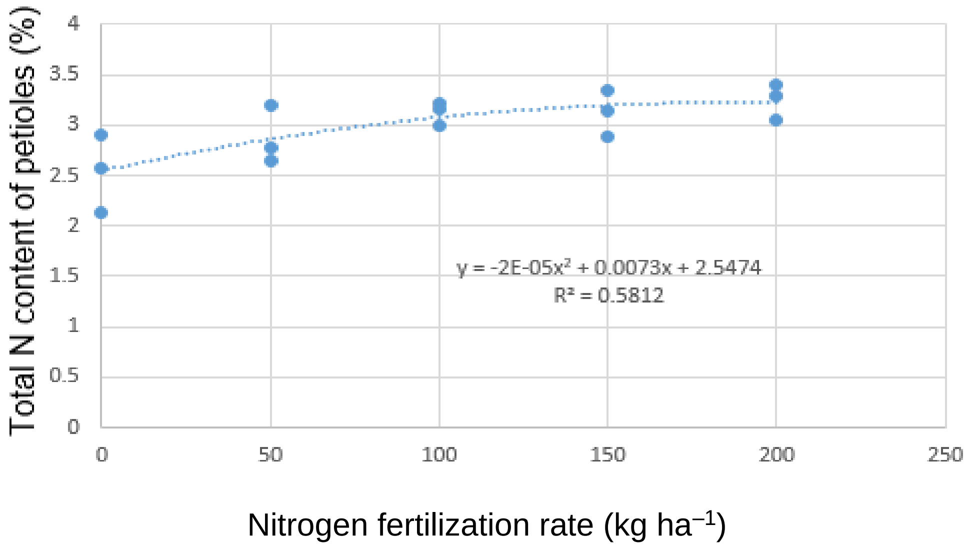


Figure 5.10 Second-order polynomial relationship between nitrogen fertilization rate and total nitrogen content of cotton leaf petioles 91 days after sowing at Rustenburg Site 2 in 1989/90, preceded by babala

5.4.4.3 Leaf petiole total nitrogen content at 112 days

The best relationship found between the total nitrogen content of cotton leaf petioles 112 days after sowing and nitrogen fertilization rate are given by a second-order polynomial regression depicted in Figure 5.11. A summary of the regression statistics and ANOVA are given in Appendix 5.11.

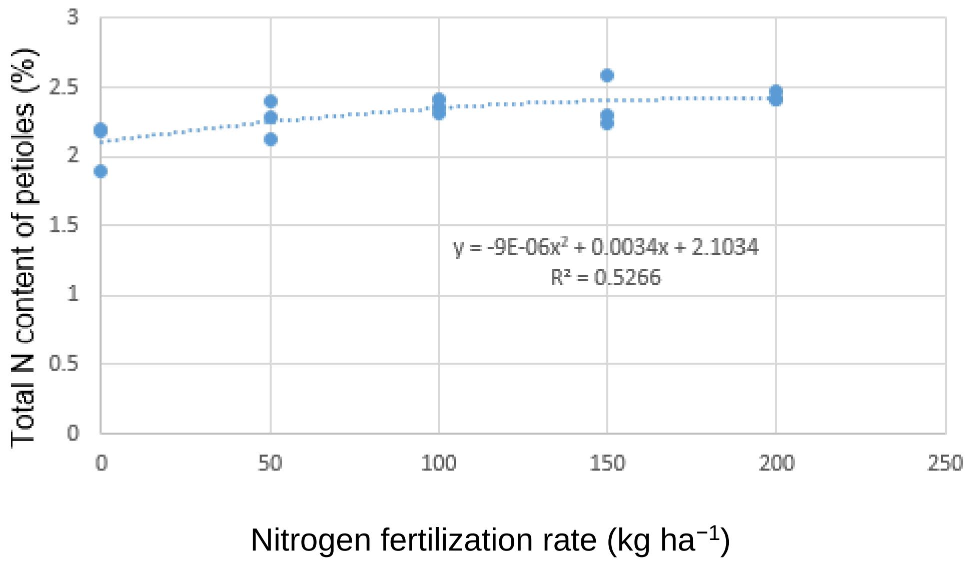


Figure 5.11 Second-order polynomial relationship between nitrogen fertilization rate and total nitrogen content of cotton leaf petioles 112 days after sowing at Rustenburg Site 2 in 1989/90, preceded by babala

5.4.4.4 Leaf petiole total nitrogen content at 147 days

The best relationship found between the total nitrogen content of leaf petioles 147 days after sowing and nitrogen fertilization rate are given by a second-order polynomial regression depicted in Figure 5.12. A summary of the regression statistics and ANOVA are given in Appendix 5.12.

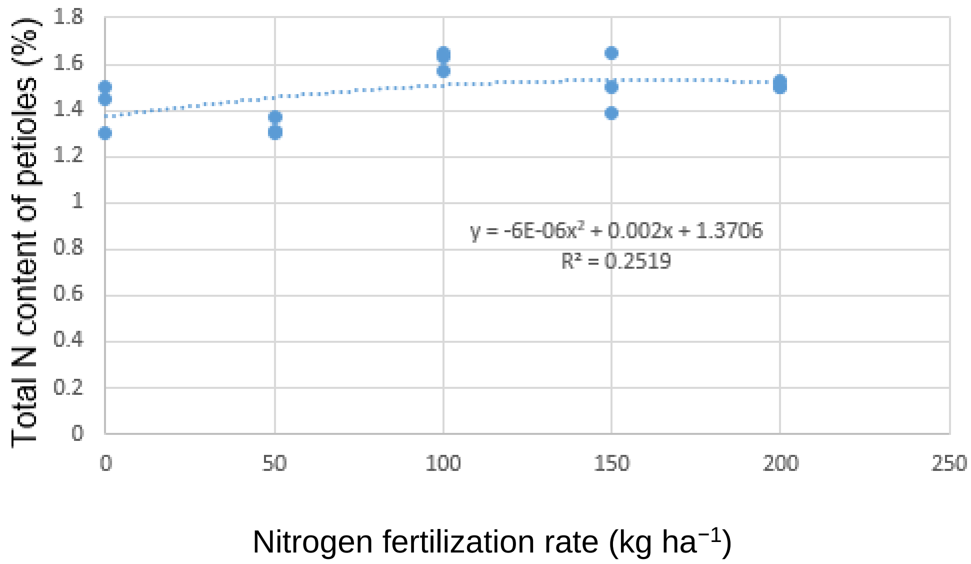


Figure 5.12 Second-order polynomial relationship between nitrogen fertilization rate and total nitrogen content of cotton leaf petioles 147 days after sowing at Rustenburg Site 2 in 1989/90, preceded by babala

5.4.4.5 Leaf petiole total nitrogen content at maximum yield and maximum profit

The yields for the trial done at Rustenburg Site 2 in 1989/90 (preceding crop was babala) were used to calculate fertilization rates for maximum yield (253 kg N ha^{-1}) and maximum profit (227 kg N ha^{-1}) (See Section 4.4.3). Concerning these fertilization rates, the leaf petiole total nitrogen content at 70, 91, 112 and 147 days after sowing was calculated using the equations given in Figures 5.9, 5.10, 5.11 and 5.12 respectively. The calculated leaf petiole total nitrogen contents are given in Table 5.8.

Table 5.8 Estimated leaf petiole total nitrogen contents for maximum yield and maximum profit 77, 91, 112 and 147 days after sowing

Parameter	N rate (kg ha^{-1})	Equation	Days	Petiole N (%)
Maximum yield	137	$Y = -3E-06X^2 + 0.0018X + 2.8904$[a]	70	3.15
Maximum profit	119		70	3.19
Maximum yield	137	$Y = -2E-05X^2 + 0.0073X + 2.5474$[b]	91	3.11
Maximum profit	119		91	3.17
Maximum yield	137	$Y = -9E-06X^2 + 0.0034X + 2.1034$[c]	112	2.39
Maximum profit	119		112	2.41
Maximum yield	137	$Y = -6E-06X^2 + 0.002X + 1.3706$[d]	147	1.42
Maximum profit	119		147	1.52

[*a]Figure 5.9, [b]Figure 5.10, [c]Figure 5.11, [d]Figure 5.12

5.4.5 Rietriver in 1989/90

The results of total nitrogen analyses on cotton leaf petioles taken from the trial done at Rietriver 1988/89 are given in Table 5.9. Samples were taken every four weeks, starting from first flowering at 77 days after planting, until 133 days after sowing.

Table 5.9 Total nitrogen content of cotton leaf petioles sampled from first flower until 133 days after sowing during the 1989/90 growing season at Rietriver

N rate (kg ha^{-1})	Repetition	Total nitrogen content of leaf petiole (%)		
		77 days	105 days	133 days
20	1	0.78	1.14	0.88
20	2	0.93	1.33	0.79
20	3	1.26	1.24	0.93
20	4	0.91	1.12	0.79
20	5	1.19	1.39	0.79
40	1	1.02	1.80	0.80
40	2	0.79	1.67	0.82
40	3	1.05	1.29	0.82
40	4	1.01	1.94	0.93
40	5	1.13	2.12	0.92
80	1	1.03	1.46	0.81
80	2	0.75	1.89	0.75
80	3	0.92	1.76	0.71
80	4	1.03	1.46	0.79
80	5	1.09	1.74	0.81
120	1	0.65	1.55	0.75
120	2	1.09	1.85	0.73
120	3	1.14	2.19	0.90
120	4	1.10	1.89	0.89
120	5	1.16	1.66	1.10
160	1	0.89	2.22	0.77
160	2	1.03	1.61	0.80
160	3	0.95	2.00	0.91
160	4	1.21	1.90	0.92
160	5	1.14	1.86	1.93
200	1	0.82	1.93	0.99
200	2	1.03	1.92	0.99
200	3	0.78	1.64	0.80
200	4	0.92	1.30	0.70
200	5	1.33	1.84	0.75

5.4.5.1 Leaf petiole total nitrogen content at 77 days

The best relationship between the total nitrogen content of cotton leaf petioles 77 days after sowing and nitrogen fertilization rate are given by a second-order polynomial regression depicted in Figure 5.13. A summary of regression statistics and ANOVA are given in Appendix 5.13.

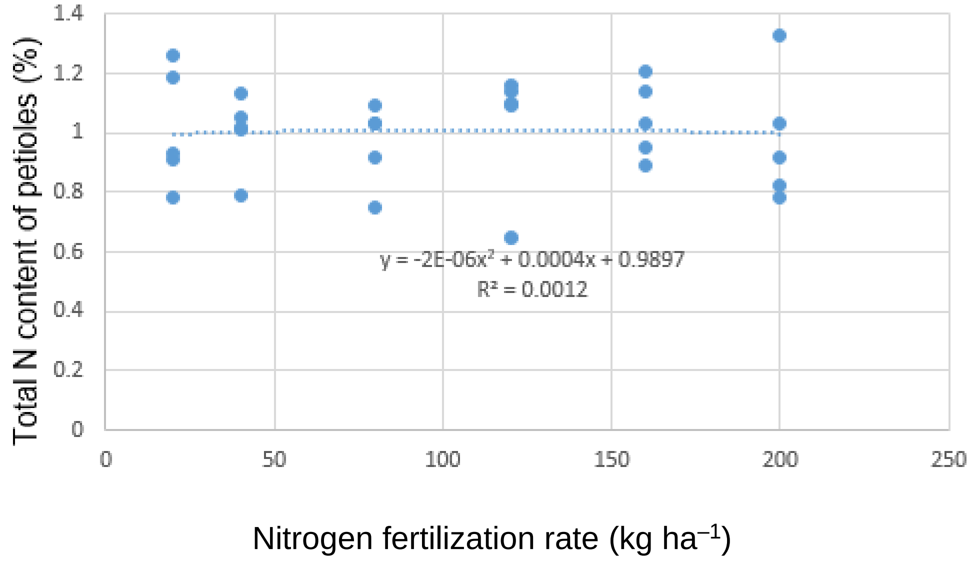


Figure 5.13 Second-order polynomial relationship between nitrogen fertilization rate and total nitrogen content of cotton leaf petioles 77 days after sowing at Rietrivier in 1989/90

5.4.5.2 Leaf petiole total nitrogen content at 105 days

The best relationship between the total nitrogen content of leaf petioles 105 days after sowing and nitrogen fertilization rate are given by a second-order polynomial regression depicted in Figure 5.14. A summary of regression statistics and ANOVA are given in Appendix 5.14.

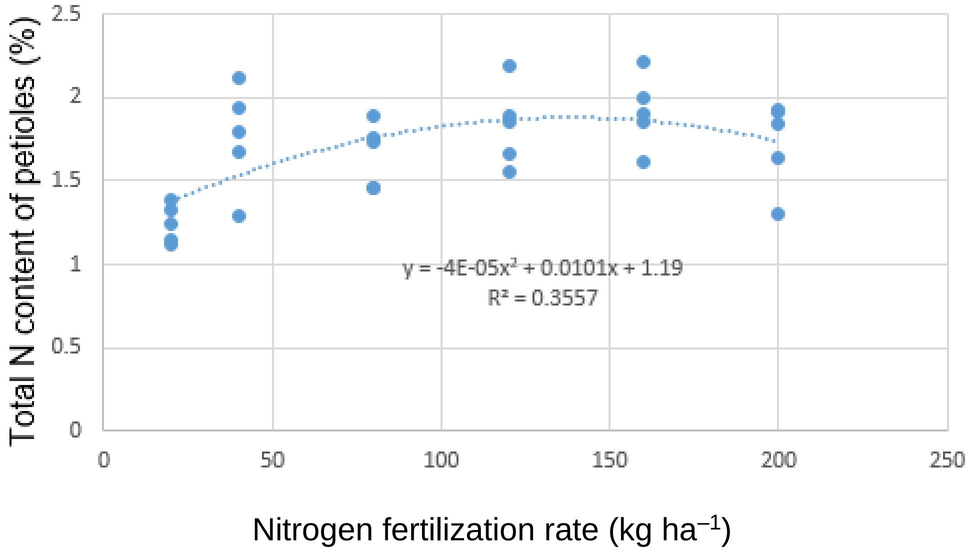


Figure 5.14 Second-order polynomial relationship between nitrogen fertilization rate and total nitrogen content of cotton leaf petioles 105 days after sowing at Rietrivier in 1989/90

5.4.5.3 Leaf petiole total nitrogen content at 133 days

The best relationship between the total nitrogen content of leaf petioles sampled 133 days after sowing and nitrogen fertilization rate are given by a second-order polynomial regression depicted in Figure 5.15. A summary of regression statistics and ANOVA are given in Appendix 5.15.

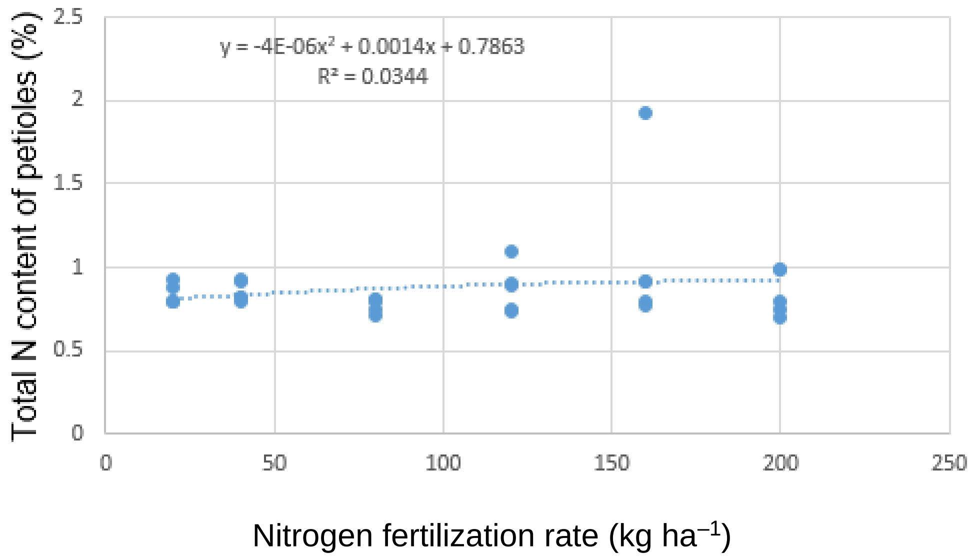


Figure 5.15 Second-order polynomial relationship between nitrogen fertilization rate and total nitrogen content of cotton leaf petioles 133 days after sowing at Rietrivier in 1989/90

5.4.5.4 Leaf petiole total nitrogen content at maximum yield and maximum profit

The yields for the trial done at Rietrivier in 1989/90 were used to calculate fertilization rates for maximum yield (159 kg N ha^{-1}) and maximum profit (149 kg N ha^{-1}) (See Section 4.5.1.2). Concerning these fertilization rates, the leaf petiole total nitrogen content at 77, 105 and 133 days after sowing was calculated using the equations given in Figure 5.13, 5.14 and 5.15, respectively. The calculated leaf petiole total nitrogen contents are given in Table 5.10.

Table 5.10 Estimated leaf petiole total nitrogen contents for maximum yield and maximum profit 77, 105 and 133 days after sowing

Parameter	N rate (kg ha^{-1})	Equation	Days	Petiole N (%)
Maximum yield	159	$Y = -2E{-}06X^2 + 0.0004X + 0.9897$[a]	77	1.00
Maximum profit	149		77	1.00
Maximum yield	159	$Y = -4E{-}05X^2 + 0.0101X + 1.19$[b]	105	1.78
Maximum profit	149		105	1.81
Maximum yield	159	$Y = -4E{-}06X^2 + 0.0014X + 0.7863$[c]	133	0.91
Maximum profit	149		133	0.91

[a]Figure 5.13, [b]Figure 5.14, [c]Figure 5.15

5.4.6 Vaalharts in 1988/89

The results of total nitrogen analyses on cotton leaf petioles taken from the trial done at Vaalharts in 1988/89 are given in Table 5.11. Samples were taken every four weeks, starting from first flowering at 77 days after planting, until 133 days after sowing.

Table 5.11 Total nitrogen content of cotton leaf petioles 77, 105 and 133 days after sowing in 1988/89 at Vaalharts

N rate (kg ha^{-1})	Repetition	Total nitrogen content of leaf petiole (%)		
		77 days	105 days	133 days
20	1	1.40	1.53	1.32
20	2	1.41	1.54	1.50
20	3	1.35	1.69	1.34
20	4	1.23	1.43	1.51
20	5	1.25	1.73	1.30
40	1	1.53	1.42	1.34
40	2	1.60	1.22	1.35
40	3	1.51	1.52	1.69
40	4	1.62	1.51	1.68
40	5	1.45	1.60	1.37
80	1	1.80	1.40	1.43
80	2	1.90	1.51	1.64
80	3	1.91	1.59	1.54
80	4	1.70	1.65	1.56
80	5	1.35	1.49	1.34
120	1	1.45	1.70	1.65
120	2	2.02	1.61	1.43
120	3	2.07	1.85	1.90
120	4	2.00	1.59	1.56
120	5	1.64	1.70	1.44
160	1	2.14	1.59	1.55
160	2	2.19	1.70	1.64
160	3	2.24	1.70	1.55
160	4	2.21	1.71	1.62
160	5	1.89	1.53	1.65
200	1	2.33	1.60	1.54
200	2	2.42	1.65	1.42
200	3	2.49	1.70	1.78
200	4	2.40	1.71	1.51
200	5	2.15	1.59	1.64

5.4.6.1 Leaf petiole total nitrogen content at 77 days

The best relationship between the total nitrogen content of cotton leaf petioles sampled 77 days after sowing and nitrogen fertilization rate are given by a second-order polynomial regression depicted in Figure 5.16. A summary of regression statistics and ANOVA are given in Appendix 5.16.

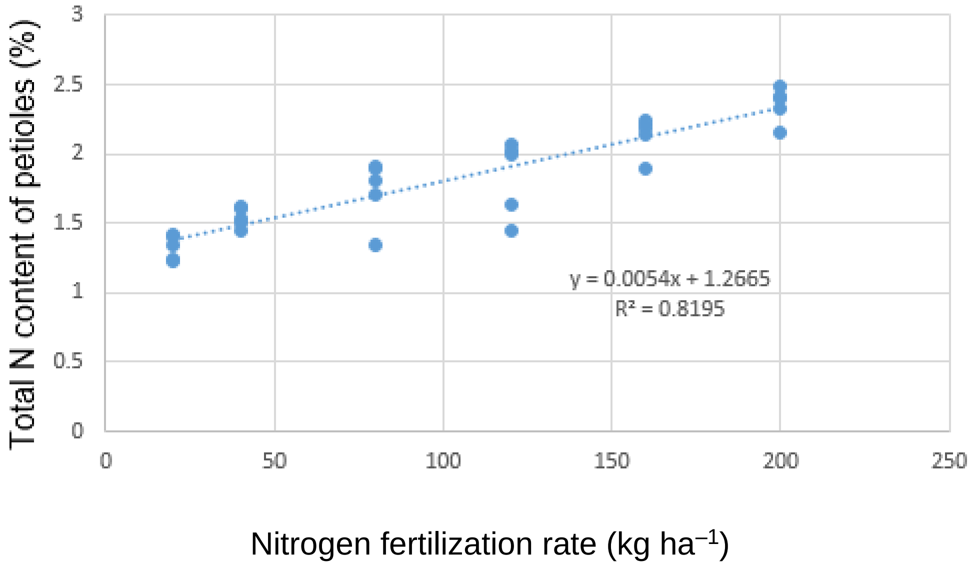


Figure 5.16 Linear relationship between nitrogen fertilization rate and total nitrogen content of cotton leaf petioles 77 days after sowing at Vaalharts in 1988/89

5.4.6.2 Leaf petiole total nitrogen content at 105 days

The best relationship between the total nitrogen content of cotton leaf petioles 105 days after sowing and nitrogen fertilization rate are given by a second-order polynomial regression depicted in Figure 5.17. A summary of regression statistics and ANOVA are given in Appendix 5.17.

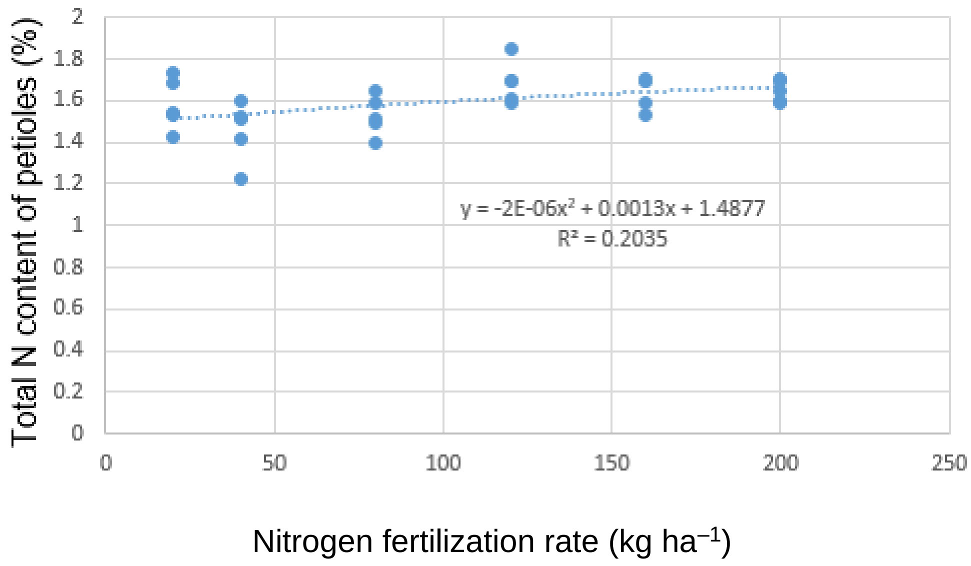


Figure 5.17 Second-order polynomial relationship between nitrogen fertilization rate and total nitrogen content of cotton leaf petioles 105 days after sowing at Vaalharts in 1988/89

5.4.6.3 Leaf petiole total nitrogen content at 133 days

The best relationship between total nitrogen content of cotton leaf petioles 133 days after sowing and nitrogen fertilization rate are given by a second-order polynomial regression depicted in Figure 5.18. A summary of regression statistics and ANOVA are given in Appendix 5.18.

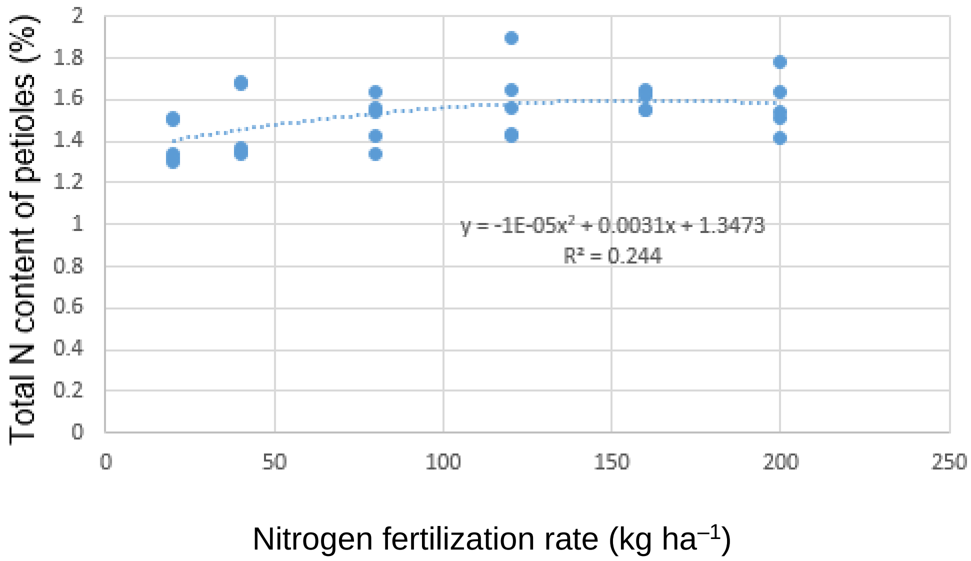


Figure 5.18 Second-order polynomial relationship between nitrogen fertilization rate and total nitrogen content of cotton leaf petioles 133 days after sowing at Vaalharts in 1988/89

5.4.6.4 Leaf petiole total nitrogen content at maximum yield and maximum profit

The yields for the trial done at Vaalharts in 1988/89 were used to calculate fertilization rates for maximum yield (221 kg N ha^{-1}) and maximum profit (193 kg N ha^{-1}) (see Section 4.5.2.1). Concerning these fertilization rates, the leaf petiole total nitrogen content at 77, 105 and 133 days after sowing was calculated using the equations given in Figure 5.16, 5.17 and 5.18, respectively. The calculated leaf petiole total nitrogen contents are given in Table 5.12.

Table 5.12 Estimated leaf petiole total nitrogen contents for maximum yield and maximum profit 77, 105 and 133 days after sowing

Parameter	N rate (kg ha^{-1})	Equation	Days	Petiole N (%)
Maximum yield	221	$Y = 0.0054X + 1.2665$[a]	77	2.46
Maximum profit	193		77	2.31
Maximum yield	221	$Y = -2E\text{-}06X^2 + 0.0013X + 1.4877$[b]	105	1.68
Maximum profit	193		105	1.66
Maximum yield	221	$Y = -1E\text{-}05X^2 + 0.0031X + 1.3473$[c]	133	1.54
Maximum profit	193		133	1.57

[a]Figure 5.16, [b]Figure 5.17, [c]Figure 5.18

5.4.7 Groblersdal in 1989/90

The results of total nitrogen analyses on cotton leaf petioles taken from the trial done at Groblersdal in 1989/90 are given in Table 5.13. Samples were taken every two weeks, starting from two weeks before first flower until 25 weeks after sowing.

Table 5.13 Total nitrogen content of cotton leaf petioles 63, 77, 91, 105, 119, 133, 147, 161 and 175 days after sowing in 1989/90 at Groblersdal

N rate (kg ha^{-1})	Repetition	Total nitrogen content of leaf petiole (%)								
		63 days	77 days	91 days	105 days	119 days	133 days	147 days	161 days	175 days
0	1	2.20	1.21	1.08	0.64	0.89	1.02	1.59	1.10	1.41
0	2	1.71	1.60	1.53	0.78	0.99	1.25	1.33	1.27	1.37
0	3	1.80	1.78	1.32	0.73	1.00	0.83	1.20	1.00	1.19
0	4	2.41	1.49	1.40	1.09	1.34	0.79	1.39	1.30	1.50
0	5	1.75	1.52	2.20	0.97	1.23	0.95	1.11	1.20	1.29
40	1	2.49	1.39	1.52	1.06	1.00	1.34	1.40	1.15	1.37
40	2	2.60	1.38	1.64	1.09	1.04	0.98	1.50	1.31	1.48
40	3	1.93	1.28	1.22	0.78	1.10	1.05	1.10	1.00	1.02
40	4	2.12	1.59	1.74	1.08	1.22	1.01	1.60	1.13	1.61
40	5	2.39	1.39	1.22	1.29	1.26	1.10	1.14	1.00	1.60
80	1	2.05	1.21	1.50	0.72	0.90	1.09	1.39	1.39	1.29
80	2	2.20	1.55	1.57	0.77	0.99	0.99	1.34	1.12	1.45
80	3	2.70	1.50	1.40	0.97	1.25	1.13	1.92	1.41	1.42
80	4	2.09	1.85	1.39	0.82	1.19	1.00	1.53	1.09	1.30
80	5	2.79	1.63	1.54	1.35	1.27	1.09	1.65	1.80	1.73
120	1	2.45	2.11	1.80	1.09	1.26	1.23	1.60	0.91	1.53
120	2	2.70	2.00	1.50	0.96	1.59	1.39	1.95	1.70	1.63
120	3	2.19	2.13	1.48	1.30	1.23	1.62	1.09	1.53	1.41
120	4	2.52	2.30	1.33	1.00	1.21	1.23	1.59	1.22	1.69
120	5	2.23	1.92	2.40	1.60	1.19	1.25	1.52	1.60	1.32
160	1	2.00	1.60	1.72	1.05	1.25	1.20	1.72	1.49	1.59
160	2	2.21	1.73	1.75	1.17	1.55	1.50	1.80	1.50	1.26
160	3	2.60	2.29	1.65	1.25	1.13	1.35	1.84	1.20	1.41
160	4	2.84	1.90	1.70	0.99	1.55	1.56	2.19	1.90	1.80
160	5	2.64	2.19	1.60	1.40	1.30	1.40	1.75	1.49	1.48
200	1	2.42	1.75	1.88	1.35	1.25	1.02	1.31	1.19	1.52
200	2	2.20	1.99	1.65	1.00	1.47	1.30	1.43	1.41	1.46
200	3	2.49	2.10	2.15	1.37	1.46	1.50	1.98	1.79	1.49
200	4	2.61	2.11	1.98	1.79	1.19	1.87	1.81	1.50	1.60
200	5	2.30	2.25	1.41	1.25	1.23	1.23	1.73	1.64	1.80

5.4.7.1 Leaf petiole total nitrogen content at 63 days

The best relationship between the total nitrogen content of cotton leaf petioles 63 days after sowing and nitrogen fertilization rate is given by a second-order polynomial regression depicted in Figure 5.19. A summary of regression statistics and ANOVA are given in Appendix 5.19.

