NITROGEN IN THE SOIL-PLANT SYSTEM OF SUCCESSIVE RAINFED WHEAT CROPS UNDER CONVENTIONAL CULTIVATION

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ABSTRACT

Soil mineral N and soil water content at planting, biomass accumulation, yield and grain quality parameters (hectolitermass and protein percentage) were measured on an unfertilized and recommended-N-application treatment during two consecutive growing seasons (1997-1998). The trials were planted in a fallow-wheat-wheat cropping system at three representative localities in the summer rainfall region of South Africa. High levels of available soil water and mineral N were measured following the fallow period preceding the start of the trials in 1997. For example, soil water content was 81.7%, 69.6%, and 78.2% of DUL at Bethlehem, Kroonstad and Petrusburg respectively. Although comparable total soil profile water contents to 1997 were measured in 1998 at all three sites, the cultivation zone (0-400 mm) had a substantially lower soil water content. This was due to erratic rainfall distribution during the fallow period, which prevented effective soil cultivation management, subsequent soil water conservation and residue decomposition.

Undecomposed residue in the cultivation layer at planting appeared to affect availability of soil mineral N to the growing crop. At planting in 1998, undecomposed crop residue amounted to 53.6% at Bethlehem, 32.5% at Kroonstad and 46.9% at Petrusburg of that added at harvest in 1997. Soil mineral N was lower at planting in 1998 compared to 1997 due to decomposing residue (C:N ratio of above 73) in the cultivation zone immobilizing soil mineral N. This reduced initial growth, N accumulation, yield, and grain protein percentage without additional fertilizer N. Distribution of soil mineral N showed notable amounts in the 600-1200 mm soil layers, with limited changes over the trial period. This was linked to low root exploration of these soil layers (10-15% of total root distribution). The ratios of soil mineral NH_4^+:NO_3^- for the different soil layers indicated similar values over the trial period.

Climatic data for the localities indicated differences in the amount and distribution of rainfall and temperatures during the study period, which influenced crop development, yield and grain protein percentage. At Bethlehem above average in-season rainfall was measured during 1997, at Kroonstad average rainfall and at Petrusburg below average in-season rainfall.

Response to applied N at the localities varied in magnitude during 1997. Nitrogen application significantly increased N concentrations of plant components, N uptake, yield and grain protein percentage, although values for all these parameters were lower in 1998 than in 1997. Indeed higher yields were produced in 1997 (mean=1.838 t ha^{-1}) compared to 1998 (mean=0.980 t ha^{-1}). A significant yield response to applied N was measured at the two higher yielding localities in both cropping years, but there was no significant response at the lower yielding locality. The limiting factors appeared to be the availability of soil water and residual soil mineral N. From the calculated response functions, the variables soil water content at planting, soil mineral N content at planting, in-season rainfall, and added fertilizer N explained the bulk of the variations in grain protein percentage, plant N uptake, and yields.

It was concluded that the present fertilizer N recommendation system for dryland wheat production, which is based on fertilizer response curves for specific yield potentials, should be augmented by using initial soil mineral N and water contents in the profile measured prior to planting.

DECLARATION

I hereby certify that the research work reported in this dissertation is the result of my own original investigation except where acknowledged.

Signed : .... Date : ....18/10/2002........

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CHAPTER 1 INTRODUCTION

Wheat is one of the important grain crops produced world-wide. It is cultivated on all the continents of the world, easily stored and transported, and an important nutritional source for humans. World production of wheat in 1997 amounted to 609.566 million tons (Mt), and together with rice (573.263 Mt) and maize (585.828 Mt), these grain crops are considered the most important crops. In South Africa, between 1.27 Mt (1992/93) and 3.49 Mt (1988/89) of wheat is produced annually on 1048000-1605000 ha, with a total domestic consumption of 2.42 Mt for the 1995/96 season. Demand is determined mainly by the need for the end products, *viz.* bread, other processed products and private consumption of flour (FAO, 1997).

Yield levels and quality of grain produced play an important part in the successful production and marketing of wheat. Traditionally, yield was economically the most important factor to the producer. However, as the end user became more demanding with regards to quality of the end product, linked to the possibility of exporting surplus production combined with higher quality standards required, the quality of produced grain became more important. The current grading system for wheat in South Africa includes hectoliter mass and grain protein percentage as part of the quality parameters to determine the marketability of wheat. Protein quantity and quality directly affect the flour protein and dough characteristics. Therefore, low protein grain is penalised by a lower price per ton, leading to significant economic losses for the wheat producer.

Wheat is cultivated in various regions of South Africa, with an average of 41.8% (18.9-58.9%) of the total annual wheat production produced in the Free State Province under rainfed conditions (Wheat Board, 1996). This production area in the Summer Rainfall Region is divided into relatively homogeneous wheat production areas namely: South-western, North-western, Central and Eastern Free State. Generally, wheat is planted during winter (May-July) utilising residual soil water. In the Western areas, residual soil water is of extreme importance to ensure economic yields, as any spring rain is regarded as an unexpected bonus. The Western areas are considered high-risk production areas because of difficult seedling establishment and occasional lack of secondary root development, regular heat and water stresses, and wind erosion. The generally duplex soils in the other production areas have lower soil water storage capacities, and crops are dependent on rain in spring and early summer to produce economic optimal yields. The reduced soil water storage capacity, differences in topsoil texture, plus the need to ensure that crops are at a growth stage to gain maximum benefit from spring and early summer rain, also necessitates later planting in the Central and Eastern areas (Anon, 1998).

Agronomic practices therefore also differ between the different production regions. Crop rotations (fallow-wheat-wheat-fallow is widely practised) and cultivation systems (mainly conventional practices) are aimed at increasing soil water conservation. Variable fallow period lengths depend on the specific crop rotation (6 -18 months), with reduced tillage practices usually followed in the Western regions. All these agronomic practices impact on the long-term yield potential of wheat production in the different regions, influencing fertilization, especially nitrogen (N) application rates.

The production of wheat in these regions is an economically risky undertaking, mainly because of erratic and fluctuating rainfall distribution. Crop yields under rainfed farming conditions are generally limited by available water. Nevertheless, optimum N management for wheat production is important for maximum economic yield, optimum water utilization, and minimum pollution of the environment (Corbeels *et al.*, 1999). Excluding available soil water, N is the next most limiting factor in dryland production as in other dryland wheat production areas (Nielson & Halvorson, 1991; Campbell *et al.*, 1993). Nitrogen frequently limits grain yields and grain protein percentage, and additional N inputs are required to optimise productivity and profitability.

Nitrogen is currently the most widely used fertilizer nutrient and the demand for it is likely to grow in the near future (Godwin & Jones, 1991). Total fertilizer use in South Africa (1998) was 384.370 ('1000t) of N, 92.782 P, and 116.240 of K fertilizer products (Fertilizer Society of South Africa, 1999). Increased N fertility can stimulate deeper rooting of wheat, making a greater quantity of stored soil water available to the plant, thereby reducing potential water stress. However, larger aboveground biomass stimulated by increased N availability results in greater transpiration demands (Ritchie & Johnson, 1990). Thus, if sufficient water reserves were not available, greater water stress in high N treatments would occur, possibly during the later critical crop development stages, thereby reducing the yield. Continuous cereal cropping, without N inputs from fertilizers or legumes has led to widespread deficiency of N in wheat (Doyle & Holford, 1993). This has occurred on soils previously regarded as high in available N and which have produced high grain protein wheat for relatively short periods (< 40 years) of wheat production.

The utilisation of N by higher plants involves several processes including, uptake mechanisms, storage, translocation, reduction, and incorporation into organic forms (Moll *et al.*, 1982). Under conditions of limited supply of N, remobilization of previously assimilated N can occur by breakdown of insoluble protein sources. Under these conditions, most of the N in wheat grain can be derived from remobilization, whereas under conditions where N adsorption is possible during grain development, remobilization may be less than 50% of grain N. Plant uptake of N and N concentration of plant material is linked to the specific plant developmental stage, N supply, and subsequent redistribution of N within the different plant parts. Nitrogen requirement is therefore related to total N removed by the crop (Osaki *et al.*, 1991). Plant analysis can provide an effective means of monitoring the nutritional status of a crop. If critical tissue concentrations are known, potential deficiencies can be identified before visual symptoms appear, and additional nutrients applied before yields are reduced (Vaughn *et al.*, 1990).

The probable response to applied N is dependant on the size of available and potentially available pools of N in the soil, and the N demand of the crop as determined by dry matter production and minimum tissue N concentration. Measurement of the soil mineral N content at planting can be a useful aid in determining optimum fertilizer levels, and an indication of the potential available N through mineralization of soil organic matter can further improve N recommendations. The available soil water and tillage methods also affect the quantity of residual soil mineral N available. The measurement of residual N in the soil profile should include critical variables like depth, time of sampling, and number of samples to account for spatial variability. Nitrogen use under dryland conditions can be ineffective, leading to high residual N values in the soil at harvest, and these values must be incorporated into N recommendations for the next crop. The fate of this residual N during the fallow period (to conserve soil water) is largely unknown.

Traditionally yield information from field experiments that tested increasing levels of a nutrient was used to calculate response curves to indicate how yield was influenced by the nutrient application. These response curves formed the basis for calculating optimum fertilization requirements. The many transformation pathways and multitude of factors affecting the dynamics of N in soils, renders it a complex plant nutrient to study. Nitrogen recommendations must incorporate the various factors influencing N in the soil-plant system, which will enable site-specific recommendations.

Variations in climate and cultural conditions influencing plant growth, mineralization and N uptake can result in varying N availability indices from year to year, making the accurate prediction of fertilizer N requirement difficult. To overcome this problem, direct and indirect measurements of soil and plant mineral N and plant response to N fertilizer have been used. For soils, these include measurement of soil mineral N content, organic matter and N mineralization, as well as measuring and predicting potentially available N and losses from the soil. For plants it includes total plant uptake and N concentration, and the use of physiologically based crop models. In compiling fertilizer recommendations, the N requirement of the crop is important as influenced by yield, N content and efficiency of N uptake from the soil, and the availability of N fertilizer to supplement soil N supply as influenced by immobilization, leaching and gaseous losses (Broadbent, 1981; Rice *et al.*, 1995).

From the above discussion it is evident that N is an important plant nutrient, and that studies aimed at improving fertilizer recommendations should include:

- Measurement of gains, losses and transformations of N in agroecosystems;
- Yield and N uptake by the crop in the different cropping systems;
- The behaviour of N in the soil during the cropping and fallow periods;
- The effects of cropping systems on soil mineral N availability to the crop.

The aim of this study was to measure and thereby interpret the dynamics of N in the soil-plant system during the growing season and subsequent fallow period in the major dryland wheat producing areas. Chapter 4 describes plant growth, cumulative biomass production and yields to provide insight to the crop response during the study period. In Chapter 5, the N concentration of measured plant components and calculated N uptake by the crop is discussed in combination with biomass production, soil mineral N availability, and decomposition of crop residue. The effect of the fertilizer treatments, and soil mineral N transformations during the trial period is linked to N uptake and growth response of the crop in Chapter 6.

Results from this study will help to explain the effectiveness of soil and applied N to the growing crop in relation to uptake and productivity, the cycling of N on three different soils under conventional tillage systems in a fallow-wheat-wheat-fallow crop rotation, and the effects of applied and residual N on grain yield and quality.

CHAPTER 2 LITERATURE REVIEW

2.1 NITROGEN- ORIGIN, DISTRIBUTION AND CYCLING IN ECOSYSTEMS

On a global scale, 90 to 97% of the N content for net primary production of plant biomass is derived from recycling of N within the biosphere, leaving only 3 to 10% as being annually fixed (Haynes, 1986a). The major forms of mineral N (NH_4^+ and NO_3^-) usually account for less than 2% of total N in soils, but it is this N that is available for direct uptake by plants (Roswall, 1976).

2.1.1 Nitrogen cycle and distribution of N

Primary (igneous) rocks of the earth's crust hold approximately 97.8% of the global N, but contribute relatively little to the N-cycle. Gaseous N in the atmosphere represents only 1.9% of the earth's total N mass, and the bulk of atmospheric N exists as molecular N_2 (Burns & Hardy, 1975). The earth's atmosphere (78.1% N on a molar basis) has constituted the sole source of N for nutrition of all forms of life. In comparison with N contained in the atmosphere and lithosphere, quantities present in the biosphere are very small (0.01%). Organic N constitutes up to 50% of N contained in oceans and 73% of the total N contained in land. On land the microbial conversion of this dead organic N into mineral forms ($NH_4^+$and NO_3^-) supports active plant growth and biomass accumulation (Haynes, 1986a).

2.1.2 Nitrogen content of soils

On average, 99% of the N in terrestrial ecosystems is organically bound, and therefore the accumulation of soil N closely follows that of soil organic matter. An equilibrium between the input of products of plant litter decomposition and their losses from the soil determine the N content of soils. However, since the soil N system is dynamic, any change to the environment may lead to a new equilibrium level of soil N, leading to a diverse range of soil N contents (Haynes, 1986a).

Nitrogen availability to crops is regulated by a biologically dynamic soil N cycle. For this reason, many of the transformations are influenced by environmental factors that regulate the activity of microorganisms. A range of climatic, edaphic and agronomic factors influences the magnitude of each of the various transformations affecting the availability of N (Haynes, 1986a; Godwin & Jones, 1991).

2.1.3 Additions, losses and transfers of N

The N cycle in the soil-plant system involves many transformations of N between inorganic and organic forms. It can be divided into N inputs or gains, N outputs or losses, and N cycling within the soil where N is neither gained or lost (Tisdale *et al.*, 1993). The various processes are identified by a circled number in

Figure 2.1 and are discussed in the following section.

Major additions of N to the soil occur through the processes of wet and dry deposition, biological fixation of atmospheric N_2 by microorganisms in association with legumes, and industrial fertilizer production (1) (Tisdale *et al.*, 1993). Mengel (1996) calculated that industrial fixation of N_2 amounts to 60% of the biological N_2 fixation and that nearly all of this "technically fixed" N is used as N fertilizer and therefore arrives in the soil environment. Further additions include electrical fixation by lightning and release of combustion gases by the burning of fossil fuels, and the adding of crop and animal residues (1) (Tisdale *et al.*, 1993).

Through the activities of green plants, and their photosynthetic binding of solar energy, primary organic substances are build up in the form of plant tissue. This is returned to the soil as crop residue or manure(1), and is used as an energy source by heterotrophic microorganisms (Jansson & Persson, 1982). The organic N is then transformed back into the simple inorganic compounds originally taken up by plants. Part of the inorganic N (NO_3^- and NH_4^+) is used by a new generation of plants (4). In this way N and other elements are used and reused through continuous circulation between autotrophic and heterotrophic phases of the ecosystem.

Mineralization (2) is responsible for the transformation of organic N in plant and animal residues back into simple inorganic forms (NH_4^+), involving two reactions; aminization and ammonification (Tisdale *et al.*, 1993). The process of nitrification (3) converts NH_4^+ formed by mineralization or applied as fertilizer into NO_3^-, with NO_2^- as intermediate product (Schmidt, 1982; Tisdale *et al.*, 1993). Both NH_4^+ and NO_3^- can be taken up by plants (4). Immobilization is the conversion of inorganic N (NO_3^- and NH_4^+) into organic N by microorganisms. This heterotrophic phase of the ecosystem responsible for mineralization and immobilization is a living, biological phenomenon, growing, changing multiplying and constantly renewing, resulting in the formation of organic matter, microbial cells and tissues (Jansson & Persson, 1982).

Thus, in all mineralization activities there is a component of immobilization, a renewal of organic matter, and assimilation of mineral nutrients providing the multiplication, growth and maintenance of the living and active microbial flora or biomass. Immobilization can therefore reduce mineral N concentrations in the soil after crop residue incorporation (Tisdale *et al.*, 1993). Losses occur through leaching of NO_3^-, erosion and surface runoff (5), volatilization of ammonia, gaseous losses of N_2 and N_2O through denitrification (6), and in crop production systems through plant and animal removal (7) (Jansson & Persson, 1982, Marchner, 1995). Denitrification which occurs under restricted O_2 supply, is by far the most important process leading to losses of N_2 (Haynes, 1986a, Tisdale *et al.*, 1993).

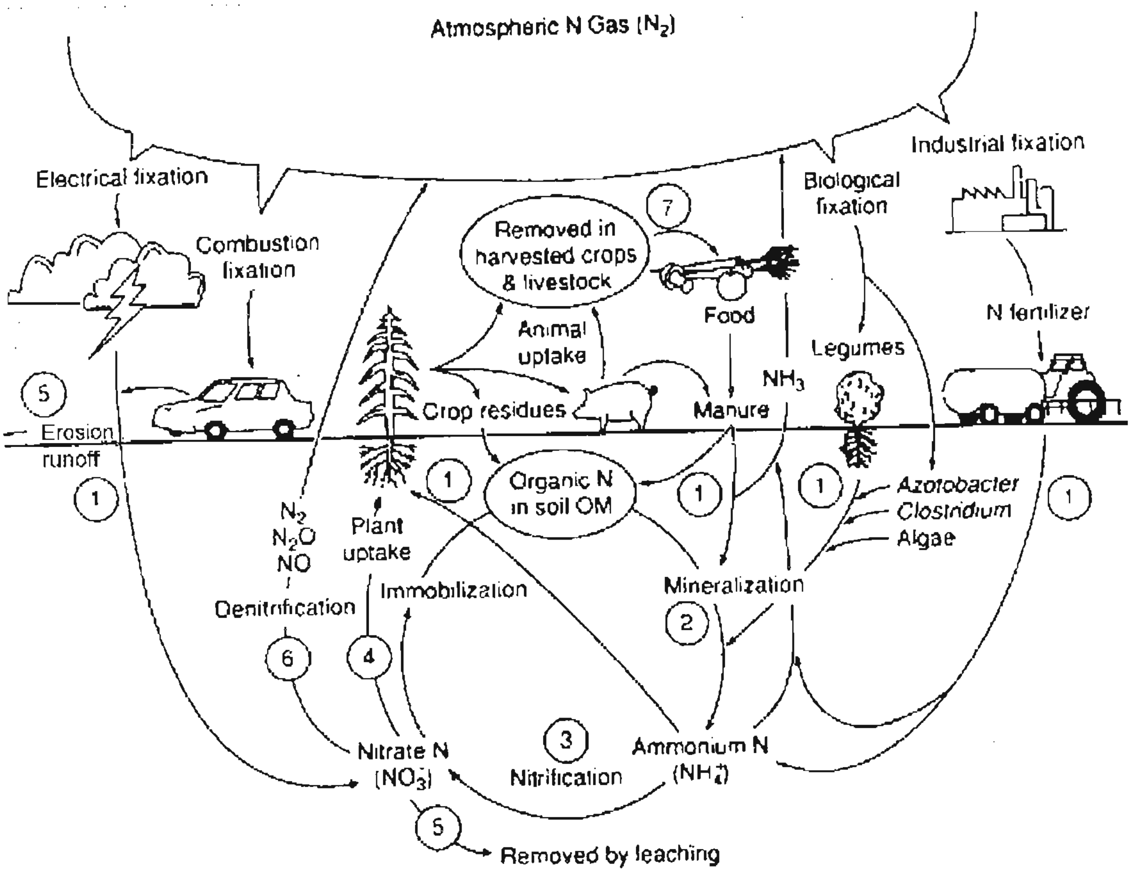

Figure 2.1 The universal N cycle (redrawn from Tisdale *et al.*, 1993)

(The various processes identified by circled numbers are discussed in section 2.1.3)

2.2 DECOMPOSITION PROCESS: MINERALIZATION, IMMOBILIZATION AND HUMUS FORMATION

Organic N containing compounds, the products of microbial decomposition of plant and animal remains, account for over 90% of total N in most soils. Decomposition constitutes the means by which N held in the structures of plant tissues is released into the soil for reuse by plants. Litter decomposition represents an important link in the N cycle of most natural and agricultural ecosystems (Haynes, 1986b). The addition of organic matter to the soil via the return of crop residues also improves soil structure, influences soil water, air, temperature relations, helps control runoff and erosion, and reduces tillage intensity (Kumar & Goh, 2000).

2.2.1 Process of decomposition and phases of N release

The decomposition of crop residues is a microbial-mediated progressive breakdown of organic materials with ultimate end products C and nutrients released into the biological circulation of the ecosystem at both a local and a global scale (Kumar & Goh, 2000). According to Swift *et al.* (1979) decomposition of crop residues consists of three interrelated processes namely, leaching, catabolism and comminution.

- Leaching is a physical process starting shortly after litter fall. It involves the removal of soluble matter from litter by action of water, and 10 to 25% of the total N content can be lost from litter in this way.
- Catabolism comprises of energy yielding enzymatic reactions that involve the transformation of complex organic compounds to smaller and simpler ones by fungi, bacteria, anthropods, and various saprophytic invertebrates. Products of catabolism include inorganic NH_4^+, and intermediate products that are resynthesized into complex compounds, while others may be incorporated into non-cellular organic matter (humus).
- Comminution is the physical reduction in particle size of the litter, and is achieved mainly by feeding habits of decomposer animals. It results in the exposure of a greater surface area for microbial colonization and attack (Anderson *et al.*, 1981).

Mineralization occurs when inorganic forms of an element (e.g. NH_4^+) are released during catabolism. The last step in mineralization of N in which simple organic nitrogenous substances are metabolized with the release of NH_4^+-N is known as ammonification. The outcome of catabolism is the release of energy for anabolic activity, which in turn results in uptake and use (immobilization) of mineral N by decomposer organisms. Thus, immobilization inevitably accompanies mineralization. In this situation, the heterotrophic decomposer biomass invariably out-competes nitrifier organisms and plants for NH_4^+ and this can cause a deficiency of mineral N in the surrounding soil. After incorporation of crop residues, net immobilization (accumulation of N in litter) is followed by a slow net release (net mineralization) of N. This is because of the decrease in C:N ratio over time resulting from the recirculation of C as CO_2 to the atmosphere. As a result, N becomes no longer limiting to microbial growth and activity, and organic N is made available (mineralized) as NH_4^+ and NO_3^- (Stevenson, 1982a; Kumar & Goh, 2000).

2.2.2 Microbial biomass

During decomposition of litter and residues, net immobilization of N by the decomposer biomass can occur, and even when net mineralization of N does occur, a significant portion of the total mineral N is absorbed by the microbial biomass. Mengel (1996) stated that 10-20% of added fertilizer is assimilated by soil microbes, and thus flows into the soil organic pool. Much of this N can be released to the soil through lysis of microbial tissues induced by faunal feeding. The decomposition of microbial biomass is therefore important in the final release of soil N originally bound in plant litter (Parsons & Tinsley, 1975). Nitrogen content of the microbial biomass amounts to about 5 to 10% of dry matter, much of this in the form of storage protein and in cell walls as amino acids and amino sugars. The soil microbial biomass is in a constant state of turnover, as remaining microflora readily mineralizes dead microbial cells (Jenkinson & Ladd, 1981). Thus, microbial biomass can contribute substantially to the pool of mobile, plant available nutrients in the soil. Sudden changes in environmental conditions cause death of a large proportion of microbial biomass, and a subsequent flush of available mineral N occurs. This can occur during drying and rewetting, and freezing and thawing cycles, because of fluctuating soil temperatures (Hart *et al.*, 1994).

Attempts to achieve the maximum use-efficiency of residues must take N cycling into consideration, since residue decomposition is intimately tied with the N cycling in the soil (Wagger *et al.*, 1985). Physical, chemical and microbial processes are all involved in loss of residue from a field (Stroo *et al.*, 1989). However, physical and chemical losses are minor compared with the weight loss caused by microbial decomposition.

Mineralization rates in field soils may be lower than those reported in controlled environment studies, since conditions are not continuously favorable for biological activity in natural ecosystems (Wagger *et al.*, 1985). The application of crop and organic residues to soil involves a substantial input of carbonaceous material and this may result in immobilization, at least temporarily of some mineral N already present in the soil. However, the balance between immobilization and mineralization changes with time, and in the long run, increasingly favors mineralization (Kumar & Goh, 2000). Thus, the C:N ratio has been of great relevance to the rate at which N is released from crop residues (Quemada & Cabrera, 1995; Janssen, 1996). It is generally accepted that residues with a wide C:N ratio decompose more slowly compared to residue with a narrow C:N ratio (Parr & Papendick, 1978).

In dryland areas, microbial activity is most active during the moist, warm fall and spring seasons, because low temperatures in winter and dry soil conditions in summer limit microbial growth (Douglas & Rickmann, 1992). Stroo *et al.* (1989) found rapid losses of residue mass during dry summer months, when little microbial activity could be expected. They also measured low levels of CO_2 respiration in the field, and deduced that these residue losses were non-microbial, with the most likely possibilities being physical disintegration and removal by macro fauna and wind.

2.2.3 Humus formation

The decomposition of any plant litter is completed over time (days to hundreds of years) (Kumar & Goh, 2000). Residues of the decomposition process contribute to the formation of soil organic matter. In the short-term, residues constitute a cellular fraction consisting of partially digested plant material, faeces, and microbial cells. A second fraction of organic residues that is not readily available as an energy source to the heterotrophic soil microflora accumulates in the soil. This constitutes humus (Haynes, 1986b). The formation, structure, and degradation of humic substances are important in that a large part of soil N is associated with such substances. An understanding of the nature of these substances is however, complex (Stevenson, 1982a).

2.2.4 Soil organic N

Soil organic matter is not an inert substance but is constantly changing as a consequence of the activities of microorganisms during immobilization, mineralization and humification of plant residues. To identify the organic substances in soil organic matter they are conventionally extracted by the acid hydrolysis method (Stevenson, 1982b). Soil organic N substances released consist mainly of: acid-insoluble N (20-35%), NH_3-N (20-30%), amino sugars (<1-13.8%), amino acids (13-52%) and hydrolyzable unknown N (>20%). This distribution in measured values varies due to differences in physical, chemical and biological properties of the soil, changes occurring during incubation or drying, cultivation effects and with depth in the soil profile (Stevenson, 1982a).

2.2.5 Factors affecting decomposition and mineralization

2.2.5.1 Substrate quality, N content, C:N ratio, lignin and polyphenol content

Substrate quality, as defined by chemical composition of the decomposing material, is a critical factor determining the rate of litter decay. The N content is an important factor controlling the rate of decomposition and mineralization. Indeed, many studies have demonstrated the beneficial effect of supplementary N to incorporated crop residues in enhancing the rate of decomposition (Bartholomew, 1965). The C:N ratio also has a significant effect on the rate of decomposition and mineralization, where residue with a high C:N ratio can cause net immobilization when added to soils, and fertilizer N must be added to avoid this and subsequent N deficiency (Bartholomew, 1965). The critical C:N ratio below which net mineralization will occur is quoted as being within the range 25 to 30:1, with an N content of 1.4 to 1.8% (Allison, 1973; Campbell, 1978; Berg & Ekbohm, 1983; Haynes, 1986b). The lignin and polyphenol content of litter influences the rate of decomposition, with high contents slowing this rate. Degradation products of these compounds are important sources of structural units for the synthesis of humic polymers (Dormaar & Carefoot, 1996).

In crop rotations, legume-based pastures can increase soil mineral and organic N and result in higher wheat grain yields. On the other hand, residues such as cereal straw, with a high C:N ratio may temporarily immobilize N. The effect of crop residues on the following crop depends on the amount of residues, type of residue (legumes or cereal) and C:N ratio of the residue. By making an estimate of the quantity and quality of added residue, it is possible to improve estimates of N fertilizer requirement of the following wheat crop (Mason & Rowland, 1992; Cheshire *et al.*, 1999).

Harper & Lynch (1981) found that crop residues decompose in distinct stages, with the initial stage of decomposition being relatively fast, becoming slower as the season and time progresses. This is linked to the differences in degradability of residue components, especially hemicellulose and cellulose. These two components constituted 78% of the weight of the oat residues that were used in their experiments. They also found that soil water content and soil temperature in the decomposition zone influenced the decomposition rate. Zaharah & Bah (1999) stated that the pattern of nutrient release and their ultimate availability to the crop is dependent on the kinetics of decomposition. This is in turn governed by environmental factors (temperature, soil water, soil texture, and mineralogy), as well as the rate and method of substrate application, and the quality (N and C content and composition) of the added materials (Mary *et al.*, 1996, Armstrong *et al.*, 1998). These authors also found that decomposition followed an initial rapid leaching phase, followed by a slower stage of decomposition. Soil water and temperature dynamics are the main external factors controlling the rate of residue decomposition and N mineralization/immobilization (Tisdale *et al.*, 1993). Another external factor influencing net N mineralization/immobilization is availability of mineral N in the soil environment (Swift *et al.*, 1979).

Low quality residues (high C:N ratio, high lignin and polyphenol contents) are known to cause temporary immobilization of inorganic soil N, and result in reduced N uptake by the growing crop and lower yields (Kumar & Goh, 2000; Nicholson *et al.*, 1997). Under conditions of high fertility in soils without limiting constraints or where long-term additions of crop residues have increased the amount of available mineral N, yields were increased by incorporation of crop residues (Dick & Christ, 1995; Kumar & Goh, 2000).

However, C:N ratios and N concentrations have not always correlated well with decomposition rates (Kumar & Goh, 2000). Although the C:N ratio and N concentration of crop residues are useful in predicting residue decomposition rates, these indices should be used with caution. This is because the C:N ratio reveals little on the availability of C and N to microorganisms. Any factor that increases the rate of decomposition and hence N demand by micro-organisms, tends to increase the threshold N concentration (lower the threshold C:N ratio) (Dendooven *et al.*, 1990).

2.2.5.2 Water content

The optimum water potential for ammonification is between 10 and 50 kPa (Stanford & Epstein, 1974). Soil water influences decomposition and mineralization in three major ways:

- water stress (water potentials below –1000 to –5000 kPa) inhibits microbial growth directly (Wilson & Griffin, 1975);
- as water content increases (>100 to 150% on dry weight basis), aeration decreases and this inhibits microbial growth and decomposition of litter (de Boois, 1974);
- cycles of drying and wetting increase the amount of available substrate due to death of microbial biomass. Subsequent decomposition causes flushes in N mineralization (Campbell & Biederbeck, 1982).

2.2.5.3 Temperature

Temperature is a major factor influencing decomposition of organic materials. Although decomposer organisms have different temperature optima, generally conditions of high temperature and water favour microbial growth and thus decomposition (Jenkinson & Ayanaba, 1977; Kumar & Goh, 2000). Over a range of temperatures above 35°C ammonification continues, but nitrification ceases at about 45 °C (Campbell, 1978). The optimum temperature for ammonification is in the 45°- 60°C range (Stanford *et al.*, 1973). Fluctuating temperatures can cause flushes of mineralization, since the soil microbial biomass is killed during these cycles and it then decomposes with the release of NH_4^+ (Campbell & Biederbeck, 1982).

2.2.5.4 Soil pH

The pH of the soil is an important factor influencing decomposition. Decomposition typically proceeds more readily in neutral than acid soils, with an optimum range of 5.0 to 6.5 (Swift *et al.*, 1979; Kumar & Goh, 2000). Liming therefore generally increases N mineralization rates (Neale *et al.*, 1997). However, the greater tolerance of mineralization than nitrification to low pH is reflected in the finding that ammonium is generally the dominant form of N in acidic soils, while nitrate predominates in non-acidic soils (Haynes & Goh, 1978).

2.2.5.5 Additions of fertilizers and organic manures

Applications of inorganic fertilizer N have been reported to stimulate, depress or have no effect on mineralization of native soil organic N (Broadbent, 1970; 1981). An apparent increase in mineralization of native organic N following the addition of ^{15}N-labelled N fertilizer has often been observed under laboratory, greenhouse, and field conditions (Westermann & Tucker, 1974). This effect is termed the "priming" effect and is often greater when NH_4^+ rather than NO_3^- fertilizer is applied (Broadbent, 1965). Controversy surrounds the origin of the priming effect (Huntjens, 1971; Jansson, 1971; Jansson & Persson, 1982). Usually, the priming effect is observed as an increase in uptake of native ^{14}N by a crop following addition of labelled fertilizer ^{15}N to the soil (Feigenbaum *et al.*, 1984; Haynes, 1986b; Rao *et al.*, 1991). Such an effect can often be attributed to mineralization-immobilization turnover. That is, part of the added labelled ^{15}N are immobilized but at the same time, some native soil organic ^{14}N is mineralized (Jansson & Persson, 1982). This does not necessarily mean that net mineralization of N has occurred.

The addition of organic residues to soils can also induce a small positive priming effect on soil organic matter decomposition (Jansson, 1971; Haynes, 1986b), and an increased uptake of native soil organic N by crops. Additions of organic N to soils could however, stimulate mineralization-immobilization turnover in a similar manner to that for fertilizer N. In addition, the application of energy-rich organic materials to soils will stimulate microbial activity and thus tend to increase the mineralization of native soil organic N (Jenkinson & Ladd, 1981).

2.2.5.6 Growing plants

The volume of soil immediately surrounding the root is termed the rhizosphere. This region is highly favourable to microbial growth, since the plant contributes excretory products (root exudates) and sloughed off tissues that act as an energy source for microbial growth. This production of readily available C in the rhizosphere means that N often becomes the limiting factor for microbial growth (Huntjens, 1971). Most of the mineral N released by decomposition in the rhizosphere is first incorporated into the microbial biomass. Huntjens (1971) found net mineralization of soil mineral N in soils with dead grass roots, but immobilization of soil mineral N where living plant roots were present. This immobilization can lead to the formation and accumulation of soil organic matter especially under permanent pasture with a large, dense root mass. In other studies plant growth has been reported to increase, retard or have no effect on mineralization (Haynes, 1986b).

2.2.5.7 Clay content and microbial activity

Generally, the organic matter content increases with increasing clay content of the soil. This can be attributed to microbial activity, and complexation with organic compounds, and with humic substances (Martin *et al.*, 1976). Clay minerals stimulate microbial activity and growth, and interact with simple organic and humic substances to form complexes that are less susceptible to biodegradation. Decomposition is therefore inhibited and this can lead to increases in humus formation (Haynes, 1986b).

2.2.5.8 Cultivation

Cultivation of soils results in the rapid decline of their soil organic matter and N content, but in contrast, reduced tillage result in the accumulation of organic matter in the surface soil layers. Cultivation is an oxidative process promoting good aeration, rapid decomposition of organic matter and increasing N mineralization (Goh & Haynes, 1986). The physical disruption of soil aggregates during cultivation results in the exposure of microsites on previously physically inaccessible organic matter to microbes or their enzymes, resulting in increased mineralization. Therefore, a characteristic flush of N mineralization follows conventional tillage operations. This can lead to increased uptake of N by the crop, but these nutrients can also be lost before utilization by the newly planted crop (Campbell, 1978).

Under zero tillage, no such flush occurs and indeed a shortage of plant-available N is relatively common. In addition to crop residues, the no-till production system also affects soil microbial biomass by promoting C accumulation at the soil surface due to a lack of incorporation of these residue (Kumar & Goh, 2000). This results in higher values for soil microbial biomass in the surface of no-till systems than in conventional tilled soils (Franzluebers *et al.*, 1995). Carefoot *et al.* (1990) found that reduced barley grain N concentration in no-till treatments was related to fertilizer N immobilization due to residue with a high C:N ratio in the surface soil layer. Increased immobilization of broadcast N with no-till treatments in comparison with conventional tillage practices suggests that banding of fertilizer N below the surface residue layer may be beneficial in these cases (Carefoot *et al.*, 1990).

2.3 NITRIFICATION

Nitrification is classically defined as the process whereby NH_4^+ is biologically oxidized to NO_3^- with NO_2^- as intermediate product, by a specialised group of soil bacteria called nitrifiers (Schmidt, 1982).

2.3.1 Processes of nitrification

The most important pathway of nitrification is through the actions of chemoautotrophic bacteria (Haynes, 1986c). One group, the NH_4^+ oxidizers, initiates the process with the formation of NO_2^- while a second group, the nitrate oxidizers, completes the process by converting NO_2^- to NO_3^- as promptly as it is formed (Schmidt, 1982). Five genera are known to be able to oxidize NH_4^+ to NO_2^- in soils: *Nitrosomonas*, *Nitrosococcus*, *Nitrosospira*, *Nitrosolobus*, and *Nitrosovibrio* (Haynes, 1986c). One genus *Nitrobacter* is known to oxidize NO_2^- to NO_3^- in soils and water (Schmidt, 1982; Haynes, 1986c). Nitrification mediated by heterotrophic microorganisms (particularly fungi) appears to be of significance in some acid soils (for example pH <5.0) (Focht & Verstraete, 1977). Other possible pathways of nitrification include oxidation of the NH_4^+ to NO_2^- by methylotrophic bacteria and the chemical oxidation of NO_2^- to NO_3^- (Allison, 1973; Whittenbury & Kelly, 1977).

2.3.2 Factors regulating nitrification

The narrow species diversity of organisms involved in autotrophic nitrification results in the process being greatly influenced by environmental factors such as pH, temperature, water and aeration (Haynes, 1986c).

In general, the optimum pH range for nitrifiers is in the range of 7 to 9, optimum temperature is 25 to 35°C, and optimum soil water potential is –10 to –33 kPa (Kowalenko & Cameron, 1976; Mahli & McGill, 1982; Haynes, 1986c). Nevertheless, natural diversity among nitrifiers and the adaptation of indigenous nitrifiers to their particular environmental conditions mean that no definite "cut-off" point can be identified.

In many situations, the rate-limiting factor for nitrification appears to be the supply of NH_4^+-N. Applications of NH_4^+-containing fertilizers to soils can massively increase populations and activities of autotrophic nitrifiers (Ardakani *et al.*, 1974). There is considerable evidence that a limiting supply of NH_4^+ regulates nitrification in many natural ecosystems (Rice & Pancholy, 1974). Some evidence also suggests that in mature natural ecosystems, allochemicals originating from the predominant plant species present might also inhibit nitrifier activity (Haynes, 1986c).

2.3.3 Significance of nitrification

The role and significance of nitrification are subject to much controversy (Haynes, 1986c). The major drawbacks of nitrification are:

- the process results in soil acidification,
- during the process N is lost as N_2O,
- NO_3^- can undergo denitrification in anoxic soil sites with the release of N_2 and N_2O gases,
- NO_3^- in contrast to NH_4^+ is very mobile in soils, and thus easily lost through leaching processes.

However, in agricultural systems nitrification is often considered as an agronomically desirable process (Allison, 1973; Verstraete, 1981). Agricultural soils are often fertilized with NH_4^+-containing fertilizers or urea, and nitrification results in (i) low levels of phytotoxic NH_4^+-N existing in soils and thus a medium conducive to good plant growth and (ii) a decrease in gaseous losses of N through NH_3 volatilization (Haynes, 1986c).

Due to the potential for N losses via leaching and denitrification, attempts have been made to regulate nitrification with the use of slow release NH_4^+ fertilizers, or with specific nitrification inhibitor chemicals (Hauck, 1972; Oertli, 1980). These have however, met with little commercial application (Hendrickson *et al.*, 1978; Haynes, 1986d).

2.4 MOVEMENT OF NITROGEN IN SOILS

Most natural terrestrial ecosystems have a reasonably closed N cycle, and inputs and losses of N are both very small. Such ecosystems lose significant amounts of N through leaching, runoff and erosion only following severe disturbances such as burning, harvesting, irrigating or fertilization (Vitousek, 1981). In contrast, losses can be large in agricultural ecosystems which are continually disturbed, with leaching often being the most important channel of N loss other than that accounted for by crop uptake (Allison, 1973). These losses of N can be limiting to plant growth, cause environmental (e.g. eutrophication) problems and health hazards (high nitrate levels in water).

2.4.1 Absorption and fixation

- Ammonium derived from mineralization of organic N, added organic materials and added fertilizers, is unlikely to be leached from soils. The reasons for this include:
- NH_4^+ is held in the soil by cation exchange (Kowalenko & Ross, 1980);
- NH_4^+ can be fixed within the interlayer of 2:1 clay minerals in non-exchangeable form;
- organic matter can fix considerable amounts of ammonia (NH_3) in a non-exchangeable form;
- NH_4^+ can be immobilized by microbial biomass or be nitrified to NO_3^-.

Soil clay and organic matter have a predominantly negative charge and are able to attract and hold positively charged cations by cation exchange. The total negative charge on soil colloid surfaces represents its ability to hold positively charged ions (i.e. cation exchange capacity – CEC). Cation exchange is a reversible process in which cations in the soil solution are in equilibrium with those on exchange sites. These exchangeable cations are therefore readily available to plants, but protected against leaching by percolating waters. Leaching of NH_4^+ is therefore, only likely to be a problem in soils with an extremely low CEC (Cameron & Haynes, 1986).

Ammonium can be fixed in a non-exchangeable form in 2:1 clays (montmorrilonites and vermiculites). The magnitude of fixation depends mainly on soil type and the type of clay minerals that are present (Scherer, 1993). The absolute amount of ammonium fixed increases with increasing amounts of added ammonium, but the percentage fixation decreases with increasing NH_4^+ additions. The rate of fixation is at its highest immediately after ammonium addition, and slows as equilibrium is reached (Nommik & Vahtras, 1982). Ammonium fixation decreases with decreasing soil pH, while drying, drying and wetting cycles and freezing increase fixation. However, under certain soil conditions, NH_4^+ fixation may be a positive factor in preventing losses through leaching, and ensuring a more even supply of N throughout the growing season (Tisdale *et al.*, 1993).

In contrast to the retention and fixation of NH_4^+, NO_3^- is not usually adsorbed by soil colloids, and is thus susceptible to diffusion and mass transport with soil water (Wild & Cameron, 1980). However, NO_3^- can be adsorbed to positively charged sites on soil minerals (including iron, and aluminium oxides and hydroxides, and 1:1 clay minerals) (Mott, 1981). Thus soils that are rich in such minerals (mainly tropical and volcanic soils), can have a significant anion exchange capacity (AEC) so that NO_3^- is held in the soil and this restricts its free movement with water (Kinjo & Pratt, 1971).

2.4.2 Erosion and runoff

Erosion represents the transfer of soil by wind and water, from one ecosystem to another. It causes a reduction in crop rooting depth, and a net loss of N from the system (Young, 1980). Raindrops impacting on a bare soil tend to disperse soil aggregates, reduce surface roughness, and lead to crust formation. This in turn restricts infiltration and increases runoff and subsequent erosion. Soil properties like texture and structure, vegetation and crop residues can greatly influence infiltration and percolation rates (Cameron & Haynes, 1986).

Wind erosion can be a problem where soils are loose and dry. It is prevalent where there is a smooth soil surface with no vegetation cover under conditions of low rainfall, high temperatures, periodic droughts and high wind velocities (Wilson & Cooke, 1980). Tillage operations that leave the soil rough with clods, and maintain residues at the soil surface can minimize wind erosion (Power, 1981).

2.4.3 Leaching

For the process of NO_3^- leaching to occur, two prerequisites must be met:
(i) there must be an accumulation of NO_3^- in the soil and (ii) there must be an appreciable downward movement of water in the soil profile. Nitrate movement in soils can be described by a combination of three processes: convection, diffusion, and dispersion (Hillel, 1980). Due to variability of soils, determining the parameters to calculate solute movement accurately is difficult (Cameron & Haynes, 1986). Several models, stochastic and empirical methods have been developed to calculate soil water and solute movement (Godwin & Jones, 1991). A number of techniques have been used to measure nitrate-leaching losses. These include the use of lysimeters, tile drains, laboratory columns and catchment studies (Cameron & Haynes, 1986).

2.4.4 Factors affecting erosion and leaching losses

2.4.4.1 Climate

The distribution and total amount of rainfall directly influence sediment and runoff losses as well as leaching (Cameron & Haynes, 1986). Some important considerations include:

- Leaching is normally minimal in summer since evapotranspiration typically exceeds rainfall. Some leaching may occur after heavy rainfall events (Williams, 1975).
- Autumn rainfall leaches residual mineral N left after harvest if the soil has already reached field capacity

(Cameron & Haynes, 1986).