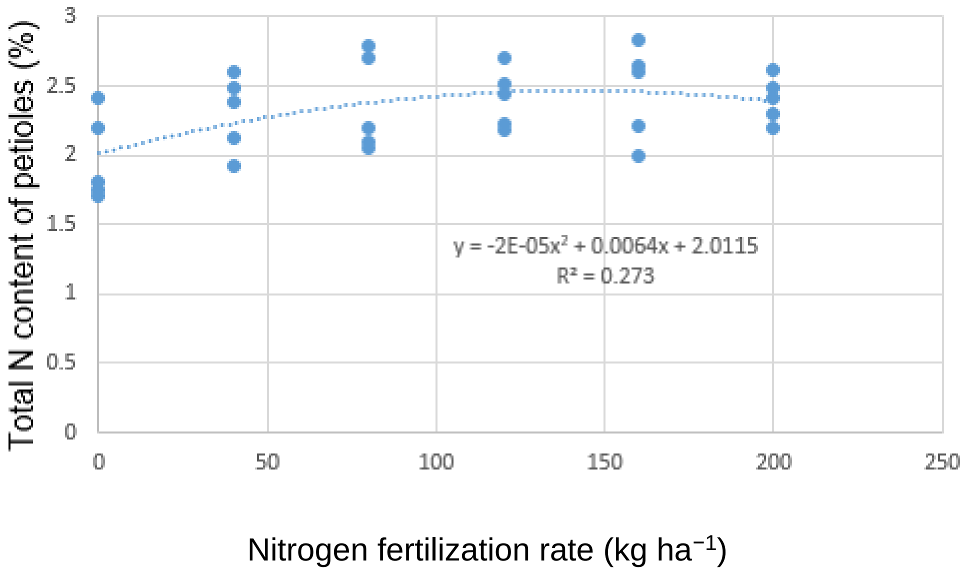


Figure 5.19 Second-order polynomial relationship between nitrogen fertilization rate and total nitrogen content of cotton leaf petioles sampled at first square emergence, 63 days after sowing at Groblersdal in 1989/90

5.4.7.2 Leaf petiole total nitrogen content at 77 days

The best relationship between the total nitrogen content of cotton leaf petioles 77 days after sowing and nitrogen fertilization rate are given by a second-order polynomial regression depicted in Figure 5.20. A summary of regression statistics and ANOVA are given in Appendix 5.20.

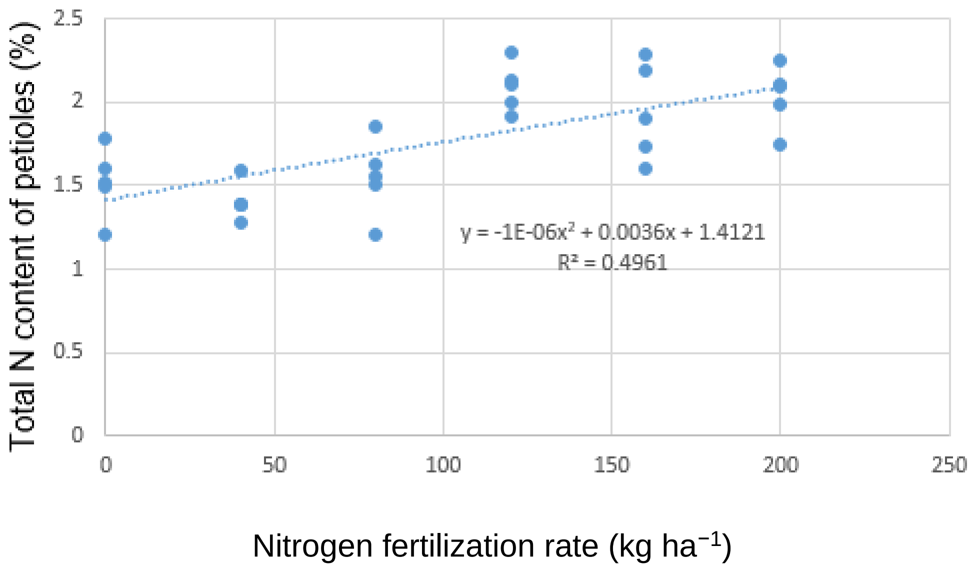


Figure 5.20 Second-order polynomial relationship between nitrogen fertilization rate and total nitrogen content of cotton leaf petioles 77 days after sowing at Groblersdal in 1989/90

5.4.7.3 Leaf petiole total nitrogen content at 91 days with outlier

The best relationship between the total nitrogen content of cotton leaf petioles 91 days after sowing and nitrogen fertilization rate are given by a second-order polynomial regression depicted in Figure 5.21. A summary of regression statistics and ANOVA are given in Appendix 5.21.

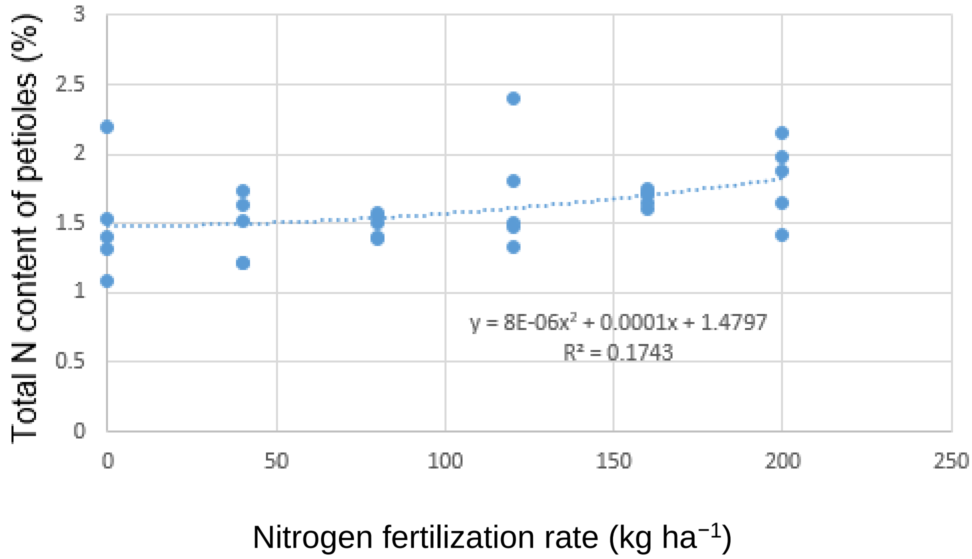


Figure 5.21 Second-order polynomial relationship between nitrogen fertilization rate and total nitrogen content of cotton leaf petioles 91 days after sowing at Groblersdal in 1989/90 with outlier

The second-order polynomial relationship obtained in the above figure is of an inverse nature, which is a-typical of the majority of other relationships. Therefore the data was inspected in order to detect any outliers that might be present. In the control treatment a measurement of 2.20% total nitrogen content of leaf petioles was observed. According to Hawkins (1980), this measurement can be identified as an outlier. Therefore this measurement will be excluded from the data and the relationship between the total nitrogen content of leaf petioles 91 days after sowing and nitrogen fertilization rate will be recalculated in Section 5.4.7.4.

5.4.7.4 Leaf petiole total nitrogen content at 91 days excluding outlier

The best relationship between total nitrogen content of cotton leaf petioles 91 days after sowing and nitrogen fertilization rate excluding the outlier is given by a second-order polynomial regression depicted in Figure 5.22. A summary of regression statistics and ANOVA are given in Appendix 5.22.

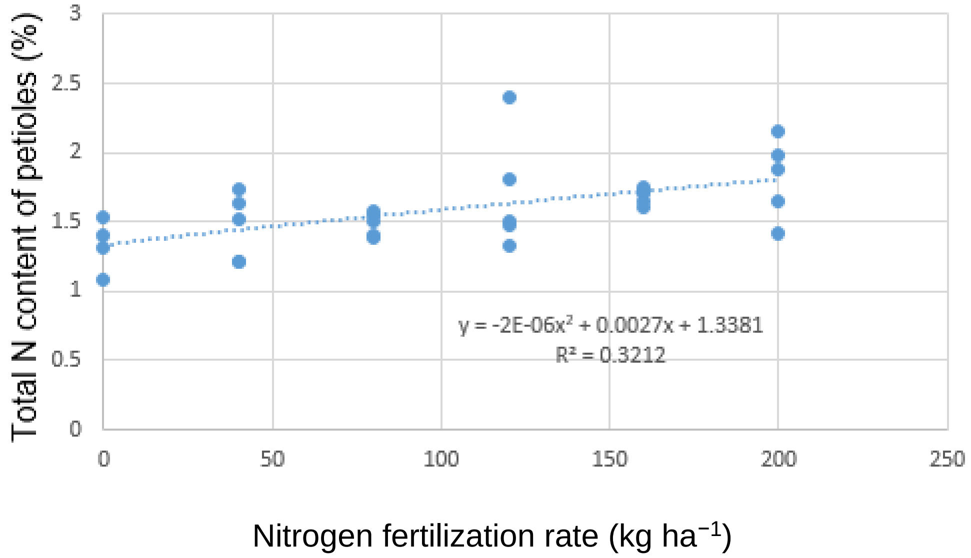
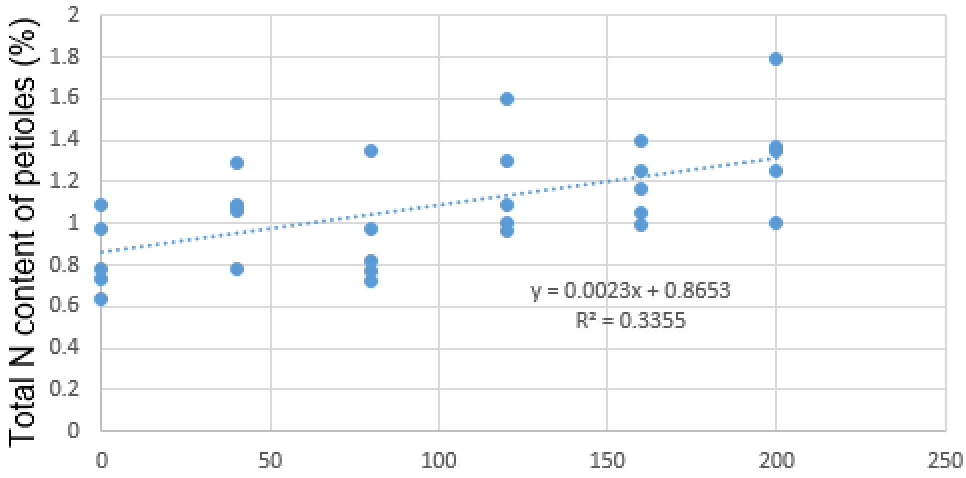


Figure 5.22 Second-order polynomial relationship between nitrogen fertilization rate and total nitrogen content of cotton leaf petioles 91 days after sowing at Groblersdal in 1989/90 without outlier

The above relationship is typical of other relationships observed in this study and will be used for further calculations.

5.4.7.5 Leaf petiole total nitrogen content at 105 days

The best relationship between total nitrogen content of cotton leaf petioles 105 days after sowing, and nitrogen fertilization rate is given by a linear regression depicted in Figure 5.23. A summary of regression statistics and ANOVA are given in Appendix 5.23.

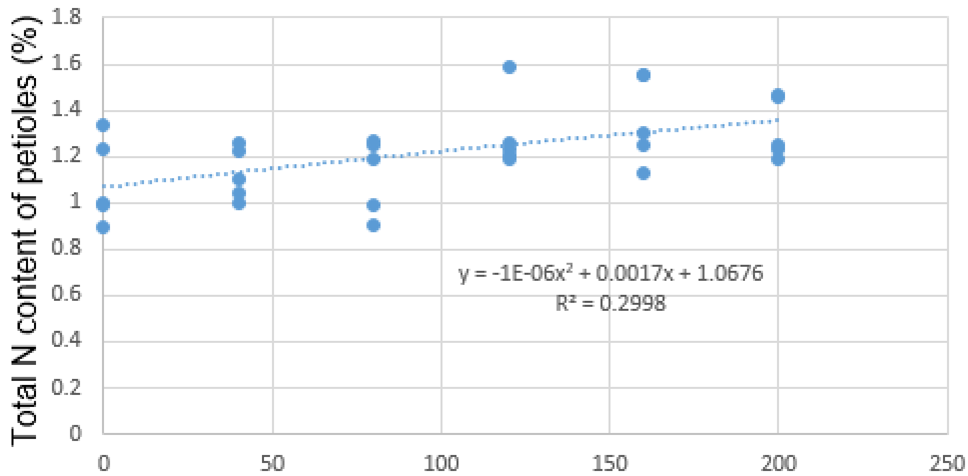


Nitrogen fertilization rate (kg ha^{-1})

Figure 5.23 Linear relationship between nitrogen fertilization rate and total nitrogen content of cotton leaf petioles sampled 105 days after sowing at Groblersdal in 1989/90

5.4.7.6 Leaf petiole total nitrogen content at 119 days

The best relationship between the total nitrogen content of cotton leaf petioles 119 days after sowing and nitrogen fertilization rate is given by a second-order polynomial regression depicted in Figure 5.24. A summary of regression statistics and ANOVA are given in Appendix 5.24.



Nitrogen fertilization rate (kg ha^{-1})

Figure 5.24 Second-order polynomial relationship between nitrogen fertilization rate and total nitrogen content of cotton leaf petioles 119 days after sowing at Groblersdal in 1989/90

5.4.7.7 Leaf petiole total nitrogen content at 133 days

The best relationship between the total nitrogen content of cotton leaf petioles 133 days after sowing and nitrogen fertilization rate is given by a second-order polynomial regression depicted in Figure 5.25. A summary of regression statistics and ANOVA are given in Appendix 5.25.

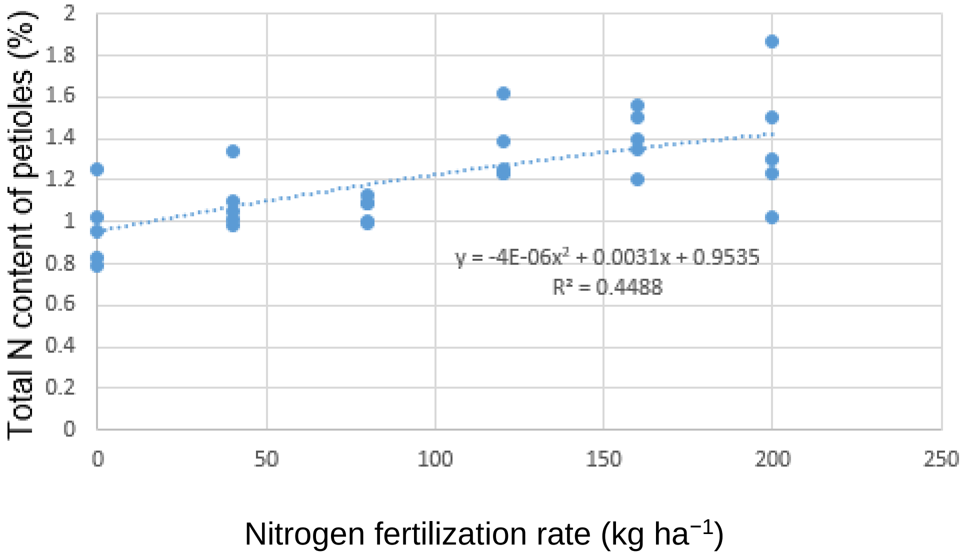


Figure 5.25 Second-order polynomial relationship between nitrogen fertilization rate and total nitrogen content of cotton leaf petioles 133 days after sowing at Groblersdal in 1989/90

5.4.7.8 Leaf petiole total nitrogen content at 147 days

The best relationship between the total nitrogen content of cotton leaf petioles 147 days after sowing, and nitrogen fertilization rate is given by a second-order polynomial regression depicted in Figure 5.26. A summary of regression statistics and ANOVA are given in Appendix 5.26.

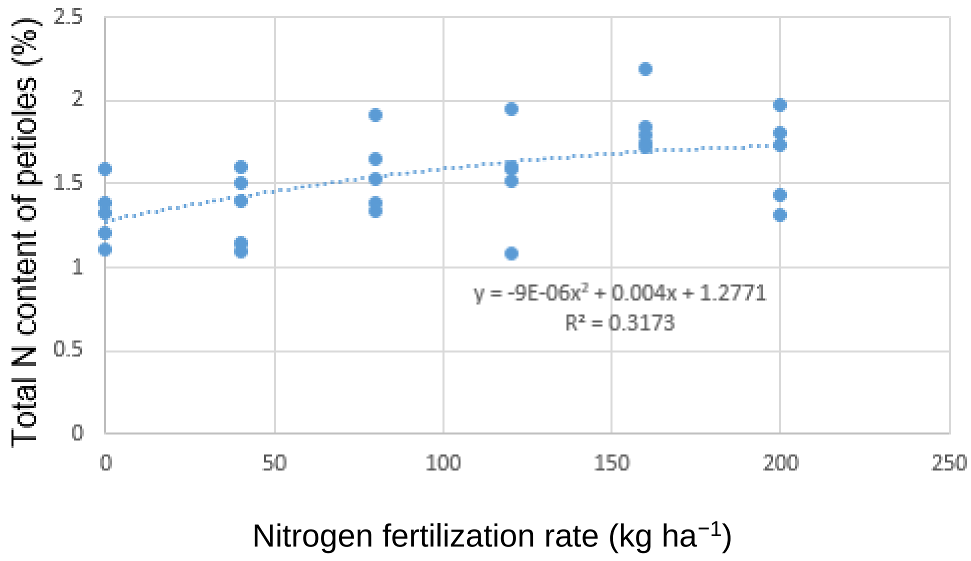


Figure 5.26 Second-order polynomial relationship between nitrogen fertilization rate and total nitrogen content of cotton leaf petioles 147 days after sowing at Groblersdal in 1989/90

5.4.7.9 Leaf petiole total nitrogen content at 161 days

The best relationship between the total nitrogen content of cotton leaf petioles 161 days after sowing, and nitrogen fertilization rate is given by a second-order polynomial regression depicted in Figure 5.27. A summary of regression statistics and ANOVA are given in Appendix 5.27.

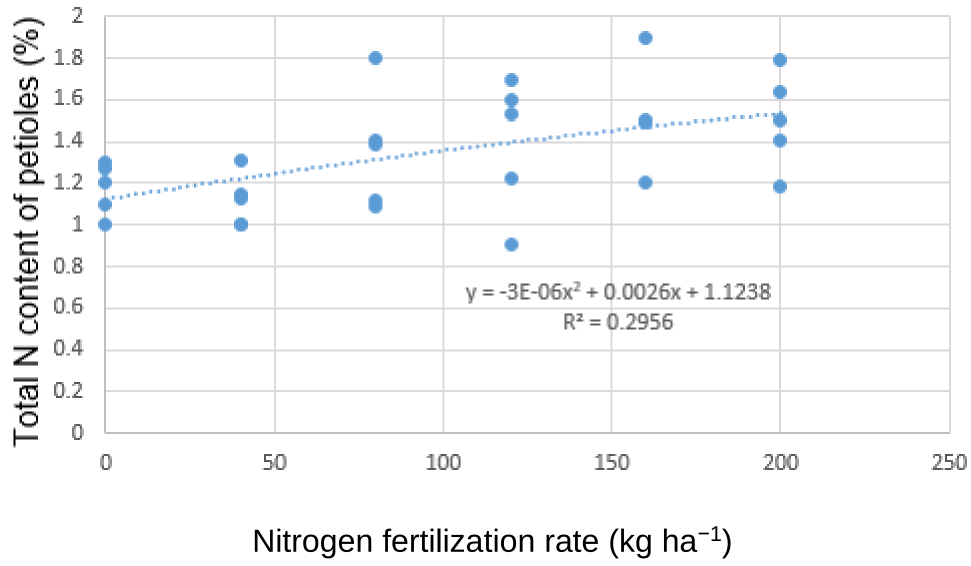


Figure 5.27 Second-order polynomial relationship between nitrogen fertilization rate and total nitrogen content of cotton leaf petioles 161 days after sowing at Groblersdal in 1989/90

5.4.7.10 Leaf petiole total nitrogen content at 175 days

The best relationship between the total nitrogen content of cotton leaf petioles 175 days after sowing and nitrogen fertilization rate is given by a second-order polynomial regression depicted in Figure 5.28. A summary of regression statistics and ANOVA are given in Appendix 5.28.

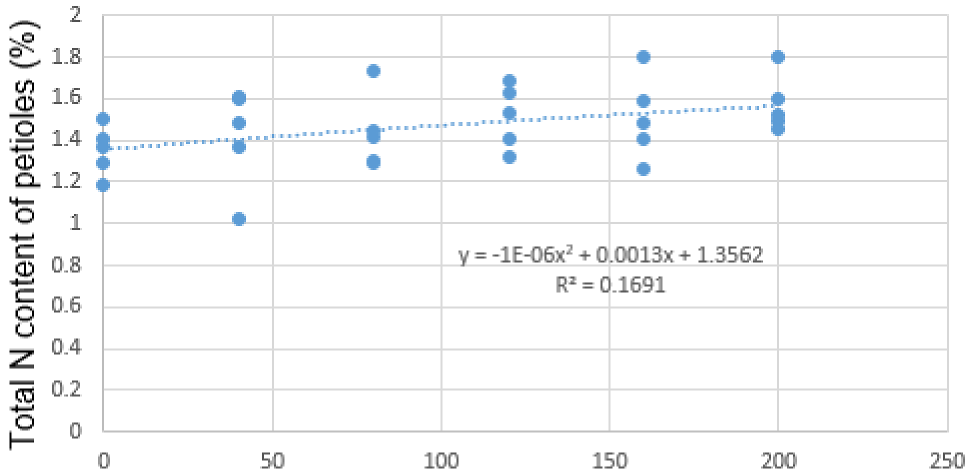


Figure 5.28 Second-order polynomial relationship between nitrogen fertilization rate and total nitrogen content of cotton leaf petioles 175 days after sowing at Groblersdal in 1989/90

5.4.7.11 Leaf petiole total nitrogen content at maximum yield and maximum profit

The yields for the trial done at Groblersdal in 1988/89 were used to calculate fertilization rates for maximum yield (150 kg N ha^{-1}) and maximum profit (141 kg N ha^{-1}) (See Section 4.6). Concerning these fertilization rates, the leaf petiole total nitrogen content at 63, 77, 91, 105, 119, 133, 147, 161 and 175 days after sowing was calculated using the equations given in Figures 5.19, 5.20, 5.22, 5.23, 5.24, 5.25, 5.26, 5.27 and 5.28, respectively. The calculated leaf petiole total nitrogen contents are given in Table 5.14.

Table 5.14 Estimated leaf petiole total nitrogen contents for maximum yield and maximum profit 63, 77, 91, 105, 119, 133, 147, 161 and 175 days after sowing

Parameter	N rate (kg ha^{-1})	Equation	Days	Petiole N (%)
Maximum yield	150	$Y = -2E-05X^2 + 0.0064X + 2.0115$[a]	63	2.52
Maximum profit	141		63	2.52
Maximum yield	150	$Y = -1E-06X^2 + 0.0036X + 1.4121$[b]	77	1.93
Maximum profit	141		77	1.90
Maximum yield	150	$Y = -2E-06X^2 + 0.0027X + 1.3381$[c]	91	1.70
Maximum profit	141		91	1.68
Maximum yield	150	$Y = 0.0023X + 0.8653$[d]	105	1.21
Maximum profit	141		105	1.19
Maximum yield	150	$Y = -1E-06X^2 + 0.0017X + 1.0676$[e]	119	1.30
Maximum profit	141		119	1.29
Maximum yield	150	$Y = -4E-06X^2 + 0.0031X + 0.9535$[f]	133	1.33
Maximum profit	141		133	1.31
Maximum yield	150	$Y = -9E-06X^2 + 0.004X + 1.2771$[g]	147	1.67
Maximum profit	141		147	1.66
Maximum yield	150	$Y = -3E-06X^2 + 0.0026X + 1.1238$[h]	161	1.45
Maximum profit	141		161	1.43
Maximum yield	150	$Y = -1E-06X^2 + 0.0013X + 1.3562$[i]	175	1.53
Maximum profit	141		175	1.52

[a]Figure 5.19, [b]Figure 5.20, [c]Figure 5.22, [d]Figure 5.23, [e]Figure 5.24, [f]Figure 5.25, [g]Figure 5.26, [h]Figure 5.27, [i]Figure 5.28

5.5 Synthesis

In order to refine nitrogen fertilization guidelines for irrigated cotton in South Africa, an in-season method that can be used as a potential guideline where the total nitrogen content of cotton leaf petioles can be used to evaluate the nitrogen status of cotton in season, the following approach is suggested:

- The correlation between total nitrogen content of cotton leaf petioles at maximum yield and the time of sampling after sowing will be considered. If the correlation is found to be statistically significant, the regression equation obtained will be used as a guideline to evaluate the nitrogen status of cotton during the growing season for the production of maximum yield.
- The same procedure as above will be followed to establish a guideline to evaluate the nitrogen status of cotton during the growing season to produce cotton that results in maximum profit.
- Once the above guidelines have been established, they will be compared with the latest petiole guideline of Gatiboni and Hardy (2021) that is currently used in North Carolina.

5.5.1 Relationship between leaf petiole total nitrogen content at maximum yield and maximum profit

The total nitrogen content of cotton leaf petioles (sampled at various times after sowing from the qualifying field trials), associated with maximum yield and maximum profit are given in Table 5.15.

Table 5.15 Total nitrogen content of cotton leaf petioles associated with maximum yield and maximum profit, taken at various times after sowing from nitrogen fertilization trials done at different locations

Location	Growing season	Time of sampling (days after sowing)	Total nitrogen content of petioles (%) associated with maximum yield and maximum profit	
			Maximum yield	Maximum profit
Rustenburg Site 1 (oats)	1987/88	77	3.66	3.50
		91	2.22	2.12
Rustenburg Site 1 (soybean)	1988/89	77	1.62	1.40
		91	1.61	1.28
Rustenburg Site 2 (soybean plough)	1989/90	70	3.14	3.13
		91	3.03	3.01
		112	2.33	2.32
		147	1.42	1.39
Rustenburg Site 2 (babala)	1989/90	70	3.15	3.19
		91	3.11	3.17
		112	2.39	2.41
		147	1.42	1.52

Location	Growing season	Time of sampling (days after sowing)	Total nitrogen content of petioles (%) associated with maximum yield and maximum profit	
			Maximum yield	Maximum profit
Rietriver	1989/90	77	1.00	1.00
		105	1.78	1.81
		133	0.91	0.91
Vaalharts	1988/89	77	2.46	2.31
		105	1.68	1.66
		133	1.54	1.57
Groblersdal	1988/89	63	2.52	2.52
		77	1.93	1.90
		91	1.70	1.68
		105	1.21	1.19
		119	1.30	1.29
		133	1.33	1.31
		147	1.67	1.66
		161	1.45	1.43
		175	1.53	1.52

5.5.1.1 Relationship between leaf petiole total nitrogen content and maximum yield

Using the data from Table 5.15, the relationship between the total nitrogen content of cotton leaf petioles and the sampling time in days after sowing for all locations, is represented by the second-order polynomial regression described in Figure 5.29. A summary of regression statistics and ANOVA are given in Appendix 5.29.

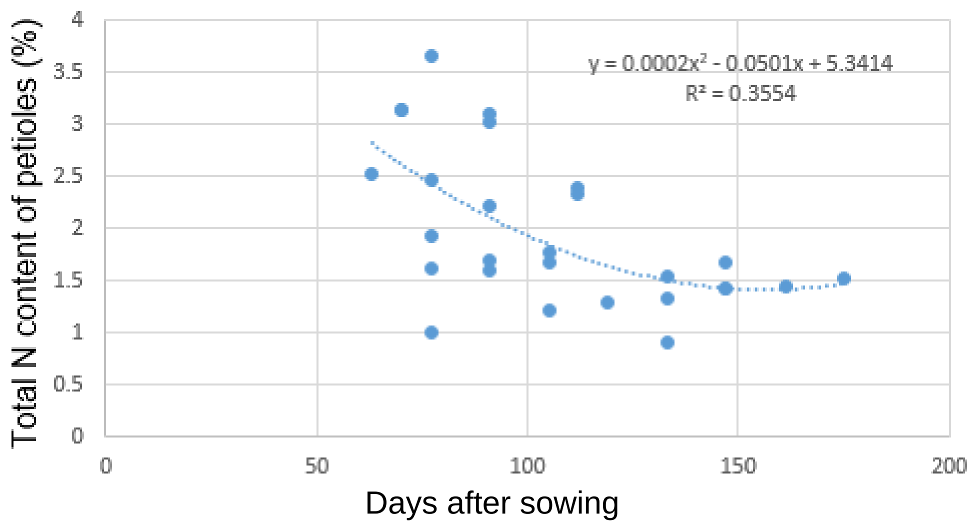


Figure 5.29 Second-order polynomial relationship between total nitrogen content of cotton leaf petioles and days after sowing (for maximum yield)

5.5.1.2 Relationship between leaf petiole total nitrogen content and maximum profit

Using the data from Table 5.15, the relationship between the total nitrogen content of cotton leaf petioles and the sampling time in days after sowing for all locations, is represented by the second-order polynomial regression described in Figure 5.30. A summary of regression statistics and ANOVA are given in Appendix 5.30.