- Winter rainfall typically leaches nitrate because of excess rainfall over evapotranspiration, and low N uptake by the crop (Dancer, 1975).
- Spring rainfall events determine whether freshly applied fertilizer or newly mineralized N is quickly leached (Williams, 1975).
- Dry summers lead to the accumulation of soil nitrate due to poor crop uptake. Higher leaching losses may then occur over the subsequent winter (Garwood & Tyson, 1977).

2.4.4.2 Soil properties

Soil properties such as hydraulic conductivity, water storage capacity, and anion exchange capacity greatly influence leaching losses. Soil properties affect both the infiltration rate and the permeability to water, which in turn influence the amount of erosion. Soil organic matter, aggregate stability, grain size, and cohesiveness, as well as land characteristics (slope angle and length) also have an effect on runoff and leaching losses (Schepers, 1988).

2.4.4.3 Land management

Losses of N through runoff are often negligible under most grassland conditions, but where vegetation cover is reduced, losses during intense rainfall events can be significant (Cameron & Wild, 1984). The potential for losses is high under arable agriculture because, for part of the year, the disturbed soil lacks vegetative cover. Zero or minimum tillage practices aim to return residue to the soil surface and reduce runoff (Unger & McCalla, 1980).

2.4.4.4 Irrigation

Irrigation generally increases crop growth and thereby N uptake. Optimum amounts of irrigation can thus reduce leaching losses. Nevertheless, excessive irrigation can cause leaching and/or surface runoff losses depending on the type of irrigation used (surface, sprinkler or trickle irrigation), and the amount, rate and frequency of water application (Bauder & Schneider, 1979).

2.4.4.5 Fertilizer application and organic wastes

Generally, if N fertilization does not exceed crop requirements, there is little residual NO_3^- available for leaching (Singh & Sekhon, 1979). Increasing the rate of N application above crop requirement generally increases residual mineral N in the profile, and thus the potential for leaching losses. Runoff shortly after surface application of fertilizer can cause significant losses (Baker & Johnson, 1981). Incorporation of fertilizer can drastically reduce such runoff losses. Land disposal of animal wastes can cause contamination of ground and surface waters with N (Vetter & Steffens, 1981). With surface applications, runoff losses of N are a potential hazard. Once the organic N in wastes has been ammonified and nitrified, leaching losses of NO_3^- can occur.

2.4.5 Consequences and control measures

Notable consequences of leaching and runoff losses of nitrogen are decreases in yield where losses are large and environmental contamination. High concentrations of NO_3^- in ground and surface waters can lead to eutrophication posing a health hazard to both livestock and humans (Cameron & Haynes, 1986). Generally, less than 5% of fertilizer input is lost in runoff, while leaching losses can be significant where fertilizer input exceeds crop requirement, or if fields are left fallow (Barker, 1980).

Control measures to prevent or decrease leaching and runoff losses of N include the following (Keeney, 1982b):

- Containment of runoff, and storage and treatment of nutrient rich effluents from agricultural lands;
- Management of cropping practices to include; soil conservation to minimize erosion, water conservation and management to optimize irrigation, and the use of crop rotations, multiple cropping and cover crops to utilize residual nitrogen (Hook & Gascho, 1988).
- Management of fertilization through improved estimation of crop nutrient requirements, timing of fertilizer applications to correspond to plant needs, fertilizer placement, slow release or nitrification inhibitors, and foliar application of fertilizers (Cameron & Haynes, 1986).

2.5 GASEOUS LOSSES

A number of mechanisms lead to gaseous losses of N from soils. These include ammonia volatilization, biological denitrification, nitrification, and chemodenitrification.

2.5.1 Ammonia volatilization

Ammonia volatilization is the term to describe the physico-chemical process by which gaseous NH_3 is released from the soil surface to the atmosphere. A prerequisite for NH_3 volatilization is a supply of free ammonium near the soil surface, and this may originate from fertilizer, organic residues, or native soil organic matter. High soil pH values and high temperatures promote volatilization losses from soils (Vlek & Craswell, 1981).

Other factors that influence NH_4^+ concentration in the soil solution also will influence the potential for volatilization. These include plant uptake, nitrification, immobilization and fixation of NH_4^+ by clay minerals.

Soils with a high CEC tend to have less NH_4^+ in the soil solution due to adsorption and thus the potential for volatilization is decreased (Haynes & Sherlock, 1986). Soil water content and water loss influence the NH_3 evolution, while drying results in the upward movement of dissolved NH_4^+ and NH_3 to the soil surface (Vlek *et al.*, 1981).

The form and placement of fertilizers directly effects NH_3 volatilization. Surface applications of alkaline fertilizers such as urea generally result in larger losses of NH_3 than do applications of neutral or acidic fertilizers such as $NH_4H_2PO_4$ or $(NH_4)_2SO_4$ (Matocha, 1976). Deep placement of fertilizers and anhydrous NH_3 (Nelson, 1982) can help in reducing losses of NH_3. Plants can absorb NH_3 from the atmosphere, but also lose NH_3 from the plant canopy (Firestone, 1982; Farquhar *et al.*, 1983; Papakosta & Gagianas, 1991). Harper *et al.* (1987) concluded from their studies that the loss of N via NH_3 from plants after anthesis is controlled by tissue senescence and redistribution of N to the developing grain. The NH_3 losses may be quite variable and could be linked to N stress in the plant during the active growth stages. As plant senescence accelerates, proteins hydrolyze to amino acids and amines that may accumulate. If deamination occurs, NH_3 can accumulate and be lost through volatilization.

2.5.2 Biological denitrification

Denitrification is a major biological process through which N from the soil is returned to the atmosphere (Haynes, 1986a). The process is carried out by a number aerobic bacteria that grow in the absence of O_2 while reducing NO_3^- or NO_2^- to gaseous products (N_2O and N_2). These bacteria are biochemically and taxonomically diverse although most are chemoautotrophs and use C-containing compounds as energy sources (Firestone, 1982; Haynes & Sherlock, 1986).

Denitrification is promoted by anaerobic conditions, high levels of soil NO_3^- and a readily available source of C (Stanford *et al.*, 1975; Ryden & Lund, 1980). The amount of N_2 emitted is generally much greater than that of N_2O, and the mole ratio of N_2O emitted generally increases with high NO_3^- concentrations and lower pH and decreases with higher temperatures and increasingly anaerobic conditions (Focht, 1974). Denitrification can be a major loss mechanism for applied fertilizer N in many agronomic situations (Bremner & Blackmer, 1981; Haynes & Sherlock, 1986).

2.5.3 Nitrification

During the process of autotrophic nitrification, the NH_4^+ oxidizing bacteria have the capacity to produce N_2O and NO during oxidation of NH_4^+ to NO_2^- (Bremner *et al.*, 1981). The potential for losses of N_2O via nitrification is likely to be greatest when NH_4^+-containing or yielding fertilizers are applied to aerobic soils.

In general, background emissions of N_2O from soils are thought to originate principally from denitrification whilst large fluxes usually originate from denitrification linked to increased temperatures (Goodroad & Keeney, 1984).

2.5.4 Chemodenitrification

This term describes the processes responsible for gaseous losses of N from soils through chemical reactions of NO_2^- (Haynes & Sherlock, 1986). A variety of gases can be evolved from soils treated with NO_2^- including N_2, N_2O, NO, and NO_2. The significance and magnitude of such losses under field conditions has not been established but is generally considered to be small (Galbally & Roy, 1983).

2.6 UPTAKE AND ASSIMILATION OF N BY PLANTS

The utilization of N by higher plants involves several processes, including uptake, storage, translocation, reduction and incorporation of N into organic forms. The predominant form of N available to plants is NO_3^- because under most soil conditions NH_4^+ is rapidly nitrified to NO_3^-. Ammonium is the major form of N available to plants under conditions that are unfavourable for nitrification. Ammonium cannot accumulate in cells to any great extent without damage to the plant. Because of this, it is normally converted to amino acids or amides in the root and translocated to the tops in these organic forms (Haynes, 1986d).

2.6.1 Functions and movement of N in plants

A requirement for N exists throughout the development of a plant to maintain growth, as N is a constituent of both structural (e.g. cell walls) and non-structural (e.g. enzymes, chlorophyll, and nucleic acids) components of the cell. Most N for vegetative growth is supplied either by the assimilation of (i) N absorbed from the soil and/or (ii) N fixed from atmospheric N_2 in the case of leguminous crop species (Schrader, 1984). Both the xylem and phloem participate in transporting N in plants (Pate, 1973).

The xylem is the principle path for long distance transport of nitrogenous solutes from the roots to organs that transpire (Pate, 1973; Schrader, 1984). The xylem therefore transports NO_3^- from the roots to shoots in addition to N reduced in the roots (Schrader, 1984). The phloem is the principal transport path of N assimilated in one part of the shoot and transported to another (e.g. leaf to seed). In contrast to the xylem, N solutes in the phloem are organic solutes, with nitrate usually absent or present only in trace amounts in the phloem (Pate, 1976).

2.6.2 Processes of uptake

Nutrients destined for use by the plant must first move through root tissues before entering the xylem, and being translocated to the shoots. Absorption of ions across the plasmalemma of root cells is generally accepted to be an active process that often overcomes an unfavourable electrochemical gradient through the expenditure of energy (Haynes, 1986d; Marchner, 1995).

2.6.2.1 Ammonium uptake

The time dependant uptake of NH_4^+ by plants can be characterised by two phases. The initial phase (not inhibited by low temperatures or metabolic inhibitors) represents passive exchange-absorption process in the negatively charged free space of roots (Nye & Tinker, 1977). The second phase of uptake is sensitive to low temperatures and metabolic inhibitors and represents active absorption of NH_4^+ (Nissen *et al.*, 1980).

2.6.2.2 Nitrate uptake

Uptake of NO_3^- by plants is an energy requiring process, and is restricted by inhibitors of RNA and protein synthesis, and inhibitors of respiratory and oxidative phosphorylation (Jackson *et al.*, 1973; Rao & Rains, 1976; Tompkins *et al.*, 1978). It is generally thought that NO_3^- transport across the plasmalemma is linked to a membrane-bound ATPase (Huffaker & Rains, 1978).

2.6.2.3 Factors affecting uptake

Uptake rates of NH_4^+ are normally unaffected by the presence or absence of NO_3^- in the nutrient solution, but ambient NH_4^+ has been shown to restrict net NO_3^- uptake (Rao & Rains, 1976; Youngdahl *et al.*, 1982). This inhibitory effect of NH_4^+ on NO_3^- uptake is, in the majority of cases, independent of any such effect on NO_3^- reductase enzyme activity.

Active uptake of anions across the plasmalemma of roots involves active excretion of OH^- or HCO_3^-, while uptake of cations results in excretion of H^+ (Nye, 1981). With NH_4^+ nutrition, the plant absorbs cations in excess of anions, so that plant growth results in the net efflux of H^+ ions into the rhizosphere, with a resultant decrease in the soil pH close to the root (Smiley, 1974). When NO_3^- is the major form of N supplied, plants absorb an excess of anions, and there is a net efflux of OH^- or HCO_3^- ions. Consequently there is an increase in rhizosphere pH (Smiley, 1974).

Generally NH_4^+, Ca^{2+}, Mg^{2+} and K^+ compete with each other during ion accumulation by plants, with NH_4^+ uptake reducing K^+ uptake (Haynes & Goh, 1978) and *vice versa*. Ammonium nutrition results in increased uptake of phosphate and sulphate, mainly because of the lowering of rhizosphere pH. Nitrate nutrition generally stimulates cation uptake and inhibits that of anions (Haynes & Goh, 1978). Because uptake of NO_3^- and NH_4^+ are active processes, carbohydrate (energy) supplies influence both processes, so that energy supply to the roots to sustain the uptake system is important. Low light intensities reduce uptake of both forms of N. Their uptake shows diurnal variation that is linked to translocation of photosynthates from the leaves and thus the availability of carbohydrate reserves in the roots. Nitrate uptake is restricted more by low temperatures than is the uptake of NH_4^+, while at around 23 to 35 °C, NO_3^- uptake exceeds that of NH_4^+ (Frota & Tucker, 1972).

2.6.2.4 Foliar absorption

Urea is widely used in foliar application of N, and it can penetrate rapidly through the cuticle into leaf cells. Foliar applied urea is metabolised in the plant to NH_3 and CO_2 by the enzyme urease (Rachhpahl-Singh & Dirk, 1993). Plant foliage can also absorb NO_2 and NH_3 gases from the air (Farquhar *et al.*, 1983; Marchner, 1995). This is assumed to be by diffusion into stomata and then into the intercellular spaces of leaves (Kannan, 1980).

2.6.3 Processes of assimilation

The first step in the assimilatory reduction of NO_3^- in higher plants is catalysed by the enzyme complex nitrate reductase. The enzyme catalyses the reduction of NO_3^- to NO_2^- by reduced pyridine nucleotides (Guerrero *et al.*, 1981), as follows;

$$NO_3^- + NAD(P)H + H+ \overset{2e-}{\Leftrightarrow} NO_2^- + NAD(P) + H_2O$$

The next step is the reduction of NO_2^- to ammonium in photosynthetic cells and is catalysed by the enzyme ferrodoxin-nitrite reductase.

$$NO_2^- + GFd_{red} + 8H^+ \overset{6e-}{\Leftrightarrow} NH_4^+ + GFd_{ox} + 2H_2O$$

Ammonia assimilation has a central role in plant N metabolism, since NH_4^+ is absorbed directly by the roots, and it is the product of NO_3^- and urea assimilation, and molecular nitrogen fixation (Miflin & Lea, 1980). The major pathway of ammonia assimilation is through the glutamate synthase cycle, catalysed by the enzymes glutamine synthetase and glutamate synthase (Miflin & Lea, 1980). The initial incorporation of NH_3 into the amide position of glutamine is catalyzed by the enzyme glutamine synthetase (Haynes, 1986d). In the presence of a reducing source, glutamate synthase catalyzes the transfer of the amide group of glutamine to α-oxoglutarate resulting in the formation of the amino acid glutamate. The incorporation of the NH_4^+ into an amino acid is then followed by transamination reactions in which the amino group ($-NH_2$) is transferred to another metabolite thus forming other amino acids or amino compounds (Haynes, 1986d). The NH_4^+ is incorporated into amino acids which are then assembled in specific sequences to form different proteins (Larsen, 1980).

Ammonium is extremely toxic if it accumulates in plant tissues, and plants generally lack any mechanism to deal with its accumulation other than assimilation. The control of N metabolism however tends to ensure that NH_4^+ is not generated internally under conditions such that it cannot be assimilated (Guerrero *et al.*, 1981). Givan (1979) has suggested that at high levels of tissue NH_4^+, the enzyme asparagine synthetase could also become a primary assimilating enzyme.

When soluble N reserves in plants are inadequate to sustain the N demand, breakdown of insoluble leaf proteins occurs (Haynes, 1986d). Protein-rich grain crops have a high demand for N during grainfilling, and mobilization of soluble N and breakdown products of insoluble N reserves in the leaves can be an important source of grain protein (Novoa & Loomis, 1981; Haynes, 1986d). With an adequate supply of N, protein losses during remobilization are high only in older leaves, but with a low supply of N, mature leaves lose protein linearly with age (Novoa & Loomis, 1981). Under extreme N deficiency, protein levels of very young leaves of wheat are reduced and most of the N in wheat grain is derived from remobilization (Evans *et al.*, 1975). Under conditions where N absorption from the soil is possible during grain development, remobilization may be the source of less than 50% of grain N (Evans *et al.*, 1975).

2.6.4 Responses to limiting or oversupply of N

In natural ecosystems, the rate of N mineralization shows a distinct seasonal trend with peaks in availability, resulting in high concentrations of mineral N, followed by periods of low supply (Taylor *et al.*, 1982). Plants take advantage of these transient levels of mineral N and show similar seasonal patterns of N uptake and in the activity of N assimilating enzymes (Taylor *et al.*, 1982). However, in agricultural ecosystems, fertilizers are commonly added to facilitate maximum growth, and these applications can result in an oversupply of mineral N.

Toxic reactions can occur when NH_4^+ accumulates in plants, but in contrast, plants can accumulate high concentrations of NO_3^- and transport it through the plant with few toxic effects (Mills & Jones, 1979). Phytotoxic effects of NH_4^+ usually do not occur in fertile soils because of rapid nitrification, but heavy applications of ammoniacal fertilizers and cool soil temperatures can result in the accumulation of toxic levels of NH_4^+ (Haynes, 1986d; Marchner, 1995). Although plants can accumulate high concentrations of NO_3^-, health problems can be caused when such plant material is ingested by humans or domesticated animals (Mills & Jones, 1979). Both NH_4^+ and NO_3^- oversupply results in the depletion of the plant's supply of storage carbohydrates that are used during assimilation of NH_4^+ (Michael *et al.*, 1970).

2.7 NITROGEN IN PLANT PRODUCTION

Nitrogen is a major essential nutrient, and is required by plants in substantial quantities. When water is non-limiting, N is commonly the next factor limiting crop production (Nielsen & Halvorson, 1991). The aim of a producer is to increase yields with a consequent economic return from the additional fertilizer costs. Accurate fertilizer N recommendations are therefore important for cost-effective and environmentally friendly agricultural production (Halvorson *et al.*, 1987).

2.7.1 Nitrogen uptake and content of plants

Bulman & Smith (1993) stated that some cultivars are known to vary in leafiness and tillering ability, with leaf tissues generally having higher N concentrations than stem tissues. Synthesis, translocation, partitioning, and accumulation of photosynthetic products within the plant are controlled genetically, but influenced by the cropping environment. Leaves, other green tissues and organs of plants that produce photosynthate are called sources. Organs or tissues that receive these products temporarily store them, and release these products at a later stage to other sites are also called sources (Snyder & Carlson, 1984). All sites within the plant, which utilize photosynthetically derived products, either *in situ* or after receiving the products, are called sinks.

There is a close relationship between net photosynthesis and crop yield, as well as the need for improved translocation (from biomass to developing grain) and larger sink capacity (ear size/number and kernels per ear). Translocation requires metabolic energy and chemical gradients for moving compounds from the source to the sink. Snyder & Carlson (1984) found that as grain matured in wheat, its sink strength or ability to accumulate photosynthate increased as compared to other competing sinks. This sink capacity (number of ears and grains m^{-2}) is significantly influenced by the harvest index (ratio of grain yield to total above ground biomass yield at harvest) of a cultivar.

Total plant uptake of N would be best expressed by total biomass N. However, N in roots, root residues and root slough materials are difficult to measure. For this reason, total above ground N is the estimate of plant N uptake most commonly used. Typically, N uptake by field crops involves a period of very slow accumulation followed by a rapid increase that coincides with rapid plant growth. Uptake rates between 3 and 5 kg N ha^{-1} day^{-1} can occur during this rapid uptake phase. This also results in high N concentrations in young seedlings, and there is a characteristic decline in the N concentration as the plant ages and accumulates dry matter (Tinker, 1978; Goh & Haynes, 1986). The response of the crop (grain yield and grain protein content) to applied N also depends on the redistribution of N within the plant. That is, there is remobilization and translocation of N within the plant during grain development.

The 'dilution effect' is referred to in plant nutrition studies to explain the results that arise when the concentration of an element is decreased (or increased - concentration effect) due to a change in plant growth induced by environmental conditions. This causes changes in the nutrient concentration in the plant as a function of time, due to increased dry matter accumulation. It has been found that young plants contain higher concentrations of nutrients (especially for N, P, and K) than older plants (Jarrell & Beverly, 1981), depending on the relative mobility of the specific nutrient in question. When a growth-limiting element is supplied, the relative rate of dry matter accumulation can increase more rapidly than rate of nutrient accumulation, resulting in lower final nutrient concentrations of treated plants (Jarrell & Beverly, 1981).

Furthermore, the remobilization and redistribution of N within the plant, causes changes in the N concentration of different plant parts over time. This causes difficulties in determining optimal N status of plants through analysis of plant parts. Several authors have suggested the use of total aboveground dry matter at different growth stages for determining the critical N concentration (Olson & Kurtz, 1982, Tucker, 1984; Goh & Haynes, 1986). Critical total N concentrations in the above ground wheat plant at flag leaf stage are presented in Table 2.7.1 (Olson & Kurtz, 1982; Goh & Haynes, 1986). For plant analysis to be useful in diagnosing the N status of a plant, a point of reference must first be established. This point differs with the kind of plant, plant part, position on the plant, stage of growth, or plant product specific to a particular plant (Tucker, 1984). As shown in Table 2.7.1, the range in the "sufficient" value for total plant analysis for N is 1.75 to 3.0%. This range separates the zone of deficiency from the zone of excessive N content, indicating to some extent the availability of N to the plant.

Table 2.7.1 Total concentrations of N (%) in above ground wheat plants at flag leaf stage (Olson & Kurtz, 1982)

Plant part measured	Form of N	Deficient	Low	Sufficient	Excessive
Total plant	Total N	<1.25	1.25-1.75	1.75-3.0	>3.0

The quantity of N removed in the crop is usually the major determinant of fertilizer N requirement of that crop. This is because the yield and N uptake of modern crops is large in comparison with the N supplying capacity of most soils (Olson & Kurtz, 1982). Nitrogen deficiency is closely related to restricted chlorophyll synthesis, and it typically results in a reduction in plant growth. Yellow coloration starts on the older leaves, since N is translocated to younger leaves, and as the severity of the deficiency increases, the entire plant turns yellow, the older leaves turn brown and die, and plant growth ceases. By comparison, vigorous plant growth with a dark green colour results from an oversupply of N (Snowball & Robson, 1991).

2.7.2 Plant responses to applied N – Yield and quality

Economic responses of crops to fertilizer N additions occur as increased yield or protein yield, or quality improvement. The simplest response of plants to applied N, when N is the limiting factor, is a linear increase in dry matter production with rates up to the maximum application rate of N, staying constant thereafter or declining (Bock, 1984). The magnitude of response to applied N is dependant on the size of the available, and potentially available pool of N in the soil, and the demand by the crop as determined by its potential dry matter production (Olson & Kurtz, 1982). The response of crops to N can be modified and affected by environmental factors from season to season (Keeney, 1982a).

Crop residue management during the fallow period will also affect potential soil mineral N availability, and hence probable response to applied N fertilizer. Incorporation of crop residues with high C:N ratios immobilize soil and fertilizer N, and can reduce yields were soil mineral N levels are low, reducing N availability and thereby depressing crop growth (Robson & Taylor, 1987; Power & Doran, 1988). Generally in these low yielding cropping environments, the amount of residue added in combination with conventional cultivation practices, leads to negligible to significant amounts of crop residues remaining in the cultivation zone at planting. This residue can potentially immobilize available mineral N in soil and from fertilizers depending on the conditions (especially soil water) during the fallow period. Crop residues, however, can have beneficial effects when it is applied to prevent losses of mineral N from the soil during fallow periods by utilizing the immobilization effect. Efficient synchronization of mineralization and N availability with crop N demand is however important (Parr & Papendick, 1978).

Soil measurements of N are taken at the beginning of the growing season, whereas yield responses to N fertilizer will be modified by seasonal weather and soil conditions (McDonald, 1989). Soil mineral N content is reduced during crop growth during the winter, but in spring mineralization rates can increase and possibly make a significant contribution to the N requirement of the wheat crop (McGarity & Myers, 1973). Consequently, the ability of soil tests of mineral N to account for differences in grain yield between sites and seasons are often low (Taylor *et al.*, 1988; McDonald, 1989).

In small grain crops, leaf area is typically increased by increasing levels of applied N (Yoshida, 1972). This is due to an increased number of tillers, leaves and increased leaf size and longevity. The potential photosynthetic capacity and rate of photosynthesis is raised, but so are respiration rates. Thus, the overall effect of applied N is an increase in the source capacity of the plant, while the number and size of the grains and their rates of growth determine the sink capacity (Yoshida, 1972):

Grain yield (ha^{-1}) = ears (ha^{-1}) x spikelets (ear^{-1}) x grains ($spikelet^{-1}$) x weight ($grain^{-1}$)

The predominant positive impact of N on crop quality is in its enhancement of the total N content of crops, and in grain crops specifically the protein content of grain (Olson & Kurtz, 1982). Grain protein typically increases with increasing rates of N above those needed for optimum yields (Jackson *et al.*, 1973). Delayed applications of fertilizer N also tend to increase grain protein content (Loffler *et al.*, 1985; Jenner *et al.*, 1990). Detrimental effects of excessive N on crop growth include lodging, delayed maturity, shrivelled kernels with a abnormally high protein content and increased susceptibility to diseases, all of which lead to reduced baking quality (Halvorson *et al.*, 1987).

2.7.3 Factors affecting crop response to N

A major obstacle in the development of reliable methods for predicting crop N requirements is the difficulty in identifying and quantifying factors that consistently affect N responses, and the variability that occurs between growing seasons (Goh & Haynes, 1986). Several factors have been identified that effect the response of crops to N (Keeney, 1982a).

2.7.3.1 Form, time and method of N application

Nitrogen should be available when required by the crop to maximize its use. The most effective time for N application generally coincides with the period of rapid N uptake by the plant (e.g. grain formation and filling) (Jenner *et al.*, 1990). Application at this time reduces the opportunity for N losses, and results in the applied N being available throughout the period of grain formation and growth (Olson & Kurtz, 1982).

There are four main methods of application (Olson & Kurtz, 1982):

- incorporation by cultivating equipment,
- surface broadcast,
- injection of liquids or gases into soils through knives, and
- distribution of soluble forms of N with irrigation water and spraying equipment.

Soil and climatic conditions influence the choice and effectiveness of these different methods. Urea is the preferred form of N for foliar applications because of rapid penetration into leaves. Nonetheless, leafburn can be a problem if the spray solution contains more than 1- 3% N, or if the urea has a high biuret content (Smith *et al.*, 1991, Tisdale *et al.*, 1993).

2.7.3.2 *Nitrogen supplying capacity of soils*

Both the amount of residual mineral N in the root zone at planting and the amount of soil organic N mineralized during the growing season greatly affect the response of plants to applied N under field conditions. Stanford *et al.* (1977) have shown that residual N in the soil profile is an important source of N for plants, and should be accounted for in fertilizer recommendations. The position of residual N in the profile in relation to available water supply and root activity also influences plant response (Vlek *et al.*, 1981). In dryland crop production, NO_3^- in the deeper soil horizons can be taken up relatively late in the season, resulting in enhanced grain protein. The upward movement of water through the soil profile due to evaporation and capillary flow can also result in NO_3^- movement from the subsoil into the rooting zone (Vlek *et al.*, 1981).

The measurement of mineral soil N content at or before sowing can be a useful aid in the determination of optimum N fertilizer levels (Halvorson *et al.*, 1987). Where such a predictive system is developed, it can identify fields not needing fertilization, or predict the optimum N fertilizer rate. This will reduce the potential for leaching of NO_3^- and decrease lodging of the crop due to over application of N (Halvorson *et al.*, 1987). Mineralization of soil organic matter is still a major source of N in crop production. Due to depletion of this source over time, other sources of N are also required. In this case the soil no longer serves as a primary source of N, but as a reservoir where biological mineralization-immobilization occurs (Tinker, 1978). Methods of predicting the N-supplying capacity of soils are discussed in section 6.4.

2.7.3.3 *Available soil water*

A positive interaction between fertilizer N and applied irrigation/available soil water often occurs (Goh & Haynes, 1986; Bonfil *et al.*, 1999). When plant growth and yields are limited by available water, the N requirement is relatively low, but with sufficient water available, crop growth is greatly increased, and therefore also N requirement (Goh & Haynes, 1986).

2.7.3.4 *Cultivation method*

As discussed in section 2.5.8, cultivation disturbs the soil, increases soil porosity and aeration, exposes less accessible organic substrates to biological mineralization, and results in a flush of mineralization of organic N (Wong & Northcliff, 1995). In contrast, the advantages of no-till systems arise from the presence of a mulch of dead vegetation and residues (with high C:N ratios) at the surface. This can result in immobilization of mineral N in the surface soil and thus a slower release of N for use by the crop. Losses of N from no-till systems can include increased leaching losses and greater denitrification losses of N_2O and N_2 due to a higher water content and a source of readily available C at the soil surface (Rice & Smith, 1982). Crop residue management alters many soil properties; physical, chemical, biological, and thereby nutrient transportation and efficiency of use is altered (Power & Doran, 1988).

2.7.3.5 Genetic effects

Differences between species and genotypes in their ability to absorb, translocate and utilize soil and fertilizer N can be ascribed to variations in plant growth rate and morphology, as well as the capacity for uptake and metabolism. High yielding cultivars are characterised by rapid growth rates resulting in high dry matter production per unit land area that must be met by an adequate supply of N (Bänziger *et al.*, 1992). Genotypes also differ in their capacity to produce dry matter at a given level of N supply (Bänziger *et al.*, 1992). They also vary in their capacity to absorb, translocate, and partition N within the plant. For grain crops this is important since remobilization of N from the tillers and leaves is an important source of grain N (Clark, 1983).

2.7.3.6 Leguminous crops

Leguminous crops obtain much of their N through symbiotic fixation by *Bradyrhizobium* and *Rhizobium* bacteria present in nodules on their root systems. Part of this N is returned to the soil in crop residue and this can sometimes be an important source of N for the next crop in the rotation (Halvorson *et al.*, 1987). Where leguminous green manure crops are grown large amounts of N can be added to the soil (Goh & Haynes, 1986). However, for grain legumes the amount of N removed in the harvested crop are often greater than the quantity of N_2 fixed (Westermann *et al.*, 1981).

2.7.4 Assessment of soil N availability

As mentioned previously, 97-99% of the N in soils is present in organic forms that are not directly available to plants until after mineralization has occurred. The amount mineralized depends on temperature, water, and other environmental factors and is therefore difficult to predict (Goh & Haynes, 1986). Because N is mostly obtained from the soil, plant available soil N has a direct influence on grain protein yields (Smika & Greb, 1973; Fowler *et al.*, 1990). Porter *et al.* (1982) linked soil factors important in determining grain protein to the depth that mineral N is found in the soil profile. This is because nutrients deep in the soil profile are only exploited late in the plant's development.

There are two major types of soil tests for N (Goh & Haynes, 1986; Campbell *et al.*, 1995);

- residual mineral N in soil profile is measured and fertilizer recommendations are modified depending on the amount present;
- the complementary approach is to obtain an estimate of the amount of potentially mineralizable N present in the soil.

The above tests are based experimentally on incubation methods and chemical extraction methods collectively known as N availability indices.

2.7.4.1 Residual N

Olson *et al.* (1976) indicated that residual soil mineral N in the soil is significant to grain production especially in non-humid areas where extensive leaching does not occur, and where fertilizer N has been used at modest to heavy rates in previous years. Differences in grain protein have also been related to differences in residual N levels in the soil rooting profile (Smika & Greb, 1973; Karathanasis *et al.*, 1980; Fiez *et al.*, 1994). For example, Smika & Greb (1973) found that soil nitrate in the profile at seeding was positively correlated with grain protein, where the protein content increased with an average of 0.15% for each kg ha^{-1} of NO_3-N present in the soil.

Fiez *et al.* (1994) also noted that pre-plant residual soil mineral N (0-152 cm) positively influenced grain protein, especially because this deep N is taken up later in the growing season when water is extracted from greater depths. Karathanasis *et al.* (1980) and Bonfil *et al.* (1999) reported significant correlations between total soil N, residual mineral N, soil water content, soil organic matter and grain yield and protein content.

Critical variables in estimating residual mineral N in the profile include; depth of sampling, time of sampling, and number of samples taken from a field (Goh & Haynes, 1986). The effective rooting depth of a crop determines the depth of sampling required to adequately assess the quantities of residual N available in the soil profile. Rooting depth can be influenced by factors such as soil type, presence of impeding soil layers and distribution of nutrients and water in the soil profile. Sampling must be done shortly before planting of the crop, or early in the growing season so that the pool of mineral N available to the crop can be adequately estimated (Halvorson *et al.*, 1987).

2.7.4.2 Potentially available N

Nitrogen availability indices are a measure of the potential of a soil to supply N to plants. Since mineralization is affected by many environmental and cultural factors, such indices can only give an indication of the amount of N that will be potentially mineralized under field conditions (Haynes, 1986b). The indices can be divided into biological (aerobic and anaerobic incubations) and chemical methods (Bundy & Meisinger, 1994; Hart *et al.*, 1994).

2.7.4.2.1 Biological indices

These tests are commonly used in soil testing laboratories, and involve the short-term incubation of soils for 1 to 6 weeks under aerobic or anaerobic conditions. The amount of N mineralized during the incubation is quantified (Goh & Haynes, 1986). With aerobic incubations, the control of the water content of samples with a wide range of waterholding capacities can be a problem (Bundy & Meisinger, 1994). Anaerobic incubation has several advantages over aerobic methods. Problems associated with the maintenance of water content are avoided, only NH_4^+ needs to be measured, more N is mineralized in a given period, and higher temperatures can be maintained during incubation, thereby shortening incubation times (Keeney, 1982b). Aerobic incubations have the advantage of providing conditions more similar to those encountered in the field (Campbell, 1978).

Generally, soil N mineralized under optimal temperature (35°C) and water content (field capacity) for a defined time has been suggested as a basis for predicting the amount of soil N mineralized under field conditions (Smith & Hoare, 1977; Stanford, 1977; Bundy & Meisinger, 1994). However, the modifying effects of soil temperature (Stanford *et al.*, 1973) and water content (Stanford, & Epstein, 1974) under field conditions must also be considered (Westermann & Crothers, 1980). Stanford & Smith (1972) proposed an incubation-leaching technique for use in quantifying the active N pool of organic matter. They also advanced the concept of potentially mineralizable N, denoted as N_o, and a related mineralizable rate constant (*k*), for use in characterising soil-available N. These constants can be estimated by statistical techniques if a soil is incubated at optimum water and temperature conditions and the N mineralized (N_s and time of incubation (t)) measured. They assumed that organic N mineralization under optimum conditions followed first-order kinetics: $N_s = N_o\ [1\text{-}e^{-kt}]$.

The incubation method proposed by Stanford & Smith (1972) uses dried crushed and sieved soil samples. This method has been used extensively for determination of N kinetics in soils. The problem is however that when results from this laboratory incubation are compared to field studies with undisturbed samples, substantial over-predictions by "disturbed soil sample"-method are found. This is mainly due to an initial flush of N mineralization when the soil is rewetted. Also to an increased potential for mineralization of organic matter as a result of the disruption of soil aggregates and increased microbial accessibility to readily mineralizable N (Cabrera & Kissel, 1988; Campbell *et al.*, 1995). The initial rate of mineralization is greatly affected by crop residues, sample preparation and other factors, so that the true rate of mineralization is established only after these effects have been overcome (Stanford & Smith, 1972). Another problem is also the variability across a field in predicting mineralization and this can lead to large numbers of samples being required to provide an adequate representation of the field. Cabrera & Kissel (1988) concluded that the ideal situation would be one in which the parameters to describe N mineralization in a field could be estimated either from the N mineralization characteristics or the chemical and physical properties of a composite (disturbed) sample.

2.7.4.2.2 Chemical indices

Although it seems impossible to devise a chemical extraction procedure that simulates the action of microorganisms in releasing plant available forms of soil N, several methods have been proposed as they are more rapid, precise and convenient than biological incubation procedures. These include weak extractants like hot water, intermediate extractants like alkaline permanganate, and strong extractants like 6N H_2SO_4 (Goh & Haynes, 1986).

Some laboratories also use 2M KCl or $NaHCO_3$ extractants for mineralizable organic N, but none of the proposed indices (biological or chemical) are in general use (Rice *et al.*, 1995). Although most indices show satisfactory correlation with greenhouse results of crop N uptake, the major problem under field conditions is that variations in climate and cultural conditions affect plant growth, N uptake, and N mineralization (Clay *et al.*, 1995). The most reliable index will give an indication of the available pool of readily mineralizable N in the soil, but no indication of what proportion of this pool will be mineralized during the growing season. For this reason, modelling approaches have also been developed. These lead to the prediction of mineralization in the field and they incorporate the effects of environmental factors (rainfall, soil water content, and soil temperature) on mineralization (Stanford *et al.*, 1977).

2.7.4.2.3 Quantification of mineralization in the field

A quantitative approach to measure field N mineralization is the use of fallow soil (Rice *et al.*, 1995). This approach avoids the disturbance that occurs with laboratory techniques, and other soil physical conditions are preserved. Westermann & Crothers (1980), Legg & Meisinger (1982) and Cabrera & Kissel (1988) used fallow plots to determine the increase in soil mineral N during the growing season. They related the difference between the amount of mineral N accumulated under cropped and fallow plots to plant uptake of N. Cabrera & Kissel (1988) obtained better predictions on the fallow than cropped plots. They related this to the negative effect that plants can have on apparent net mineralization rate through enhanced N immobilization in the rhizosphere and possible gaseous N losses from leaves.

Hadas *et al.* (1989a) evaluated soil N mineralization (up to 120 cm in the profile) *in situ* in plots with and without fertilizer. Rice *et al.* (1995) stated that the plant is the ultimate integrator of all the environmental variables controlling the N transformations within the soil cycle. Nitrogen uptake by an unfertilized crop is considered by many to represent the best method for quantifying net N mineralization (Broadbent, 1981). The advantage of this approach is that it integrates field temperature, water, and aeration conditions that influence N mineralization potential.

2.7.4.3 Fertilizer N recommendations

The uncertainty in soil N availability generated by the N cycle and seasonal changes in plant-N utilization make it difficult to predict the N requirement of a crop. Methods of monitoring soil and plant-N status have been developed to alleviate these difficulties. These methods include both direct and indirect measurements of soil and plant mineral N and plant response to fertilizer (Gerik *et al.*, 1998). For soils, direct methods include the measurement of soil nitrate and ammonium, soil organic matter, and N mineralization. For plants, direct methods include measurements of total plant N, stem nitrate concentration and nitrate reductase activity. Indirect methods include measurements of leaf chlorophyll content and the use of physiologically based crop models (Gerik *et al.*, 1998).

The capacity of the soil to supply N to the crop is determined by a number of key factors (Halvorson *et al.*, 1987; Goh & Haynes, 1986). These include:

- the amount of residual mineral N present in the potentially active root zone at planting or before crop growth commences,
- the amount of potentially mineralizable N present in the soil,
- the proportion of this potentially mineralizable pool of soil N that is mineralized during the growing season, and
- the amount of residual and mineralizable N that is immobilized or lost from the soil-plant systems by leaching or gaseous losses.

For fertilizer recommendations, the nutrient requirement of the crop is important (Olson & Kurtz, 1982; Legg & Meisinger, 1982), with the N requirement under field conditions influenced by:

- the crop requirement as determined by yield and N content,
- the effectiveness of the crop to recover available mineral N from the soil profile as affected by growth stage and root development,
- the availability of N fertilizer when added to supplement soil N supply as influenced by immobilization,

leaching and gaseous losses.

The availability of residual N to the crop is normally considered equal to that of fertilizer N. However, Habey *et al.* (1983) concluded that residual soil NO_3^- was only one-third as efficient for grain production as fertilizer N, irrespective of water supply. They concluded that further research is needed to estimate substitution rates of soil mineral N in different soil layers for fertilizer N if the recommendations for fertilizer applications are to be improved.

Traditionally, information from field experiments that tested increasing levels of N applications was used to generate response curves to show how fertilizer affects crop yields. This response information then formed the basis for calculating optimum application rates (Sutherland *et al.*, 1986; Rice *et al.*, 1995). These regression models of fertilizer response, however, are static in nature and are unable to account for within-season variability in the supply of either water or nutrients (Sutherland *et al.*, 1986). In the case of N, previous N recommendations were based on the application of rapidly released fertilizer N, a lack of appreciation for spatial variability, and minimal environmental concerns.

Our ability to make fertilizer recommendations is becoming more sophisticated, as we learn more about the soil/plant/atmosphere system. Future N recommendations in environmentally sensitive areas will need to be as site specific as possible (Rice *et al.*, 1995). Fertilizer N recommendations need to be calibrated across broad areas, and critical variables required for determining the optimum N rate of a crop must be identified and measured. Important site variables include soil texture, pH, and organic matter content, and management variables such as tillage systems, irrigation, and crop rotations. The inclusion of existing and projected amounts of available N in the root zone can potentially improve the accuracy of N recommendations. All these variables need to be incorporated in a recommendation model, with the model consequently tested over a range of environmental conditions and N levels (Rice *et al.*, 1995). Additional detailed information about the complex N transformations within both plant and soil will be needed before new ideas for managing soils and plants can be generated and placed into practice (Hauck, 1984). Nitrogen management is the key to establishing a balance between yield and quality of the grain produced and systems of N management must be directed towards these specific objectives.

CHAPTER 3 MATERIALS AND METHODS

Localities representative of the major wheat production regions in the summer rainfall area of the Free State were selected for this study. Selection of these localities was based on the determination of relatively homogeneous farming areas (RHFA) in the different magisterial districts of the Highveld Region (Ludick & Wooding, 1991). Additional information from the Food Strategy Survey (Ludick, 1989), which presents the soil-depth classes of the areas under cultivation and cropping patterns for each RHFA and magisterial districts was also used. The following localities were selected:

Eastern Free State – Bethlehem (Bethlehem/Avalon ecotope)
Central Free State – Kroonstad (Kroonstad/Avalon ecotope)
South western Free State – Petrusburg (Petrusburg/Bloemdal ecotope)

3.1 LOCALITY DESCRIPTIONS

3.1.1 Bethlehem

The trial site has been cultivated for more than 25 years, using a fallow-wheat-fallow-wheat rotation system with conventional tillage practices being followed during the past ten years. The trial was planted after a fallow period (18 months) following the previous wheat crop. The soil profile at the trial site was described by Snyman *et al.* (1994) according to the Soil Classification Workgroup (1991) as the following:

Soil Form: *Avalon*
Soil Family: *Mafikeng*

0-200 mm	Ap	*Orthic A horizon; structureless*
200-300 mm	A12	*Orthic A horizon; structureless with some concretions present*
300-500 mm	B1	*Yellow brown apedal B horizon; weak structure with mottling, concretions and sesquioxides present*
500-700 mm	B2	*Soft plinthic B horizon; with mottling and concretions present*
700-1000 mm	B3	*Gleycutanic B horizon; gray mottling, illuvial and sesquioxides mottling present, medium structured*
1000-1230 mm	C	*Saprolite (gleyed clay) horizon; gray, illuvial, clay and sesquioxides mottling present, weathered mudstone*

3.1.2 Kroonstad

The trial site has been cultivated for more than 30 years, with a maize-fallow-wheat-fallow rotation under conventional tillage practices being followed the past ten years. The trial was planted after a fallow period (15 months) following the previous maize crop. The soil profile was described by Anderson *et al.* (1996) according to the Soil Classification Workgroup (1991) as the following:

Soil Form: *Avalon*
Soil Family: *Mafikeng*

0-260 mm	Ap	*Orthic A horizon; structureless*
260-550 mm	B1	*Yellow brown apedal B horizon; with few concretions and oxidized iron oxide mottling*
550-800 mm	B2	*Soft plinthic B horizon; medium angular blockstructure, gray and yellow reduced iron oxide mottling*
800-1200 mm	C	*Gleycutanic clay B horizon; gray and white reduced iron oxide and concretions present, medium subangular blockstructure*

3.1.3 Petrusburg

The trial site is situated on a field that has been under conventional tillage for more than 30 years with maize and wheat cultivated during this time. A wheat-fallow-wheat-fallow system has been followed during the past ten years. The trial was planted after a fallow period (18 months) following the previous wheat crop. The soil profile was described by Snyman *et al.* (1994) according to the Soil Classification Workgroup (1991) as the following:

Soil Form: *Bloemdal*
Soil Family: *Vrede*

0-230 mm	A1	*Orthic A horizon; structureless*
230-400 mm	B1	*Red apedal B horizon, macroscopically structureless*
400-770 mm	B2	*Red apedal B horizon, macroscopically structureless*
770-1500 mm	B3	*Red apedal B horizon, macroscopically structureless; gray reduced iron oxide mottling*
1500-1900 mm	C	*Unspecified material with signs of wetness; gray reduced iron oxide mottling, red and black oxidized iron oxide mottling, and few sesquioxide concretions*

3.2 TRIAL DESIGN AND LAYOUT

A randomized block design was used with the following treatments replicated four times:

- Recommended nitrogen application (N_{rec}) for each production region based on long-term wheat yield predictions; Bethlehem 45 kg N ha^{-1} (2.5 t ha^{-1}), Petrusburg 10 kg N ha^{-1} (1.0 t ha^{-1}), and Kroonstad 20 kg N ha^{-1} (1.5 t ha^{-1});
- 0 kg N ha^{-1} as a control fertilizer treatment (N_{0N});
- Fallow treatment for the duration of the trial.