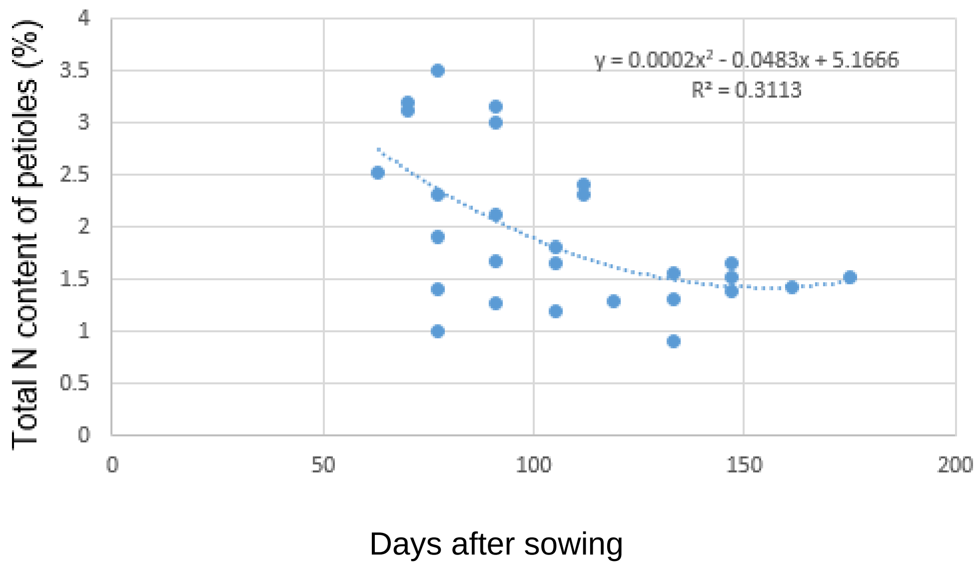


Figure 5.30 Second-order polynomial relationship between total nitrogen content of cotton leaf petioles and days after sowing (for maximum profit)

5.5.1.3 Comparison with existing guidelines

As can be seen from the summary of the statistical analysis in Appendix 5.29 and Appendix 5.30 the correlations between the total nitrogen content of the cotton leaf petioles associated with both maximum yield and maximum profit, and days after sowing are statistically significant. Therefore the regression equations obtained from them, as shown in Figure 5.29 and Figure 5.30 can be used as guidelines to evaluate the nitrogen fertilization status of cotton in the field, during the growing season.

The second-order polynomial regression model that describes the total nitrogen content of cotton leaf petioles at a specified number of days after sowing, so as to produce maximum seed cotton yield, is:

$$Y = 0.0002X^2 - 0.0501X + 5.3414 \text{ (Figure 5.29)}$$

It is proposed that the line itself indicate adequate nitrogen in the leaf petiole. The area above the line would indicate excess nitrogen and the area below the line would indicate a low nitrogen status.

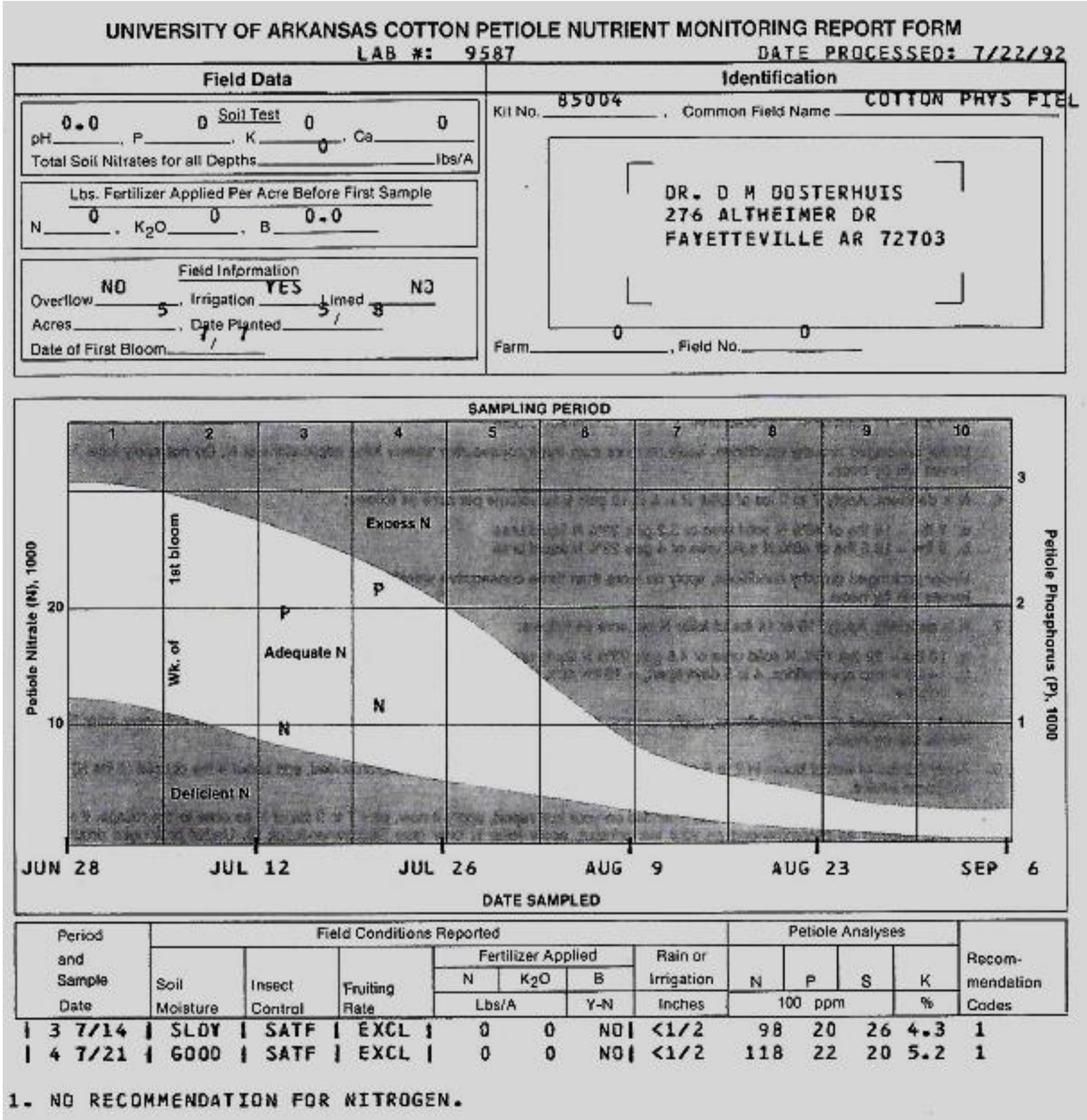
The second-order polynomial regression model that describes the total nitrogen content of cotton leaf petioles at a specified number of days after sowing, so as to produce maximum profit, is:

$$Y = 0.0002X^2 – 0.0483X + 5.1666 \text{ (Figure 5.30)}$$

It is proposed that the line itself indicate adequate nitrogen status in the leaf petiole. In this regard, the area above the line would indicate excess nitrogen and the area below the line would indicate a low nitrogen status.

The above two models have a high level of confidence for predictions between 63 and 175 days after sowing, wherein leaf petiole data was gathered for the purpose of this study. The University of Arkansas allow for the collection of data from 1 week before flowering (about 63 days after sowing) until 9 weeks after the week of first flower (about 133 days after sowing), as can be seen in Figure 2.12 (Oosterhuis 1992) in Chapter 2. For ease of reference, Figure 2.12 will be provided again here as Figure 5.31.

Considering Figure 5.31, it shows a marked resemblance with the above two models (Figure 5.29 and Figure 5.30). The above two models are similar to the top end of the adequate zone given in Figure 5.31. The latter most probably being explained by the fact that the above two models are based on total nitrogen content of leaf petioles and Figure 5.31 is based on only the nitrate nitrogen content of leaf petioles.



UNIVERSITY OF ARKANSAS COTTON PETIOLE NUTRIENT MONITORING REPORT FORM

LAB #: 9587 DATE PROCESSED: 7/22/92

Field Data

Soil Test

pH 0.0, P 0, K 0, Ca 0

Total Soil Nitrates for all Depths 0 lbs/A

Lbs. Fertilizer Applied Per Acre Before First Sample

N 0, K2O 0, B 0.0

Field Information

Overflow NO, Irrigation YES, Limed NO

Acres 5, Date Planted 5/ 8

Date of First Bloom 7/ 7

Identification

Kit No. 85004, Common Field Name COTTON PHYS FIEL

DR. D M OOSTERHUIS
276 ALTHEIMER DR
FAYETTEVILLE AR 72703

Farm 0, Field No. 0

Period and Sample Date	Soil Moisture	Insect Control	Fruiting Rate	Fertilizer Applied N (Lbs/A)	Fertilizer Applied K2O (Lbs/A)	Fertilizer Applied B (Y-N)	Rain or Irrigation (Inches)	Petiole Analyses N (100 ppm)	P (100 ppm)	S (100 ppm)	K (%)	Recommendation Codes
3 7/14	SLOY	SATF	EXCL	0	0	NO	<1/2	98	20	26	4.3	1
4 7/21	GOOD	SATF	EXCL	0	0	NO	<1/2	118	22	20	5.2	1

1. NO RECOMMENDATION FOR NITROGEN.

Figure 5.31 University of Arkansas cotton petiole nutrient monitoring report (Oosterhuis 1992)

While the two models represented is Figure 5.29 and Figure 5.30, compare well with the leaf petiole guideline of Arkansas, given in Figure 5.31, the values in these models are higher than those used in the guideline of North Carolina as depicted in Chapter 2, Figure 2.11 (Gatiboni and Hardy 2021). For ease of reference, Figure 2.11 will be provided here again as Figure 5.32.

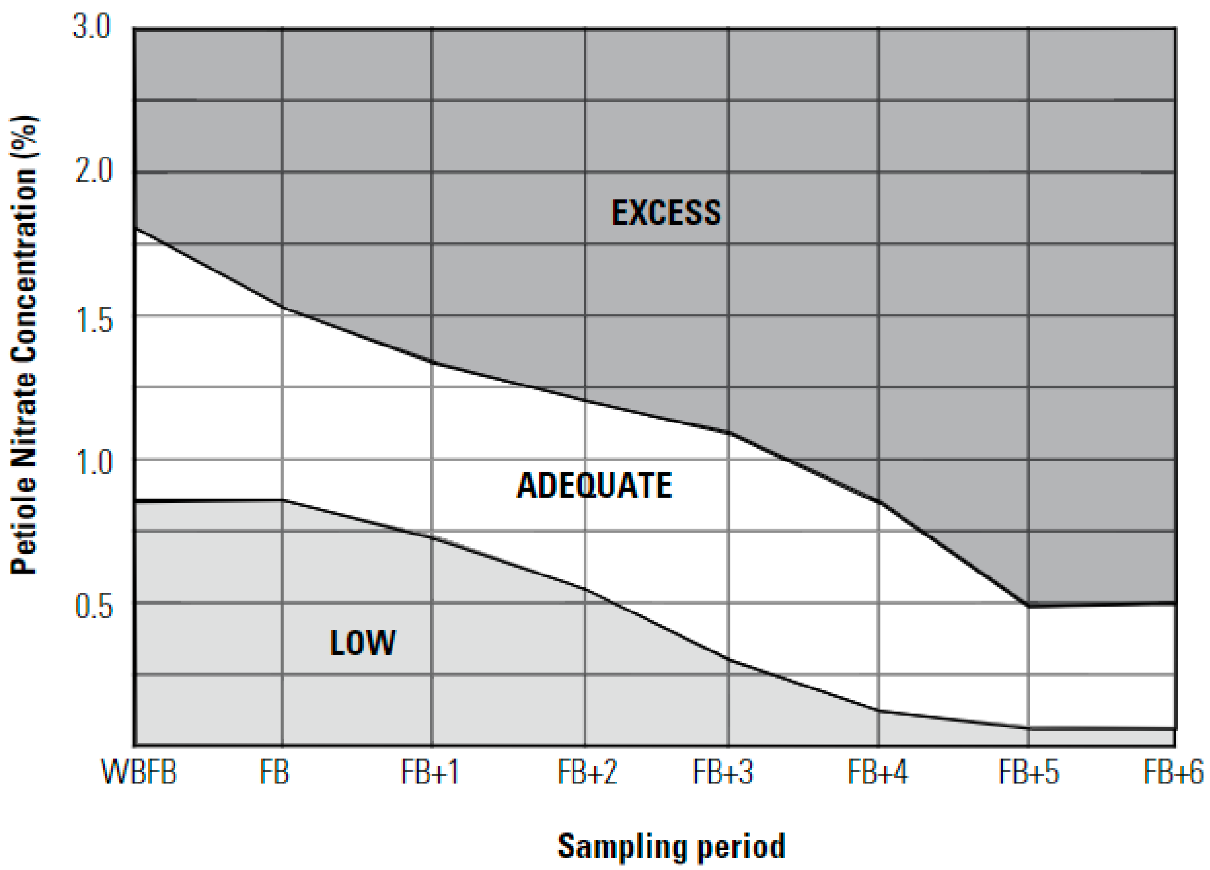


Figure 5.32 Ratings for petiole nitrate concentrations during the bloom period North Carolina (Gatiboni and Hardy 2021). Note: WBFB = Week before bloom, FB = First bloom, and the FB number indicates weeks after first bloom

Although the nitrogen levels in the models presented in Figure 5.29 and 5.30 are higher than the North Carolina guideline (Figure 5.32) the tendency for the nitrogen content of leaf petioles to reduce over time is the same. Once again, the higher levels measured in the local models can be explained by the fact that total nitrogen content is measured in the local models, whereas only nitrate nitrogen is measured by the North Carolina model depicted in Figure 5.32.

5.6 Conclusions

It is concluded that the two models as depicted in Figure 5.29 and Figure 5.30 can be used as guidelines to evaluate the nitrogen status of cotton during the growing season. One with the objective of producing maximum seed cotton yield and the other with the objective to produce the cotton crop that results in the maximum profit.

It is proposed that the two cotton leaf petiole guidelines be used in combination with the guidelines based on residual soil nitrogen as described in Chapter 4. By so-doing, the cotton leaf petiole guidelines can contribute to refining the nitrogen fertilization guidelines for irrigated cotton in South Africa.

By taking cotton leaf petiole samples from 63 days after sowing until 175 days after sowing the results of these analyses can indicate if the nitrogen status of the cotton plants sampled is low, adequate or excessive.

If diagnosed as being low, additional nitrogen can be applied to the crop in order to improve the nitrogen status thereof.

As this is a new fertilization guideline for cotton production in South Africa, it is suggested that the quantity of nitrogen to be applied to correct low nitrogen status be calculated as follows:

$$\text{Nitrogen to apply } = \frac{Model\ Petiole\ N - Petiole\ N}{Model\ Petiole\ N}\ X\ Target\ N$$

where:

Nitrogen to apply = The amount of nitrogen to apply as a corrective in season application (kg N ha^{-1})

Petiole N = The total nitrogen content of the cotton leaf petiole as sampled at the specific number of days after sowing (%)

Model Petiole N = The total nitrogen content of the cotton petiole to be sufficient as predicted by the model (%)

Target N = Target nitrogen fertilization rate as determined by the residual nitrogen content of the soil as elucidated upon in Chapter 4 (kg N ha^{-1})

The suggested cotton leaf petiole guidelines can provide a useful mechanism whereby additional nitrogen applications can be made in order to compensate for leaching and denitrification that are increasingly affecting cotton production in South Africa. Particularly so during wet seasons, such as we are currently experiencing under La Niña weather conditions.

5.7 Further research

Although the above guidelines can contribute to the refining of nitrogen fertilization guidelines for irrigated cotton in South Africa, further research in order to calibrate the quantities of nitrogen to be applied in order to improve the nitrogen status of the crop, based entirely on the total nitrogen content of cotton leaf petioles in field may prove to be useful.

Chapter 6
Glasshouse Evaluation of Nitrogen Guidelines Developed from Field Trials

6.1 Introduction

A glasshouse trial was done to evaluate the principles upon which the nitrogen fertilization guidelines for cotton, derived from data obtained in field trials (Chapter 4), was based on. When a nitrogen fertilization guideline compiled from data of this glasshouse trial corresponds with the nitrogen fertilization guideline compiled from that of the field trials, it would serve to support the validity of the latter.

6.2 Methodology

6.2.1 Experimental site, design and layout

The trial was planted in a glasshouse at the University of Pretoria, using five soils (prepared from milled quartzite) with known residual and mineralised nitrogen levels (Table 6.1). The soils had nitrogen levels which are representative of the cotton producing areas in South Africa, ranging from low to high.

Table 6.1 Location and nitrogen concentrations of the five soils used in the glasshouse trial

Soil	Location	Residual N (kg N ha^{-1})	Mineralised N (kg N ha^{-1})	Total N content (kg N ha^{-1})
1	Vaalwater	29	37	67
2	Brits	39	52	91
3	Skuinsdrif	68	70	138
4	Rustenburg	81	118	199
5	Oudestad	144	118	262

Five levels of nitrogen were applied to each soil, namely 0, 75, 150, 225 and 300 kg N ha^{-1} (Over and above the total N concentration of each soil).

The trial was laid out as a random block design with the five soils in combination with the five nitrogen levels. Each combination was repeated three times. Due to the possibility of spatial variation inside the glasshouse, the trial was fully randomised inside the glasshouse (Table 6.2).

Table 6.2 Experimental outlay of the glasshouse trial

Soil	Treatment number	Nitrogen application (kg N ha^{-1})
1	N3	150
5	N1	0
1	N2	75
1	N4	225
5	N3	150
2	N3	150
5	N5	300
2	N1	0
1	N1	0
3	N2	75
1	N5	300
5	N2	75
3	N3	150
3	N1	0
4	N5	300
2	N5	300
5	N4	225
4	N2	75
4	N3	150
4	N1	0
4	N4	225
2	N2	75
2	N4	225
3	N4	225
3	N5	300

6.2.2 Pot preparation and maintenance

Four seeds of the cotton variety Acala 1517-70 were planted in a pot. Within four days after germination the three weakest seedlings were removed. Milled quartzite was used as growth medium. Nine kilogram of the quartzite was weighed off into each pot and leached, firstly with tap water and then with deionised water. The water holding capacity of the quartzite in each pot was about four litre. Each pot had a container that could hold five litre of water. The nutrient solution used in each pot was diluted in nine litre of water.

The ratios amongst Ca, Mg and K in the nutrient solution was kept constant at 6:3:4. The ammonium level was kept constant at 10% of applied nitrogen. Phosphate was consistently applied at 0.5 me litre^{-1}. Iron and the other micronutrients were also consistently applied at the same levels throughout the trial. The sulphur content of the nutrient solutions was varied to balance the amount of nitrate applied.

The following sources of macronutrients were used: $CaSO_4$, $Ca(NO_3).4H_2O$, $MgSO_4.7H_2O$, $Mg(NO_3)_2$, KNO_3, K_2SO_4, KH_2PO_4, $NH_4H_2PO_4$, and $(NH_4)_2SO_4$.

The $CaSO_4$ was weighed off, and applied individually, per pot. All other macronutrients were weighed and dissolved in deionised water to prepare 1N stock solutions of each of the above substances.

The iron solution was prepared by dissolving 19.9 g $FeSO_4.7H_2O$ and 25.0 g of Fe EDTA in four litre of deionised water.

The general micronutrient stock solution was prepared by dissolving the following in four litres of deionised water: 2.4 g $Na_2B_4O_7$, 1.6 g $MnCl_2.4H_2O$, 0.0948 g $ZnSO_4$, 0.1365 g $CuSO_4$ and 0.1195 g $NaMoO_4.2H_2O$.

Both the iron and general micronutrient solutions were always applied at 1 ml litre^{-1} of nutrient solution.

Nitrogen fertilizations were split into three applications, namely at four, seven and ten weeks after planting. Nitrogen that was not utilised during this period was applied at thirteen and sixteen weeks after planting, to allow the full quota of nitrogen to be taken up by the plant.

The quantity of nitrogen that was applied during the trial is given in Table 6.3.

Table 6.3 Nitrogen applications made per plant (milli-equivalents N) during the trial

Soil and N level		me N applied per plant at weeks after planting						
		Initial	4 weeks	7 weeks	10 weeks	13 weeks	16 weeks	Total me N
1	N1	18	36	36	36	0	0	126.0
1	N2	18	63	63	63	46	0	253.0
1	N3	18	90	90	90	80	0	368.0
1	N4	18	117	117	117	106	0	475.0
1	N5	18	144	144	144	126	9	585.0
2	N1	27	54	54	54	0	0	189.0
2	N2	27	81	81	81	36	0	306.0
2	N3	27	108	108	108	64	4.5	419.5
2	N4	27	135	135	135	93	4.5	529.5
2	N5	27	162	162	162	141	18	672.0
3	N1	36	72	72	72	26	0	278.0
3	N2	36	99	99	99	50	0	383.0
3	N3	36	126	126	126	63	4.5	481.5
3	N4	36	153	153	153	108	9	612.0
3	N5	36	180	180	180	166	22.5	764.5
4	N1	54	99	99	99	8	0	359.0
4	N2	54	126	126	126	71	0	503.0
4	N3	54	153	153	153	81	4.5	598.5
4	N4	54	180	180	180	140	9	743.0
4	N5	54	207	207	207	132	13.5	820.5
5	N1	72	126	126	126	15	0	465.0
5	N2	72	153	153	153	57	0	588.0
5	N3	72	180	180	180	97	4.5	713.5
5	N4	72	207	207	207	90	4.5	787.5
5	N5	72	234	234	234	150	18	942.0

6.2.3 Sampling and analysis

Samples of the nutrient solution were taken from each of the three replications of a treatment combination, combined to make one sample, and analysed as a representative sample. These samples were taken at 4, 7, 10, 13, 16 and 19 weeks after planting and analysed for total nitrogen by steam distillation.

From the above analyses, the amount of nitrogen that was used by the plants during the preceding period, was calculated. Corrective applications, to supplement the quantities of nitrogen not used by the plants, were made at 13 and 16 weeks after planting. All the required nitrogen was utilised by the plants by week 19 after planting. Boll counts were done on each plant, at harvesting. The seed cotton yield of each plant was determined by harvesting and weighing ripe bolls that had burst open. All the bolls had ripened and burst open between weeks 19 to 26 after planting.

6.2.4 Statistical analysis

All the data obtained from the trial concerning the combinations of the five soils, five treatments and three repetitions, was subjected to an ANOVA, using Microsoft Excel. If a maximum seed cotton yield can be identified pertaining to the five treatments on each of the five soils, then a correlation was sought between the nitrogen contents of the five soils and the nitrogen fertilization required to achieve the maximum yield.

6.3 Results and discussion

In Table 6.4 the utilisation of applied nitrogen, measured at each time period, as well as the NUE is given. The NUE varied between 71% in Soil 3 for the 0 kg N ha^{-1} application, to 90% in Soil 1 at the 300 kg N ha^{-1} application. A tendency is observed that the NUE increased with higher levels of nitrogen fertilization, with an average NUE of 82% over all treatments for nitrogen applications that varied between 1.330 and 11.288 g $plant^{-1}$. Applications of nitrogen were successfully executed and achieved target with minimal deviations (Table 6.4).

Table 6.4 Average nitrogen uptake (me per plant) during the trial and nitrogen use efficiency

Soil	N level	Target me N per plant	N utilised weeks after planting (me per plant)						Total me N utilised	Total me N applied	NUE %
			4 weeks	7 weeks	10 weeks	13 weeks	16 weeks	19 weeks			
1	N1	95	1.80	28.35	36.00	35.55	0.00	0.00	101.70	126.0	80.71
1	N2	202	1.80	28.44	62.82	63.00	45.91	0.00	201.97	253.0	79.83
1	N3	309	1.80	46.44	90.00	90.00	79.91	0.00	308.15	368.0	83.74
1	N4	416	1.80	80.10	110.70	116.73	106.00	0.00	415.33	475.0	87.44
1	N5	523	1.80	113.67	137.07	138.96	123.84	9.00	524.34	585.0	89.63
2	N1	131	1.80	28.26	53.46	53.46	0.00	0.00	137.16	189.0	72.57
2	N2	238	1.80	39.07	80.82	81.00	36.00	0.00	238.69	306.0	78.00
2	N3	345	1.80	72.09	99.36	104.94	64.00	4.50	346.69	419.5	82.64
2	N4	452	1.80	97.38	124.83	131.67	93.00	4.50	453.18	529.5	85.59
2	N5	559	1.80	124.29	130.05	155.07	131.55	18.00	560.76	672.0	83.45
3	N1	197	1.80	25.83	71.64	72.00	25.73	0.00	197.00	278.0	70.86
3	N2	304	1.80	55.53	98.10	99.00	49.73	0.00	304.16	383.0	79.42
3	N3	411	1.80	96.66	123.93	123.75	62.19	4.50	412.83	481.5	85.74
3	N4	518	1.80	118.17	137.43	146.34	106.47	9.00	519.21	612.0	84.84
3	N5	625	1.80	138.33	139.32	177.03	148.63	22.50	627.61	764.5	82.09
4	N1	284	6.30	74.52	96.21	99.00	7.91	0.00	283.94	359.0	79.09
4	N2	391	6.30	72.54	115.47	124.29	70.73	0.00	389.33	503.0	77.40
4	N3	498	6.30	126.63	131.40	148.14	80.55	4.50	497.52	598.5	83.13
4	N4	605	6.30	133.29	145.89	177.39	131.63	9.00	603.50	743.0	81.22
4	N5	713	6.30	176.13	192.51	204.30	121.56	13.50	714.30	820.5	87.01
5	N1	373	22.70	89.73	119.79	126.00	14.73	0.00	372.95	465.0	80.20
5	N2	480	22.70	116.01	131.94	151.47	56.46	0.00	478.58	588.0	81.39
5	N3	588	22.70	150.84	138.15	176.49	96.73	4.50	589.41	713.5	82.61
5	N4	695	22.70	178.20	197.37	204.12	89.82	4.50	696.71	787.5	88.47
5	N5	802	22.70	194.31	201.33	228.87	138.75	18.00	803.96	942.0	85.35

6.3.1 Soil 1

Soil 1 was a simulation of cotton producing soils at Vaalwater, had a residual nitrogen content of 29 kg N ha^{-1} and a contribution of 37 kg N ha^{-1} from mineralisation, providing a total nitrogen content of 67 kg N ha^{-1} at sowing. As mentioned previously nitrogen fertilization levels were simulated to be 0, 75, 150, 225, and 300 kg N ha^{-1}. The seed cotton yields measured in the glasshouse trial are given in Table 6.5.

Table 6.5 Seed cotton yields measured in the glasshouse trial with Soil 1

Replication	N level (kg N ha^{-1})	Yield (g pot^{-1})	Bolls (pot^{-1})	Boll weight (g boll^{-1})	Yield (kg ha^{-1})
1	0	43.7	10	4.370	2 185
2	0	42.3	8	5.288	2 115
3	0	22.0	5	4.400	1 100
1	75	89.1	17	5.241	4 455
2	75	52.0	12	4.333	2 600
3	75	64.7	17	3.806	3 235
1	150	121.9	22	5.541	6 095
2	150	117.7	25	4.708	5 885
3	150	73.1	17	4.300	3 655
1	225	126.8	25	5.072	6 340
2	225	119.5	28	4.269	5 975
3	225	126.5	32	3.953	6 325
1	300	134.1	30	4.470	6 705
2	300	115.8	32	3.618	5 790
3	300	140.3	32	4.394	7 015

The best relationship between the seed cotton yields and nitrogen fertilization rates are given by a second-order polynomial regression depicted in Figure 6.1. A summary of regression statistics and ANOVA are given in Appendix 6.1.

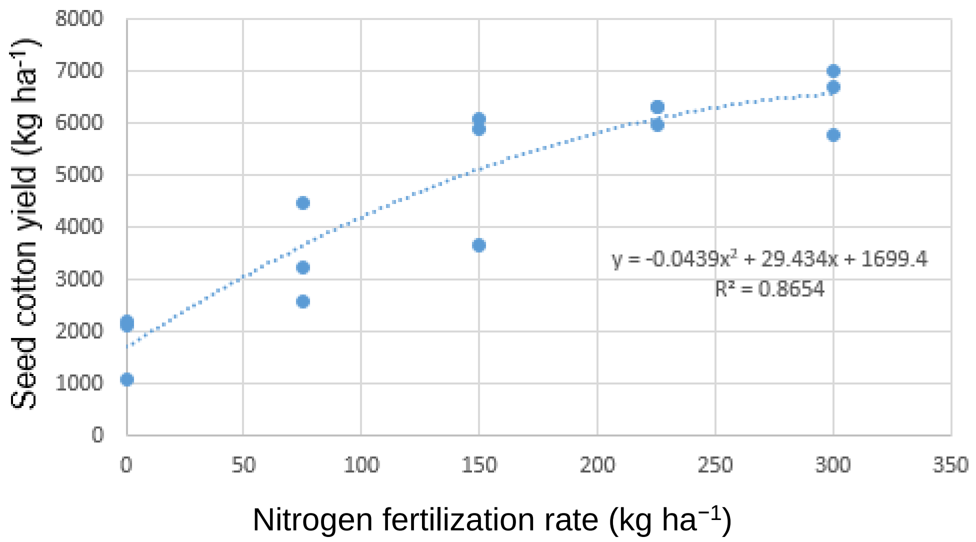


Figure 6.1 Second-order polynomial relationship between nitrogen fertilization rate and seed cotton yield for Soil 1

The second-order polynomial regression obtained between the nitrogen fertilization rate and seed cotton yield for Soil 1 as depicted in Figure 6.1 is highly significant, as can be seen in the summary of the ANOVA in Appendix 6.1. The turning point is at 335 kg N ha^{-1} for a maximum yield of 6 633 kg seed cotton ha^{-1}. From the latter it can be calculated that the total amount of nitrogen taken up by the plant over the growing season to achieve the above-mentioned maximum yield was 402 kg N ha^{-1} (Residual N at planting = 29.25 kg ha^{-1}, mineralised N = 37.35 kg ha^{-1} and N fertilization for maximum yield = 335.24 kg ha^{-1}).