The decision to test these treatments was based on the recommended N application levels the wheat producer should apply for specific yield and quality targets in the mentioned production regions (Anon., 1998). The cultivar '*Gariep*', adapted to all three production regions, was planted at recommended seeding rates (25 kg ha^{-1}) during the recommended planting time for each region (Anon., 1998).

Standard applications of 15 kg P ha^{-1} as single superphosphate (10,5% P), 10 kg K ha^{-1} as potassium chloride (50% K) were banded (100 mm below the seed) together with the N treatments as limestone ammonium nitrate (28% N) during the planting process. Basal P and K applications were also banded for the N_{0N} treatments. These basal P and K applications were not changed in the second cropping season, although plant uptake could have been different. Soil analysis values confirmed that the availability of these nutrients were still above recommended norms, so that differential applications were not needed (Anon., 1998).

Plots consisted of 12 rows each 14 m in length, with an interrow spacing of 0.4 m. To eliminate border effects between plots, eight of the innermost rows were used for biomass and yield determinations. Two-meter borders were allowed in-row between plots. Net harvest area was eight rows x 0.4 m row width x 10 m row lengths (32m^2).

3.3 AGRONOMIC PRACTICES

3.3.1 Cultivation

Conventional tillage practices - ploughing (250 mm depth), discing (100-150 mm depth) and tine-cultivation (*ca* 100 mm depth) - were followed on all the sites from time of harvest of the previous crop and during the fallow period. Trials were planted with a pneumatic *Gaspardo* precision planter adapted for in-row banding (150 mm below soil surface) of metered fertilizer applications.

3.3.2 Weed control

Weed control during the growing season included spraying with a sulfonylurea-product at recommended applications rates and spraying intervals supplemented by hand weeding where necessary.

3.3.3 Insect and disease control

Although the wheat cultivar *'Gariep'* is Russian wheat aphid resistant, the occurrence of slight infestations were controlled by preventative spraying with demeton-S-methyl/parathion insecticide combinations at recommended intervals. During 1997, stripe rust (*Puccinia striiformis f.sp tritici*) infected susceptible wheat cultivars like '*Gariep*' in the Eastern Free State, however this disease was successfully controlled by spraying with suitable fungicides.

3.4 DATA COLLECTION AND MEASUREMENTS

3.4.1 Soil sampling and mineral analysis

Soil analysis values of a specific soil layer is an indication of available nutrients in that particular soil layer, and of importance in fertilization practices, especially for fertilizer P and K applications, are the 0-200, and 200-400 mm soil layers (Anon., 1998). With regards to N fertilization, other than soil mineral N content, the organic carbon content, clay percentage, C:N ratio, total N, and CEC can be important indicators of potential mineralization of N from organic matter, and possible movement of N in the profile (Van der Mey *et al.*, 1994). Soil acidity levels can directly influence mineralization by affecting soil biological populations.

Soil mineral N content (kg N ha^{-1}) in the soil profile was periodically measured over the trial period. Soil samples were collected from the N_{rec}, N_{0N} and fallow treatments. Soil sampling commenced at planting, and continued at intervals coinciding with biomass determinations throughout the growing season, as well as during the fallow period. Bucket augers (100 mm inner diameter) were used, and samples were collected from the following depths: 0-50, 50-200, 200-400, 400-600, 600-900 and 900-1200 mm. These layers were chosen according to the IBSNAT specifications for model testing (IBSNAT, 1990), and coincided largely with the different soil profile layers.

Two soil cores per depth (in-row sampling to include the fertilizer band) were combined into a composite sample for each replication of each treatment. Samples were collected in brown paper bags (370 mm x 170 mm) to prevent heat buildup and facilitate moisture loss during collection and transportation. Samples were air-dried (48-72 hours) at a room temperature range of 25-30°C. Air-dried samples were crushed and sieved (<2 mm), and stored in dry and cool conditions until analysis.

Soil NH_4^+ and NO_3^- were extracted with 1N KCl (10 g soil:100 ml KCl) during a 30 minute end over end shaking, and after filtration, analyzed using colorimetric methods. The basic analytical steps for NO_3^- are: NO_3^- reduction to NO_2 with a modified *Griess-Millosvay* procedure by diazotizing with sulfanilamide and coupling with N - (1-naphtyl)-ethylene-diamine to form a purple-colored dye, which is measured by absorbance at 520 nm (Keeney & Nelson, 1982), following the automated Cu-Cd reduction technique using a Technicon autoanalyzer system (Technicon, 1977; 1978). Soil NH_4^+ was determined by reacting NH_4^+ with phenol and hypochlorite in an alkaline solution to form an intense blue color that is measured by absorbance at 630 nm. This colorimetric procedure is widely known as the *Bethelot* reaction or the indophenol blue method (Keeney & Nelson, 1982).

It is usual practice to extract exchangeable NH_4^+ and NO_3^- from field-moist soil samples. The decision to use air-dried samples in this study was motivated by the practical difficulty of using field-moist samples for routine analysis (Wiltshire & du Preez, 1994), and the potential for delays in transporting samples from distant localities to the analytical laboratory at Bethlehem. It is accepted that small changes in mineral N content of samples may have occurred during air-drying. The most frequently observed changes are a small increase in exchangeable NH_4^+ and some loss of NO_3^- although often no significant changes are observed (Sereviratne & Wild, 1985; Wiltshire & du Preez, 1994).

The initial soil samples taken at time of planting in both growing seasons, were analyzed for the following: $pH_{(KCl)}$, extractable phosphorus (Bray No 1-method), potassium, calcium, magnesium, sodium (ammoniumacetate-method), exchangeable acidity, acid saturation, clay percentage (pipette-method) (The Non-affiliated Soil Analysis Work Committee, 1990), organic carbon percentage (Walkley-Black-method), and total soil N (Kjeldahl-method) (Bremner & Mulvaney, 1982).

3.4.1.1 Bethlehem

3.4.1.1.1 Soil analysis in1997

The initial soil chemical and physical characteristics are presented in Appendix 3.1. The soil analysis indicated that the trial site had an overall acceptable fertility status regarding pH, Ca, Mg, and K. The P analysis of the 0-50 and 50-200 mm soil layers indicated medium to low values (Anon., 1998), with the P content decreasing in deeper soil layers of the profile. Organic carbon values were low in the cultivation/fertilization zone (0-50 mm and 50-200 mm), and decreased with increasing depth, with the lowest values 0.19% and 0.26% in the 600-900 mm, and 900-1200 mm soil layers respectively. Clay percentage increased with increasing soil depth from 12.5% (0-50 mm) to 35.8% (900-1200 mm). The highest values for total N were found in the 0-200 mm soil layers, with the other soil layers marginally lower. The CEC values increased with depth, with the highest values at 600-900 mm and 900-1200 mm.

Measured bulk densities showed values of 1.60 to 1.63 g cm^{-3} (0-400 mm), and 1.50 to 1.57 g cm^{-3} (400-900 mm), with 1.68 g cm^{-3} at 900-1200 mm. The measured soil water content values (0-1200 mm) indicated a drained upper limit value of 371.2 mm, a lower limit of extractable soil water of 221.4 mm, with 149.8 mm of plant available water available (Appendix 3.2).

3.4.1.1.2 Soil analysis in1998

Soil analysis indicated a marginal decrease in pH values and Ca content in the 50-900 mm soil layers, and an increase in Na content in all soil layers when compared to 1997 (Appendix 3.3). No significant changes in analysis values of P, Mg and K were found. The CEC values decreased in the 0-50 mm and 50-200 mm soil layers, linked to the decrease in Ca content of these layers.

3.4.1.2 Kroonstad

3.4.1.2.1 Soil analysis in 1997

Analysis results indicate acceptable levels of P, K, Ca, Mg, and high pH values in all soil layers (Appendix 3.4). Notable were high levels of Ca, K, Mg, and Na in the 600-900 mm and 900-1200 mm soil layers. Organic carbon values were low, ranging from 0.13% to 0.29%. Low acid saturation values were measured with the highest values in the 0-50 mm and 50-200 mm soil layers. Total N values were the highest in the 600-900 mm soil layer, followed by 400-600 mm, with the other soil layers in the 0.036 to 0.038% range. Typical of duplex soils, clay content, CEC, and concentrations of exchangeable cations were considerably higher in the 400-1200 mm soil layers than the 0-400 mm layer. Measured bulk densities increased with increasing depth, ranging from 1.50 to 1.70 g cm^{-3}. Soil water content values for the 0-1200 mm soil layers indicated a drained upper limit value of 349.7 mm, a lower limit of extractable soil water of 188.0 mm, with 161.7 mm of plant extractable water available (Appendix 3.2).

3.4.1.2.2 Soil analysis in 1998

A decrease in pH and an increase in acid saturation percentage with a decrease in Mg content were observed (Appendix 3.5). The other nutrients did not change significantly in comparison to 1997. Measured bulk densities were higher than in 1997, with the increase in values being more pronounced in the 50-200 mm, 200-400 mm, 600-1200 mm soil layers.

3.4.1.3 Petrusburg

3.4.1.3.1 Soil analysis in 1997

Soil pH values and acid saturation percentages in the 0-50 and 50-200 mm soil layers indicated slightly acidic conditions (Appendix 3.6). These values are, however, still below the 8% value, above which yield reductions due to increased acidity could be expected (Anon., 1998). Phosphorus values in the cultivation/fertilization zone were in the medium range of availability, with a decreasing P content as depth increased. Other analysis values were at acceptable levels, but with organic carbon extremely low in all soil layers (0.18% to 0.21%).

The CEC, clay percentage and total N values increased with depth. Measured bulk densities ranged from 1.60 to 1.71 g cm^{-3}, with the highest value in the 200-400 mm soil layer. The measured soil water content values for the 0-1200 mm soil layers indicated a DUL value of 216.4 mm, a lower limit of extractable soil water of 77.1 mm, with 139.3 mm of plant extractable water available (Appendix 3.2).

3.4.1.3.2 Soil analysis in 1998

In comparison to 1997, soil analyses values indicated a decrease in pH, Ca, and Mg values, with an accompanying rise in the acid saturation percentage (Appendix 3.7). The analysis values of the other nutrients did not change significantly. Bulk density values showed marginal increases in the 400-1200 mm soil layers, with a more pronounced increase in the 50-200 mm, and 200-400 mm soil layers. In general, soil analysis values of the 0-50 and 50-200 mm soil layers of the different localities indicated that the overall fertility status with regards to P, K, Ca, and Mg was acceptable for wheat production providing adequate fertilizer application. The increase in measured clay percentages with increasing depth in the soil profiles at Bethlehem and Kroonstad indicates the extent of the duplex nature of these soils. At Petrusburg, a similar increase in clay percentage with increasing depth was found, but with overall lower values, and according to the soil classification system, the profile is of a macroscopically structureless nature.

The plant available water content was the highest at Kroonstad, followed by Bethlehem and the lowest value found at Petrusburg. The lower water availability at Petrusburg also indicates the potential risk involved in wheat production in this region. If significant spring rains are delayed, yield potential of the crop can be severely reduced due to water depletion if accompanied by high temperatures in the growing season.

Soil analysis values in 1998 also indicated a decrease in pH values and an increase in acidity levels in the upper soil levels. Increases in acidity are the combined result of soil cultivation, N fertilization, and removal of harvested products. This indicates that continuous crop production can be detrimental to soil fertility, and that soil fertility and fertilization must be optimally managed.

3.4.2 Soil water content

Soil water content (SWC) was measured gravimetrically for each measurement layer at planting. Bulk densities of the measurement layers were measured using the clod method (Blake & Harge, 1986), and used in calculations of volumetric SWC. Profile soil water characteristics including field capacity (drained upper limit (DUL)), wilting point (lower limit (LL)) and plant available soil water were determined *in situ* at each trial site (Snyman *et al.*, 1994; Anderson *et al.*, 1996).

The mean SWC of the soil layers (0-1200 mm) at Bethlehem, Kroonstad and Petrusburg (planting 1997) are shown in Appendix 3.8, with values for 1998 in Appendix 3.9. The SWC at Bethlehem was 81.7% of the drained upper limit (DUL), amounting to 303.08 mm of total soil water, and 81.66 mm of plant-available soil water. Total SWC at Bethlehem (planting 1998) was measured at 367.90 mm, which is 98.9% of DUL, and amounts to 146.48 mm of plant-available soil water. Although the 0-50 mm soil layer had a SWC of 69.9% of DUL, the other soil layers were measured at above 80% of DUL values.

Total SWC at Kroonstad was 243.19 mm, which is 69.6% of DUL, and amounts to 55.1 mm of plant available soil water. The SWC of the 0-50 mm soil layer was measured at 94.3% of DUL, with the soil layers 400-1200 mm showing decreased water contents. Total SWC in 1998 was measured at 348.03 mm, which is 99.5% of the DUL value. However, the 0-50 mm, and 50-200 mm soil layers was at 50.3% and 61.3% of DUL respectively, with the deeper soil layers showing values close to DUL. The plant available soil water was measured at 159.94 mm for the 0-1200 mm soil profile.

Total SWC at Petrusburg (planting 1997) amounted to 169.55 mm, (78.2% of DUL) and 98.5 mm of plant-available soil water. Except for the 0-50 mm soil layer with a low SWC, the other soil layers showed water contents of between 73.8% and 91.0% of DUL. Total SWC in 1998 was 163.15 mm (75.2% of DUL), and amounts to 92.1 mm of plant available soil water. Although the soil layers 200-1200 mm showed high SWC values, values for the 0-50 mm, and 50-200 mm layers were low, with values of 19.6% and 29.6% of DUL respectively.

3.4.3 Crop residue measurements

Crop residue returned at harvest (1997 and 1998) was calculated as the total above-ground biomass as measured at maturity minus grain yield (Soon, 1999), plus the root weight (0-400 mm) measured during the late grain filling stage. Several methods of studying crop residue decomposition (above and below soil surface) have been used, each appropriate for a specific purpose. These include the measurement of carbon dioxide evolution, recording residue weight loss using mesh bags, *in vitro* profusion methods, lignin analysis, size density fractionation, isotopic techniques, as well as modeling approaches (Conteh *et al.*, 1997). The measurement method of remaining residue in the cultivation zone in this study is related to the buried mesh bag method, but with random soil samples containing the crop residue removed from the cultivation layer. The soil samples were washed thereby eliminating the problem with mesh bags where soil adhering to the crop residues can confound results.

Remaining crop residue (root plus harvest residue) was measured at planting and harvest in 1998 and at the end of the trial period in 1999 (Aita *et al.*, 1997). Care was taken after each harvest and before soil cultivation to distribute the crop residue evenly across the plot area to lessen variability in measurements. Four replicate samples were collected by combining soil from two 20 cm x 20 cm x 40 cm deep pits into a composite sample per replicate for each treatment. These soil samples were wet sieved (<0.5 mm), the residue collected, hand picked to remove foreign material, dried and weighed.

3.4.4 Growth and biomass measurements

Above ground biomass development was measured at intervals coinciding with agronomically important growth stages (Zadoks *et al.*, 1974). Representative above ground biomass samples from a sample area of 0.2m^2 (0.5m X 0.4m row width) were taken from each replicate of the treatments, and separated into tillers, leaves and ears (where applicable). Tiller count, leaf area index (Li-cor 3100 leaf area meter, Li-cor, Lincoln, Nebraska, USA), tiller, leaf blade, and ear mass (oven-dried at 55°C for 24 hours and expressed in g m^{-2}) were determined.

Above ground plant samples taken throughout the growing season were milled (<0.5 mm) and analyzed for total N concentration (%N - Leco-combustion analysis). The C:N ratio (C method - Walkley-Black) of residue was determined at harvest. Nitrogen uptake (kg N ha^{-1}) was calculated as the product of biomass m^{-2} and N concentration of plant components at each sampling. Grain N content (Protein (%) = %N x 5.7) was calculated from the grain N percentage and measured yield. Total N concentration was chosen as the method of plant analysis because of its widespread use and reliable analysis technique. There are however certain considerations to be kept in mind. The total N concentration may have a wide range of variation, according to stage of development and supply of N, and can therefore be influenced by climatic conditions (Greenwood, 1978; Verstraeten & Vlassak, 1981). At maturity, hectoliter mass (kg hl^{-1}) and yield (t ha^{-1}) were measured. Grain protein percentage was determined by Near-Infrared Reflectometry (NIR) methods, calibrated against Leco-combustion analysis (Leco FP–2000, Nitrogen/ Protein Analyzer; Leco Corporation, St. Joseph, MI).

3.4.5 Root development

Sub-soil biomass (roots) was measured by the soil core sampling method (Kumar *et al.*, 1993) during the late grain filling stage of the growing season at sampling depths of 0-200 mm, 200-400 mm, 400-600 mm, 600-900 mm and 900-1200 mm. Four sub-samples per plot were combined into a representative sample per measurement layer. Roots were washed from the soil over a 0.7 mm mesh under running water, and foreign material removed by handpicking. Root lengths were determined by root length scanner (Delta T-scan V2.03 & HP Deskscan II V2.3; Delta T Devices Ltd. 1994, Cambridge, England). Samples were then ovendried (at 55°C for 24 hours), weighed, and the total N concentration (Leco-combustion analysis) measured. Root length (presented in two ways; cm cm^{-3} or m ha^{-1}), and root weight (kg ha^{-1}) for each measurement layer were calculated. As noted above, root weights for the 0-400 mm soil layers were included in calculations of added crop residue (aerial and sub-soil) to the cultivation zone.

3.4.6 Meteorological measurements

Rainfall, minimum and maximum aerial temperatures, and soil temperatures (0-50, 50-200 and 200-400 mm) were measured by an automatic weather station operational at each site, or conventional weather stations in the immediate vicinity. The ISCW weather database (Monnik *et al.*, 1996) supplied long-term mean data for each locality.

3.4.6.1 Bethlehem

Rainfall in 1997 was above the long-term mean values for all the months except January, February, June and October. This resulted in a total of 816 mm of precipitation for the year, in comparison to the long-term mean of only 686.6 mm (Appendix 3.10). The amount of rainfall measured in the growing season (June-December) was 459.1 mm (November 121 mm: above mean) is above the long-term mean of 332.6 mm. Close to mean temperatures occurred at Bethlehem during 1997 for the early part of the growing season (May-June) followed by a period with above mean temperatures during July, August, and September.

Total rainfall at Bethlehem during 1998 was 891.3 mm. This was above the long-term mean of 686.6 mm, but the rainfall distribution varied during the different months. Rainfall measured during the growing season (June-December) was 584.9 mm, which was above the long-term mean of 332.6 mm for this period. The 270 mm during November was above the normal rain expected for this month. Aerial temperatures were above the long-term mean for most of the year except November and December. The rainfall measured in the fallow period (January-June) of 306.4 mm largely contributed to the recharge of the profile SWC.

Above mean rainfall was measured in February, March and May of 1999. The total amount of rainfall of 374.3 mm measured for the period January to September is however below the long-term mean of 416.6 mm. Temperatures measured were generally above long-term mean values except for September.

3.4.6.2 Kroonstad

Above-mean rainfall was measured in 1997 during February, March, April, July, and September, with below mean values during October, November, and December. Total rainfall for the year was 688 mm compared with the long-term mean of 680.3 mm (Appendix 3.11). Rainfall measured during the growing season (June-December) was 108.6 mm and similar to the long-term mean of 106 mm for this period. Mean temperatures measured during 1997 were above long-term values.

Close to mean rainfall was measured in 1998 during the January to March period (Appendix 3.11), with mean to above-mean rainfall measured during the rest of the year. Measured rainfall of 389.5 mm in the fallow period (January-June) recharged the profile SWC to the high values at planting. Total rainfall for the year was 658.5 mm compared with the long-term mean at 680.3 mm. Rainfall measured during the growing season (June-December) was 269 mm in 1998 in comparison to the long-term mean of 106 mm for this period. Mean temperatures in 1998 were below the long-term mean in February, August, and December and above these in March, April, and September. Rainfall of 157 mm was measured for the period January to August in 1999 while the long-term mean for this period is 317.5 mm. In January to April, temperatures were above the long-term values, with May to August showing close to mean values (Appendix 3.11).

3.4.6.3 Petrusburg

Although above-mean rainfall occurred during January, March, May, June and October of 1997, dry conditions prevailed during April resulting in less favorable planting conditions (Appendix 3.12). Rainfall during the growing season (June-December) was 115.9 mm with the mean value for this period being 176.3 mm. Total rainfall measured was 374.4 mm in comparison to the long-term mean of 427.8 mm. Warm and dry weather during September and October had a negative influence on yield potential at Petrusburg with above mean aerial temperatures in July, August, September, October, and December.

Rainfall of 483.7 mm was measured during 1998, compared to the long-term mean of 427.8 mm (Appendix 3.12). The fallow rainfall of 278.8 mm measured during January to June contributed to the recharge of the profile SWC at planting. The months January to March had above-mean rainfall, and the 23.2 mm of rain measured in September were close to the long-term mean for this month. The months August, November, and December had below-mean rainfall values. However, the 151 mm measured in October is well above the long-term mean for this month of 40.8mm. Rainfall during the growing season (June-December) was 204.9 mm in 1998, with the mean value for this period at 176.3 mm. Below-mean aerial temperatures were measured in January and February, with the rest of the year showing above mean values. The total rainfall measured during the period January to August in 1999 was 224.4 mm, with the long-term mean being 266.6 mm (Appendix 3.12). Only in May was above mean rainfall of 76.6 mm recorded. Mean temperatures were measured in all the months with the exception of January that showed above mean values.