The above nitrogen fertilization rate corresponds, with the calculated nitrogen fertilization rate of 330 kg N ha^{-1} for a maximum yield of 5 009 kg seed cotton ha^{-1} at Rustenburg Site 1 (oats) during the 1987/88 growing season as discussed in Chapter 4 (Table 4.6). At Rustenburg Site 1 (oats) during the 1987/88 growing season, the residual nitrogen content of the soil to a depth of 900 mm was 38 kg N ha^{-1}, nitrogen mineralisation was an additional 131 kg N ha^{-1} and the nitrogen fertilization required to produce maximum yield was 330 kg N ha^{-1}, resulting in the total amount of nitrogen available to the plant over the growing season being 499 kg N ha^{-1}.

The latter is 97 kg N ha^{-1} more than observed in Soil 1 during the glasshouse trial. This discrepancy can most probably be explained by the fact that the 402 kg N ha^{-1} in the glasshouse trial is nitrogen that has been taken up by the plant. At Rustenburg Site 1 (oats) during the 1987/88 growing season, the 499 kg N ha^{-1} referred to is plant available.

As the average NUE measured during the glasshouse trial was 82.1%, it implies that the calculated 402 kg N ha^{-1} taken up by the plants is the result of an application of 490 kg N ha^{-1}. As the difference of total available nitrogen over the growing season, between Soil 1 in the glasshouse trial and the field trial at Rustenburg Site 1 (oats) during the 1987/88 growing season is only 9 kg N ha^{-1}, it can be concluded that the results obtained in the glasshouse trial compare well with the field study results in this specific case.

6.3.2 Soil 2

Soil 2 was a simulation of cotton producing soils at Brits. The soil had a residual nitrogen content of 39 kg N ha^{-1} and a contribution of 52 kg N ha^{-1} from mineralisation, providing a total nitrogen content of 91 kg N ha^{-1} at sowing. Simulated nitrogen fertilization levels were 0, 75, 150, 225, and 300 kg N ha^{-1}. The seed cotton yields measured in the glasshouse trial are given in Table 6.6.

Table 6.6 Seed cotton yields measured from the glasshouse trial for Soil 2

Repetition	N level (kg N ha^{-1})	Yield (g pot^{-1})	Bolls (pot^{-1})	Boll weight (g boll^{-1})	Yield (kg ha^{-1})
1	0	21.7	9	2.411	1 085
2	0	28.4	11	2.582	1 420
3	0	45.9	11	4.173	2 295
1	75	109.1	24	4.546	5 455
2	75	120.9	22	5.495	6 045
3	75	90.6	18	5.033	4 530
1	150	98.2	18	5.456	4 910
2	150	127.3	23	5.535	6 365
3	150	127.5	25	5.100	6 375
1	225	88.3	22	4.014	4 415
2	225	142.7	28	5.096	7 135
3	225	148.1	28	5.289	7 405
1	300	130.9	27	4.848	6 545
2	300	133.3	25	5.332	6 665
3	300	135.8	25	5.432	6 790

The best relationship between the seed cotton yields and nitrogen fertilization rates are given by the second-order polynomial regression depicted in Figure 6.2. A summary of regression statistics and ANOVA is given in Appendix 6.2.

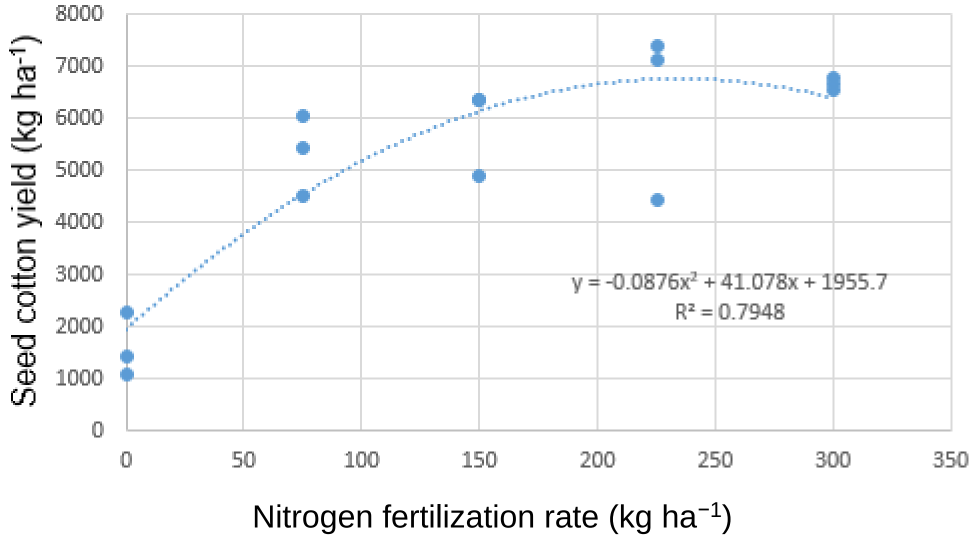


Figure 6.2 Second-order polynomial relationship between nitrogen fertilization rate and seed cotton yield for Soil 2 in the glasshouse trial

The second-order polynomial regression depicted in Figure 6.2 is highly significant, as can be seen in the summary of the ANOVA in Appendix 6.2. The turning point is at 235 kg N ha^{-1} at a maximum yield of 6 771 kg seed cotton ha^{-1}. From the latter it can be calculated that the total amount of nitrogen taken up by the plant over the growing season to achieve the maximum yield was 326 kg N ha^{-1} (Residual N at planting = 39.38 kg ha^{-1}, mineralised N = 51.75 kg ha^{-1} and N fertilization for maximum yield = 234.46 kg ha^{-1}).

The nitrogen fertilization rate corresponds with the calculated nitrogen fertilization rate of 253 kg N ha^{-1} for maximum yield of 5 314 kg seed cotton ha^{-1} at Rustenburg Site 2 (babala) during the 1989/90 growing season as discussed in Chapter 4 (Table 4.6). At Rustenburg Site 2 (babala) during the 1989/90 growing season, the residual nitrogen content of the soil to a depth of 900 mm was 34 kg ha^{-1}, nitrogen mineralisation was an additional 110 kg N ha^{-1} and the nitrogen fertilization required to produce maximum yield was 253 kg ha^{-1}, resulting in the total amount of nitrogen available to the plant over the growing season being 397 kg ha^{-1}.

The latter is 71 kg N ha^{-1} more than that observed in Soil 2 in the glasshouse trial. This discrepancy can most probably be explained by the fact that the 326 kg N ha^{-1} in the glasshouse trial is nitrogen that has been taken up by the plant. At Rustenburg Site 2 (babala) during the 1989/90 growing season, the 397 kg ha^{-1} referred to is plant available nitrogen.

As the average NUE measured during the glasshouse trial was 82.1%, it implies that the calculated 326 kg N ha^{-1} taken up by the plants is the result of an application of 397 kg N ha^{-1}. As the amount of total available nitrogen over the growing season, between Soil 2 of the glasshouse trial and the field trial performed at Rustenburg Site 2 (babala) during the 1989/90 growing season is exactly the same, the conclusion can be made that the results obtained in the glasshouse trial compare well to the field results in this specific case.

6.3.3 Soil 3

Soil 3 was a simulation of cotton producing soils at Skuinsdrif. The soil had a residual nitrogen content of 68 kg N ha^{-1} and a contribution of 70 kg N ha^{-1} from mineralisation, providing a total nitrogen content of 138 kg N ha^{-1} in the soil at sowing. The nitrogen fertilization levels were simulated to be 0, 75, 150, 225, and 300 kg N ha^{-1}. Seed cotton yields measured in the glasshouse trial are given in Table 6.7.

Table 6.7 Seed cotton yields measured from the glasshouse trial for Soil 3

Repetition	N level (kg N ha^{-1})	Yield (g pot^{-1})	Bolls (pot^{-1})	Boll weight (g boll^{-1})	Yield (kg ha^{-1})
1	0	5.5	3	1.833	275
2	0	83.5	14	5.964	4 175
3	0	89.1	17	5.241	4 455
1	75	85.6	19	4.505	4 280
2	75	110.3	23	4.796	5 515
3	75	102.4	22	4.655	5 120
1	150	144.2	25	5.768	7 210
2	150	130.6	30	4.353	6 530
3	150	133.3	27	4.937	6 665
1	225	134.9	32	4.216	6 745
2	225	135.1	30	4.503	6 755
3	225	150.3	26	5.781	7 515
1	300	112.0	24	4.692	5 630
2	300	123.9	26	4.765	6 195
3	300	176.9	37	4.781	8 845

The best relationship between the seed cotton yields and nitrogen fertilization rates are given by the second-order polynomial regression depicted in Figure 6.3. A summary of regression statistics and ANOVA are given in Appendix 6.3.

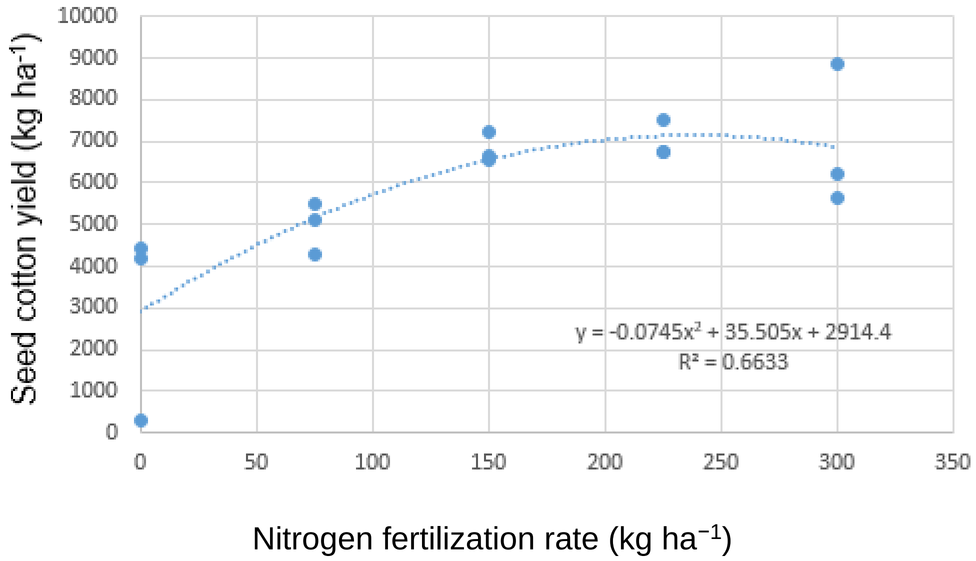


Figure 6.3 Second-order polynomial relationship between nitrogen fertilization rate and seed cotton yield for Soil 3 in the glasshouse trials

The second-order polynomial regression between nitrogen fertilization rate and seed cotton yield for Soil 3 as depicted in Figure 6.3 is highly significant, as can be seen in the summary of the ANOVA in Appendix 6.3. The turning point is at 238 kg N ha^{-1} for a maximum yield of 7 145 kg seed cotton ha^{-1}. From the latter it can be calculated that the total amount of nitrogen taken up by the plant over the growing season in the glasshouse to achieve the maximum yield was 376 kg N ha^{-1} (Residual N at planting = 68.40 kg ha^{-1}, mineralised N = 69.5 kg ha^{-1} and N fertilization for maximum yield = 238 kg ha^{-1}).

The nitrogen fertilization rate corresponds with the calculated nitrogen fertilization rate of 221 kg N ha^{-1} for maximum yield of 5 260 kg seed cotton ha^{-1} observed at Vaalharts during the 1988/89 growing season as discussed in Chapter 4 (Table 4.6). At Vaalharts during the 1988/89 growing season, the residual nitrogen content of the soil to a depth of 900 mm was 50 kg ha^{-1}, nitrogen mineralisation was an additional 147 kg N ha^{-1} and the nitrogen fertilization required to produce maximum yield was 221 kg ha^{-1}, resulting in the total amount of nitrogen available to the plant over the growing season being 418 kg ha^{-1}.

The latter is 42 kg N ha^{-1} more than observed in Soil 3 during the glasshouse trial. This discrepancy can most probably be explained by the fact that the 37 kg N ha^{-1} in the glasshouse trial is nitrogen that has been taken up by the plant. At Vaalharts during the 1988/89 growing season, the 418 kg ha^{-1} referred to is plant available nitrogen.

As the average NUE measured during the glasshouse trial was 82.1%, it implies that the calculated 376 kg N ha^{-1} taken up by the plants is the result of an application of 458 kg N ha^{-1}. As the difference of total available nitrogen over the growing season, between Soil 3 of the glasshouse trial and the field trial performed at Vaalharts during the 1988/89 growing season is 40 kg N ha^{-1}, the conclusion can be made that the results obtained in the glasshouse trial compare reasonably well to the field results in this specific case.

6.3.4 Soil 4

Soil 4 was a simulation of cotton producing soils at Rustenburg. The soil had a residual nitrogen content of 81 kg N ha^{-1} and a contribution of 118 kg N ha^{-1} from mineralisation, providing a total nitrogen content of 199 kg N ha^{-1} in the soil at sowing. The nitrogen fertilization levels that were simulated are 0, 75, 150, 225, and 300 kg N ha^{-1}. The seed cotton yields measured in the glasshouse trial are given in Table 6.8.

Table 6.8 Seed cotton yields measured from the glasshouse trial for Soil 4

Repetition	N level (kg N ha^{-1})	Yield (g pot^{-1})	Bolls (pot^{1})	Boll weight (g boll^{-1})	Yield (kg ha^{-1})
1	0	84.4	19	4.442	4 220
2	0	76.7	18	4.261	3 835
3	0	51.9	16	3.244	2 595
1	75	124.1	24	5.171	6 205
2	75	71.2	20	3.560	3 560
3	75	143.4	25	5.736	7 170
1	150	70.1	16	4.381	3 505
2	150	62.5	16	3.906	3 125
3	150	150.0	30	5.000	7 500
1	225	97.8	21	4.657	4 890
2	225	87.1	20	4.355	4 355
3	225	124.1	26	4.773	6 205
1	300	109.2	25	4.368	5 460
2	300	50.4	13	3.877	2 520
3	300	130.9	28	4.675	6 545

The best relationship between the seed cotton yields for Soil 4 and the nitrogen fertilization rates are given by a second-order polynomial regression depicted in Figure 6.4. A summary of regression statistics and ANOVA are given in Appendix 6.4.

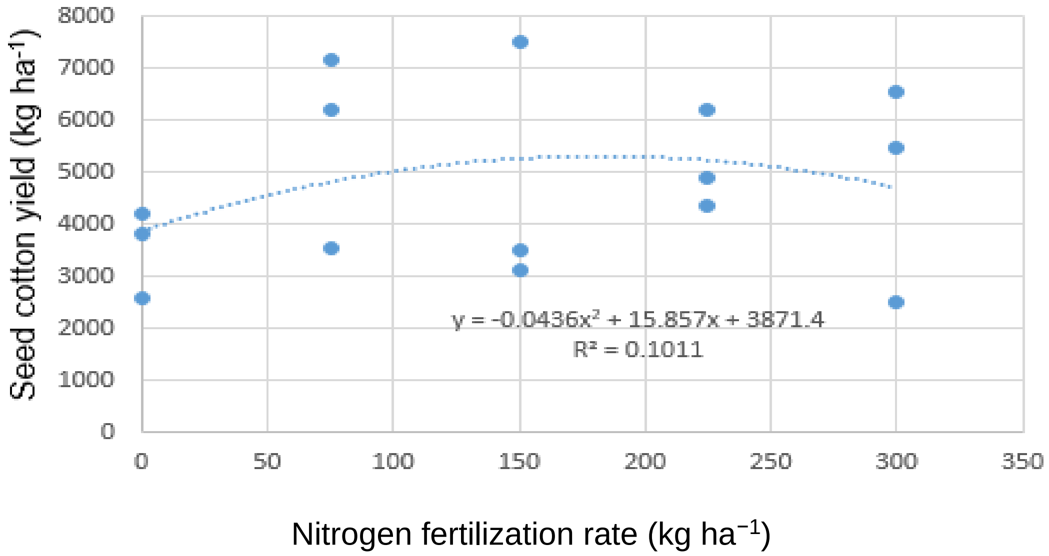


Figure 6.4 Second-order polynomial relationship between nitrogen fertilization rate and seed cotton yield for Soil 4 in the glasshouse trials

The second-order polynomial regression between nitrogen fertilization rate and seed cotton yield for Soil 4 as depicted in Figure 6.4 is significant, as can be seen in the summary of ANOVA in Appendix 6.4. The turning point is at 182 kg N ha^{-1} for a maximum yield of 5 313 kg seed cotton ha^{-1}. From the latter it can be calculated that the total amount of nitrogen taken up by the plant over the growing season to achieve the maximum yield was 381 kg N ha^{-1} (Residual N at planting = 81 kg ha^{-1}, mineralised N = 118 kg ha^{-1} and N fertilization for maximum yield = 182 kg ha^{-1}).

The nitrogen fertilization rate corresponds with the calculated nitrogen fertilization rate of 137 kg N ha^{-1} for a maximum yield of 5 262 kg seed cotton ha^{-1} at Rustenburg Site 2 (soybeans plough) during the 1989/90 growing season as discussed in Chapter 4 (Table 4.6). At Rustenburg Site 2 (soybeans ploughed in) during the 1989/90 growing season, the residual nitrogen content of the soil to a depth of 900 mm was 71 kg ha^{-1}, nitrogen mineralisation was an additional 243 kg N ha^{-1} and the nitrogen fertilization required to produce a maximum yield was 137 kg ha^{-1}, resulting in a total amount of nitrogen available to the plant over the growing season being 451 kg ha^{-1}.

The latter is 70 kg N ha^{-1} more than observed in Soil 4 in the glasshouse trial. This discrepancy can most probably be explained by the fact that the 381 kg N ha^{-1} in the glasshouse trial is nitrogen that has been taken up by the plant. At Rustenburg Site 2 (soybeans ploughed in) during the 1989/90 growing season, the 451 kg ha^{-1} referred to is plant available nitrogen.

As the average NUE measured during the glasshouse trial was 82.1%, it implies that the calculated 381 kg N ha^{-1} taken up by the plants is the result of an application of 464 kg N ha^{-1}. As the difference of total available nitrogen over the growing season, between Soil 4 of the glasshouse trial and the field trial at Rustenburg Site 2 (soybeans ploughed in) during the 1989/90 growing season is 13 kg N ha^{-1}, the conclusion can be made that the results obtained in the glasshouse trial compare well to the field results in this specific case.

6.3.5 Soil 5

Soil 5 was a simulation of cotton producing soils at Oudestad. The soil had a residual nitrogen content of 145 kg N ha^{-1} and a contribution of 118 kg N ha^{-1} from mineralisation, providing a total nitrogen content of 262 kg N ha^{-1} in the soil at sowing. The nitrogen fertilization levels were 0, 75, 150, 225, and 300 kg N ha^{-1}. The seed cotton yields measured in the glasshouse trial are given in Table 6.9.

Table 6.9 Seed cotton yields measured from the glasshouse trial for Soil 5

Repetition	N level (kg N ha^{-1})	Yield (g pot^{-1})	Bolls (pot^{-1})	Boll weight (g boll^{-1})	Yield (kg ha^{-1})
1	0	85.9	16	5.369	4 295
2	0	93.4	21	4.448	4 670
3	0	83.4	21	3.971	4 170
1	75	130.2	28	4.650	6 510
2	75	75.4	25	3.016	3 770
3	75	68.1	19	3.584	3 405
1	150	54.4	16	3.400	2 720
2	150	37.9	18	2.106	1 895
3	150	150.0	32	4.688	7 500
1	225	71.3	16	4.457	3 565
2	225	112.7	25	4.507	5 635
3	225	95.8	21	4.564	4 790
1	300	63.9	21	3.047	3 195
2	300	76.5	24	3.188	3 825
3	300	102.8	25	4.112	5 140

The best relationship between the seed cotton yields and nitrogen fertilization rates is described by a second-order polynomial regression depicted in Figure 6.5. A summary of regression statistics and ANOVA are given in Appendix 6.5.

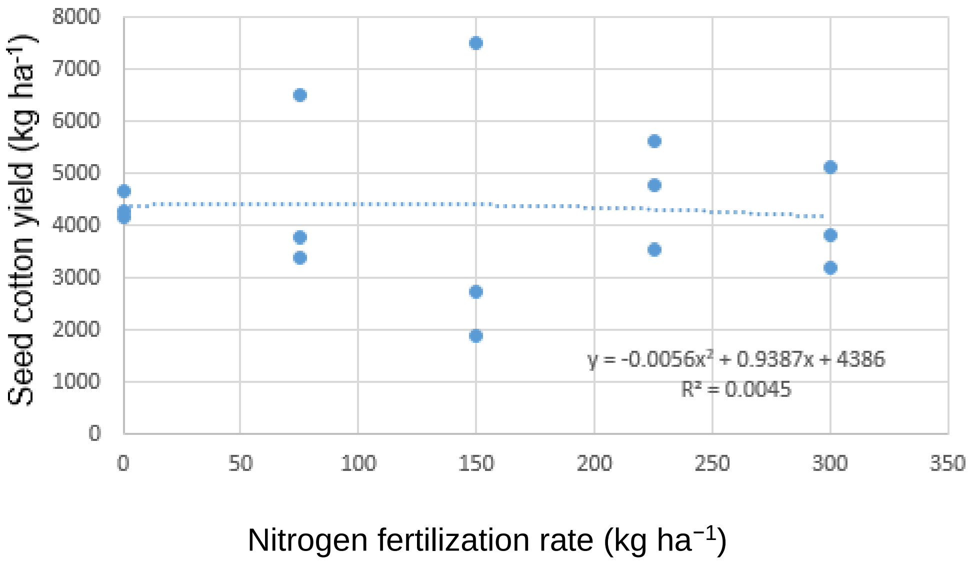


Figure 6.5 Second-order polynomial relationship between nitrogen fertilization rate and seed cotton yield for Soil 5 in the glasshouse trials

The second-order polynomial regression between the nitrogen fertilization rate and seed cotton yield for Soil 5 as depicted in Figure 6.5 is not significant, as can be seen in the summary of ANOVA in Appendix 6.5. However, the turning point is at 84 kg N ha^{-1} for a maximum yield of 4 425 kg seed cotton ha^{-1}. From the latter it can be calculated that the total amount of nitrogen taken up by the plant over the growing season to achieve the maximum yield was 346 kg N ha^{-1} (Residual N at planting = 144.45 kg ha^{-1}, mineralised N = 117.9 kg ha^{-1} and N fertilization for maximum yield = 83.81 kg ha^{-1}).

The nitrogen fertilization rate corresponds with the calculated nitrogen fertilization rate of 137 kg N ha^{-1} for a maximum yield of 5 262 kg seed cotton ha^{-1} observed at Rustenburg Site 2 (soybeans ploughed in) during the 1989/90 growing season as discussed in Chapter 4 (Table 4.6). At Rustenburg Site 2 (soybeans ploughed in) during the 1989/90 growing season, the residual nitrogen content of the soil to a depth of 900 mm was 71 kg ha^{-1}, nitrogen mineralisation was an additional 243 kg N ha^{-1} and the nitrogen fertilization required to produce maximum yield was 137 kg ha^{-1}, resulting in a total amount of nitrogen available to the plant over the growing season being 451 kg ha^{-1}.

The latter is 105 kg N ha^{-1} more than observed in Soil 5 during the glasshouse trial. This discrepancy can most probably be partly explained by the fact that the 346 kg N ha^{-1} in the glasshouse trial is nitrogen that has been taken up by the plant. At Rustenburg Site 2 (soybeans ploughed in) during the 1989/90 growing season, the 451 kg ha^{-1} referred to is plant available nitrogen.

As the average NUE measured during the glasshouse trial was 82.1%, it implies that the calculated 346 kg N ha^{-1} taken up by the plants is the result of an application of 421 kg N ha^{-1}. As the difference of total available nitrogen over the growing season, between Soil 5 of the glasshouse trial and the field trial at Rustenburg Site 2 (soybeans ploughed in) during the 1989/90 growing season is 30 kg N ha^{-1}, the conclusion can be made that the results obtained in the glasshouse trial compare well to the field results in this specific case.

The data of the glasshouse study corresponds well with the data of the field study. Therefore, a similar approach as with the data of the field study was followed to develop a nitrogen fertilization guide with data of the glasshouse study as discussed below.

6.3.6 Nitrogen fertilization guideline based on glasshouse data

A summary of the data pertaining to the total residual nitrogen content of the soils at planting and the nitrogen fertilization level associated with maximum seed cotton yield is given in Table 6.10.

Table 6.10 Total residual nitrogen content of simulated soils and nitrogen fertilization level associated with maximum seed cotton yield

Soil number	Residual N (kg N ha^{-1})	Total residual N content of soil (kg N ha^{-1})	Nitrogen fertilization level associated with maximum yield (kg N ha^{-1})
1	29	67	335
2	39	91	234
3	68	138	238
4	81	199	182
5	144.45	262	84

The relationship between the total residual nitrogen content and nitrogen fertilization rate required to produce maximum seed cotton yield in each of the soils, is given in Figure 6.6. A summary of regression statistics and ANOVA are given in Appendix 6.6.

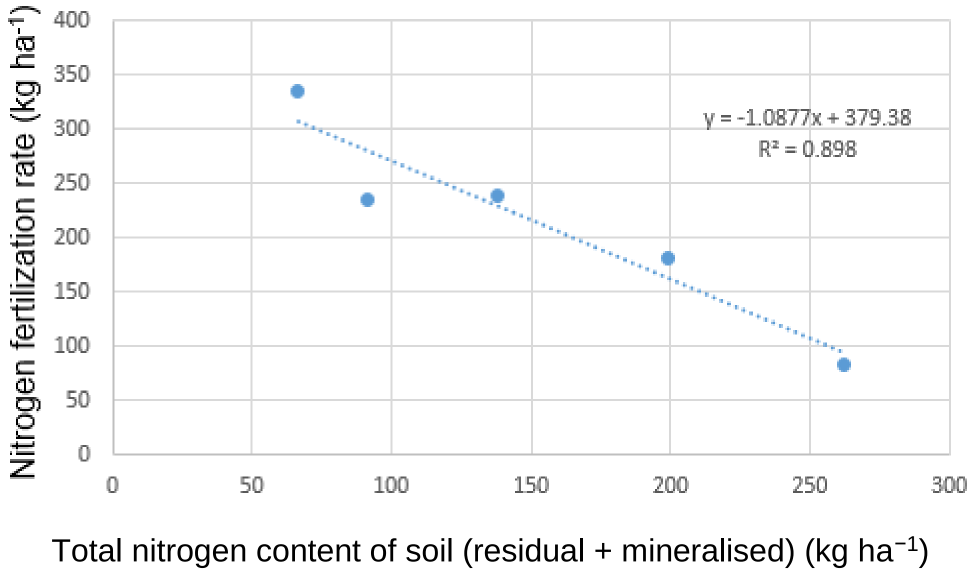


Figure 6.6 Linear relationship between nitrogen fertilization rate associated with maximum yield and total residual nitrogen in the simulated soils at planting in the glasshouse trials

From the linear regression equation given in Figure 6.6 ($Y = -1.0877X + 379.38$) it can be calculated that the intersection with the Y-axis is at 379 kg N ha^{-1}. This implies that if there was no residual nitrogen in the soil or any contribution of nitrogen through mineralisation from the soil during the growing season, a cotton crop would have to be fertilized with 379 kg N ha^{-1} to produce the maximum achievable yield.

Furthermore, using the above linear regression equation, it can be determined that the intersection with the X-axis is at 349 kg N ha^{-1}, implying that if the total nitrogen contribution from the soil during the growing season amounted to 349 kg N ha^{-1} if no additional nitrogen fertilization would be required to produce a maximum cotton yield.

The guideline compiled using data of the field trials, correlating the residual nitrogen content of the soil to a depth of 900 mm at planting with the nitrogen fertilization rate required to produce maximum seed cotton yield is previously given in Chapter 4 in Figure 4.46. For ease of reference and comparison, it is given again here as Figure 6.7.

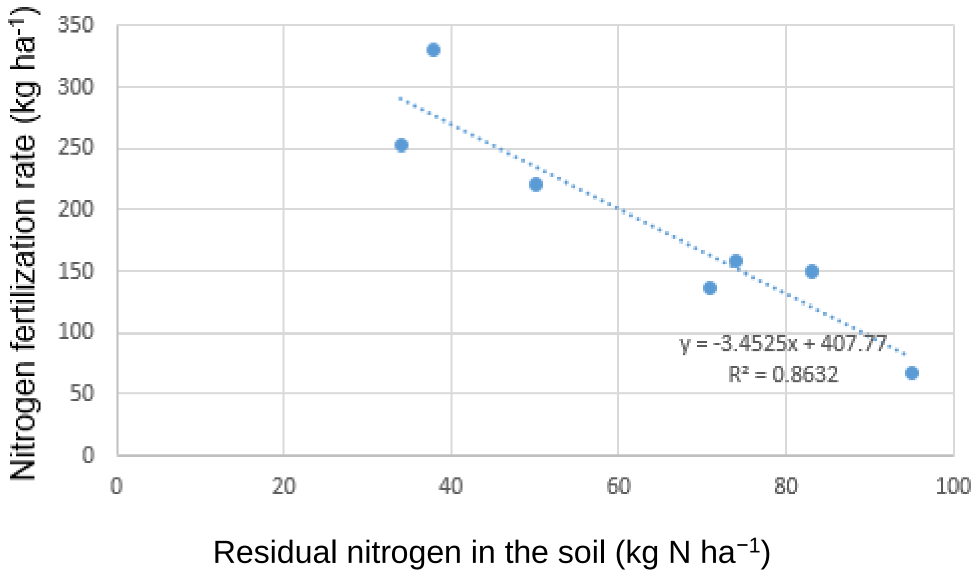


Figure 6.7 Linear regression between residual soil nitrogen (0–900 mm) in kg N ha^{-1} at planting time and nitrogen fertilization for maximum yield in kg N ha^{-1} as obtained from field trials

From the linear correlation equation given in Figure 6.7, it can be calculated that the interception with the Y-axis is at 408 kg N ha^{-1}. This implies that if there were no residual nitrogen in the soil to a depth of 900 mm at planting a nitrogen fertilization rate of 408 kg ha^{-1} would be required to produce the maximum seed cotton yield. This amount is higher than the 379 kg N ha^{-1} derived from the glasshouse regression equation.

Furthermore, using the linear regression equation in Figure 6.7, it can be determined that the intersection with the X-axis is at 118 kg N ha^{-1}. This implies that if the total residual nitrogen content of the soil at planting is 118 kg ha^{-1} no further nitrogen fertilization would be required to produce a maximum cotton yield. This figure is lower than the 349 kg N ha^{-1} calculated from the regression equation obtained in the glasshouse trial.

As the glasshouse trial was based on nitrogen that has been taken up by the plant and the average NUE was 82.1%, the X- and Y-intercepts must be adjusted to be comparable to the data obtained from the field trials which were based on plant available nitrogen in the soil. Once the data from the glasshouse trial is adjusted, the Y-axis intercept is at 462 kg N ha^{-1} and the X-axis intercept is 424.84 kg N ha^{-1}.

These amounts are substantially higher than the amounts obtained from the relationship between residual nitrogen at planting and nitrogen fertilization rate required to produce maximum yield as depicted in Figure 6.7. The difference can most probably be partly explained by the contribution of nitrogen mineralisation over the growing season in the field trials. To establish a relationship from the glasshouse trial data that is comparable to the one in Figure 6.7, the nitrogen mineralisation component is removed and residual nitrogen content of the soil at planting is related to the nitrogen fertilization rate required to produce maximum yield (Figure 6.8). A summary of the ANOVA of the relationship is given in Appendix 6.7.

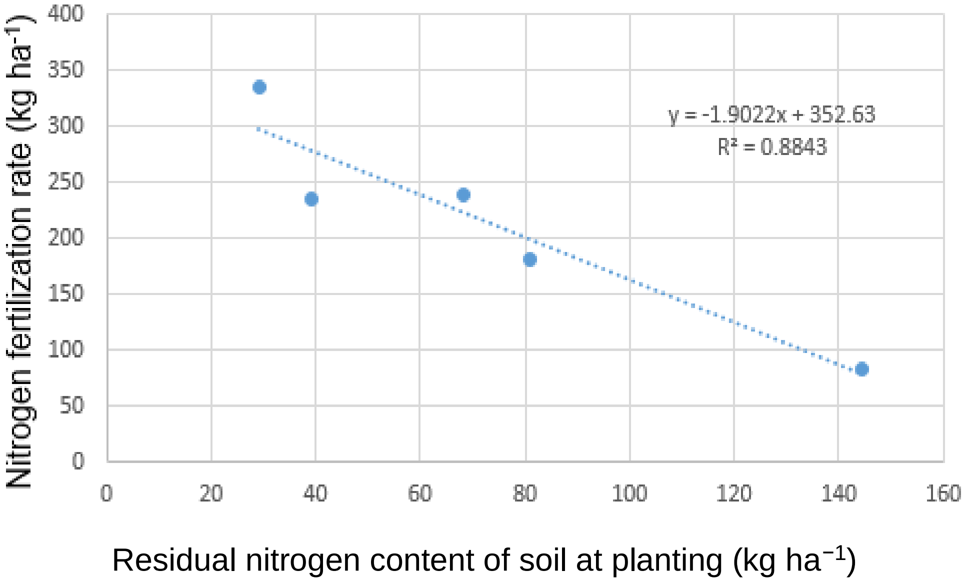


Figure 6.8 Linear relationship between nitrogen fertilization rate associated with maximum yield and residual nitrogen in the simulated soils at planting time in the glasshouse trials

From the linear regression equation given in Figure 6.8 ($Y = -1.9022X + 352.63$), it can be calculated that the intersection with the Y-axis is at 353 kg N ha^{-1}. This implies that if there was no residual nitrogen in the soil or any contribution of nitrogen through mineralisation from the soil during the growing season, a cotton crop would have to be fertilized with 353 kg N ha^{-1} to produce the maximum achievable yield. As this value is based on nitrogen that has been taken up by the plant and not on plant available nitrogen, it implies that the value for plant available nitrogen, using the average NUE of 82.1% for the glasshouse trial, is 430 kg N ha^{-1}.

Similarly, the X-axis intercept of 185 g N ha^{-1} taken up by the plant would equate to 226 N ha^{-1} plant available nitrogen, comparable to the relationship in Figure 6.7.

The Y-axis intercept of the guideline obtained using data from the field trials is at 408 kg N ha^{-1} compared to the 430 kg N ha^{-1} determined using data from the glasshouse trial. The Y-axis intercept of the relationship given in Figure 6.8 is 22 kg N ha^{-1} plant available nitrogen higher than the amount predicted by the relationship in Figure 6.7. This difference could be attributed to a difference in environmental factors influencing cotton growth and nitrogen uptake in the glasshouse, compared to that experienced in field trials.

The X-axis intercept of the guideline obtained using data from the field trials is at 118 kg N ha^{-1} compared to the 226 kg N ha^{-1} determined using data from the glasshouse trial. The X-axis intercept of the relationship given in Figure 6.8 is 108 kg N ha^{-1} plant available nitrogen, higher than the amount predicted by the relationship in Figure 6.7. This difference is substantial and could most probably be explained by the range of residual nitrogen used in Figure 6.7 (varying between 38 and 95 kg N ha^{-1}) and the range in the compilation of Figure 6.8 (varying between 29 and 145 kg N ha^{-1}), which is a 52% wider range.

6.4 Conclusion

The results of the glasshouse study agreed well with those of the field study, implying that the guidelines developed from the field study can be applied with confidence.

Although the intercepts of the Y-axis and the X-axis as calculated from the regression equation obtained from the glasshouse trials seem high, Rochester (2014) is of the opinion that nitrogen fertilization rates as high as 320 to 420 kg ha^{-1} would be required to produce a yield of 5 000 kg cotton lint ha^{-1}. The amounts observed from the data collected from the glasshouse trials (Figure 6.8) are within the range envisaged by Rochester (2014), as are the levels obtained from the field trials (Figure 6.7).

Although the gradients and exact intersections with the X- and Y-axis differ, the general trend of the relationships obtained were adapted for plant available nitrogen ($Y = -1.9022X + 429.51$; Figure 6.8) and ($Y = -3.4525X + 407.77$; Figure 6.7) are similar in nature. The range of predictions that can be made from the nitrogen fertilization guideline as given in Figure 6.7 is comparable to the results obtained from data collected during the glasshouse trials.

In conclusion, the glasshouse trial confirms the nature and validity of the nitrogen fertilization guideline of the field study as presented in Figure 4.46. Following this confirmation, the nitrogen fertilization guideline as given in Figure 6.7 can be used for the purpose of refining the existing nitrogen fertilization guidelines for irrigated cotton in South Africa.

Chapter 7

Summary, Synthesis and Conclusion

7.1 Introduction

As mentioned in Chapter 1, cotton has been cultivated for many millennia. In Southern Africa it has been documented by Portuguese explorers as early as 1516 (Van Heerden 1988). Commercial cotton production in South Africa was initiated by an American missionary, Dr Adams who brought cotton seed from North America in 1846. Currently approximately 450 commercial farmers and 2000 developing farmers are producing cotton in South Africa.

With a potential income of R102 140 ha^{-1} for irrigated cotton, and R23 498 ha^{-1} for dryland cotton (Botha 2020), the crop is an excellent potential wealth generator. As 75% of the South African cotton crop is picked by hand, it also has the potential to create employment on a large scale, sustain livelihoods and feed families in a time where South Africa faces wide-spread job losses due to the corona virus pandemic. The cotton industry currently provides employment for 65 000 workers from production to retail sales (Agriculture 2020).

During 2019/20 the global cotton production was 25 826 400 tons, produced from an area of 33 760 000 ha (Johnson and Soley 2020). The South African crop accounted for 0.09% of global cotton production. If directly extrapolated from the South African scenario, it is possible that almost 75 million people are employed by the cotton industry worldwide. If each person employed by the cotton industry provides for a family of five individuals, it is possible that the lives of about 375 million people are affected by the global cotton industry. Therefore, any contribution towards ensuring the stability and sustainability of the cotton industry will have a positive impact on many people.

Apart from the vast socio-economic impact that successful cotton production can have on South Africa and the rest of the world, so can the environmental effects of unsustainable production practices impact negatively on the globe. Therefore, environmentally sustainable fertilization practices of cotton and in particular nitrogen fertilization, is essential. Nitrogen fertilization is of particular importance due to the fact that over fertilization thereof potentially contributes to elevated levels of N_2O in the atmosphere, which is the worst greenhouse gas of all, as well as the potential pollution of groundwater with nitrate. Both these contaminants have potentially disastrous consequences on the environment.

Therefore, cotton production has the potential to harbour vast advantages for humanity if managed well, or have devastating consequences if managed in an environmentally unsustainable manner.

In addition to the above, the tendency of the clothing market in the developed world is towards natural fibres, such as cotton. The market is driven by well-informed consumers with the desire to support sustainable agriculture producing renewable resources with a low carbon footprint.

Considering the above, the decision was made to contribute towards the cotton industry by investigating and refining existing nitrogen fertilization guidelines for cotton produced under irrigation in South Africa. The purpose of this refinement is to reduce the number of assumptions or “guess-timations” that need to be made by cotton producers and so-doing contribute to the economically optimal and environmentally sustainable production of cotton.

7.2 Current South African nitrogen fertilization guideline

The nitrogen fertilization guideline that is currently in use for irrigated cotton production in South Africa (Fertasa 2016), was proposed by Steenkamp and Jansen (1998), who based the guideline in principle on a nitrogen balance sheet developed by Halevy (1976; 1979) and Halevey and Bazelet (1989) from research done in Israel. The current nitrogen fertilization guideline is represented by the following equation:

$$E = A - (B + C + D)$$

where:

E = the nitrogen fertilization required to produce the crop of a selected yield (at an assumed utilization factor of 80%). Bronson (2008), reported nitrogen utilization factors of up to 75%, depending on the method of fertilizer application in the west Texas cotton belt

A = the amount of nitrogen removed by the crop for a specific yield (250 kg N ha^{-1} for a seed cotton yield of 4 500 kg ha^{-1} or higher

B = the residual inorganic nitrogen in the soil to a depth of 900 mm prior to planting (of which 66.7% is estimated to be utilised by the cotton crop)

C = the estimated mineralisation of organic nitrogen in the soil over the growing season, namely 60 kg N ha^{-1} for sandy soils, 120 kg N ha^{-1} for loam soils and 160 kg N ha^{-1} for clay soils (of which 66.7% is estimated to be utilised by the cotton crop)

D = the nitrogen present in 400 mm of the irrigation water used to grow the crop (of which 80% is estimated to be utilised by the cotton crop)

Good results have been obtained by using this approach in South Africa and it has been used by the local cotton industry for the past 24 years. However, the need has arisen for nitrogen fertilization on cotton to be done more precisely due to the rising price of nitrogen fertilizers as well as pressing environmental factors as discussed.

No nitrogen fertilization guideline that is based on the in-season nitrogen analysis of cotton leaf petioles is currently in use in South Africa.

7.3 Objectives of study

The objectives of this research were the following:

- To refine and simplify the existing nitrogen fertilization guidelines of cotton under irrigation that are based on the residual nitrogen content of the soil prior to, or at planting.
- To evaluate the above refined nitrogen fertilization guidelines under controlled glasshouse conditions.
- To develop a cotton leaf petiole guideline for in season use, based on the total nitrogen content of the leaf petiole.

7.4 Use of soil nitrogen analysis

7.4.1 Refining of nitrogen fertilization guideline for maximum yield based on residual soil nitrogen

Several field trials (discussed in detail in Chapter 3 and 4) were done in the irrigated areas of South Africa where cotton is cultivated. In these trials the residual nitrogen content of the soil (0–300 mm, 0–600 mm and 0–900 mm soil depth) was determined and the response of seed cotton yields to nitrogen application levels was quantified. The data was subjected to analyses of variance and presented in the format of either tables or box plots. Moreover, the relationships between nitrogen application rates and seed cotton yields were subjected to polynomial regressions, allowing the calculation at which nitrogen application, maximum seed cotton yield is achieved. Polynomial regressions were also done between profits and levels of nitrogen application to establish which rate gave the maximum profit. In a few instances, however, the data did not allow for the establishment of a nitrogen rate at which either the maximum yield or maximum profit realised.

Once the nitrogen application rate that has led to the maximum yield in seed cotton on a specific trial has been determined, this level of nitrogen was correlated with the residual nitrogen content of the soil at planting (together with the amount of nitrogen produced by incubation), for all the different trials performed. This correlation then provided a guideline between residual nitrogen in the soil and nitrogen fertilization required to produce maximum yield or maximum profit.

The relationship between the residual soil nitrogen content of the soil (0–300 mm) in kg N ha^{-1} at planting time versus the nitrogen fertilization level in kg N ha^{-1} that produced the maximum seed cotton yield measured in the field trials is given in Figure 4.43 of Chapter 4. For ease of reference Figure 4.43 is given here again as Figure 7.1.

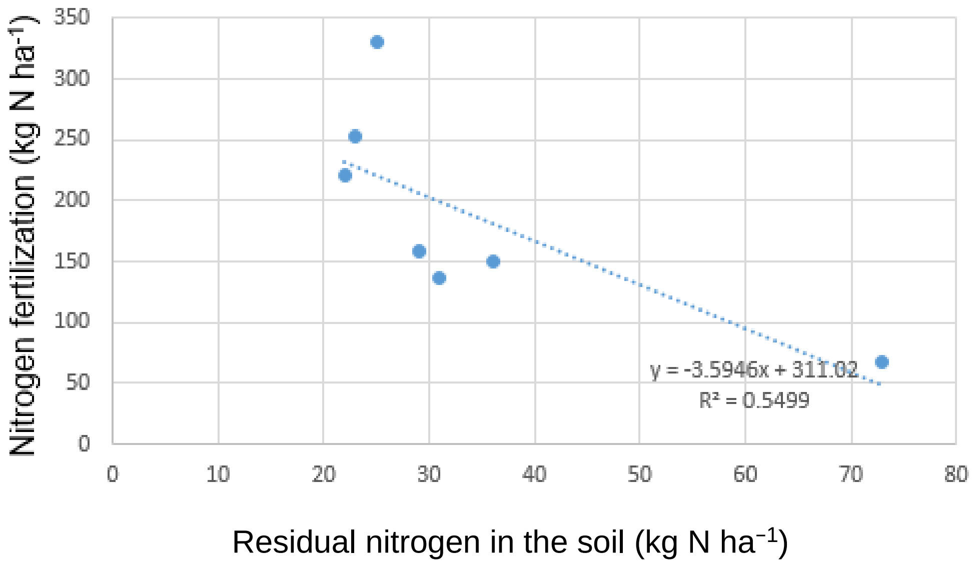


Figure 7.1 Linear regression between residual soil nitrogen (0–300 mm) in kg N ha^{-1} at planting time and nitrogen fertilization for maximum yield in kg N ha^{-1}

The correlation coefficient for the above linear regression is significant ($R^2 = 0.55$) which indicates that there is a significant relationship between the residual nitrogen content of the soil at planting time and the nitrogen fertilization level required to produce maximum seed cotton yield. A summary of the statistical analysis of data used in Figure 4.43 is given in Appendix 4.8. Figure 7.1 confirms similar findings in Australia by Smith and Welsh (2018) as depicted in Figure 2.7 in Chapter 2. For ease of reference, Figure 2.7 will be given here again as Figure 7.2.

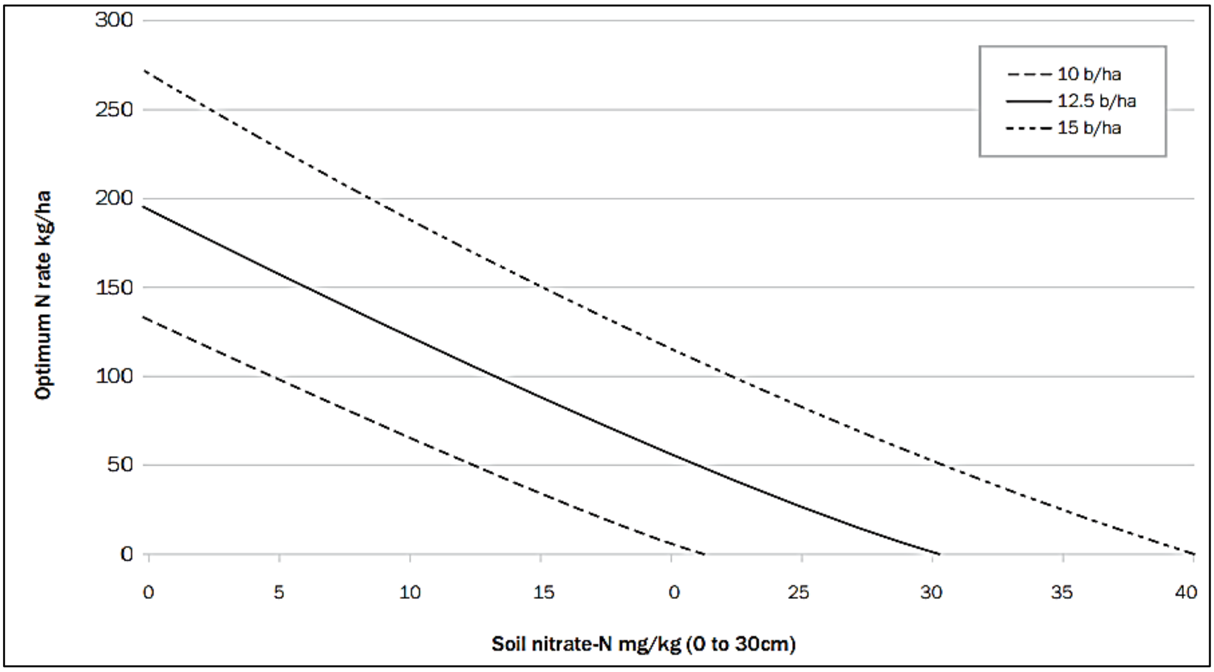


Figure 7.2 Relationship between the optimum nitrogen fertilization requirement for irrigated cotton, based on the residual nitrate content of the soil (0–300 mm depth) taken in Australia during September, one month before planting cotton (Smith and Welsh 2018)

It is interesting to note that the linear regression in Figure 7.1 intersects the Y-axis at 311 kg N ha^{-1}, slightly higher than the 275 kg N ha^{-1} of Smith and Welsh (2018) for the higher yield. The intersection of the regression line with the X-axis in Figure 7.1 is at a residual nitrogen content of 86.5 kg N ha^{-1} in the soil, which is close to the 21 mg N kg^{-1} (94.5 kg N ha^{-1}) residual soil nitrate-N, and the X-axis intersection for lower yield in Figure 7.2 (Smith and Welsh 2018). Although the regression line obtained in Figure 7.1 is not exactly the same as in Figure 7.2, it is within the same range, considering that the soil analyses for Figure 7.2 were taken one month before planting and those for Figure 7.1 were taken at planting.

The relationship between the residual soil nitrogen content of the soil (0–600 mm) at planting versus the nitrogen fertilization level that produced the maximum seed cotton yield measured in the field trials was also determined. It is however the relationship obtained for the 0–900 mm soil depth that will be proposed as a refined nitrogen fertilization guideline for the nitrogen fertilization of irrigated cotton to produce maximum yield and is given in Figure 4.45 of Chapter 4. For ease of reference Figure 4.45 will be given again here as Figure 7.3.

The relationship between the residual soil nitrogen content of the soil (0–900 mm) in kg N ha^{-1} at planting time versus the nitrogen fertilization level in kg N ha^{-1} that produced the maximum seed cotton yield measured in the field trials is given in Figure 7.3.

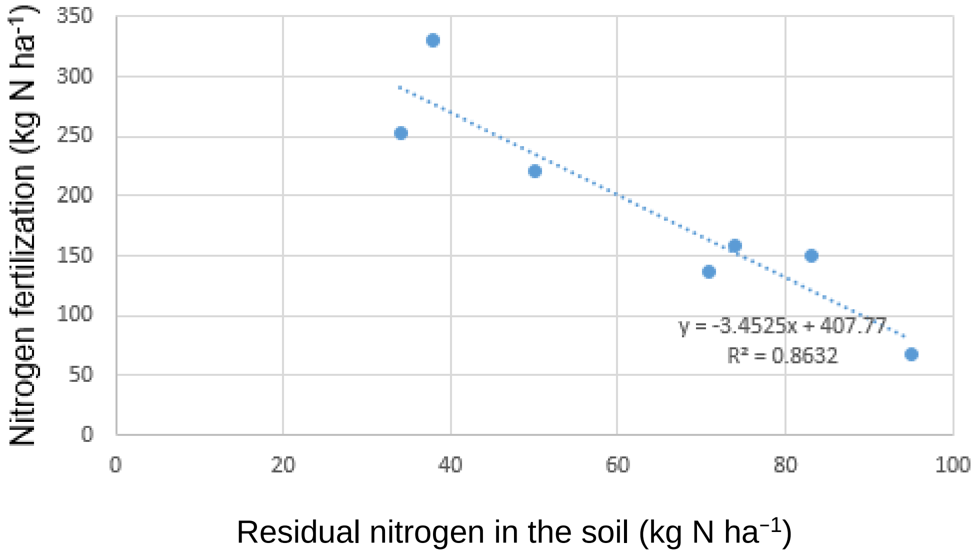


Figure 7.3 Linear regression between residual soil nitrogen (0–900 mm) in kg N ha^{-1} at planting time and nitrogen fertilization for maximum yield in kg N ha^{-1}

The correlation coefficient for the above linear regression is highly significant ($R^2 = 0.86$) which indicates that there is a highly significant relationship between the residual nitrogen content of the soil to a depth of 0–900 mm at planting time and the nitrogen fertilization level required to produce maximum seed cotton yield. A summary of the statistical analysis of data used in Figure 7.3 is given in Appendix 4.10. The Y-axis intercept of the regression in Figure 4.46 is at nitrogen fertilization rate of 407.8 kg N ha^{-1} and the X-axis intercept is at 118.1 kg N ha^{-1} residual in the soil at planting time.

Due to the high level of significance of the above linear correlation it is suggested that this regression equation can be used as an additional aid in the calculation of the nitrogen fertilization of cotton to achieve maximum yield in South Africa and thereby contribute to the refining of nitrogen fertilization guidelines for irrigated cotton in South Africa. The correlations and regression equations obtained from the 0–300 mm (Figure

4.43), as well as the 0–600 mm (Figure 4.45) soil depths may also prove to be useful for this purpose where residual soil nitrogen data is not available to a depth of 0–900 mm.

7.4.2 Refining of nitrogen fertilization guideline for maximum profit based on residual soil nitrogen

The relationship between the residual soil nitrogen content of the soil at depths of 0–300 mm and 0–600 mm in kg N ha^{-1} at planting time versus the nitrogen fertilization level that produced the maximum profit measured in the field trials was determined in Chapter 4. It is however the relationship obtained for the 0–900 mm soil depth that will be proposed as a refined nitrogen fertilization guideline for the nitrogen fertilization of irrigated cotton to produce maximum profit and is given in Chapter 4 as Figure 4.49. For ease of reference Figure 4.49 will be given again here as Figure 7.4.

The relationship between the residual soil nitrogen content (0–900 mm) in kg N ha^{-1} at planting time versus the nitrogen fertilization level in kg N ha^{-1} that produced the maximum profit measured in the field trials is given in Figure 7.4.

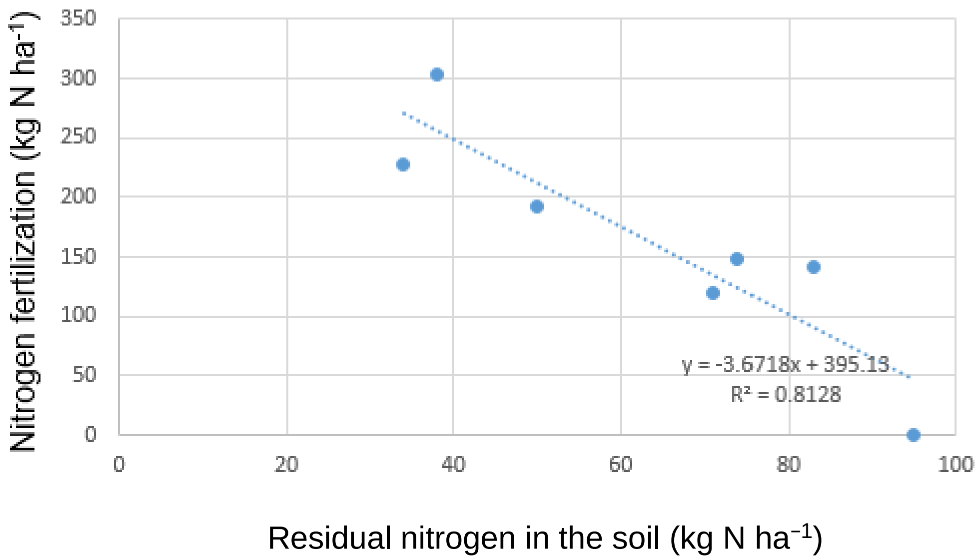


Figure 7.4 Linear regression between residual soil nitrogen (0–900 mm) in kg N ha^{-1} at planting time and nitrogen fertilization for maximum profit in kg N ha^{-1}

The correlation coefficient for the above linear regression is highly significant (R^2 = 0.81) which indicates that there is a highly significant relationship between the residual nitrogen content of the soil to a depth of 0–900 mm at planting time and the nitrogen fertilization level required to produce maximum seed cotton yield. A summary of the statistical analysis of data used in Figure 7.4 is given in Appendix 4.13. The Y-axis intercept of the regression in Figure 7.4 is at nitrogen fertilization rate of 395.1 kg N ha^{-1} and the X-axis intercept is at 107.6 kg N ha^{-1} residual in the soil at planting time.

Due to the high level of significance of the above linear correlation it is suggested that this regression equation be used as an additional aid in the calculation of the nitrogen fertilization of cotton to achieve maximum profit in cotton production in South Africa. The correlations and regression equations obtained from the 0–300 mm (Figure 4. 47), as well as the 0–600 mm (Figure 4.48) soil depths may also prove to be useful for this purpose where residual soil nitrogen data is not available to a depth of 0–900 mm. These findings can contribute to the refinement of nitrogen fertilization guidelines for irrigated cotton in South Africa.

From the field trials done nitrogen fertilization guidelines for irrigated cotton that allow for the use of residual nitrogen plus nitrogen mineralisation for a soil depth of 0–900 mm to produce maximum yield as well as maximum profit have been determined. All the regressions obtained that are proposed for nitrogen fertilization guidelines are given in Table 7.1.

Table 7.1 Proposed nitrogen fertilization guidelines for maximum yield and maximum profit using residual nitrogen content of the soil at planting as well as nitrogen mineralisation

Soil analysis	Maximum yield or maximum profit	Soil depth (mm)	Guideline equation	Significance
Residual	Maximum yield	0–300	$Y = -3.5946X + 311.02$	$r^2 = 0.5499^{**}$
Residual	Maximum yield	0–600	$Y = -3.9067X + 383.06$	$r^2 = 0.7736^{**}$
Residual	Maximum yield	0–900	$Y = -3.4525X + 407.77$	$r^2 = 0.8632^{**}$
Residual	Maximum profit	0–300	$Y = -4.4737X + 314.46$	$r^2 = 0.709^{**}$
Residual	Maximum profit	0–600	$Y = -4.4870X + 385.42$	$r^2 = 0.8495^{**}$
Residual	Maximum profit	0–900	$Y = -3.6718X + 395.13$	$r^2 = 0.8128^{**}$
Res+ min	Maximum yield	0–900	$Y = -0.7402X + 335.48$	$r^2 = 0.2662^{**}$
Res+ min	Maximum profit	0–900	$Y = -0.8268X + 326.12$	$r^2 = 0.2764^{**}$

*Res+min = Residual and mineralisation; **Statistically significant

The last two proposed guidelines in Table 7.1 use residual soil nitrogen at planting plus mineralised soil nitrogen to predict the required nitrogen fertilization rate. It is suggested that actual determined nitrogen mineralisation levels (using soil incubation methods) are used when calculating the nitrogen requirement of irrigated cotton where they are available. This is in preference to the nitrogen mineralisation levels provided by the Fertasa (2016) procedure, which rely on generalised nitrogen mineralisation values based on soil texture. Actual soil nitrogen mineralisation measurements will obviously be more accurate and contribute to a better prediction of the required nitrogen fertilization rate.

7.4.3 Refining of nitrogen fertilization guideline by adjustment of the existing guideline for yields above 4 500 kg ha^{-1}

From this study it is evident that the South African nitrogen fertilization guidelines for cotton as supported by Fertasa (2016), correlate well with data obtained with the field trials done at various locations. However once seed cotton yields exceed 4 500 kg ha^{-1}, the existing nitrogen fertilization recommendations are apparently not as accurate as below 4 500 kg ha^{-1}. A nitrogen extraction of 250 kg N ha^{-1} is not sufficient under conditions where seed cotton yields in excess of 4 500 kg ha^{-1} are produced. Therefore, it is recommended that the existing nitrogen fertilization guidelines for cotton should be refined by amending it to provide for an additional nitrogen extraction of 56 kg ha^{-1} for every 1 000 kg of seed cotton produced or fertilized for a yield in excess of 4 500 kg ha^{-1}. The amount of 56 kg N ha^{-1} is suggested until further research has been conducted under South African conditions to provide accurate, scientifically based data regarding nitrogen extraction data for seed cotton yields exceeding 4 500 kg ha^{-1}.

This finding is supported by a significant correlation that was obtained between the adjusted predicted nitrogen fertilization rate (Fertasa 2016) and the observed nitrogen fertilization rate required to produce maximum yield in the field trials. The latter compared to an insignificant correlation found between the unadjusted nitrogen fertilization rates predicted and observed nitrogen fertilization rates required to produce maximum seed cotton yield in the field trials (discussed in detail in Section 4.8.3.5).