3.4.6.4 Soil temperatures measured at Bethlehem, Kroonstad and Petrusburg

Measured soil temperatures (0-50, 50-200, and 200-400 mm soil layers) for the localities showed similar patterns (Appendix 3.13). Soil temperatures decreased to lower levels at Bethlehem during winter, followed by Kroonstad and Petrusburg. Petrusburg showed the highest soil temperatures during the summer, followed by Kroonstad and Bethlehem.

3.5 DATA ANALYSES

The ANOVA's of data collected, regressions, and other calculations were performed by using the Genstat software package (Genstat 5, 1993), and significant and highly significant differences indicated by "*" and "**" to signify LSD (P=0.05) and LSD (P=0.01) levels.

3.6 APPROACH TO LAYOUT OF CHAPTERS

Measurement of the soil and plant N in this cropping system emphasized the interrelations between the different components, and the direct and indirect influences of components on each other. However, in the explanation and discussion of the different components, a linear approach was followed. The sequence of discussion of the relevant components is arranged in such a way that forward referencing to results discussed in later chapters be minimized in order to facilitate readability of the text.

CHAPTER 4 PLANT GROWTH, CUMULATIVE BIOMASS PRODUCTION, AND YIELD RESPONSE TO NITROGEN TREATMENTS

The major small grain cereal growing areas of South Africa and especially the Summer Rainfall Region have in recent years, experienced declining crop yields and grain protein content, especially in a wheat monoculture cropping system. With changes in the marketing system of wheat in South Africa, the quality of produced grain, especially with regards to grain protein content, has become increasingly important. Profitability of wheat production thus depends on yield and grain protein content, with available N influencing both (Dalal *et al.*, 1998).

Nitrogen applications for adequate N availability early in crop development promotes tillering, leaf growth, and potential grain number. However, ultimate responses to N are modified by environmental conditions, in particular temperature and rainfall, as well as inherent and continued soil N fertility (Jenner *et al.*, 1990). Characteristic of responses to N fertilizer in semi-arid environments is the large season-to-season variability, which is mainly due to the unreliability of seasonal rainfall and soil water availability (Taylor *et al.,* 1974; McDonald, 1989). The importance of rainfall emphasizes the interaction between water availability (soil water and amount of rainfall) and N responses measured as plant N concentration and accumulation, yield, and quality of the grain. Because N is a relatively mobile element in soils, it is transported to roots mainly by mass flow. Lowering the supply of soil water will reduce response to N fertilizer both directly, by reducing flow of N to roots, and indirectly by reducing growth of the crop and thereby demand for N (Haynes & Goh, 1978; McDonald, 1989).

Environmental factors also markedly influence dry matter accumulation and its partitioning (Snyder & Carlson, 1984). Water and nutrient stress result in lower photosynthetic rates, and alter partitioning of synthesized products (Snyder & Carlson, 1984). The effect of water stress on dry matter accumulation in cereal grains depends on the time and intensity of stress (Donald & Hamblin, 1976). The severity of water stress and the rate at which it develops depends on the amount and distribution pattern of rainfall during the growing season as well as on soil type. The critical phase of growth when water stress reduces grain yield is the period from anthesis to grain physiological maturity. To obtain high grain yields, the stress level in the crop should be minimized during this stage (McDonald, 1989). High temperatures (>30°C) during the post floral stage decrease the total amounts of assimilated products transported to grain and generally produce lower yields (Spiertz, 1974, Yoshida, 1972; Bhullar & Jenner, 1986; Jenner *et al.*, 1990). Elevated temperatures during the post anthesis stage may cause premature cessation of starch deposition in the endosperm of developing grain, even in well watered crops (Bhullar & Jenner, 1986). While the rate of starch deposition may be faster under high temperatures, it does not compensate adequately for the shortened duration, so the total amount of starch deposited is less, thereby leading to lowered yields (Yoshida, 1972). On the other hand, deposition of protein appears to be largely unaffected by elevated temperatures, and an increase in grain protein percentage can therefore result (Bhullar & Jenner, 1986; Smith & Gooding, 1996). The response to mild water stress in the reproductive phase of growth is similar to the response to elevated temperatures. Stress induced by a water deficit typically results in premature yellowing of the leaves implying the induction of premature senescence (Jenner *et al.*, 1990). The development of all plant organs is enhanced at high temperatures, so accelerated grain development is accompanied by hastened senescence of leaves (Jenner *et al.*, 1990).

Generally, assimilates contributing to grain yields are derived from current photoassimilate, but when conditions such as drought occur, currently available assimilate supplies are reduced, and the plant relies more heavily on previously stored assimilates for grain filling (Simmons, 1987; Gallagher *et al.*, 1976). If demands on stored assimilates are excessive, they are remobilized from various vegetative plant parts inducing senescence, and are translocated to the grain, providing nutrients, including N, for grain development. Herwaarden *et al.* (1998b) suggested that one of the consequences of soil water depletion or lack of sufficient soil water at anthesis is a reduced assimilation rate during grain filling. In wheat, grain size can be variable, so that the influence of environmental factors during grain filling can directly influence yield potential by modifying the grain size (Yoshida, 1972 and Jenner *et al.*, 1990). Simmons (1987) suggested that between 70% and 90% of the grain yield is derived from photoassimilate produced after anthesis, by the flag leaf, penultimate leaf, peduncle and ear.

The physical constraints imposed by soil on roots are substantially different from those imposed on the aboveground fraction of the plant. Measurements of root distribution of growing plants as a function of distance from the surface shows a pattern that is simply described as a logarithmic decrease in root density with distance from the soil surface, with this logarithmic distribution moving downwards as the plant grows (Andrew, 1987). The root distribution of a plant is primarily governed by its genome, which determines the morphology of its root system (Andrén *et al.*, 1991). Within the genetic restraints, root distribution is also governed by availability of nutrients and soil water content as well as the penetration resistance of the soil (Scott-Russell, 1977). In general, roots grow rapidly in those parts of the soil that are rich in needed resources, which thus become efficiently exploited. Therefore, it can be assumed that root density will be positively correlated with the availability of scarce resources. As the root system grows and increasingly exploits the resource, the initial positive correlation should weaken and may even become negative (Drew, 1975).

The objective for the measurement of total above ground dry matter and distribution among different plant components at the two levels of N application was to explain growth and yields responses linked to environmental and other variables (soil water content and residual soil mineral N) during the growing seasons. An understanding of these interrelationships will explain the effect of the fertilizer treatments, cropping system and related factors on growth, biomass accumulation, and yields of the wheat crop.

4.1 PLANT COMPONENT RESULTS

The results of plant component measurements during the growing seasons 1997 and 1998 at Bethlehem, Kroonstad and Petrusburg are listed in Figures 4.1 and 4.2. The pattern of vegetative growth and response to N at all localities in 1998 and at Kroonstad in 1997 were similar where N_{rec} enhanced tiller numbers and mass compared to N_{0N} (Fig. 4.1). However, as spikes began to develop, tiller numbers stabilized at about 200 tillers m^{-2} in 1998 at all localities, with no differences between N treatments. At Kroonstad in 1997, the final tiller number was higher at 300 tillers m^{-2} (Fig 4.1b).

Similarly, the N_{rec} treatment showed significant increases in leaf blade mass during the early part of the 1997 season at Bethlehem and Kroonstad, and to a lesser extent at Petrusburg with values decreasing thereafter up to senescence (Fig. 4.2). Ear mass increased steadily during grain filling, but with no significant differences between treatments at Petrusburg (1997 and 1998) and Kroonstad in 1997. Likewise, increases in leaf area indexes (LAI) were measured up to the flag leaf stage and decreased as the growing season progressed. Ear mass increased during grain filling with the N_{rec} treatment showing higher values (Fig. 4.1). Lower LAI and leaf blade mass were measured in 1998 compared to 1997, with significantly higher values measured in the N_{rec} treatment at the different localities. Likewise, lower tiller mass values were measured in both years at Petrusburg compared to the other localities (Fig. 4.1c).

Response in leaf area index (LAI) at Kroonstad and Bethlehem in 1997 was linked to the higher soil water and soil mineral N availability at planting following the preceding extended fallow period. At Petrusburg lower leaf mass and LAI were measured compared to the other localities, indicating reduced plant development (Fig. 4.1c). Although the tiller number m^{-2} at Petrusburg was comparable to the other localities in both years, tiller mass was lower, also showing reduced growth of tillers once formed in response to environmental conditions in particular rainfall and temperature (Fig. 4.1c; Chapter 3.4.6.3).

4.2 CUMULATIVE BIOMASS PRODUCTION

4.2.1 1997

At all localities the initial rate of biomass accumulation early in the growing season was similar and low between the N treatments up to middle September (Fig. 4.3). This relatively slow growth rate is mainly due to cooler temperatures during the early spring. From then on to maturity, the rate of biomass accumulation at N_{rec} was greater than that of N_{0N}.

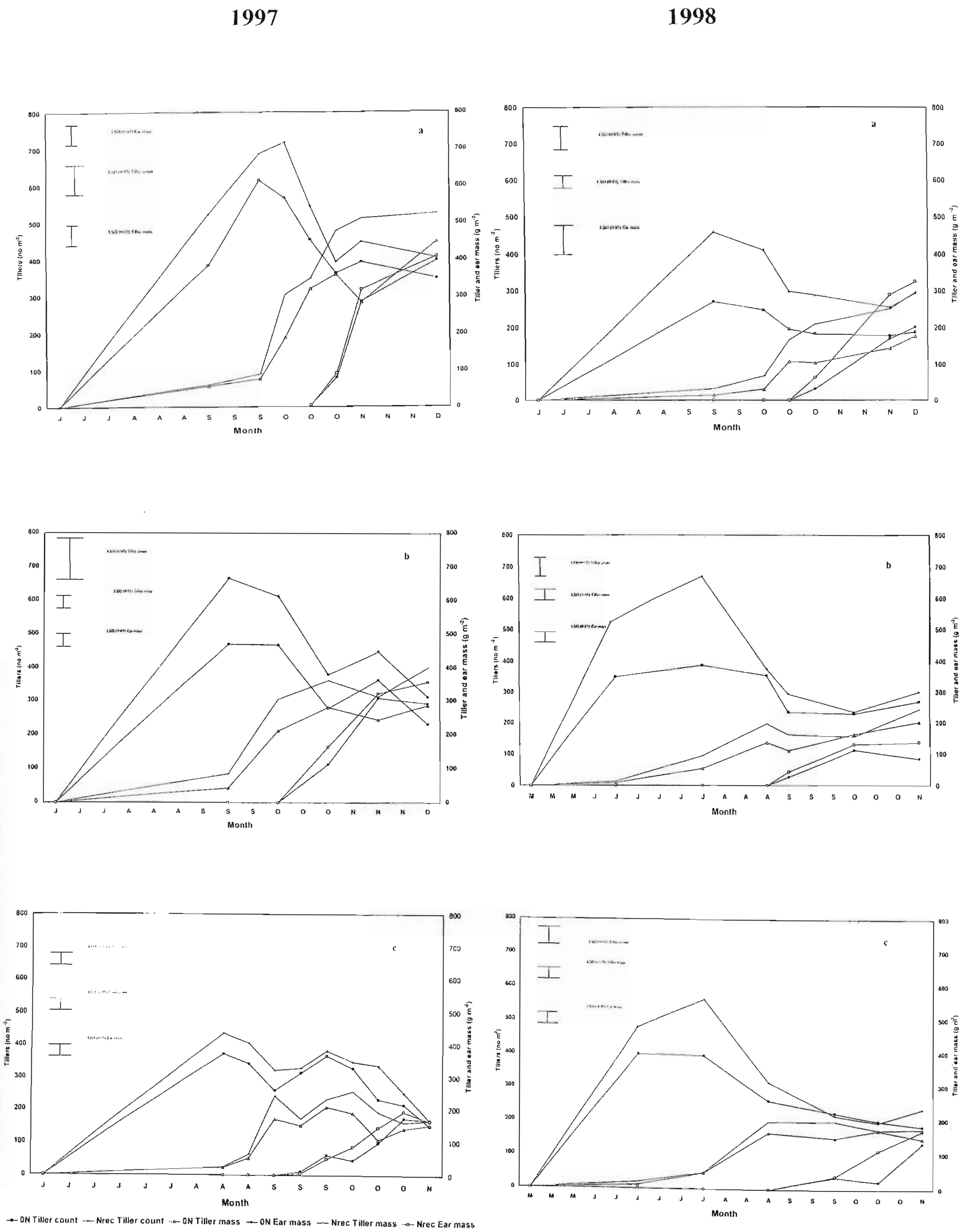

Figure 4.1 Tiller count, and tiller and ear mass of wheat grown without N (N_{0N}) and with recommended fertilizer N application (N_{rec}) in 1997 and 1998 at Bethlehem (a), Kroonstad (b), and Petrusburg (c).

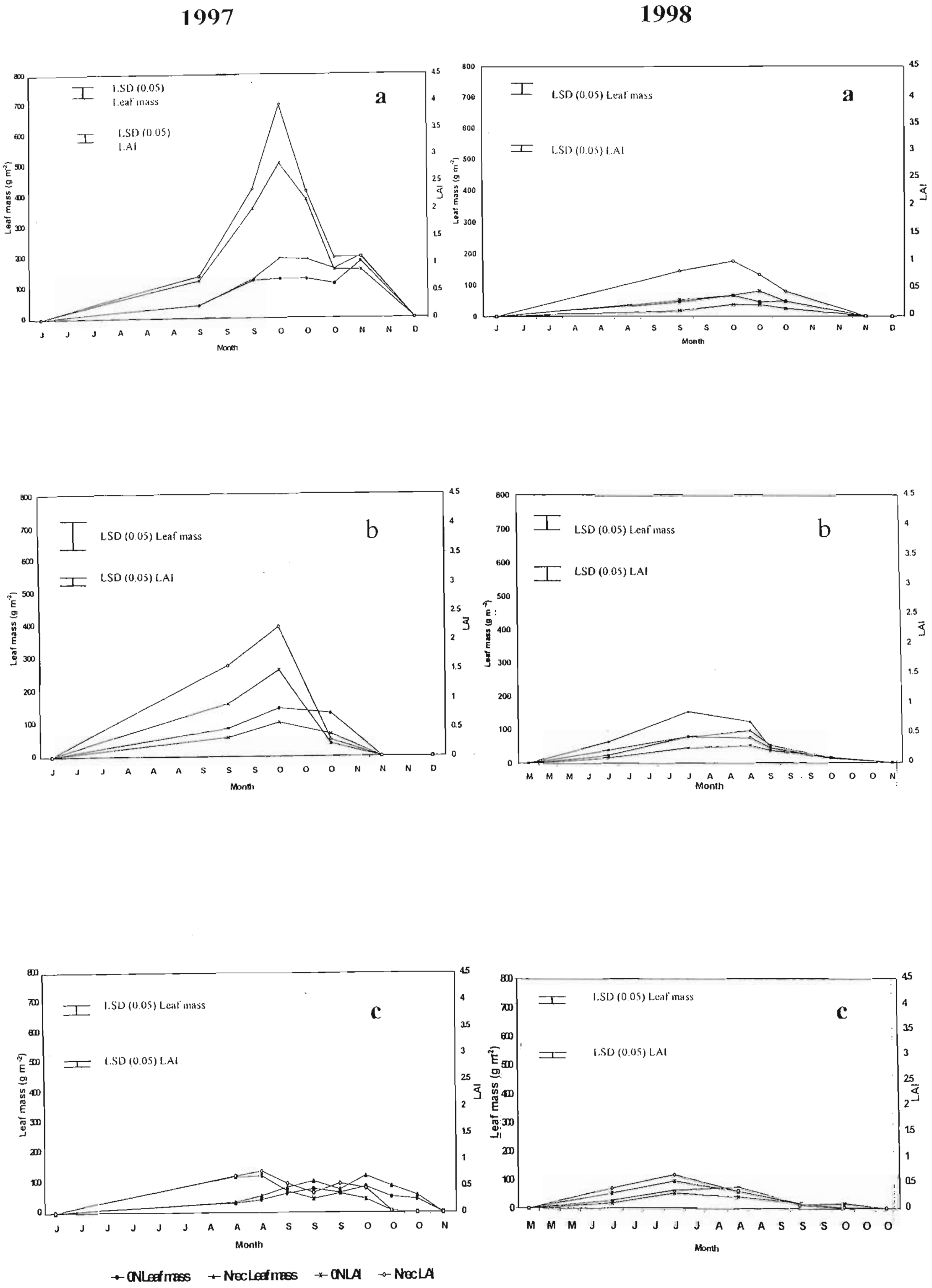

Figure 4.2 Leaf mass and leaf area index of wheat grown without N (N_{0N}) and with recommended fertilizer N application (N_{rec}) in 1997 and 1998 at Bethlehem (a), Kroonstad (b), and Petrusburg (c).

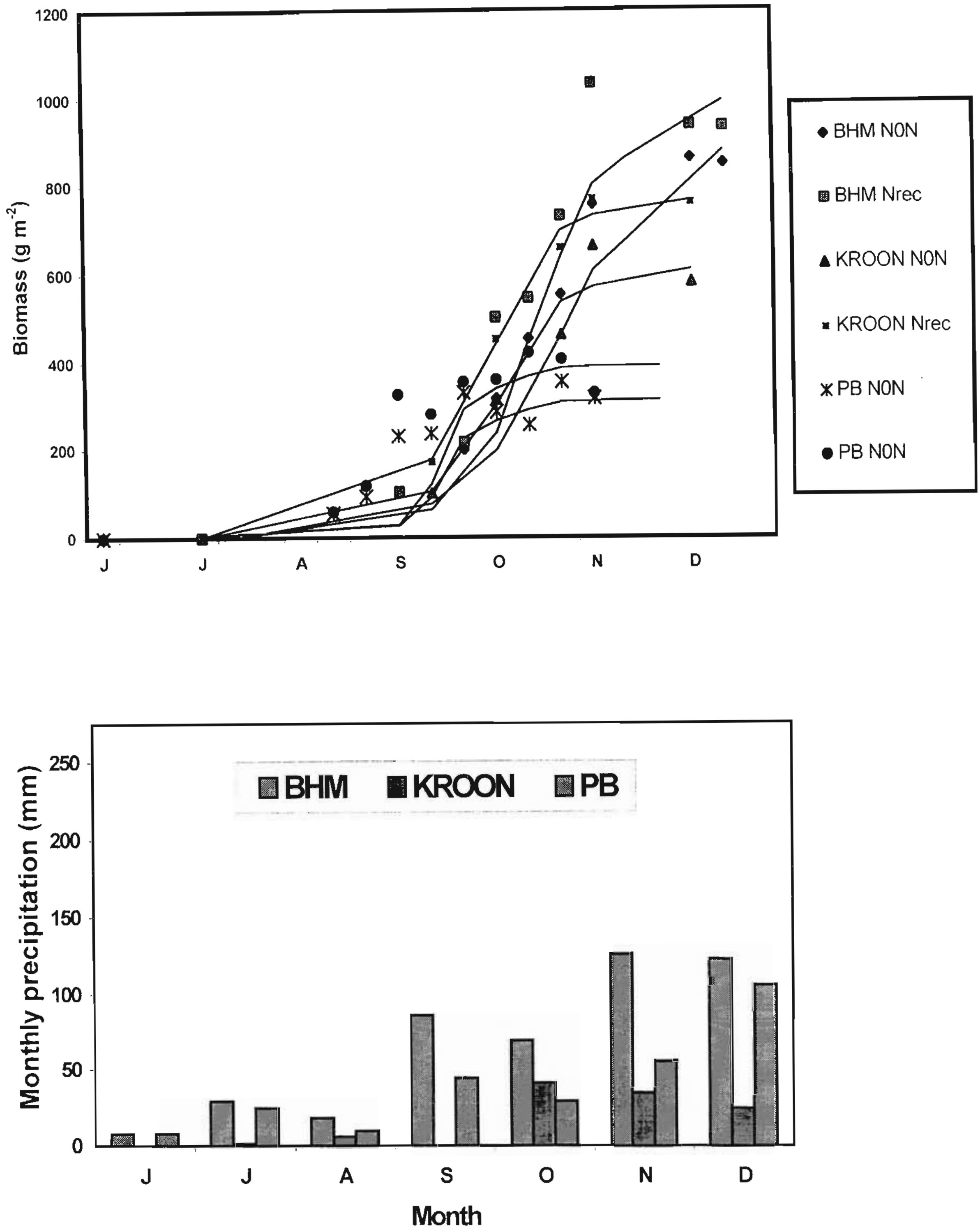

Figure 4.3. Cumulative seasonal biomass production of wheat grown with no N (N_{0N}) and recommended N fertilization (N_{rec}) treatments, their fitted Gompertz response curves, and in-season rainfall measured at Bethlehem (BHM), Kroonstad (KROON), and Petrusburg (PB) in 1997

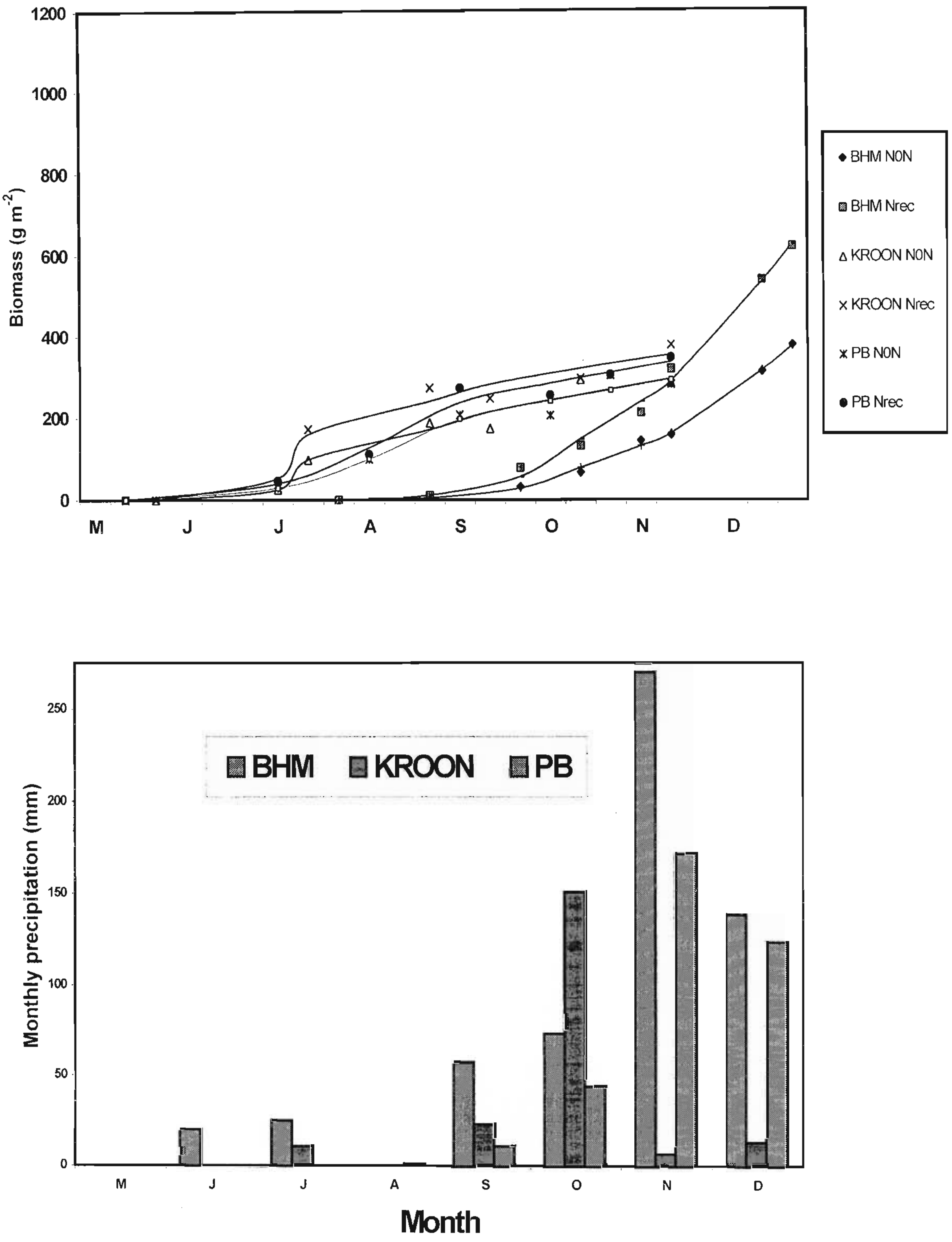

Figure 4.4. Cumulative seasonal biomass production of wheat grown with no N (N_{0N}) and recommended N fertilization (N_{rec}) treatments, their fitted Gompertz response curves, and in-season rainfall measured at Bethlehem (BHM), Kroonstad (KROON), and Petrusburg (PB) in 1998

Biomass accumulation was reduced at Petrusburg during the middle of October, and towards the end of October at Kroonstad, and continued up to grain maturity in December at Bethlehem. This lead to higher biomass measured at maturity for this latter locality. The continued growth at Bethlehem is in part due to the average temperatures during the period August to December being lower than that at Kroonstad, with Petrusburg even slightly higher. Also, 55.8% of the in-season rainfall was measured from the flag leaf stage to harvest at Bethlehem, compared to 26.7% at Kroonstad and 93.7% at Petrusburg. Consequently, a rapid rate of biomass accumulation was maintained longer at Bethlehem than at the other two localities.