Although the correlation coefficient for the mentioned linear regression is low, it is significant (R^2 = 0.12) with F = 0.45 and F critical = 0.68 which is better than the relationship found with the Fertasa (2016) procedure. This indicates that the adjusted procedure is indeed an improvement on the Fertasa (2016) procedure and can contribute to the refining of nitrogen fertilization guidelines for irrigated cotton in South Africa. A summary of the statistical analysis of data used in Figure 4.54 is given in Appendix 4.18.

7.4.4 Refining of nitrogen fertilization guideline by introduction of nitrogen use efficiency

The NUE of cotton was determined from the data obtained from the trials.

TNUE was determined by the following equation:

$$\mathrm{TNUE} = \frac{\mathrm{Yc}}{(\mathrm{Nr} + \mathrm{Nm} + \mathrm{Na})}$$

where,

Y_c = seed cotton yield (kg ha^{-1})

N_r = residual nitrogen in the soil (kg ha^{-1})

N_m = mineralised nitrogen in the soil (kg ha^{-1})

N_a = applied nitrogen (kg ha^{-1})

The NFUE as used by MacDonald et al. (2019) in Australia, was also determined using the following equation:

$$\mathrm{NFUE} = \frac{\mathrm{Yc}}{\mathrm{Na}}$$

Although TNUE is a unique calculation to this study, and average values vary between 12.1 and 13.8, there are no existing references to TNUE in literature. However, Rochester (2014) and MacDonald et al. (2018), have done extensive work on NFUE, the calculation of which has been elucidated on in the introduction. According to their findings long term nitrogen fertilization trials in Australia have shown that the optimum NFUE range for irrigated cotton grown under nitrogen fertilization rates of between 100 and 300 kg ha^{-1}, varies between 13 and 18 kg cotton lint ha^{-1} for every kilogram of nitrogen applied as fertilizer. As seed cotton contains between 33% and 40% lint, the optimum range (for yield measured as seed cotton) would equate to between 32.5 and 39.0 and between 45 and 54, respectively. For the purpose of this study, NFUE levels of between 32.5 and 54 will be viewed as optimal. Lower than optimal levels indicate potential nitrogen losses and higher than optimum levels indicate potentially excessive extraction of soil nitrogen (MacDonald et al. 2018).

It is suggested that the use of NUE measurements such as TNUE and NFUE be introduced into the nitrogen fertilization recommendation program in South Africa. This can contribute to the refinement of nitrogen fertilization guidelines for irrigated cotton in South Africa. It is suggested that the initial parameters for TNUE and NFUE be between 32.5 and 54.0 for seed cotton production until further research can be done on the topic. The use of TNUE and NFUE measurements as a management tool to assist farmers to ensure the best possible utilization of applied nitrogen during the growing of a cotton crop, will not only be financially rewarding to the farmer, but also be environmentally responsible, by limiting losses of nitrogen into the atmosphere and ground water.

7.4.5 Evaluation of field guideline under controlled glasshouse conditions

A glasshouse trial (discussed in detail in Chapter 6) was designed to evaluate the principles upon which the nitrogen fertilization guideline for cotton, derived from data obtained during field trials in Chapter 4, was based and compiled. If a similar nitrogen fertilization guideline can be compiled using data obtained from a glasshouse trial, it would serve to support the validity of the guideline obtained under field conditions.

Five different soils with known residual and mineralised nitrogen levels were simulated in the glasshouse trial. The soils were selected to represent known soils used for cotton production in South Africa, ranging from low to high nitrogen levels.

A summary of the data obtained from the glasshouse trial is given in Table 6.15 in Chapter 6. For ease of reference, Table 6.15 is given again here as Table 7.2.

Table 7.2 Total residual nitrogen content of simulated soils and nitrogen fertilization level associated with maximum seed cotton yield

Soil number	Residual N (kg N ha^{-1})	Total residual N content of soil (kg N ha^{-1})	Nitrogen fertilization level associated with maximum yield (kg N ha^{-1})
1	29	67	335
2	39	91	234
3	68	138	238
4	81	199	182
5	144	262	84

The relationship between the total residual nitrogen content of the simulated soils and the nitrogen fertilization rate required to produce maximum seed cotton yield in each of the simulated soils, is given in Figure 6.6, which for ease of reference is given again here as Figure 7.5.

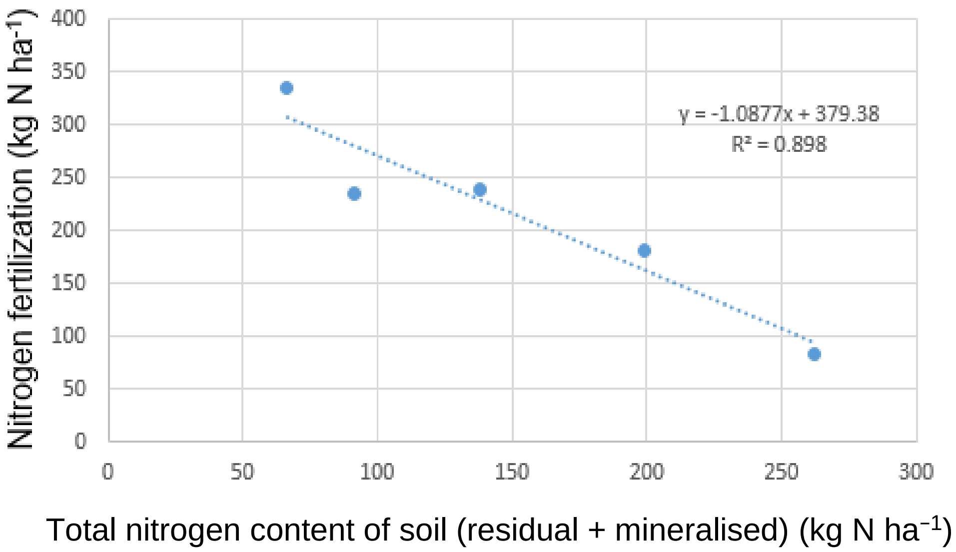


Figure 7.5 Linear relationship between nitrogen fertilization rate associated with maximum yield and total residual nitrogen in the simulated soils at planting in the glasshouse trials

The relationship between the residual nitrogen content of the soils and the nitrogen fertilization rate required to produce maximum seed cotton yield in each of the simulated soils, is given in Figure 6.7, which for ease of reference is given again here as Figure 7.6.

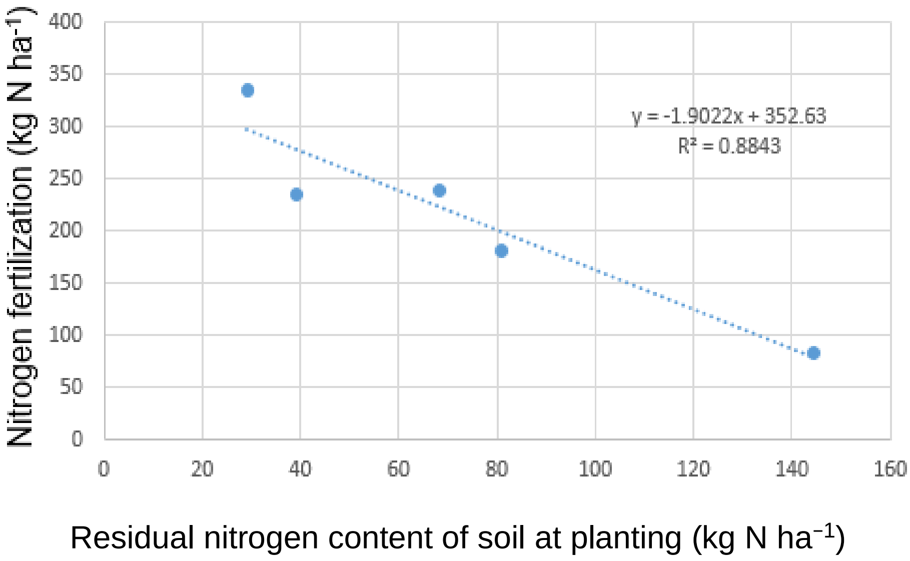


Figure 7.6 Linear relationship between nitrogen fertilization rate associated with maximum yield and residual nitrogen in the simulated soils at planting time in the glasshouse trials

The guideline compiled using data obtained from the field trials correlating with the residual nitrogen content of the soil to a depth of 900 mm at planting time, and the nitrogen fertilization rate required to produce maximum seed cotton yield is previously given in Figure 4.46 of Chapter 4. For ease of reference and comparison, it is given again here as Figure 7.7.

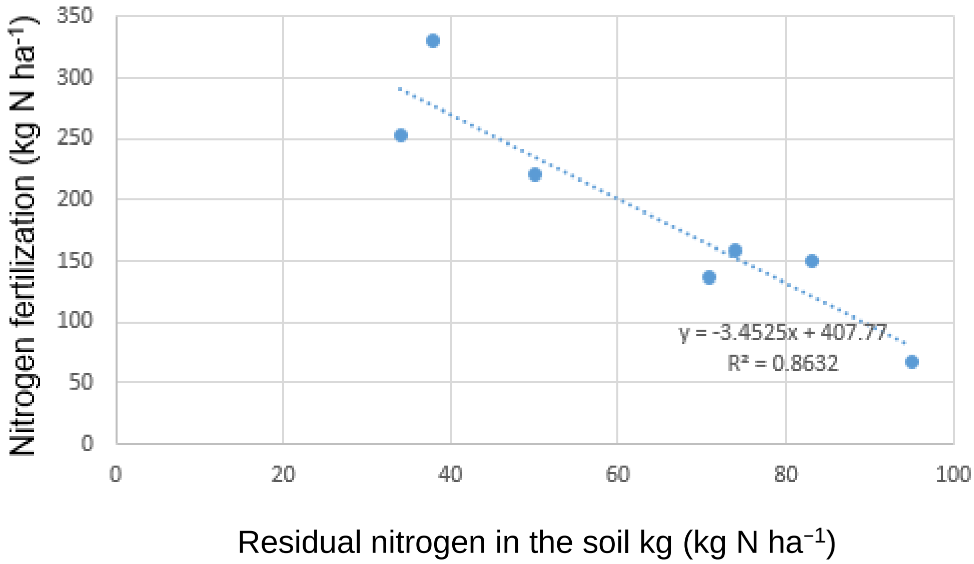


Figure 7.7 Linear regression between residual soil nitrogen (0–900 mm) in kg N ha^{-1} at planting time and nitrogen fertilization for maximum yield in kg N ha^{-1}

Although the intercepts of the Y-axis and the X-axis as calculated from the regression equation obtained from the glasshouse trials seem high, Rochester (2014) is of the opinion that nitrogen fertilization rates as high as 320 to 420 kg ha^{-1} would be required to produce a yield of 5 000 kg cotton lint ha^{-1}. The figures observed from the data collected from the glasshouse trials (Figure 7.6) are within the range envisaged by Rochester (2014), as are the levels obtained from the field trials (Figure 7.3).

Although the gradients and exact intersections with the X- and Y-axes differ, the general trend of the relationships reported in Figure 7.6 adapted for plant available nitrogen ($Y = -1.9022X + 429.51$) and Figure 4.46 ($Y = -3.4525X + 407.77$) are similar in nature. The range of predictions that can be made from the nitrogen fertilization guideline as given in Figure 7.3 is comparable to the results found from data collected from the glasshouse trials.

Therefore, the conclusion can be made that the glasshouse trials confirm the nature and validity of the nitrogen fertilization guideline presented in Figure 7.3. Following this confirmation, the nitrogen fertilization guideline as given in Figure 7.3 can be used for the purpose of refining the existing nitrogen fertilization guidelines for irrigated cotton in South Africa.

7.5 Use of cotton nitrogen leaf petiole analyses

Leaf petiole samples were taken from the cotton plants in each field trial plot at regular intervals during the growing season and the total nitrogen content was determined (as discussed in detail in Chapter 5). The results thereof were used to produce a graph of the total nitrogen content of the cotton leaf petiole over time.

The concept of using leaf petioles to evaluate the in-field nitrogen nutrition status of cotton originated at the Texas Agricultural Experiment Station form research done by Joham (1951).

In many of the eastern US states that experience high rainfall (Texas, Georgia, Arkansas, North Carolina and South Carolina) preference is given to the use of in-season cotton leaf petiole analyses of nitrate nitrogen to estimate the nitrogen fertilization of cotton above the use of preplant soil analyses of residual nitrogen (Oosterhuis 1992, Cleveland 2012, Jones et al. 2019, Gatiboni and Hardy 2021). This is most probably due to various losses of nitrogen, such as the leaching and denitrification that occur in the soil under these conditions and can lead to changes in the amount of plant available soil nitrogen between the time of sampling and plant uptake (Baird and Smith 2019).

However, because leaf petiole nitrate is prone to large fluctuations, caused by factors such as soil water content, air temperature, time of day and boll load, many of the other US states do not use leaf petiole nitrate analyses to evaluate the nitrogen status of cotton in field (Mitchell and Baker 1997) and preference is given to soil analyses for residual nitrogen.

As soil nitrogen losses are presumably less under arid and semi-arid conditions (such as encountered in the western US states, Israel. Australia and South Africa) it seems that more success is obtained using residual soil nitrogen measured preplant to predict the optimal nitrogen fertilization of cotton under these conditions (Breitenbeck 1990). Under these conditions, it can be expected that residual nitrogen soil tests would be preferred above leaf petiole tests for nitrate nitrogen, as residual nitrogen soil tests are potentially more stable.

However, this is not necessarily the case, as nitrate nitrogen analyses on cotton leaf petioles are used successfully to predict the optimal nitrogen fertilization of cotton in California (Hutmacher 2017). It is interesting to note that the critical values used in nitrogen fertilization guidelines in California (Table 2.4) are more than twice as high as the values used in South Carolina, depicted in Table 2.5 (Jones et al. 2019). This could possibly be due to higher uptake of nitrogen in the generally drier climate of California and a more diluted uptake of nitrogen in the generally wetter climate of South Carolina.

Rochester (2012) confirms the complimentary use of both residual soil nitrogen analyses as well as cotton leaf petiole nitrate nitrogen analyses for the determination of optimal nitrogen fertilization of cotton in Australia. Soil analyses for residual soil nitrogen taken before planting provide cotton growers with a target nitrogen application that can be commenced with before and during planting. Final topdressings of nitrogen are then made pending the results of the nitrate nitrogen analyses of cotton leaf petioles taken in-season, commencing at 750 degree-days after sowing.

Considering the above, the fact that in South Africa, no guidelines for the optimal nitrogen fertilization of cotton based on the in-season sampling and nitrogen analysis of cotton leaf petioles currently exist, needs to be addressed. If such guidelines were to be introduced, they could contribute to refining the guidelines that are currently available for the nitrogen fertilization of irrigated cotton in South Africa.

Due to the dynamic character of nitrate nitrogen in leaf petioles and the many factors that contribute to the variation thereof, cotton leaf petioles taken from the above field trials were analysed for total nitrogen (which is considered to be less exposed to large fluctuations) using the determination procedure as described by Ferrari (1960).

7.5.1 Relationship between leaf petiole total nitrogen content and maximum yield

Using the data from Table 5.35 in Chapter 5, the relationship between the total nitrogen content of cotton leaf petioles and the sampling time in days after sowing for all locations, is represented by the second-order polynomial regression described in Figure 5.29 in Chapter 5. For ease of reference and comparison, it is given again here as Figure 7.8. A summary of regression statistics and ANOVA are given in Appendix 5.29.

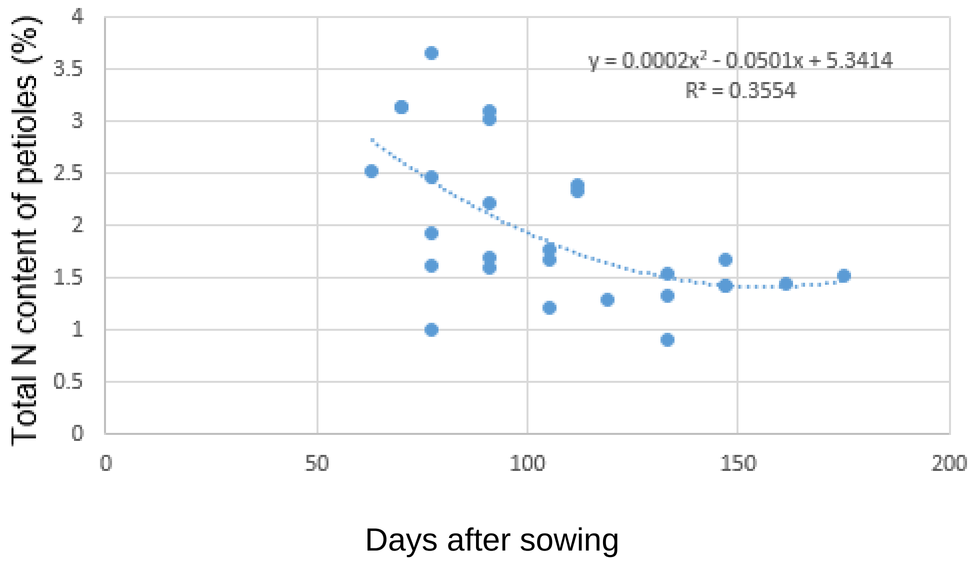


Figure 7.8 Second-order polynomial relationship between total nitrogen content of cotton leaf petioles and days after sowing for obtaining maximum yield

7.5.2 Relationship between leaf petiole total nitrogen content and maximum profit

Using the data from Table 5.35 in Chapter 5, the relationship between the total nitrogen content of cotton leaf petioles and the sampling time in days after sowing for all locations, is represented by the second-order polynomial regression described in Figure 5.30 in Chapter 5. For ease of reference and comparison, it is given again here as Figure 7.9. A summary of regression statistics and ANOVA are given in Appendix 5.30.

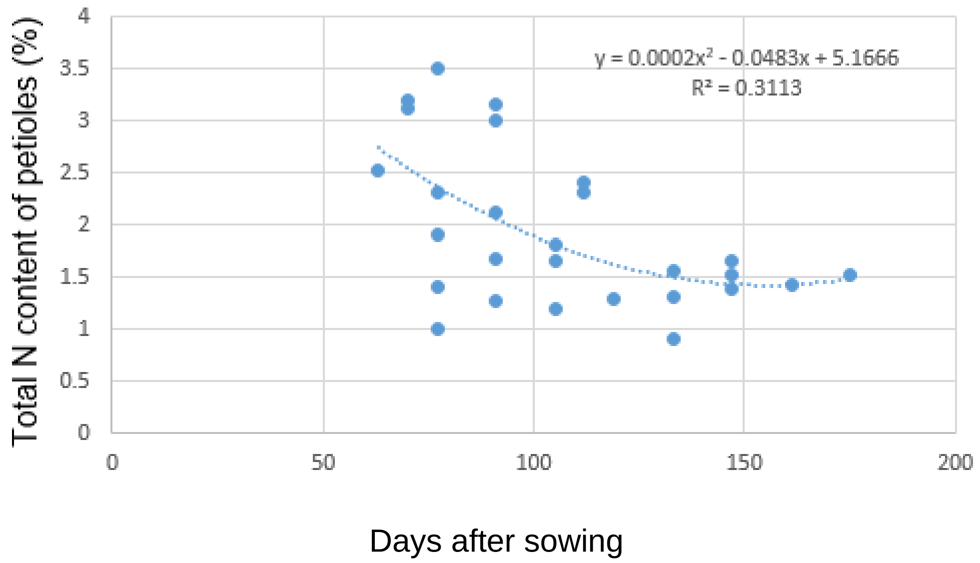


Figure 7.9 Second-order polynomial relationship between total nitrogen content of cotton leaf petioles and days after sowing for obtaining maximum profit

7.5.3 Comparison with existing guidelines

As can be seen from the summary of the statistical analysis in Appendix 5.29 and Appendix 5.30 the correlations between the total nitrogen content of the cotton leaf petioles associated with both maximum yield and maximum profit, and days after sowing are statistically significant. Therefore, the regression equations described in Figure 7.8 and Figure 7.9 can be used as guidelines to evaluate the nitrogen fertilization status of cotton in the field, during the growing season.

The second-order polynomial regression model that describes the total nitrogen content of cotton leaf petioles at a specified number of days after sowing, that is required to produce maximum seed cotton yield, is:

$$Y^{max\ yield} = 0.0002X^2 - 0.0501X + 5.3414 \text{ (Figure 7.8)}$$

It is proposed that the line itself indicate adequate nitrogen in the leaf petiole. The area above the line would indicate excess nitrogen and the area below the line would indicate a low nitrogen status.

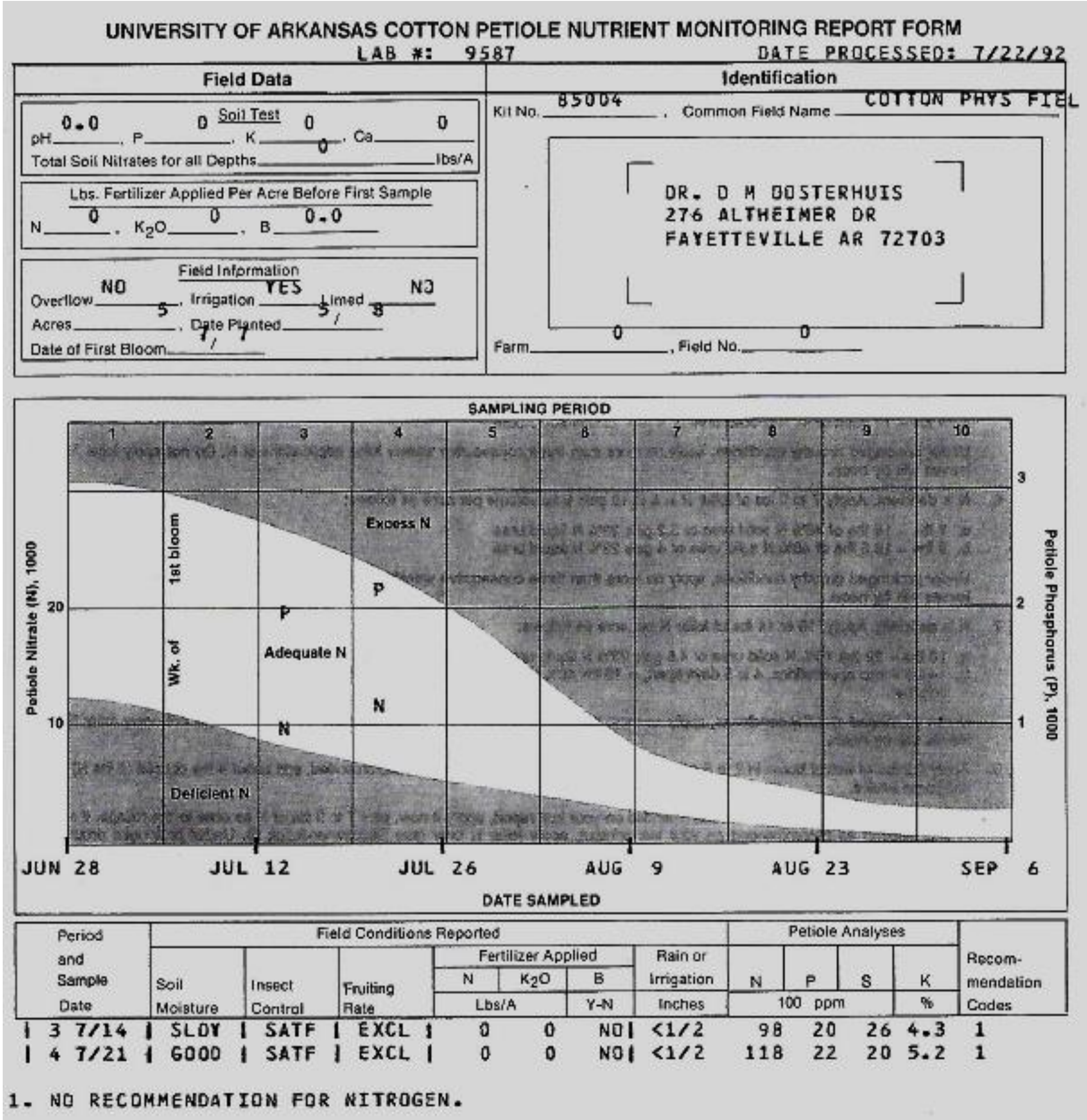
The second-order polynomial regression model that describes the total nitrogen content of cotton leaf petioles at a specified number of days after sowing, that is required to produce maximum profit, is:

$$Y^{max\ profit} = 0.0002X^2 - 0.0483X + 5.1666 \text{ (Figure 7.9)}$$

As above, it is proposed that the line itself indicate adequate nitrogen in the leaf petiole. The area above the line would indicate a high nitrogen status and the area below the line would indicate a low nitrogen status

The above two models have a high level of confidence for predictions in the period between 63 and 175 days after sowing, wherein leaf petiole data was gathered for the purpose of this study. The University of Arkansas allows for the collection of data from one week before flowering (about 63 days after sowing) until nine weeks after the week of first flower (about 133 days after sowing), as can be seen in Figure 2.12 (Oosterhuis 1992) in Chapter 2. For ease of reference, Figure 2.12 will be provided again here as Figure 7.10.

Considering Figure 7.10, it shows a marked resemblance with the above two models (Figure 7.8 and Figure 7.9). The above two models are similar to the top end of the adequate zone given in Figure 7.10. The latter most probably being explained by the fact that the above two models are based on total nitrogen content of leaf petioles while Figure 7.10 is based on only the nitrate nitrogen content of leaf petioles.



UNIVERSITY OF ARKANSAS COTTON PETIOLE NUTRIENT MONITORING REPORT FORM

LAB #: 9587 DATE PROCESSED: 7/22/92

Field Data

Soil Test
pH 0.0, P 0, K 0, Ca 0
Total Soil Nitrates for all Depths 0 lbs/A

Lbs. Fertilizer Applied Per Acre Before First Sample
N 0, K_2O 0, B 0.0

Field Information
Overflow NO, Irrigation YES, Limed NO
Acres 5, Date Planted 5 / 8
Date of First Bloom 7 / 7

Identification

Kit No. 85004, Common Field Name COTTON PHYS FIEL

DR. D M OOSTERHUIS
276 ALTHEIMER DR
FAYETTEVILLE AR 72703

Farm 0, Field No. 0

Period and Sample Date	Soil Moisture	Insect Control	Fruiting Rate	Fertilizer Applied N (Lbs/A)	Fertilizer Applied K_2O (Lbs/A)	Fertilizer Applied B (Y-N)	Rain or Irrigation (Inches)	Petiole Analyses N (100 ppm)	P (100 ppm)	S (100 ppm)	K (%)	Recommendation Codes
3 7/14	SLOY	SATF	EXCL	0	0	NO	<1/2	98	20	26	4.3	1
4 7/21	GOOD	SATF	EXCL	0	0	NO	<1/2	118	22	20	5.2	1

1. NO RECOMMENDATION FOR NITROGEN.

Figure 7.10 University of Arkansas cotton petiole nutrient monitoring report form (Oosterhuis 1992)

While the two models given in Figure 7.8 and Figure 7.9, compare well with the leaf petiole guideline of Arkansas (given in Figure 7.10), the values in these models are higher than those used in the guideline of North Carolina as depicted in Figure 2.11 (Gatiboni and Hardy 2021) of Chapter 2. For ease of reference, Figure 2.11 will be provided here again as Figure 7.11.

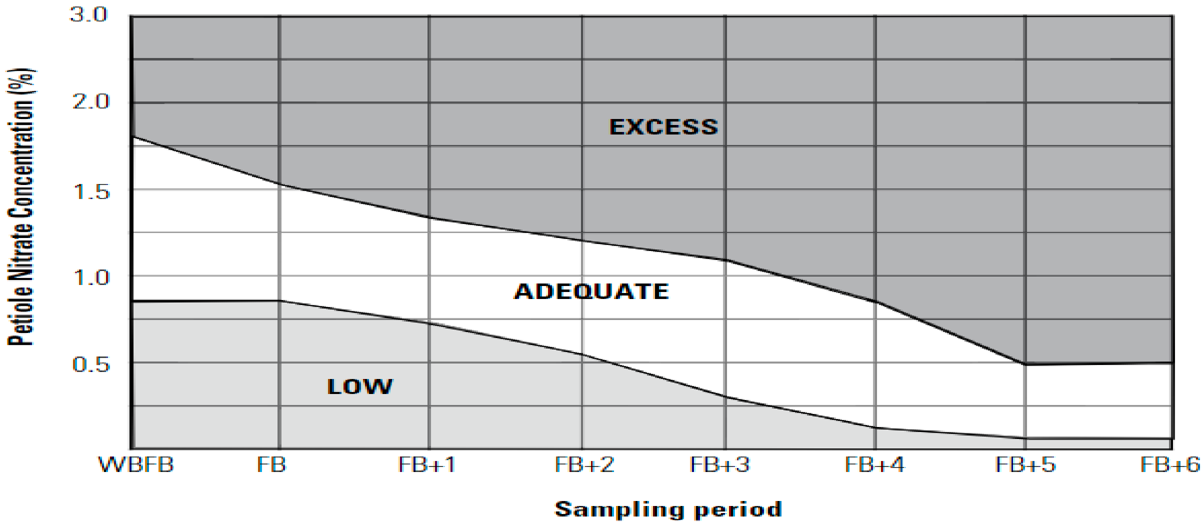


Figure 7.11 Ratings for petiole nitrate concentrations during the bloom period – North Carolina (Gatiboni and Hardy 2021). Note: WBFB = Week before bloom, FB = First bloom, and the FB number indicates weeks after first bloom

Although the nitrogen levels in the models presented in Figures 7.8 and 7.9 are higher than the North Carolina guideline (Figure 7.11) the tendency for the nitrogen content of leaf petioles to reduce over time is the same. Once again, the higher levels measured in the local models can be explained by the fact that total nitrogen content is measured in the local models, whereas only nitrate nitrogen is measured by the North Carolina model depicted in Figure 7.11.

7.6 Conclusion

From the results obtained during this research, it is concluded that the following refinements to the nitrogen fertilization guidelines of irrigated cotton in South Africa can be made in the following ways:

1. By adjusting the existing Fertasa (2016) guideline to allow for an additional nitrogen extraction of 56 kg ha^{-1} for every 1 000 kg of seed cotton produced or fertilized for a yield in excess of 4 500 kg ha^{-1} as discussed in Sections 7.2 and 7.3. The amount of 56 kg N ha^{-1} is suggested until further research has been conducted under South African conditions to provide accurate, scientifically based data regarding nitrogen extraction for seed cotton yields exceeding 4 500 kg ha^{-1}.

2. The equations given in Table 7.1 may be used as additional nitrogen fertilization guidelines to the adjusted Fertasa (2016) guidelines for irrigated cotton in South Africa. This will allow the cotton grower to choose among eight different options according to which they would like to fertilize their crops, depending on the scope of soil nitrogen data available at the time of planting. The guidelines also allow for the producer to choose between nitrogen fertilization guidelines derived from these models for the production of maximum yield or for the achievement of maximum profit during production.
3. Where the soil is cultivated, it is proposed that soil samples be taken as close as possible to four weeks after cultivation to allow most of the nitrogen mineralisation to take place and by so doing, account for it in the soil analysis, as found by Laubscher and Du Preez (1989).
4. By the introduction of NUE calculations to assist producers to have a measurable parameter to evaluate how their nitrogen fertilization practices compare to best practice benchmarks. It is proposed that TNUE be determined for each field and growing season as discussed in detail in Section 7.3.3. Based on research done by Rochester (2014) and MacDonald et al. (2018), TNUE values of between 32.5 and 54.0 kg of seed cotton produced per kilogram of nitrogen available in the soil (residual, mineralised and fertilized) can be viewed as acceptable until further research can be done on the topic under South African conditions. As far as NFUE is concerned, the same range of values will have to be used until further research can be done under South African conditions.
5. It is proposed that the two models using total nitrogen content of leaf petiole samples as depicted in Figure 7.8 and Figure 7.9 can be used as guidelines to evaluate the nitrogen status of cotton during the growing season. One with the objective of producing maximum seed cotton yield and the other with the objective to produce the cotton crop that results in the maximum profit.

By taking cotton leaf petiole samples from 63 days after sowing until 175 days after sowing, the results of these analyses can indicate if the nitrogen status of the cotton plants sampled is low, adequate or excessive.

If diagnosed as being low, additional nitrogen can be applied to the crop in order to improve the nitrogen status thereof. The conundrum has always been how to determine the quantity of nitrogen to be applied if the leaf petiole analysis indicated that the nitrogen content is low for the time (after planting) of sampling. If this problem were to be solved, it would greatly promote the use of cotton leaf petiole analysis as a management tool for accurately correcting the nitrogen nutrition of cotton in-season.

As this is an additional nitrogen fertilization guideline for cotton production in South Africa, it is suggested that the quantity of nitrogen to be applied to correct low nitrogen status be calculated as follows:

$$\text{Nitrogen to apply } = \frac{Model\ Petiole\ N - Petiole\ N}{Model\ Petiole\ N}\ X\ Target\ N$$

where:

Nitrogen to apply	=	the amount of nitrogen to apply as a corrective in season application (kg N ha^{-1})
Petiole N	=	the total nitrogen content of the cotton leaf petiole as sampled at the specific number of days after sowing (%)
Model Petiole N	=	the total nitrogen content of the cotton petiole to be sufficient as predicted by the model (%)
Target N	=	target nitrogen fertilization rate as determined by the residual nitrogen content of the soil as elucidated upon in Chapter 4 (kg N ha^{-1})

The suggested cotton leaf petiole guidelines can provide a useful mechanism whereby additional nitrogen applications can be made to compensate for leaching and denitrification that are increasingly affecting cotton production in South Africa. This is especially so during wet seasons, such as those experienced during La Niña weather conditions.

7.7 Further research

Although the proposed guidelines can contribute to the refining of nitrogen fertilization guidelines for irrigated cotton in South Africa, further research to calibrate the quantities of nitrogen to be applied in order to improve the nitrogen status of the crop, based entirely on the total nitrogen content of cotton leaf petioles in-field may prove to be useful.

As the careless use of nitrogen in the fertilization of crops can have devastating consequences on our environment, further research on TNUE and NFUE in irrigated cotton production may prove to be useful to determine South African parameters that can be used to guide best practice.

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Appendix Chapter 4

Appendix 4.1 Seed cotton yield of trials performed on the oats field at Site 1, Rustenburg during the 1987/88 and 1988/89 seasons

Repetition number	Nitrogen application (kg N ha^{-1})	Seed cotton yield (kg ha^{-1})	
		1987/88	1988/89
1	0	1 971.00	1 474.00
2	0	2 538.00	1 933.00
3	0	1 760.00	3 672.00
4	0	2 087.00	3 276.00
5	0	1 735.00	2 453.00
1	50	2 515.00	1 608.00
2	50	2 655.00	2 597.00
3	50	2 320.00	3 136.00
4	50	3 826.00	2 392.00
5	50	2 001.00	2 300.00
1	100	3 569.00	1 932.00
2	100	3 345.00	3 266.00
3	100	3 840.00	2 992.00
4	100	4 145.00	2 323.00
5	100	3 543.00	2 448.00
1	150	3 873.00	2 892.00
2	150	3 815.00	3 892.00
3	150	3 645.00	3 536.00
4	150	4 697.00	3 702.00
5	150	4 239.00	3 268.00

Appendix 4.2 Seed cotton yield of trials on the soy bean field at Site 1, Rustenburg during the 1987/88 and 1988/89 seasons

Repetition number	Nitrogen application (kg N ha^{-1})	Seed cotton yield (kg ha^{-1})	
		1987/88	1988/89
1	0	5 197.00	4 504.00
2	0	5 458.00	4 153.00
3	0	4 274.00	4 844.00
4	0	4 594.00	4 275.00
5	0	4 875.00	4 483.00
1	50	4 802.00	4 348.00
2	50	4 927.00	4 397.00
3	50	5 003.00	4 391.00
4	50	4 543.00	4 776.00
5	50	4 760.00	5 329.00
1	100	5 339.00	4 402.00
2	100	5 835.00	4 568.00
3	100	5 195.00	4 639.00
4	100	5 064.00	4 599.00
5	100	5 480.00	3 862.00
1	150	5 288.00	4 434.00
2	150	5 919.00	4 002.00
3	150	5 952.00	4 513.00
4	150	4 911.00	5 133.00
5	150	4 827.00	4 439.00

Appendix 4.3 Seed cotton yield of trials performed at Site 2, Rustenburg during the 1989/90 growing season

Repetition number	Nitrogen application (kg N ha^{-1})	Seed cotton yield (kg ha^{-1})		
		Soy beans harvest Field 1	Soy beans plough Field 2	Babala Field 3
1	0	3 424.00	5 234.00	4 742.00
2	0	3 200.00	4 491.00	3 477.00
3	0	3 007.00	3 622.00	3 184.00
1	50	3 612.00	5 123.00	4 912.00
2	50	3 281.00	5 122.00	3 978.00
3	50	3 290.00	4 283.00	3 561.00
1	100	3 832.00	5 487.00	5 629.00
2	100	3 798.00	4 829.00	4 330.00
3	100	3 998.00	5 564.00	4 530.00
1	150	3 514.00	5 980.00	4 819.00
2	150	3 398.00	4 872.00	5 018.00
3	150	4 260.00	4 793.00	4 180.00
1	200	4 672.00	6 060.00	5 498.00
2	200	3 786.00	4 695.00	5 817.00
3	200	4 174.00	4 501.00	4 770.00

Appendix 4.4 Seed cotton yield of trials performed at Rietrivier and Vaalharts during the 1988/89 and 1989/90 growing seasons

Repetition number	Nitrogen application (kg N ha^{-1})	Seed cotton yield (kg ha^{-1})			
		Rietrivier		Vaalharts	
		1988/89	1989/90	1988/89	1989/90
1	20	3 185.79	2 851.00	3 633.90	4 810.00
2	20	2 987.58	3 518.00	3 645.85	4 784.00
3	20	3 143.61	2 329.00	4 855.15	4 878.00
4	20	2 785.70	3 642.00	4 221.85	5 688.00
5	20	3 183.77	4 609.00	3 876.30	4 262.00
1	40	3 496.61	5 408.00	4 673.00	5 409.00
2	40	3 502.22	4 692.00	4 316.85	4 725.00
3	40	3 367.74	4 447.00	4 827.15	4 660.00
4	40	3 527.85	6 592.00	4 454.60	4 530.00
5	40	3 435.26	5 740.00	3 773.53	4 207.00
1	80	3 696.06	4 563.00	4 648.85	5 191.00
2	80	3 681.03	5 059.00	4 601.85	4 993.00
3	80	3 747.68	4 946.00	4 702.35	4 516.00
4	80	3 689.08	5 502.00	4 809.90	4 606.00
5	80	3 593.51	5 235.00	4 996.85	4 970.00
1	120	3 931.37	4 629.00	4 746.65	4 554.00
2	120	3 848.06	4 862.00	4 804.50	4 054.00
3	120	3 845.80	6 039.00	5 146.95	5 483.00
4	120	3 817.50	5 451.00	4 743.15	4 030.00
5	120	3 797.43	4 317.00	5 139.10	5 632.00
1	160	4 069.85	5 199.00	4 943.25	4 543.00
2	160	4 230.68	5 259.00	4 605.35	5 686.00
3	160	4 092.26	5 507.00	5 212.55	5 506.00
4	160	4 190.39	5 091.00	5 280.45	5 737.00
5	160	3 977.33	5 904.00	5 570.20	5 548.00
1	200	4 246.46	5 977.00	5 239.20	5 636.00
2	200	4 520.46	5 897.00	5 078.50	4 437.00
3	200	4 406.30	5 138.00	5 560.65	6 188.00
4	200	4 716.14	4 547.00	4 978.20	6 602.00
5	200	4 264.68	6 032.00	5 531.35	6 031.00

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Appendix 4.5 Seed cotton yield of trials performed at Groblersdal during the 1988/89 growing season

Repetition number	Nitrogen application (kg N ha^{-1})	Seed cotton yield (kg ha^{-1}) Groblersdal 1988/89
1	0	2 995.00
2	0	2 804.00
3	0	3 205.00
4	0	2 693.00
5	0	2 719.00
1	40	3 739.00
2	40	3 696.00
3	40	4 332.00
4	40	4 128.00
5	40	3 446.00
1	80	4 386.00
2	80	4 806.00
3	80	4 180.00
4	80	4 512.00
5	80	3 611.00
1	120	4 209.00
2	120	4 466.00
3	120	4 151.00
4	120	4 932.00
5	120	3 893.00
1	160	4 222.00
2	160	4 465.00
3	160	4 838.00
4	160	4 572.00
5	160	4 526.00
1	200	4 679.00
2	200	4 819.00
3	200	4 599.00
4	200	4 130.00
5	200	4 085.00

Appendix 4.6 Seed cotton yield of trials performed at Bela Bela during the 1988/89 growing season

Repetition number	Nitrogen application (kg N ha^{-1})	Seed cotton yield (kg ha^{-1})
		Towoomba
		1988/89
1	0	2 296.67
2	0	2 412.92
3	0	2 620.83
4	0	2 874.58
5	0	2 512.50
1	15	2 233.75
2	15	2 213.33
3	15	2 222.92
4	15	2 474.17
5	15	2 440.00
1	30	2 322.08
2	30	2 457.50
3	30	2 595.42
4	30	2 645.00
5	30	2 481.67
1	45	2 019.58
2	45	2 832.92
3	45	2 625.83
4	45	2 745.42
5	45	2 366.67

Appendix 4.7 Procedure to determine the nitrogen requirement of irrigated cotton according to the Fertasa guideline and the adjusted guideline

The FERTASA guideline is discussed in the introduction of Chapter 4 and is given by the equation:

$$E = A – (B + C + D)$$

where:

E = the nitrogen fertilization required to produce the crop of a selected yield (at an assumed utilization of 80%). Therefore, once E has been calculated, it must be multiplied by 1.25 to determine the nitrogen fertilization for a specific target yield.

A = the amount of nitrogen removed kg N ha^{-1} by the crop for a specific yield (the N requirement for a yield of 1 000 kg ha^{-1} seed cotton is 90 kg.ha^{-1} , a yield 2 000 kg.ha^{-1} seed cotton requires 175 kg N ha^{-1}, a yield 2 500 kg.ha^{-1} seed cotton requires 220 kg N ha^{-1}, and a yield 4 500 kg.ha^{-1} seed cotton requires 250 kg N ha^{-1}).

B = the residual inorganic nitrogen content of the soil (of which 66.7% is estimated to be utilized by the cotton crop),

C = the estimated mineralization of organic nitrogen in the soil over the growing season, namely 60 kg N ha^{-1} for sandy soils, 120 kg N ha^{-1} for loamy soils, and 160 kg N ha^{-1} for clay soils (of which 66.7% is estimated to be utilized by the cotton crop).

D = the nitrogen present in 400 mm of the irrigation water used to grow the crop (of which 80% is estimated to be utilized by the cotton crop).

FIRST EXAMPLE

For example:

At Rustenburg Site 1 (oats) 1987/88 season (Line 1 of Table 4.6)

A = 250 kg N ha^{-1} required for a crop of 4 500 kg ha^{-1} seed cotton

B = 38 kg Residual N ha^{-1} x 0.667 = 25.346 kg N ha^{-1},

C = 160 kg estimated mineralised nitrogen in clay x 0.667 = 106,72 kg N ha^{-1}

D = 0 kg N ha^{-1} in the irrigation water therefore according to the FERTASA guideline,

E = 250 – (25.346 + 106.72 + 0) kg N ha^{-1}

E = 117.934 kg N ha^{-1}

117.934 x 1.25 = 147.4175 kg N ha^{-1} required to be fertilized to the cotton crop.

THE PROPOSED ADJUSTED GUIDELINE

The proposed adjusted guideline is calculated exactly the same as the FERTASA guideline, with the exception that 56 kg N ha^{-1} is added for every 1 000 kg ha^{-1} of seed cotton to be produced above the removal figures given by the FERTASA guideline.

As the maximum yield measured at Rustenburg Site 1 (oats) 1987/88 was 5 009 kg ha^{-1}

it is 509 kg ha^{-1} more than the 4 500 kg ha^{-1} set by the FERTASA guideline, for which 250 kg N ha^{-1} is required to produce.

The additional nitrogen requirement to be added to the 250 kg N ha^{-1} is calculated as follows:

56 kg N ha^{-1} x 0.509 = 28.504 kg N ha^{-1}

Therefore for this calculation A = 250 + 28.504 = 278.504 kg N ha^{-1}

Solving the equation using the adjusted A is done as follows:

E = 278.504 – (25.346 + 106.72 + 0) kg N ha^{-1}

E = 146.438 kg N ha^{-1}

146.438 x 1.25 = 183.0475 kg N ha^{-1} required to be fertilized to the cotton crop calculated according to the adjusted guideline.

SECOND EXAMPLE

The above is an example of a yield above 4 500 kg ha^{-1}. An example of the calculations of thr FERTASA guideline done for lower yields can be found at Bela Bela 1988/89 (the last line of Table 4.6). The calculation is as follows:

A = 220 kg N ha^{-1} required for a crop of 2 500 kg ha^{-1} seed cotton

B = 125 kg Residual N ha^{-1} x 0.667 = 83.375 kg N ha^{-1},

C = 160 kg estimated mineralised nitrogen in clay x 0.667 = 106,72 kg N ha^{-1}

D = 0 kg N ha^{-1} in the irrigation water

therefore according to the FERTASA guideline,

E = 220 – (83.375 + 106.72 + 0) kg N ha^{-1}

E = 29.905 kg N ha^{-1}

29.905 x 1.25 = 37.381 kg N ha^{-1} required to be fertilized to the cotton crop.

The adjusted guideline makes provision for a lower nitrogen removal as well as as a higher removal than the standard figures used by the FERTASA guideline. The correction of nitrogen requirement to be calculated for the 2 454 kg ha^{-1} seed cotton yield measured from this trial where the FERTASA removal rate for 2 500 kg ha^{-1} yield is 220 kg N ha^{-1}

The nitrogen removal rate is calculated as follows:

$N\ removal = \frac{2454}{2500}$ x 220 kg N ha^{-1} = 215.95 = A

Solving the equation using the adjusted A is done as follows:

E = 215.95 – (83.375 + 106.72 + 0) kg N ha^{-1}

E = 25.855 kg N ha^{-1}

25.855 x 1.25 = 32.318 kg N ha^{-1} required to be fertilized to the cotton crop calculated according to the adjusted guideline.

Appendix 4.8 Summary of calculations to determine Fertasa nitrogen requirement and proposed adjusted nitrogen requirement

The Fertasa guideline (first calculation) and the adjusted guideline (second calculation) are given below for each experimental site and season:

Rustenburg Site 1 (oats) 1987/88

250 – (25.346 + 106.72) = 117.934 x 1.25 = 147.4175 kg N ha^{-1}

250 + 28.504 = 278.504 – (25.346 + 106.72) = 146.438 kg N ha^{-1} x 1.25 = 183.0475 kg N ha^{-1}

Rustenburg Site 1 (oats) 1988/89

250 – (20.677 + 106.72) = 122.603 x 1.25 = 153.25375 kg N ha^{-1}

220 + 14.28 = 234.28 – (20.677 + 106.72) = 106.883 kg N ha^{-1} x 1.25 = 133.60375 kg N ha^{-1}

Rustenburg Site 1 (soy beans) 1987/88

250 – (96.715 + 106.72) = 46.565 x 1.25 = 58.20625 kg N ha^{-1}

250 + 34.272 = 284.272 – (96.715 + 106.72) = 80.837 kg N ha^{-1} x 1.25 = 101.04625 kg N ha^{-1}

Rustenburg Site 1 (soy beans) 1988/89

250 – (63.365 + 106.72) = 79.915 x 1.25 = 99.89375 kg N ha^{-1}

250 + 2.128 = 252.128 – (63.365 + 106.72) = 82.043 kg N ha^{-1} x 1.25 = 102.55375 kg N ha^{-1}

Rustenburg Site 2 (soy beans harvest) 1989/90

250 – (30.682 + 80.04) = 139.278 x 1.25 = 174.0975 kg N ha^{-1}

250 – 30 = 220 – (30.682 + 80.04) = 109.278 kg N ha^{-1} x 1.25 = 136.5975 kg N ha^{-1}

Rustenburg Site 2 (soy beans plough) 1989/90

250 – (47.357 + 80.04) = 122.603 x 1.25 = 153.25375 kg N ha^{-1}

250 + 42.672 = 292.672 – (47.357 + 80.04) = 165.275 kg N ha^{-1} x 1.25 = 206.59375 kg N ha^{-1}

Rustenburg Site 2 (babala) 1989/90

250 – (22.678 + 80.04) = 147.282 x 1.25 = 184.1025 kg N ha^{-1}

250 + 45.584 = 295.584 – (22.678 + 80.04) = 192.866 kg N ha^{-1} x 1.25 = 241.0825 kg N ha^{-1}

Rietrivier 1988/89

250 – (46.023 + 40.02) = 163.957 x 1.25 = 204.94625 kg N ha^{-1}

250 + 42.84 = 292.84 – (46.023 + 40.02) = 206.797 kg N ha^{-1} x 1.25 = 258.49625 kg N ha^{-1}

Rietrivier 1989/90

250 – (49.355 + 40.02) = 160.622 x 1.25 = 201.7775 kg N ha^{-1}

250 + 55.72 = 305.72 – (49.358 + 40.02) = 216.34 kg N ha^{-1} x 1.25 = 270.4275 kg N ha^{-1}

Vaalharts 1988/89

250 – (33.35 + 40.02) = 176.63 x 1.25 = 220.7875 kg N ha^{-1}

250 + 42.56 = 292.56 – (33.35 + 40.02) = 219.19 kg N ha^{-1} x 1.25 = 273.9875 kg N ha^{-1}

Vaalharts 1989/90

250 – (31.349 + 40.02) = 178.631 x 1.25 = 223.28875 kg N ha^{-1}

250 + 31.528 = 281.528 – (31.349 + 40.02) = 201.159 kg N ha^{-1} x 1.25 = 262.69875 kg N ha^{-1}

Groblersdal 1988/89

250 – (55.36 + 80.04) = 114.60 x 1.25 = 143.25 kg N ha^{-1}

250 + 5.488 = 255.488 – (55.36 + 80.04) = 120.088 kg N ha^{-1} x 1.25 = 150.11 kg N ha^{-1}

Bela Bela 1988/89

220 – (83.375 + 106.72) = 29.905 x 1.25 = 37.38125 kg N ha^{-1}

220 x (2454/2500) = 215.952 – (83.375 + 80.04) = 25.857 kg N ha^{-1} x 1.25 = 32.32125 kg N ha^{-1}

Appendix 4.9 Residual nitrogen and mineralized nitrogen for the different soil depths for the trial sites and seasons

Site and season	Residual soil nitrogen (kg ha^{-1})				Mineralized soil nitrogen (kg ha^{-1})				Total nitrogen (kg ha^{-1})
	0 – 300 mm	300 – 600 mm	600 – 900 mm	Total 0 – 900 mm	0 – 300 mm	300 – 600 mm	600 – 900 mm	Total 0 – 900 mm	
Rustenburg Site 1 (oats): 1987/88	25.20	7.80	4.80	37.80	*	*	*	131.40	169.20
Rustenburg Site 1 (oats): 1988/89	21.64	5.81	3.75	31.20	*	*	*	131.40	162.60
Rustenburg Site 1 (soy beans): 1987/88	82.50	39.30	22.80	144.60	*	*	*	143.55	288.15
Rustenburg Site 1 (soy beans): 1988/89	72.96	13.74	8.46	95.16	*	*	*	143.55	238.71
Rustenburg Site 2 (soy beans harvest): 1989/90	18.90	10.80	16.20	45.90	27.32	20.70	25.20	73.22	119.12
Rustenburg Site 2 (soy beans plough): 1989/90	30.60	18.00	22.50	71.10	175.82	47.38	20.12	243.32	314.42
Rustenburg Site 2 (babala) 1989/90	23.40	8.10	2.70	34.20	54.00	38.70	17.1	109.80	144.00
Rietrivier 1988/89	32.85	23.63	12.60	69.08	53.78	32.17	22.05	108.00	177.08
Rietrivier 1989/90	29.25	23.63	21.38	74.26	53.78	32.17	22.05	108.00	182.26
Vaalharts 1988/89	22.05	13.50	13.95	49.50	74.48	47.70	24.30	146.48	195.98
Vaalharts 1989/90	21.38	16.88	9.00	47.26	74.48	47.70	24.30	146.48	193.74
Groblersdal 1988/89	36.00	23.40	23.99	83.39	31.50	20.39	12.01	63.90	147.29
Bela Bela 1988/89	42.30	35.55	47.15	125.00	42.98	58.50	41.62	143.10	268.10

* Data not available.

Appendix 4.10 Results of statistical analysis of data used in the correlation of residual soil nitrogen (0 – 300 mm) at planting time and nitrogen fertilization measured in field trials to produce maximum yield

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.741525
R Square	0.549859
Adjusted R Square	0.459831
Standard Error	63.48207
Observations	7

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	24613.56	24613.56	6.107625	0.056436
Residual	5	20149.87	4029.973		
Total	6	44763.43			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95%*	*Upper 95%*
Intercept	311.0172	55.15409	5.63905	0.002432	169.2391	452.7953	169.2391	452.7953
X Variable 1	-3.59465	1.454521	-2.4713	0.056436	-7.33361	0.144319	-7.33361	0.144319

Appendix 4.11 Results of statistical analysis of data used in the correlation of residual soil nitrogen (0 – 600 mm) at planting time and nitrogen fertilization measured in field trials to produce maximum yield

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.901563
R Square	0.812816
Adjusted R Square	0.775379
Standard Error	44.86596
Observations	7

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	43704.66	44704.66	21.7117	0.005534
Residual	5	10064.77	2012.954		
Total	6	53769.43			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95%*	*Upper 95%*
Intercept	395.1345	52.88706	7.47128	0.000678	259.184	531.085	259.184	531.085
X Variable 1	-3.67178	0.788006	-4.6596	0.005534	-5.69741	-1.64614	-5.69741	-1.64614

Appendix 4.12 Results of statistical analysis of data used in the correlation of residual soil nitrogen (0 – 900 mm) at planting time and nitrogen fertilization measured in field trials to produce maximum yield

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.929104
R Square	0.863234
Adjusted R Square	0.835881
Standard Error	34.99179
Observations	7

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	38641.3	38641.3	31.55873	0.002474
Residual	5	6122.126	1224.425		
Total	6	44763.43			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95%*	*Upper 95%*
Intercept	407.7685	41.24759	9.88587	0.000181	301.7382	513.7988	301.7382	513.7988
X Variable 1	-3.45254	0.61458	-5.6177	0.002474	-5.03237	-1.87271	-5.03237	-1.87271

Appendix 4.13 Results of statistical analysis of data used in the correlation of residual soil nitrogen (0 – 300 mm) at planting time and nitrogen fertilization measured in field trials to produce maximum profit

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.842031
R Square	0.709016
Adjusted R Square	0.650819
Standard Error	55.93932
Observations	7

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	38123.39	38123.39	12.18308	0.017462
Residual	5	15646.04	3129.207		
Total	6	53769.43			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95%*	*Upper 95%*
Intercept	314.4584	48.60085	6.470224	0.001314	189.5259	439.3908	189.5259	439.3908
X Variable 1	-4.47368	1.281699	-3.49043	0.017462	-7.76839	-1.17896	-7.76839	-1.17896

Appendix 4.14 Results of statistical analysis of data used in the correlation of residual soil nitrogen (0 – 600 mm) at planting time and nitrogen fertilization measured in field trials to produce maximum profit

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.921698
R Square	0.849527
Adjusted R Square	0.819433
Standard Error	40.22643
Observations	7

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	45678.6	45678.6	28.22863	0.003158
Residual	5	8090.829	1618.166		
Total	6	53769.43			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95%*	*Upper 95%*
Intercept	385.4216	44.76618	8.60966	0.000349	270.3465	500.4967	270.3465	500.4967
X Variable 1	-4.48697	0.844516	-5.3131	0.003158	-6.65786	-2.31607	-6.65786	-2.31607

Appendix 4.15 Results of statistical analysis of data used in the correlation of residual soil nitrogen (0 – 900 mm) at planting time and nitrogen fertilization measured in field trials to produce maximum profit

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.901563
R Square	0.812816
Adjusted R Square	0.775379
Standard Error	44.86596
Observations	7

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	43704.66	43704.66	21.7117	0.005534
Residual	5	10064.77	2012.954		
Total	6	53769.43			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95%*	*Upper 95%*
Intercept	395.1345	52.88706	7.47129	0.000678	259.184	531.085	259.184	531.085
X Variable 1	-3.67178	0.788006	-4.6596	0.005534	-5.69741	-1.64614	-5.69741	-1.64614

Appendix 4.16 Results of statistical analysis of data used in the correlation of residual soil nitrogen (0 – 900 mm) at planting time plus mineralized soil nitrogen versus nitrogen fertilization measured in field trials to produce maximum yield

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.515914
R Square	0.266167
Adjusted R Square	0.119401
Standard Error	81.05414
Observations	7

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	11914.56	11914.56	1.813542	0.235904
Residual	5	32848.87	6569.774		
Total	6	44763.43			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95%*	*Upper 95%*
Intercept	335.4769	133.5118	2.95544	0.031686	43.68568	627.2682	43.68568	627.2682
X Variable 1	-0.74019	0.549638	-1.3467	0.235904	-2.15308	0.672704	-2.15308	0.672704

Appendix 4.17 Results of statistical analysis of data used in the correlation of residual soil nitrogen (0 – 900 mm) at planting time plus mineralized soil nitrogen versus nitrogen fertilization measured in field trials to produce maximum profit

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.525783
R Square	0.276448
Adjusted R Square	0.131737
Standard Error	88.20997
Observations	7

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	14864.43	14864.43	1.91035	0.225481
Residual	5	38904.99	7780.999		
Total	6	53769.43			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95%*	*Upper 95%*
Intercept	326.1201	123.5331	2.63994	0.045979	8.568162	643.672	8.568162	643.672
X Variable 1	-0.82675	0.598163	-1.3822	0.225481	-2.36438	0.710873	-2.36438	0.710873

Appendix 4.18 Results of statistical analysis of data used in the correlation of nitrogen predicted by the FERTASA (2016) procedure versus nitrogen fertilization measured in field trials to produce maximum yield

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.4105577
R Square	0.16855762
Adjusted R Square	0.00226915
Standard Error	40.8587967
Observations	7

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	1692.22223	1692.222	1.0136459	0.360240055
Residual	5	8347.206342	1669.441		
Total	6	10039.42857			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95%*	*Upper 95%*
Intercept	127.67700	39.50503	3.23191	0.023156	26.1261028	229.22791	26.1261028	229.22791
X Variable 1	0.1944316	0.193119	1.0068	0.360240	-0.3019952	0.6908586	-0.3019952	0.6908586

Appendix 4.19 Results of statistical analysis of data used in the correlation of nitrogen predicted by the FERTASA (2016) procedure versus nitrogen fertilization measured in field trials to produce maximum profit

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.49318319
R Square	0.24322966
Adjusted R Square	0.0918756
Standard Error	38.9808716
Observations	7

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	2441.886824	2441.887	1.607024	0.260737683
Residual	5	7597.541747	1519.508		
Total	6	10039.42857			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95%*	*Upper 95%*
Intercept	129.823479	30.92097	4.19856	0.00851	50.3385838	209.30837	50.3385838	209.30837
X Variable 1	0.21310569	0.168106	1.26769	0.260738	-0.2190252	0.6452365	-0.2190252	0.6452365

Appendix 4.20 Results of statistical analysis of data used in the correlation of nitrogen predicted by the adjusted procedure versus nitrogen fertilization measured in field trials to produce maximum yield

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.4205095
R Square	0.1768282
Adjusted R Square	0.0121938
Standard Error	63.109701
Observations	7

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	4277.827908	4277.828	1.074066	0.347526613
Residual	5	19914.17209	3982.834		
Total	6	24192			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95%*	*Upper 95%*
Intercept	145.79405	61.01869	2.38933	0.062439	-11.059494	302.6476	-11.059494	302.6476
X Variable 1	0.3091363	0.298287	1.03637	0.347527	-0.4576351	1.0759077	-0.4576351	1.0759077