4.2.2 1998

At Kroonstad and Petrusburg, there was a similar pattern of increase in biomass accumulation (Fig. 4.4). Although not significantly different, biomass production at Petrusburg for the N_{rec} treatment at maturity was higher during 1998 than 1997, while the N_{0N} produced a lower biomass than during 1997. Generally, no significant differences were measured between the N treatments in biomass. However, the initial rate of biomass accumulation during the early growing season was low, followed by a short increasing exponential phase during July. The rate of biomass accumulation then resumed its former growth rate up to harvest. The slow growth rate in the latter part of crop development is explained by the increase in average temperatures to above mean levels from August to December, in combination with rainfall. In contrast to 1997, 95.5% and 81.1% of the in-season rainfall was measured from the flag leaf stage (middle to end of September) to harvest at Kroonstad and Petrusburg respectively.

The pattern of accumulation of biomass at Bethlehem differed from that found during 1997, with a lower initial rate of biomass accumulation, followed by an increasing rate up to middle November, and with the rate further increasing to harvest. Mean to below mean temperatures during the growing season, combined with 73.3% of the in-season rainfall occurring between flag leaf stage and harvest, resulted in this growth response pattern that followed a relatively slow initial rate of biomass accumulation.

Significant fitted curves (Van Ark, 1995) were calculated from the biomass accumulation measurements. Generally, response curves of the treatments showed similar fitted relationships in 1997 (Appendix 4.1). The response curves differed in 1998 with a consistently increasing response measured at Bethlehem in this growing season. The N application at Bethlehem resulted in a relatively larger increase in biomass produced during 1998 than 1997, but with the response to N at Kroonstad decreasing in 1998.

The significance of calculated coefficients indicated that values of $A+C$ coefficients differed between localities over years, but not coefficients B and M. This indicates that growth saturation ($A+C$) was reached in 1997 at a point higher than in 1998, with the highest value at Bethlehem followed by Kroonstad, and Petrusburg. Due to the different growth response patterns measured at Bethlehem in

1998, a higher saturation value was calculated compared to 1997. At Kroonstad, values were lower in 1998 than 1997, with similar values calculated at Petrusburg for the two growing seasons.

Although the calculated inflection points (*M*) did not differ significantly over localities and years, it was noted that these points of maximum growth showed the same trends as found in saturation values. Inflection points at all three localities were in the range 82.9 to 96.6 days after planting (DAP) in 1997. In 1998, calculated values were 153.4 DAP at Bethlehem, 98.4 DAP at Kroonstad, and 93.0 DAP at Petrusburg, again indicating the increasing biomass accumulation towards the end of the growing season at Bethlehem. The calculated growth rates (*B*) for the locality x Year interaction, and the respective inflection points did not differ significantly. A lower mean value was calculated for 1998 compared to 1997 indicating the reduced growth response as influenced by rainfall, soil water and mineral N availability.

4.2.3 Combined analysis of biomass at harvest

Overall, the biomass production in 1997 was 64.4% larger than 1998 (626.8 g m^{-2} and 381.3 g m^{-2} respectively) (Table 4.1, Appendix 4.2a), with biomass production at the localities also significantly different. Biomass production at the N treatments showed the N_{rec} significantly higher on 560.4 g m^{-2} compared to N_{0N} at 447.8 g m^{-2}.

There was a statistically significant difference in biomass for the Year X locality interaction (Fig. 4.1). There was a significant reduction in biomass production at Bethlehem and Kroonstad during 1998, while at Petrusburg no significant differences were measured averaged over N treatments. The N X Year interaction was not significant. The significant locality X N interaction showed that the highest biomass was produced at Bethlehem followed by Kroonstad at the N_{rec} treatment, with no significant differences measured between N_{0N} and N_{rec} at Petrusburg. The Year X locality X N treatment interaction showed generally a significantly higher production at Bethlehem, followed by Kroonstad and Petrusburg.

Higher values were measured at the N_{rec} treatment at Bethlehem and Kroonstad. Responses in biomass at Petrusburg between the N treatments were not significant. In addition, during 1997 significantly higher values were found at Bethlehem and Kroonstad than at Petrusburg where non-significant responses between N treatments over years were found. Significant increases in biomass at N_{rec} were found compared to N_{0N} at Bethlehem and Kroonstad in 1997. In 1998 however, lower biomass was measured at Bethlehem and Kroonstad compared with 1997, however the N_{rec} treatment still produced higher values compared to N_{0N}. At Petrusburg, there was a non-significant reduction in biomass values in 1998 compared to 1997, but the N treatments did not differ in measured biomass.

Table 4.1 Biomass (g m^{-2}) measured at harvest at three localities (Bethlehem, Kroonstad and Petrusburg) and two N treatments (N_{0N} and N_{rec}) in 1997 and 1998

		Year		Mean N response and locality mean
Locality	**Treatment**	**1997**	**1998**	
Bethlehem	N_{0N}	846.7	377.9	612.3
	N_{rec}	931.5	619.6	775.6
Mean year and locality response		889.1	498.38	693.9
Kroonstad	N_{0N}	580.0	284.4	432.2
	N_{rec}	757.9	378.1	568.0
Mean year and locality response		669.0	331.3	500.1
Petrusburg	N_{0N}	316.3	281.2	298.8
	N_{rec}	328.4	346.6	337.5
Mean year and locality response		322.4	313.9	318.1

N treatment means for measured biomass at harvest

Treatment	**Mean**
N_{0N}	447.8
N_{rec}	560.4
Mean	504.1

LSD (P0.05) for year	:	25.02
LSD (P0.05) for locality	:	30.63
LSD (P0.05) for N treatment	:	33.28
LSD (P0.05) for year x locality	:	43.32
LSD (P0.05) for N treatment x locality	:	50.99
LSD (P0.05) for year x locality x N treatment	:	72.11

4.3 COMBINED ANALYSIS OF GRAIN YIELD

The interaction between Year, locality, and N treatments in the combined analysis of measured grain yields was highly significant (Table 4.2, Appendix 4.2b). The Year, locality, and N treatment main effects were significantly different. In 1997, higher average yields were produced than 1998. Bethlehem produced the highest yield averaged over the two seasons, followed by Kroonstad and Petrusburg. The N_{rec} treatment produced the highest yield averaged over years and localities. Measured yields were fitted by the least-squares method to N treatments, in-season rainfall (plant to flag leaf stage, flag leaf to harvest, and total), soil water content at planting (0-1200mm) and soil mineral N content (0-1200 mm) (Chapter 6.1) at planting, to determine associated relationships between variables. The linear multivariate functions calculated (standard errors of coefficients in italics) are presented in Appendix 4.3 (a, b). However, exponential functions calculated from the data gave a better biological explanation of the responses measured (Table 4.3), with increasingly significantly by progressive inclusion of the measured variables.

Table 4.2 Yield (t ha^{-1}) measured at three localities (Bethlehem, Kroonstad and Petrusburg) and two N treatments (N_{0N} and N_{rec}) in 1997 and 1998

Locality	Treatment	Year 1997	Year 1998	Mean N response and locality mean
Bethlehem	N_{0N}	2.321	0.970	1.645
	N_{rec}	2.441	1.593	2.017
Mean	year and locality response	2.381	1.282	1.831
Kroonstad	N_{0N}	2.255	0.717	1.486
	N_{rec}	2.371	0.953	1.662
Mean	year and locality response	2.313	0.835	1.574
Petrusburg	N_{0N}	0.820	0.813	0.816
	N_{rec}	0.822	0.834	0.828
Mean	year and locality response	0.821	0.823	0.822

Interaction between year and N treatment in measured yield at harvest

Treatment	Year 1997	Year 1998	Mean N response
N_{0N}	1.799	0.833	1.316
N_{rec}	1.878	1.127	1.502
Mean year response	1.838	0.980	1.409

LSD (P0.05) for year	:	0.043
LSD (P0.05) for locality	:	0.053
LSD (P0.05) for N treatment	:	0.049
LSD (P0.05) for year x locality	:	0.075
LSD (P0.05) for year x N treatment	:	0.066
LSD (P0.05) for N treatment x locality	:	0.080
LSD (P0.05) for year x locality x N treatment	:	0.114

Care was taken to only include factors that are independent, although under field conditions all factors influencing yields are to some extent interrelated. It must also be remembered that a good relationship between two variables does not necessarily indicate a cause and effect situation. A logical deliberation of biological facts is required for an explanation of the relationship present.

Soil mineral N at planting (0-1200 mm) explained 78% of the variation in yields (Table 4.3), and including fertilizer treatments and soil water content at planting (0-1200 mm) increased the explanation to 87%. This is part due to the lower soil mineral N measured in 1998 together with lower yields. Total in-season rainfall, although acknowledged as a major influencing factor on successful production and yields under rainfed conditions, did not make an extensive contribution (4%) in this analysis. The reason for this is that in the cropping years studied, in-season rainfall above or comparable to long-term means for this period was measured, thereby possibly minimizing the effect of this factor on yields in this analysis. The function including all four variables explained 91% of the variation in yields over the two growing seasons, indicating the importance of this combination of variables in affecting growth response and yields.

Table 4.3 Calculated exponential functions explaining variation in yields (t ha^{-1}) measured in 1997 and 1998 at Bethlehem, Kroonstad, and Petrusburg (standard errors of coefficients in italics)

Intercept	Mineral soil N (kg N ha^{-1})	Fertilizer (kg N ha^{-1})	Soil water content (mm)	Total in-season rainfall (mm)	R^2	F-value
0.3336 *(0.2332)*	1.00664 *(0.0001)*				0.78	2.11**
0.3185 *(0.1885)*	1.0063 *(0.0008)*	1.0089 *(0.0035)*			0.87	30.93**
0.32103 *(0.2647)*	1.00632 *(0.00096)*	1.00898 *(0.0039)*	0.99996 *(0.0008)*		0.87	18.30**
0.2770 *(0.2599)*	1.00656 *(0.0008)*	1.0103 *(0.0036)*	1.00114 *(0.0010)*	0.999 *(0.0005)*	0.91	16.98**

Example of calculated function: Soil mineral N- 200 kg N ha^{-1}, Fertilizer- 25 kg N ha^{-1}, Soil water content- 225 mm, Total in-season rainfall- 200 mm.

y = 0.2770* (1.00656**200)* (1.0103**25)* (1.00114**225)* (0.999**200)
y = 1.400 t ha^{-1}

The total soil mineral N content and soil water content at planting (at 0-1200 mm soil depth) was divided into 0-600 and 600-1200 mm soil layers, and included into the analysis of yield response (Table 4.4). This division is guided by the relative root distribution generally being more than 80% in the 0-600 mm soil layer at the localities. Total in-season rainfall was divided into rainfall received during the growth phases planting to flag leaf stage, and flag leaf to harvest.

Table 4.4 Calculated exponential functions explaining variation in yields (t ha^{-1}) measured in 1997 and 1998 at Bethlehem, Kroonstad, and Petrusburg (standard errors of coefficients in italics): Division of parameters

Intercept	Mineral soil N (0-600 mm) (kg N ha^{-1})	Mineral soil N (600-1200 mm) (kg N ha^{-1})	In-season rainfall (mm) (planting-flag)	Fertilizer N (kg N ha^{-1})	Soil water content (0-600 mm) (mm)	In-season rainfall (flag-harvest)	Soil water content (600-1200 mm) (mm)	R^2	F-value
0.37757	1.01035							0.85	57.94**
(0.1688)	*(0.00135)*								
0.35066	1.0094	1.00225						0.86	27.63**
(0.2052)	*(0.00201)*	*(0.0033)*							
0.32677	1.0109	1.00192	0.9991					0.87	17.30**
(0.2405)	*(0.00318)*	*(0.00349)*	*(0.00151)*						
0.3065	1.0102	1.00325	0.9986	1.0054				0.89	14.41**
(0.2370)	*(0.0031)*	*(0.00352)*	*(0.00150)*	*(0.00422)*					
0.3224	1.01023	1.00303	0.99878	1.00537	0.9996			0.89	9.91**
(0.4554)	*(0.0034)*	*(0.00412)*	*(0.00214)*	*(0.00456)*	*(0.0030)*				
2.4525	1.0020	0.99155	1.00902	1.00418	0.9986	0.9961		0.98	61.62**
(0.3832)	*(0.00188)*	*(0.0025)*	*(0.0019)*	*(0.00177)*	*(0.00116)*	*(0.00066)*			
2.3711	1.00218	0.9918	1.00895	1.0042	0.99797	0.9961	1.00519	0.99	42.28**
(0.8283)	*(0.00381)*	*(0.00649)*	*(0.00258)*	*(0.00221)*	*(0.0135)*	*(0.00074)*	*(0.01909)*		

Example of calculated function: Soil mineral N (0-600 mm)- 100 kg N ha^{-1}, Soil mineral N (600-1200 mm)- 100 kg N ha^{-1}, Fertilizer- 25 kg N ha^{-1}, Soil water content (0-600 mm)- 125 mm, Soil water content (600-1200 mm)- 125 mm, In-season rainfall (planting to flag leaf)- 100 mm, In-season rainfall (flag leaf to harvest)- 100 mm

y = 0.45272 * (1.00283*100) * (1.01158**100) * (1.00653**100) * (1.0018**25) * (0.980**125) * (0.9954**100) * (1.01687**100)
y = 1.025 t ha^{-1}

4.4 COMBINED ANALYSIS OF HECTOLITER MASS

From the combined analysis on hectoliter mass, the Year main effect was significant, with 1998 values lower than 1997 (Appendix 4.3c, Table 4.5). The localities also differed significantly, with Petrusburg showing higher values than Bethlehem and Kroonstad that did not differ significantly. The N_{0N} treatment had significantly higher values than N_{rec}.

From the Year X locality interaction analysis, Bethlehem had higher values during 1997 than Kroonstad and Petrusburg. Hectoliter mass decreased significantly at Bethlehem and Kroonstad during 1998 and could be attributed to rainfall during maturity and harvesting, while at Petrusburg no significant differences were found. For the Year X N treatment interaction, the values for 1997 did not differ significantly between N_{rec} and N_{0N}. During 1998 hectoliter mass decreased at N_{rec} with values significantly lower compared to N_{0N}. The locality X N treatment and Year X locality X N treatment interactions were not significantly different.

Table 4.5 Hectoliter mass (kg hl^{-1}) measured at three localities (Bethlehem, Kroonstad and Petrusburg) and two N treatments (N_{0N} and N_{rec}) in 1997 and 1998

	Year		**Locality**
Locality	**1997**	**1998**	**means**
Bethlehem	78.12	69.08	73.60
Kroonstad	75.46	71.45	73.46
Petrusburg	75.90	75.90	75.90

Interaction between year and N treatment in measured hectoliter mass at harvest

	Year		**N response**
Treatment	**1997**	**1998**	**means**
N_{0N}	76.59	72.89	74.74
N_{rec}	76.39	71.40	73.90
Mean year and N response	76.49	72.14	74.32

LSD (P0.05) for year : 0.55
LSD (P0.05) for locality : 0.67
LSD (P0.05) for N treatment : 0.64
LSD (P0.05) for year x locality : 0.96
LSD (P0.05) for year x N treatment : 0.85

4.5 ROOT MEASUREMENTS

Results of root length and root dry matter measured during the late grain filling stage are presented in Appendices 4.4, 4.5, and 4.6. Root distribution was measured up to a depth of 1200 mm with generally more than 55% and 80% of roots found in the 0-400 and 0-600 mm soil layers respectively. The application of N increased the measured root length as well as root weight during both growing seasons, although the differences were not always significant.

4.6 DISCUSSION

The application of N to cereals commonly result in increasing biological yield (Donald & Hamblin, 1976). Nitrogen fertilization had a significant effect on measured dry matter production in both cropping years, through the stimulation of vegetative growth as can be seen from the measured plant components (tiller mass, leaf blade mass, and LAI) at the three localities. As can be seen in Figs. 4.3 and 4.4, biomass accumulated during 1998 relative to 1997 was similar at Petrusburg (88.9% at N_{0N} and 105.5% at N_{rec} respectively), but at Kroonstad and Bethlehem it was lower during 1998 than 1997. At Kroonstad biomass accumulation values of 49% (N_{0N}) and 49.9% (N_{rec}) and at Bethlehem 67.9% (N_{0N}) and 75.5% (N_{rec}) were measured in 1998 in comparison to 1997.

The reduction of biomass at the N_{rec} treatment during 1997 at Bethlehem during grain filling can be explained by the decrease in leaf blade mass during this time which resulted from accelerated senescence. There was an increase in biomass at the N_{0N} treatment, mainly due to favorable moisture conditions during this period (Chapter 3.4.6.1). This resulted in delayed senescence of leaves in the N_{0N} treatment, and caused an increase in biomass up to maturity. Jarrell & Beverly (1981) listed the following factors that can lead to a decrease in dry matter accumulation of crops; a decrease in photosynthesis, increases in respiration, reduced photosynthate translocation, limited water availability, accelerated senescence, hastened maturity, decreased growth period, greater disease-, pest-, or temperature related losses of yield potential. Most of these factors were prevalent during the study period, especially limited water availability at certain periods during the growing season at Petrusburg.

Although aerial temperatures at Bethlehem during 1997 were close to long-term mean values for December, maximum temperatures during early December ranged from 22.8 to 31.3 °C. These high temperatures during this period of grain filling lead to an increase in leaf senescence, which may have reduced the accumulation of carbohydrates more than that of N (Spiertz, 1974; Bhullar & Jenner, 1986; Jenner *et al.*, 1990). Higher temperatures during grain filling can reduce the duration of grain growth and limit the maximum size of the grain (Smith & Gooding, 1996). Nitrogen translocation is however less retarded and this can lead to an increased grain protein content (Smith & Gooding, 1996; Chapter 5.1).

During the early growing season of 1998, the grain yield potential was depressed by decreased initial growth and biomass accumulation at Bethlehem. The combined effect of undecomposed crop residue in the cultivation zone (0-400 mm), low in-season rainfall (planting to flag leaf), and decreased availability of soil mineral N that at the N_{0N} treatment resulted in low grain yields. Nitrogen application, however, significantly increased grain yields at the N_{rec} treatment. Low hectoliter mass values were measured for both N treatments at Bethlehem resulting from rainfall (Chapter 3.4.6.1) during the period from physiological maturity to harvest.

Favorable growing conditions at Kroonstad during 1997 significantly increased biomass production at N_{rec}. Grain yields were above the long-term mean yield potential for this region, although hectoliter mass values were somewhat reduced. Low rainfall in October, November, and December linked with above-mean aerial temperatures during these months (Chapter 3.4.6.2) coincided with the development stages between flag leaf and maturity, although not reducing yields, lowered hectoliter mass values of the grain. Mean rainfall was measured in the summer months during the fallow period in 1998, enabling timely soil cultivation. Following soil cultivation, below-mean rainfall during April and May at Kroonstad in 1998 resulted in low soil water contents in the 0-50 mm, and 50-200 mm soil layers at planting. This depressed early plant development and root growth limiting soil N and water use from these layers. August and October were below-mean rainfall months and this further reduced growth and biomass production lowering grain yields.