Appendix 4.21 Results of statistical analysis of data used in the correlation of nitrogen predicted by the adjusted procedure versus nitrogen fertilization measured in field trials to produce maximum profit

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.50248892
R Square	0.25249512
Adjusted R Square	0.10299414
Standard Error	60.1392353
Observations	7

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	6108.361902	6108.362	1.6889195	0.2504324
Residual	5	18083.6381	3616.728		
Total	6	24192			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95%*	*Upper 95%*
Intercept	149.494158	47.70452	3.13375	0.025848	26.8657856	272.12253	26.8657856	272.12253
X Variable 1	0.33705026	0.259352	1.29958	0.250432	-0.3296362	1.0037367	-0.3296362	1.0037367

Appendix Chapter 5

Appendix 5.1 Summary of regression statistics and ANOVA for nitrogen fertilization rate and total nitrogen content of cotton leaf petioles 77 days after sowing at Rustenburg Site 1 in 1987/88, preceded by harvested oats

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.626446
R Square	0.392435
Adjusted R Square	0.358681
Standard Error	0.42789
Observations	20

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	2.128681	2.128681	11.62644	0.003123
Residual	18	3.295614	0.18309		
Total	19	5.424295			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95%*	*Upper 95%*
Intercept	1.7468	0.160102	10.9106	2.3E-09	1.410439	2.083161	1.410439	2.083161
X Variable 1	0.005836	0.001712	3.40976	0.003123	0.00224	0.009432	0.00224	0.009432

Appendix 5.2 Summary of regression statistics and ANOVA for nitrogen fertilization rate and total nitrogen content of cotton leaf petioles 91 days after sowing at Rustenburg Site 1 in 1987/88, preceded by harvested oats

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.804938
R Square	0.647926
Adjusted R Square	0.628366
Standard Error	0.163844
Observations	20

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	0.889249	0.889249	33.12559	1.87E-05
Residual	18	0.483206	0.026845		
Total	19	1.372455			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95%*	*Upper 95%*
Intercept	0.9656	0.061305	15.7508	5.68E-12	0.836804	1.094396	0.836804	1.094396
X Variable 1	0.003772	0.000655	5.75548	1.87E-05	0.002395	0.005149	0.002395	0.005149

Appendix 5.3 Summary of regression statistics and ANOVA for nitrogen fertilization rate and total nitrogen content of cotton leaf petioles 77 days after sowing at Rustenburg Site 1 in 1988/89, preceded by harvested soybean

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.527145
R Square	0.277882
Adjusted R Square	0.192927
Standard Error	0.178593
Observations	20

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	0.208656	0.104328	3.270929	0.06283
Residual	17	0.542224	0.031896		
Total	19	0.75088			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95%*	*Upper 95%*
Intercept	1.4468	0.077847	18.5852	9.89E-13	1.282557	1.611043	1.282557	1.611043
X Variable 1	0.003216	0.0025	1.28624	0.215601	-0.00206	0.008491	-0.00206	0.008491
X Variable 2	-9.6E-06	1.6E-05	-0.6010	0.555781	-4.3E-05	2.41E-05	-4.3E-05	2.41E-05

Appendix 5.4 Summary of regression statistics and ANOVA for nitrogen fertilization rate and total nitrogen content of cotton leaf petioles 91 days after sowing at Rustenburg Site 1 in 1988/89, preceded by harvested soybean

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.781878
R Square	0.611333
Adjusted R Square	0.565608
Standard Error	0.148257
Observations	20

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	0.587736	0.293868	13.36965	0.000325
Residual	17	0.373664	0.02198		
Total	19	0.9614			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95%*	*Upper 95%*
Intercept	1.3228	0.064624	20.4692	2.05E-13	1.186456	1.459144	1.186456	1.459144
X Variable 1	0.004876	0.002076	2.34919	0.03116	0.000497	0.009255	0.000497	0.009255
X Variable 2	-1.2E-05	1.33E-05	-0.9351	0.362828	-4E-05	1.56E-05	-4E-05	1.56E-05

Appendix 5.5 Summary of regression statistics and ANOVA for nitrogen fertilization rate and total nitrogen content of cotton leaf petioles 70 days after sowing at Rustenburg Site 2 in 1989/90, preceded by ploughed-in soybean

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.615363
R Square	0.378672
Adjusted R Square	0.275118
Standard Error	0.097917
Observations	15

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	0.07012	0.03506	3.656739	0.057534
Residual	12	0.115053	0.009588		
Total	14	0.185173			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95%*	*Upper 95%*
Intercept	2.865333	0.053204	53.8555	1.11E-15	2.749412	2.981255	2.749412	2.981255
X Variable 1	0.00336	0.00126	2.66563	0.020576	0.000614	0.006106	0.000614	0.006106
X Variable 2	-1.5E-05	6.04E-06	-2.4268	0.031918	-2.8E-05	-1.5E-06	-2.8E-05	-1.5E-06

Appendix 5.6 Summary of regression statistics and ANOVA for nitrogen fertilization rate and total nitrogen content of cotton leaf petioles 91 days after sowing at Rustenburg Site 2 in 1989/90, preceded by ploughed-in soybean

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.462157
R Square	0.213589
Adjusted R Square	0.153096
Standard Error	0.185582
Observations	15

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	0.121603	0.121603	3.530796	0.082842
Residual	13	0.44773	0.034441		
Total	14	0.569333			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95%*	*Upper 95%*
Intercept	2.856	0.082995	34.4118	3.73E-14	2.6767	3.0353	2.6767	3.0353
X Variable 1	0.001273	0.000678	1.87904	0.082842	-0.00019	0.002737	-0.00019	0.002737

Appendix 5.7 Summary of regression statistics and ANOVA for nitrogen fertilization rate and total nitrogen content of cotton leaf petioles 112 days after sowing at Rustenburg Site 2 in 1989/90, preceded by ploughed-in soybean

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.425835
R Square	0.181335
Adjusted R Square	0.044891
Standard Error	0.177983
Observations	15

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	0.0842	0.0421	1.329007	0.301049
Residual	12	0.380133	0.031678		
Total	14	0.464333			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95%*	*Upper 95%*
Intercept	2.133333	0.096708	22.0595	4.43E-11	1.922624	2.344043	1.922624	2.344043
X Variable 1	0.002433	0.002291	1.06205	0.309121	-0.00256	0.007425	-0.00256	0.007425
X Variable 2	-7.3E-06	1.1E-05	-0.6676	0.517049	-3.1E-05	1.66E-05	-3.1E-05	1.66E-05

Appendix 5.8 Summary of regression statistics and ANOVA for nitrogen fertilization rate and total nitrogen content of cotton leaf petioles 147 days after sowing at Rustenburg Site 2 in 1989/90, preceded by ploughed-in soybean

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.790988
R Square	0.625662
Adjusted R Square	0.563272
Standard Error	0.083061
Observations	15

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	0.138371	0.069186	10.0283	0.002752
Residual	12	0.082789	0.006899		
Total	14	0.22116			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95%*	*Upper 95%*
Intercept	1.188762	0.045132	26.3399	5.49E-12	1.090429	1.287095	1.090429	1.287095
X Variable 1	0.00221	0.001069	2.06645	0.061071	-0.00012	0.004539	-0.00012	0.004539
X Variable 2	-4.4E-06	5.13E-06	-0.8546	0.409536	-1.6E-05	6.79E-06	-1.6E-05	6.79E-06

Appendix 5.9 Summary of regression statistics and ANOVA for nitrogen fertilization rate and total nitrogen content of cotton leaf petioles 70 days after sowing at Rustenburg Site 2 in 1989/90, preceded by babala

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.781818
R Square	0.61124
Adjusted R Square	0.546447
Standard Error	0.080569
Observations	15

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	0.122476	0.061238	9.433685	0.003452
Residual	12	0.077897	0.006491		
Total	14	0.200373			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95%*	*Upper 95%*
Intercept	2.890381	0.043778	66.0235	9.67E-17	2.794997	2.985765	2.794997	2.985765
X Variable 1	0.001838	0.001037	1.77222	0.101723	-0.00042	0.004098	-0.00042	0.004098
X Variable 2	-2.9E-06	4.9E-06	-0.5746	0.57621	-1.4E-05	7.98E-06	-1.4E-05	7.98E-06

Appendix 5.10 Summary of regression statistics and ANOVA for nitrogen fertilization rate and total nitrogen content of cotton leaf petioles 91 days after sowing at Rustenburg Site 2 in 1989/90, preceded by babala

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.762336
R Square	0.581156
Adjusted R Square	0.511349
Standard Error	0.239128
Observations	15

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	0.952105	0.476052	8.325158	0.005399
Residual	12	0.686189	0.057182		
Total	14	1.638293			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95%*	*Upper 95%*
Intercept	2.547429	0.129932	19.6058	1.76E-10	2.26433	2.830527	2.26433	2.830527
X Variable 1	0.00731	0.003078	2.37453	0.035111	0.000602	0.014017	0.000602	0.014017
X Variable 2	-2E-05	1.48E-05	-1.3357	0.206423	-5.2E-05	1.24E-05	-5.2E-05	1.24E-05

Appendix 5.11 Summary of regression statistics and ANOVA for nitrogen fertilization rate and total nitrogen content of cotton leaf petioles 112 days after sowing at Rustenburg Site 2 1989/90, preceded by babala

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.725674
R Square	0.526602
Adjusted R Square	0.447702
Standard Error	0.124097
Observations	15

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	0.205571	0.102786	6.674328	0.011255
Residual	12	0.184802	0.0154		
Total	14	0.390373			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95%*	*Upper 95%*
Intercept	2.103429	0.067429	31.1946	7.41E-13	1.956513	2.250344	1.956513	2.250344
X Variable 1	0.003376	0.001598	2.11341	0.05619	-0.0001	0.006857	-0.0001	0.006857
X Variable 2	-9E-06	7.66E-06	-1.1812	0.260391	-2.6E-05	7.64E-06	-2.6E-05	7.64E-06

Appendix 5.12 Summary of regression statistics and ANOVA for nitrogen fertilization rate and total nitrogen content of cotton leaf petioles 147 days after sowing at Rustenburg Site 2 in 1989/90, preceded by babala

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.501934
R Square	0.251938
Adjusted R Square	0.127261
Standard Error	0.113633
Observations	15

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	0.052185	0.026092	2.020726	0.175237
Residual	12	0.154949	0.012912		
Total	14	0.207133			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95%*	*Upper 95%*
Intercept	1.370571	0.061743	22.1979	4.12E-11	1.236044	1.505098	1.236044	1.505098
X Variable 1	0.002004	0.001463	1.36985	0.19582	-0.00118	0.005191	-0.00118	0.005191
X Variable 2	-6.3E-06	7.01E-06	-0.8962	0.387759	-2.2E-05	9E-06	-2.2E-05	9E-06

Appendix 5.13 Summary of regression statistics and ANOVA for nitrogen fertilization rate and total nitrogen content of cotton leaf petioles 77 days after sowing at Rietrivier in 1988/89

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.034981
R Square	0.001224
Adjusted R Square	-0.07276
Standard Error	0.168698
Observations	30

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	0.000941	0.000471	0.01654	0.983606
Residual	27	0.768395	0.028459		
Total	29	0.769337			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95%*	*Upper 95%*
Intercept	0.989709	0.09437	10.4875	5.06E-11	0.796077	1.183341	0.796077	1.183341
X Variable 1	0.000389	0.002146	0.18129	0.857493	-0.00401	0.004791	-0.00401	0.004791
X Variable 2	-1.7E-06	9.6E-06	-0.1799	0.858558	-2.2E-05	1.81E-05	-2.2E-05	1.81E-05

Appendix 5.14 Summary of regression statistics and ANOVA for nitrogen fertilization rate and total nitrogen content of cotton leaf petioles 105 days after sowing at Rietrivier in 1989/90

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.59638
R Square	0.35567
Adjusted R Square	0.307941
Standard Error	0.253963
Observations	30

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	0.961267	0.480634	7.451984	0.002648
Residual	27	1.74143	0.064497		
Total	29	2.702697			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95%*	*Upper 95%*
Intercept	1.19004	0.142068	8.37655	5.49E-09	0.89854	1.481539	0.89854	1.481539
X Variable 1	0.010057	0.00323	3.11349	0.004342	0.003429	0.016684	0.003429	0.016684
X Variable 2	-3.7E-05	1.45E-05	-2.5188	0.018003	-6.6E-05	-6.8E-06	-6.6E-05	-6.8E-06

Appendix 5.15 Summary of regression statistics and ANOVA for nitrogen fertilization rate and total nitrogen content of cotton leaf petioles 133 days after sowing at Rietrivier in 1989/90

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.185448
R Square	0.034391
Adjusted R Square	-0.03714
Standard Error	0.223707
Observations	30

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	0.048125	0.024062	0.480815	0.623472
Residual	27	1.351212	0.050045		
Total	29	1.399337			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95%*	*Upper 95%*
Intercept	0.786288	0.125143	6.28314	1.01E-06	0.529517	1.043059	0.529517	1.043059
X Variable 1	0.001368	0.002845	0.48071	0.634594	-0.00447	0.007206	-0.00447	0.007206
X Variable 2	-3.5E-06	1.28E-05	-0.2757	0.784899	-3E-05	2.27E-05	-3E-05	2.27E-05

Appendix 5.16 Summary of regression statistics and ANOVA for nitrogen fertilization rate and total nitrogen content of cotton leaf petioles 77 days after sowing at Vaalharts in 1988/89

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.905236
R Square	0.819453
Adjusted R Square	0.813005
Standard Error	0.166227
Observations	30

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	3.511533	3.511533	127.0842	6.41E-12
Residual	28	0.773684	0.027632		
Total	29	4.285217			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95%*	*Upper 95%*
Intercept	1.266526	0.057845	21.8951	3.73E-19	1.148035	1.385017	1.148035	1.385017
X Variable 1	0.005372	0.000477	11.2732	6.41E-12	0.004396	0.006349	0.004396	0.006349

Appendix 5.17 Summary of regression statistics and ANOVA for nitrogen fertilization rate and total nitrogen content of cotton leaf petioles 105 days after sowing at Vaalharts in 1988/89

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.451099
R Square	0.203491
Adjusted R Square	0.14449
Standard Error	0.116374
Observations	30

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	0.093418	0.046709	3.448953	0.046353
Residual	27	0.365662	0.013543		
Total	29	0.45908			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95%*	*Upper 95%*
Intercept	1.48766	0.0651	22.8518	3.38E-19	1.354086	1.621235	1.354086	1.621235
X Variable 1	0.001276	0.00148	0.86220	0.39617	-0.00176	0.004313	-0.00176	0.004313
X Variable 2	-1.9E-06	6.65E-06	-0.2808	0.78101	-1.6E-05	1.18E-05	-1.6E-05	1.18E-05

Appendix 5.18 Summary of regression statistics and ANOVA for nitrogen fertilization rate and total nitrogen content of cotton leaf petioles sampled 133 days after sowing at Vaalharts in 1988/89

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.493968
R Square	0.244004
Adjusted R Square	0.188005
Standard Error	0.132636
Observations	30

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	0.153307	0.076654	4.357243	0.022909
Residual	27	0.47499	0.017592		
Total	29	0.628297			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95%*	*Upper 95%*
Intercept	1.347275	0.074197	18.1581	1.16E-16	1.195035	1.499514	1.195035	1.499514
X Variable 1	0.003122	0.001687	1.85059	0.0752	-0.00034	0.006583	-0.00034	0.006583
X Variable 2	-9.7E-06	7.58E-06	-1.2845	0.209876	-2.5E-05	5.82E-06	-2.5E-05	5.82E-06

Appendix 5.19 Summary of regression statistics and ANOVA for nitrogen fertilization rate and total nitrogen content of cotton leaf petioles 63 days after sowing at Groblersdal in 1988/89

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.522486
R Square	0.272992
Adjusted R Square	0.219139
Standard Error	0.271098
Observations	30

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	0.745122	0.372561	5.069249	0.013514
Residual	27	1.984348	0.073494		
Total	29	2.72947			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95%*	*Upper 95%*
Intercept	2.0115	0.109882	18.3059	9.48E-17	1.786041	2.236959	1.786041	2.236959
X Variable 1	0.006385	0.002584	2.47109	0.020072	0.001083	0.011687	0.001083	0.011687
X Variable 2	-2.2E-05	1.24E-05	-1.8089	0.081616	-4.8E-05	3.01E-06	-4.8E-06	3.01E-06

Appendix 5.20 Summary of regression statistics and ANOVA for nitrogen fertilization rate and total nitrogen content of cotton leaf petioles 77 days after sowing at Groblersdal in 1988/89

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.704323
R Square	0.496071
Adjusted R Square	0.458743
Standard Error	0.246398
Observations	30

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	1.613659	0.806829	13.28948	9.59E-05
Residual	27	1.639221	0.060712		
Total	29	3.25288			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95%*	*Upper 95%*
Intercept	1.412143	0.09987	14.1398	5.33E-14	1.207226	1.61706	1.207226	1.61706
X Variable 1	0.003635	0.002349	1.54793	0.133281	-0.00118	0.008454	-0.00118	0.008454
X Variable 2	-1.2E-06	1.13E-05	-0.1069	0.915629	-2.4E-05	2.19E-05	-2.4E-05	2.19E-05

Appendix 5.21 Summary of regression statistics and ANOVA for nitrogen fertilization rate and total nitrogen content of cotton leaf petioles 91 days after sowing at Groblersdal in 1988/89 with outlier

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.41752
R Square	0.174323
Adjusted R Square	0.113162
Standard Error	0.279626
Observations	30

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	0.445721	0.222861	2.850221	0.075325
Residual	27	2.111149	0.078191		
Total	29	2.55687			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95%*	*Upper 95%*
Intercept	1.479714	0.113338	13.0557	3.52E-13	1.247163	1.712266	1.247163	1.712266
X Variable 1	0.000114	0.002665	0.04288	0.966113	-0.00535	0.005583	-0.00535	0.005583
X Variable 2	8.04E-06	1.28E-05	0.62820	0.535149	-1.8E-05	3.43E-05	-1.8E-05	3.43E-05

Appendix 5.22 Summary of regression statistics and ANOVA for nitrogen fertilization rate and total nitrogen content of cotton leaf petioles 91 days after sowing at Groblersdal in 1988/89 without outlier

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.56674
R Square	0.321194
Adjusted R Square	0.268978
Standard Error	0.239418
Observations	29

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	0.705196	0.352598	6.151281	0.006497
Residual	26	1.490348	0.057321		
Total	28	2.195545			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95%*	*Upper 95%*
Intercept	1.33812	0.106152	12.6057	1.4E-12	1.119921	1.556318	1.119921	1.556318
X Variable 1	0.002654	0.002409	1.10163	0.280717	-0.0023	0.007605	-0.0023	0.007605
X Variable 2	-1.6E-06	1.13E-05	-0.1397	0.88998	-2.5E-05	2.17E-05	-2.5E-05	2.17E-05

Appendix 5.23 Summary of regression statistics and ANOVA for nitrogen fertilization rate and total nitrogen content of cotton leaf petioles 105 days after sowing at Groblersdal in 1988/89

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.579227
R Square	0.335503
Adjusted R Square	0.311771
Standard Error	0.223906
Observations	30

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	0.70875	0.70875	14.13717	0.000797
Residual	28	1.403747	0.050134		
Total	29	2.112497			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95%*	*Upper 95%*
Intercept	0.865333	0.072471	11.9403	1.68E-12	0.716882	1.013784	0.716882	1.013784
X Variable 1	0.00225	0.000598	3.75994	0.000797	0.001024	0.003476	0.001024	0.003476

Appendix 5.24 Summary of regression statistics and ANOVA for nitrogen fertilization rate and total nitrogen content of cotton leaf petioles 119 days after sowing at Groblersdal in 1988/89

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.547572
R Square	0.299836
Adjusted R Square	0.247971
Standard Error	0.159069
Observations	30

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	0.292561	0.14628	5.781184	0.008132
Residual	27	0.683176	0.025303		
Total	29	0.975737			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95%*	*Upper 95%*
Intercept	1.067643	0.064474	16.5593	1.15E-15	0.935353	1.199933	0.935353	1.199933
X Variable 1	0.001654	0.001516	1.09099	0.284918	-0.00146	0.004765	-0.00146	0.004765
X Variable 2	-1E-06	7.28E-06	-0.1442	0.886433	-1.6E-05	1.39E-05	-1.6E-05	1.39E-05

Appendix 5.25 Summary of regression statistics and ANOVA for nitrogen fertilization rate and total nitrogen content of cotton leaf petioles 133 days after sowing at Groblersdal in 1988/89

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.669942
R Square	0.448823
Adjusted R Square	0.407995
Standard Error	0.187973
Observations	30

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	0.776854	0.388427	10.99303	0.000322
Residual	27	0.954016	0.035334		
Total	29	1.73087			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95%*	*Upper 95%*
Intercept	0.9535	0.07619	12.5148	9.43E-13	0.797172	1.109828	0.797172	1.109828
X Variable 1	0.003134	0.001792	1.74948	0.091568	-0.00054	0.006811	-0.00054	0.006811
X Variable 2	-4E-06	8.6E-06	-0.4595	0.649578	-2.2E-05	1.37E-05	-2.2E-05	1.37E-05

Appendix 5.26 Summary of regression statistics and ANOVA for nitrogen fertilization rate and total nitrogen content of cotton leaf petioles 147 days after sowing at Groblersdal in 1988/89

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.563314
R Square	0.317322
Adjusted R Square	0.266754
Standard Error	0.244556
Observations	30

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	0.750594	0.375297	6.275072	0.00578
Residual	27	1.614806	0.059808		
Total	29	2.3654			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95%*	*Upper 95%*
Intercept	1.277143	0.099124	12.8843	4.79E-13	1.073758	1.480528	1.073758	1.480528
X Variable 1	0.004025	0.002331	1.72675	0.095639	-0.00076	0.008808	-0.00076	0.008808
X Variable 2	-8.8E-06	1.12E-05	-0.7901	0.436343	-3.2E-05	1.41E-05	-3.2E-05	1.41E-05

Appendix 5.27 Summary of regression statistics and ANOVA for nitrogen fertilization rate and total nitrogen content of cotton leaf petioles 161 days after sowing at Groblersdal in 1988/89

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.543646
R Square	0.295551
Adjusted R Square	0.243369
Standard Error	0.229728
Observations	30

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	0.597824	0.298912	5.663906	0.00883
Residual	27	1.424922	0.052775		
Total	29	2.022747			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95%*	*Upper 95%*
Intercept	1.123786	0.093114	12.0689	2.18E-12	0.932732	1.314839	0.932732	1.314839
X Variable 1	0.002618	0.00219	1.19565	0.242229	-0.00187	0.007111	-0.00187	0.007111
X Variable 2	-2.8E-06	1.05E-05	-0.2655	0.792638	-2.4E-05	1.88E-05	-2.4E-05	1.88E-05

Appendix 5.28 Summary of regression statistics and ANOVA for nitrogen fertilization rate and total nitrogen content of cotton leaf petioles 175 days after sowing at Groblersdal in 1988/89

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.41122
R Square	0.169102
Adjusted R Square	0.107554
Standard Error	0.167307
Observations	30

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	0.153813	0.076906	2.747479	0.082015
Residual	27	0.755774	0.027992		
Total	29	0.909587			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95%*	*Upper 95%*
Intercept	1.356214	0.067813	19.9993	1.02E-17	1.217073	1.495355	1.217073	1.495355
X Variable 1	0.001291	0.001595	0.80973	0.425177	-0.00198	0.004563	-0.00198	0.004563
X Variable 2	-1.2E-06	7.65E-06	-0.1604	0.873754	-1.7E-05	1.45E-05	-1.7E-05	1.45E-05

Appendix 5.29 Summary of regression statistics and ANOVA for total nitrogen content of cotton leaf petioles and days after sowing for maximum yield

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.596141
R Square	0.355384
Adjusted R Square	0.301666
Standard Error	0.618503
Observations	27

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	5.061648	2.530824	6.615731	0.005148
Residual	24	9.181115	0.382546		
Total	26	14.24276			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95%*	*Upper 95%*
Intercept	5.341443	1.676106	3.18682	0.003965	1.882129	8.800756	1.882129	8.800756
X Variable 1	-0.05007	0.030774	-1.6271	0.116781	-0.11359	0.013443	-0.11359	0.013443
X Variable 2	0.00016	0.000133	1.20054	0.241646	-0.00011	0.000434	-0.00011	0.000434

Appendix 5.30 Summary of regression statistics and ANOVA for the total nitrogen content of cotton leaf petioles and days after sowing for maximum profit

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.557932
R Square	0.311288
Adjusted R Square	0.253895
Standard Error	0.640336
Observations	27

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	4.44787	2.223935	5.423829	0.011388
Residual	24	9.84073	0.41003		
Total	26	14.2886			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95%*	*Upper 95%*
Intercept	5.166588	1.735272	2.97739	0.006548	1.585162	8.748013	1.585162	8.748013
X Variable 1	-0.04833	0.031861	-1.5168	0.142381	-0.11408	0.017431	-0.11408	0.017431
X Variable 2	0.000156	0.000138	1.13306	0.268384	-0.00013	0.00044	-0.00013	0.00044

Appendix Chapter 6

Appendix 6.1 Summary of regression statistics and ANOVA for nitrogen fertilization rate and seed cotton yield for Soil 1 in the glasshouse trials

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.930248
R Square	0.865362
Adjusted R Square	0.842922
Standard Error	781.8227
Observations	15

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	47144173	23572086	38.56395	5.96E-06
Residual	12	7334960	611246.7		
Total	14	54479133			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95%*	*Upper 95%*
Intercept	1699.381	424.8097	4.00033	0.001761	773.8	2624.962	773.8	2624.962
X Variable 1	29.43429	6.709605	4.38689	0.000886	14.81531	44.05326	14.81531	44.05326
X Variable 2	-0.04394	0.021447	-2.0486	0.063023	-0.09066	0.002792	-0.09066	0.002792

Appendix 6.2 Summary of regression statistics and ANOVA for nitrogen fertilization rate and seed cotton yield for Soil 2 in the glasshouse trials

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.891503
R Square	0.794777
Adjusted R Square	0.760574
Standard Error	1007.853
Observations	15

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	47205883	23602942	23.23656	7.47E-05
Residual	12	12189210	1015768		
Total	14	59395093			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95%*	*Upper 95%*
Intercept	1955.667	547.6251	3.57118	0.003844	762.494	3148.839	762.494	3148.839
X Variable 1	41.07778	8.649398	4.74921	0.000473	22.23236	59.9232	22.23236	59.9232
X Variable 2	-0.08756	0.027647	-3.1669	0.008116	-0.14779	-0.02732	-0.14779	-0.02732

Appendix 6.3 Summary of regression statistics and ANOVA for nitrogen fertilization rate and seed cotton yield for Soil 3 in the glasshouse trials

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.814458
R Square	0.663342
Adjusted R Square	0.607232
Standard Error	1244.693
Observations	15

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	36631423	18315711	11.82223	0.001456
Residual	12	18591120	1549260		
Total	14	55222543			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95%*	*Upper 95%*
Intercept	2914.381	676.314	4.3092	0.001015	1440.819	4387.943	1440.819	4387.943
X Variable 1	35.5054	10.68196	3.3239	0.006067	12.23141	58.77938	12.23141	58.77938
X Variable 2	-0.07446	0.034144	-2.181	0.049839	-0.14885	-6.2E-05	-0.14885	-6.2E-05

Appendix 6.4 Summary of regression statistics and ANOVA for nitrogen fertilization rate and seed cotton yield for Soil 4 in the glasshouse trials

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.318037
R Square	0.101148
Adjusted R Square	-0.04866
Standard Error	1684.531
Observations	15

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	3831841	1915921	0.67518	0.527387
Residual	12	34051752	2837646		
Total	14	37883593			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95%*	*Upper 95%*
Intercept	3871.429	915.3039	4.2297	0.001169	1877.153	5865.704	1877.153	5865.704
X Variable 1	15.85746	14.45666	1.0969	0.294211	-15.6409	47.35581	-15.6409	47.35581
X Variable 2	-0.04358	0.04621	-0.943	0.364268	-0.14426	0.057105	-0.14426	0.057105

Appendix 6.5 Summary of regression statistics and ANOVA for nitrogen fertilization rate and seed cotton yield for Soil 5 in the glasshouse trials

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.066924
R Square	0.004479
Adjusted R Square	-0.16144
Standard Error	1559.938
Observations	15

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	131372.9	65686.43	0.026994	0.973426
Residual	12	29200887	2433407		
Total	14	29332260			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95%*	*Upper 95%*
Intercept	4386.048	847.6052	5.1747	0.000231	2539.275	6232.821	2539.275	6232.821
X Variable 1	0.93873	13.3874	0.070	0.945253	-28.2299	30.10736	28.2299	30.10736
X Variable 2	-0.00557	0.042792	-0.130	0.898662	-0.0988	0.087669	-0.0988	0.087669

Appendix 6.6 Summary of regression statistics and ANOVA for the linear relationship between nitrogen fertilization rate associated with maximum yield and total residual nitrogen in the simulated soils at planting in the glasshouse trials

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.947624
R Square	0.897992
Adjusted R Square	0.863989
Standard Error	33.84512
Observations	5

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	30251.67	30251.67	26.40933	0.014275
Residual	3	3436.476	1145.492		
Total	4	33688.15			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95%*	*Upper 95%*
Intercept	379.3847	35.43549	10.7064	0.001742	266.6132	492.1563	266.6132	492.1563
X Variable 1	-1.08768	0.211651	-5.139	0.014275	-1.76125	-0.41411	-1.76125	-0.41411

Appendix 6.7 Summary of regression statistics and ANOVA for the linear relationship between nitrogen fertilization rate associated with maximum yield and residual nitrogen in the simulated soils at planting in the glasshouse trials

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.940373
R Square	0.884302
Adjusted R Square	0.845736
Standard Error	36.04466
Observations	5

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	29790.5	29790.5	22.92957	0.017321
Residual	3	3897.652	1299.217		
Total	4	33688.15			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95%*	*Upper 95%*
Intercept	352.63	33.00279	10.6849	0.001752	247.6004	457.6596	247.6004	457.6596
X Variable 1	-1.90217	0.397239	-4.7885	0.017321	-3.16637	-0.63798	-3.16637	-0.63798