During 1997 at Petrusburg, the mean biomass production was lower than at the other two localities, and the biomass did not differ significantly in response to N applications. Initial growth response to increased residual soil water was depressed after the flag leaf stage due to above-mean temperatures during September and October resulting in water/heat stress. Consequently, grain yields did not differ in 1997 between the treatments. A similar yield response was measured in 1998, with no significant differences between treatments at maturity.

There was a significant reduction in yield in 1998 compared to 1997 at Bethlehem and Kroonstad. Overall, the N_{rec} treatment produced higher yields than N_{0N} in both years at Bethlehem and Kroonstad, but similar yields at Petrusburg. This response was proportionally greater in 1998 than 1997 (Table 4.2). The increase in yield due to N application in 1997 was 5.1% at Bethlehem and Kroonstad. The response in grain yield to N application in 1998 was 64% at Bethlehem and 32.9% at Kroonstad, although the mean seasonal yield level was lower. This response to N application indicates a reduced availability of N (lower soil mineral N content, as well as a different profile distribution) in 1998. Soil mineral N content and fertilizer N application played a dominant role in explaining responses in measured grain yields in this study, as shown in the calculated regression functions. The response to N application is reflected in the greater tillering observed in response to N application in 1998 at these sites in the vegetative growth phase (Fig. 4.1). However, at harvest, tiller numbers were similar between N treatments, and yield differences were determined by ear mass (Fig. 4.1).

Soil mineral N content (0-600 mm) explained 85% of the variation in yields (Table 4.4). Soil mineral content, rainfall (planting-flag leaf), and fertilizer N added explained 89% of the variation in yields, and inclusion of all the variables increased this value to 99%. These results indicate the importance of available soil N during the vegetative growth phases, together with rainfall and fertilizer N during this period on the development of potential yield. Inclusion of soil water content for the 0-600 and 600-900 mm layers, and rainfall (flag leaf-harvest) accounted for an additional 10% in the analysis. This indicates that rainfall during the vegetative growth phases can increase grain yield potential by increasing growth and biomass accumulation. In contrast, the relative amount of in-season rainfall measured during the later growth stages (flag leaf-harvest), negatively impacted on early development of yield potential, but resulted in extended biomass accumulation at a lower rate towards physiological maturity.

Soil mineral N at planting is an indication of the extent of soil N dynamics (mineralization and nitrification linked to residue decomposition) and the environmental influences (rainfall amounts and distribution, and temperature) during the preceding fallow period. Undecomposed crop residue measurements at planting explained less than 1% of the variation in yields. However, the major impact of crop residue was on available soil mineral N content, which was a major factor in this analysis. The length of the fallow period preceding the wheat crop is linked to the efficiency of soil cultivation practices including crop residue management during this time. These factors affect the amount and distribution of soil mineral N in the profile at planting and will be discussed in Chapter 6.1.

Undecomposed crop residue in the cultivation zone at planting immobilized soil mineral N during the fallow period and growing season (Chapter 6.2), which in turn resulted in the reduction of crop growth and biomass accumulation, especially at the N_{0N} treatment. Harper & Lynch (1981) and Mason & Rowland (1992) found that fewer tillers and lower yields were produced when a crop was planted in undecomposed residues and attributed this mainly to the immobilization of soil mineral N by microbial decomposers, resulting in low soil mineral N availability to the growing crop.

Although soil water content at planting and total in-season rainfall were not major contributing factors in the explanation of variation in grain yields in this case, significant crop response to available soil water was found by Corbeels *et al.* (1999). This might be the case in cropping seasons with different rainfall and distribution. Donald & Hamblin (1976) noted that when water supply is limited, applied N might cause grain yield declines due to increased vegetative growth and earlier depletion of soil water supply.

The ability to efficiently remobilize previously accumulated photosynthate to the grain influences the harvest index and grain yield at maturity (Gent & Kiyomoto, 1989). Up to one-half of the photosynthate fixed before anthesis can be lost from wheat plants by maturity. Rainfall later in the growing season may cause N dilution in the grain by extending leaf life and maintaining photosynthesis, and, therefore carbon assimilation (Smith & Gooding, 1996). This was the case at Bethlehem in 1998, when a higher than normal distribution of rainfall occurred late in the growing season. At Petrusburg in 1997 and 1998, and Kroonstad in 1997 a decrease in dry matter accumulation was measured from grain filling to maturity. However, at Bethlehem in 1997, and at both Bethlehem and Kroonstad in 1998, there were increases in dry matter accumulation throughout grain filling to maturity. This increase was due to favorable rainfall distribution during that period of growth, resulting in favorable soil water conditions delaying senescence of leaves and physiological maturity, allowing translocation of photosynthate to developing grain over an extended period of time.

Results over the two growing seasons indicated that in wheat monoculture, favorable rainfall distribution is critical for effective soil cultivation and crop residue management during the fallow period. Rainfall distribution in the fallow period can indirectly lower available soil mineral N at planting by reducing residue decomposition, or inducing leaching of NO_3^- following heavy rain showers. Low soil water content at planting, especially in the cultivation zone, can reduce emergence, initial growth, plant development, and yield potential particularly if early spring rains are delayed.

CHAPTER 5 NITROGEN UPTAKE, CONCENTRATION AND DISTRIBUTION IN PLANT COMPONENTS IN RESPONSE TO NITROGEN TREATMENTS

Nitrogen is one of the most important minerals that determine crop productivity. The evaluation and understanding of the pattern of N uptake and its distribution in the crop throughout the growing season, can be used to predict N requirements for improving N fertilizer management (Bauer *et al.*, 1987; Baethgen & Alley, 1989b). Knowledge of plant nutrient concentrations in relation to plant development stage is valuable as it provides information for management decisions relative to timing of nutrient applications to avoid the occurrence of deficiency or surplus situations (Bauer *et al.*, 1987). High N use efficiency by crops should be expected when the N availability and mobilization matches the crop's needs throughout the growing season.

Changes occur in dry matter and nutrient accumulation and in mass distribution among plant components of wheat plants with continued plant development (Bauer *et al.*, 1987). Wheat tissue N concentrations (in particular stem and leaf tissues) have been observed to decrease during the growing season because of the slower rate of N relative to C assimilation (Harper *et al.*, 1987). Nitrogen concentrations of leaves is typically high during the vegetative stage, then decreases during the growing season, with large amounts of N in the leaves and stems redistributed to reproductive organs during maturation (Osaki *et al.*, 1991).

The basic principle in the use of plant nutrient analysis is that the chemical composition of a plant reflects the interaction of nutrient supply and plant growth at that point in development (Martin & Matocha, 1973). Even though nutrient concentration of plant tissue decreases, the total accumulation of this nutrient as calculated by the product of concentration and dry matter yield may increase significantly. This indicates that plant growth had proceeded more rapidly than nutrient uptake (Jarrell & Beverly, 1981). These authors also noted that the nutrient concentration of plant tissue is a single-point measurement resultant from plant growth history and in particular, integration of the processes of nutrient uptake, transport, and dry matter accumulation.

Plant tissue analysis at a specific growth stage and under optimal environmental conditions can provide an effective means of monitoring the nutritional status of the crop. Reliable N recommendations for wheat based on plant analysis must be based on accurate critical nutrient concentration levels (Vaughn *et al.*, 1990), but the total nutrient uptake and dry matter yield must also be considered (Jarrell & Beverly, 1981). The measurement of organic N (total tissue N analysis) reflects the cumulative effect of N supply to the plant (Tucker, 1984), necessitating whole plant samples when total N uptake is part of fertilizer use efficiency or N balance studies.

The plant is the ultimate genetic integrator of all environmental variables controlling N transformations and ultimately available N within the soil N cycle (Broadbent, 1981; Rice *et al.*, 1995). Crop N uptake can provide an estimate of N availability during the growing season, while N uptake by an unfertilized (N) crop can give an indication of net N mineralization in the field (Rice *et al.*, 1995). The advantages of this approach are the integration of field temperature, moisture, and aeration conditions that can greatly influence N mineralization potential, and furthermore it can be adapted to include crop and soil management variables. Nitrogen uptake in unfertilized (N) plots also includes the normal rooting depth of the crop and integrates spatial and temporal influences on N mineralization (Broadbent, 1981; Rice *et al.*, 1995).

The objectives for N analysis and calculating N uptake of different plant tissues were to explain the pattern of N uptake during the growing season in response to N application; to measure the redistribution of N to the different plant organs; and to explain the consequent growth differences as influenced by various factors affecting N availability.

5.1 PLANT N ANALYSIS AND N UPTAKE RESULTS

5.1.1 Bethlehem

5.1.1.1 1997

Nitrogen application resulted in a higher N concentration in leaves and tillers (Fig. 5.1; Appendix 5.1) from Zadoks (Z) 30 to Z60 than the control (N_{ON}). Leaf N concentration decreased during this period from 4.18% (N_{ON}) and 5.29% (N_{rec}) to 0.82% and 0.94% respectively at senescence. The N concentration of tillers decreased from 3.25% (N_{ON}) and 4.07% (N_{rec}) to 0.36% and 0.49% respectively at maturity (Table 5.1; Appendix 5.2). Nitrogen concentration of the ears initially increased, levelling off during grain filling, with the N_{rec} having significantly higher values up to physiological maturity, when no differences between the two treatments were evident.

Calculated tiller N uptake values at Z30 for N_{rec} were higher than for N_{ON}, and although leaf uptake did not differ significantly, it still resulted in a higher total N uptake (Appendix 5.1). At Z40 tiller N and leaf uptake for the N_{rec} treatment was significantly higher than the N_{ON} treatment. Total N uptake reached 86.59 kg N ha^{-1} (N_{rec}) in comparison with 59.84 kg N ha^{-1} for N_{ON} for this sampling time (Fig. 5.2). The major portion of accumulated N at maturity was found in the grain, with N_{ON} having 37.6 kg N ha^{-1} and N_{rec} being significantly higher at 52.49 kg N ha^{-1} (Table 5.3; Appendix 5.4a). The remainder of N was found in above ground crop residue (leaf and tiller biomass). This amounted to 22.25 kg N ha^{-1} at N_{ON} and 34.10 kg N ha^{-1} at N_{rec} (Tables 5.4, 5.5 Appendices 5.4b, 5.4c).

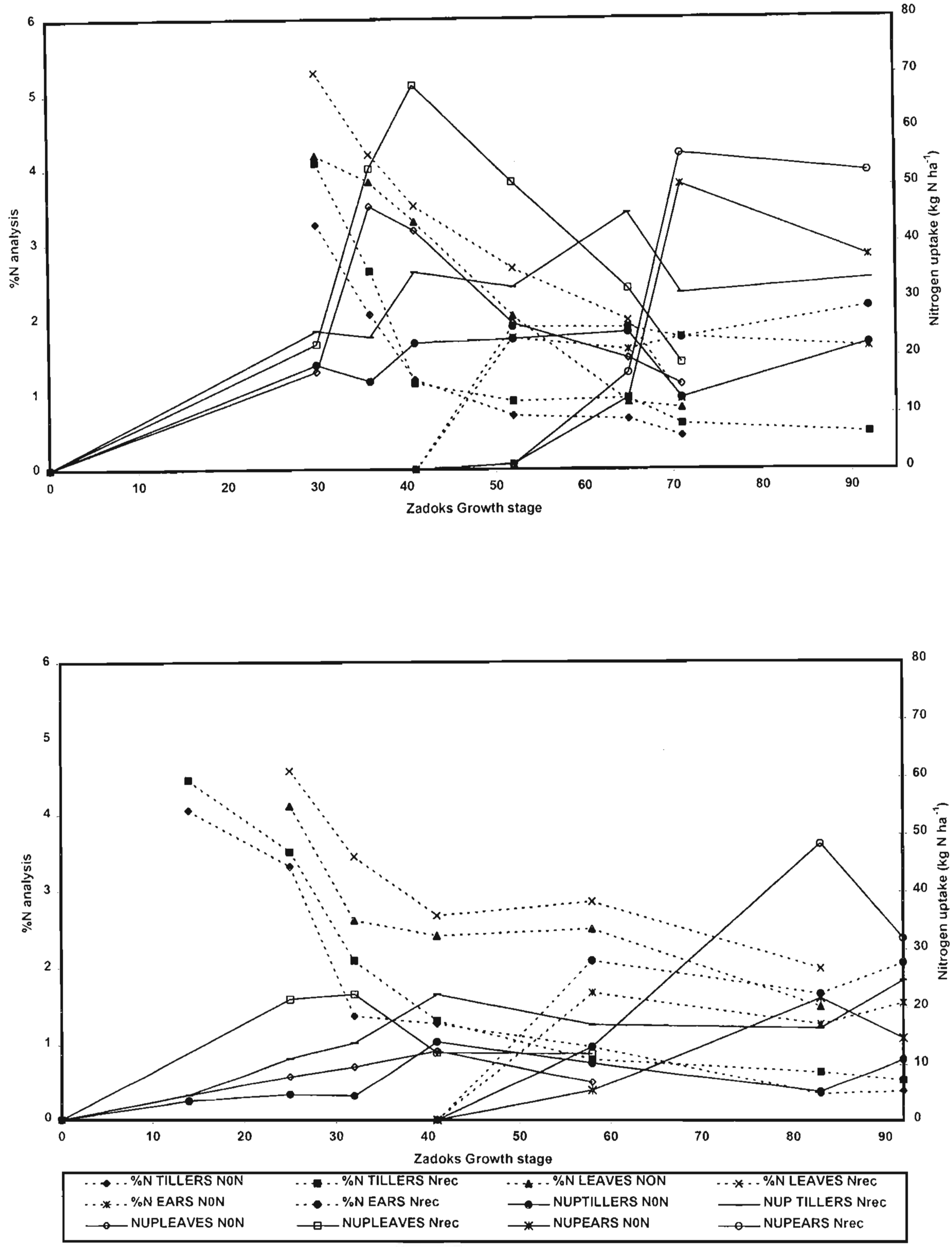

Figure 5.1 **Nitrogen concentration (%N) and uptake of tillers, leaves, and ears at Bethlehem for the N treatments (N_{0N} and N_{rec}) for 1997 and 1998**

Table 5.1 Tiller N concentration (%) at harvest at three localities (Bethlehem, Kroonstad and Petrusburg) and two N treatments (N_{0N} and N_{rec}) in 1997 and 1998

	Year		
Locality	**1997**	**1998**	**Mean**
Bethlehem	0.43	0.47	0.45
Kroonstad	0.47	0.37	0.42
Petrusburg	0.34	0.70	0.52
Means	0.41	0.51	0.46

Tiller N concentration at harvest in response to N treatments

N Treatment	**Mean**
N_{0N}	0.43
N_{rec}	0.49
Means	0.46

LSD (P0.05) for year : 0.06
LSD (P0.05) for locality : 0.07
LSD (P0.05) for N treatment : 0.05
LSD (P0.05) for year x locality : 0.11

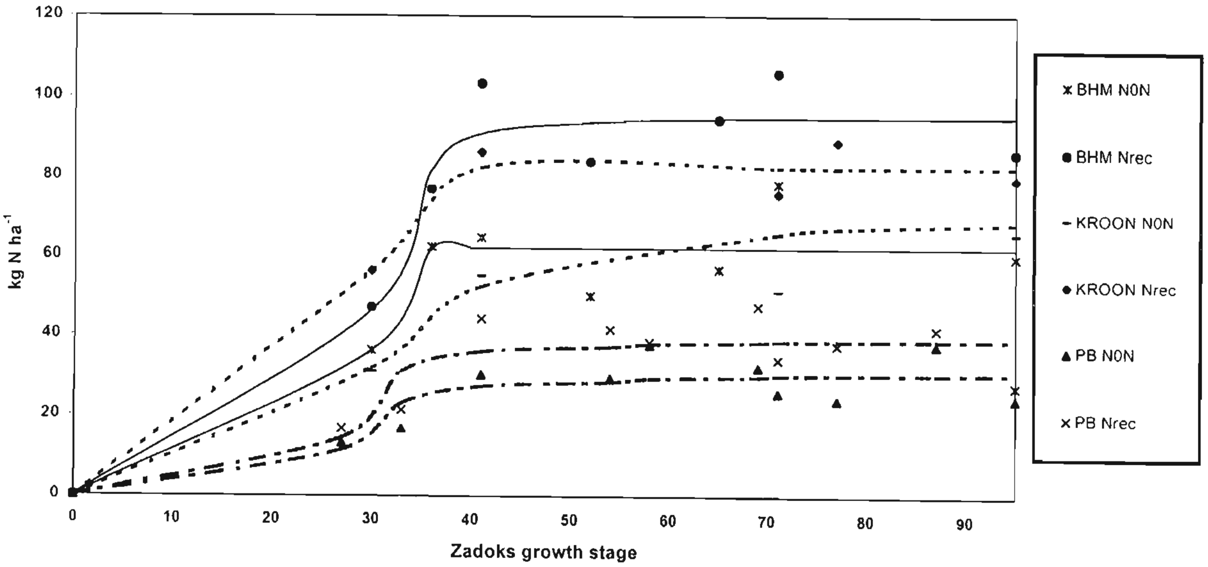

Figure 5.2 Cumulative N uptake and fitted curves (total N uptake) for the N_{0N} and N_{rec} treatments at Bethlehem (BHM), Kroonstad (KROON), and Petrusburg (PB) in 1997

Table 5.2 Protein percentage at harvest at three localities (Bethlehem, Kroonstad and Petrusburg) and two N treatments (N_{0N} and N_{rec}) in 1997 and 1998

	Year		
Locality	**1997**	**1998**	**Mean**
Bethlehem	10.74	10.02	10.38
Kroonstad	12.82	11.50	12.16
Petrusburg	11.60	13.23	12.41
Locality/year means	11.72	11.58	11.65

Locality and N treatment means for protein percentage at harvest

	N Treatment		
Locality	**N_{0N}**	**N_{rec}**	**Mean**
Bethlehem	8.91	11.85	10.38
Kroonstad	11.90	12.43	12.16
Petrusburg	12.09	12.74	12.41
Locality/N treatment means	10.97	12.34	11.65

LSD (P0.05) for locality : 0.27
LSD (P0.05) for N treatment : 0.22
LSD (P0.05) for year x locality : 0.38
LSD (P0.05) for N treatment x locality : 0.39

Table 5.3 Total N uptake (grain, kg N ha^{-1}) at harvest at three localities (Bethlehem, Kroonstad and Petrusburg) at two N treatments (N_{0N} and N_{rec}) during 1997 and 1998

Locality	Year		Mean
	1997	1998	
Bethlehem	45.04	23.30	34.17
Kroonstad	52.12	16.85	34.48
Petrusburg	16.71	19.12	17.91
Locality/year means	37.96	19.76	28.86

Mean Locality/ N treatment response in measured total N uptake (grain) at harvest

Locality	Treatment		Mean
	N_{0N}	N_{rec}	
Bethlehem	26.11	42.22	34.17
Kroonstad	31.60	37.37	34.48
Petrusburg	17.31	18.51	17.91
Locality/N treatment means	25.01	32.70	28.86

LSD (P0.05) for year	:	1.15
LSD (P0.05) for locality	:	1.40
LSD (P0.05) for N treatment	:	1.39
LSD (P0.05) for year x locality	:	1.98
LSD (P0.05) for N treatment x locality	:	2.20

Table 5.4 Total N uptake (residue, kg N ha^{-1}) at harvest at three localities (Bethlehem, Kroonstad and Petrusburg) at two N treatments (N_{0N} and N_{rec}) over 1997 and 1998

	Year		
Locality	**1997**	**1998**	**Mean**
Bethlehem	28.17	17.82	23.00
Kroonstad	20.17	9.20	14.69
Petrusburg	8.11	16.31	12.21
Locality/year means	18.82	14.44	16.63

Mean Year and N treatment response in measured total N uptake (residue) at harvest

	N treatment		
Locality	**N_{0N}**	**N_{rec}**	**Mean**
Bethlehem	16.58	29.41	23.00
Kroonstad	11.70	17.68	14.69
Petrusburg	11.15	13.26	12.21
Locality/N treatment means	13.14	20.12	16.63

LSD (P0.05) for year : 2.50

LSD (P0.05) for locality : 3.06

LSD (P0.05) for N treatment : 2.64

LSD (P0.05) for year x locality : 4.32

LSD (P0.05) for N treatment x locality : 4.45

Table 5.5 Total N uptake (kg N ha^{-1}) at harvest at three localities (Bethlehem, Kroonstad and Petrusburg) at two N treatments (N_{0N} and N_{rec}) over 1997 and 1998

	Year		
Locality	**1997**	**1998**	**Mean**
Bethlehem	73.21	41.12	57.17
Kroonstad	72.29	26.06	49.17
Petrusburg	24.82	35.43	30.12
Locality/year means	56.77	34.20	45.49

Mean Year and N treatment response in measured total N uptake at harvest

	N treatment		
Locality	**N_{0N}**	**N_{rec}**	**Mean**
Bethlehem	42.69	71.64	57.17
Kroonstad	43.30	55.04	49.17
Petrusburg	28.47	31.77	30.12
Locality/N treatment means	38.15	52.82	45.49

LSD (P0.05) for year	:	2.77
LSD (P0.05) for locality	:	3.39
LSD (P0.05) for N treatment	:	2.82
LSD (P0.05) for year x locality	:	4.80
LSD (P0.05) for N treatment x locality	:	4.84

5.1.1.2 1998

Nitrogen application significantly increased the N concentration of leaves and tillers (Fig. 5.1; Appendix 5.5). Leaf N concentration decreased during the growing season from 4.12% (N_{0N}) and 4.58% (N_{rec}) at Z30 to 2.52% and 2.87% respectively at senescence. Nitrogen concentration of tillers decreased from 3.33% (N_{0N}) and 3.52% (N_{rec}) to 0.39% and 0.54% respectively at maturity. These values for N_{rec} are lower compared to 1997. Nitrogen concentration of the ears increased during initial ear growth, but leveled-off thereafter. Ear N concentrations were significantly higher at physiological maturity for N_{rec} than N_{0N} treatment.

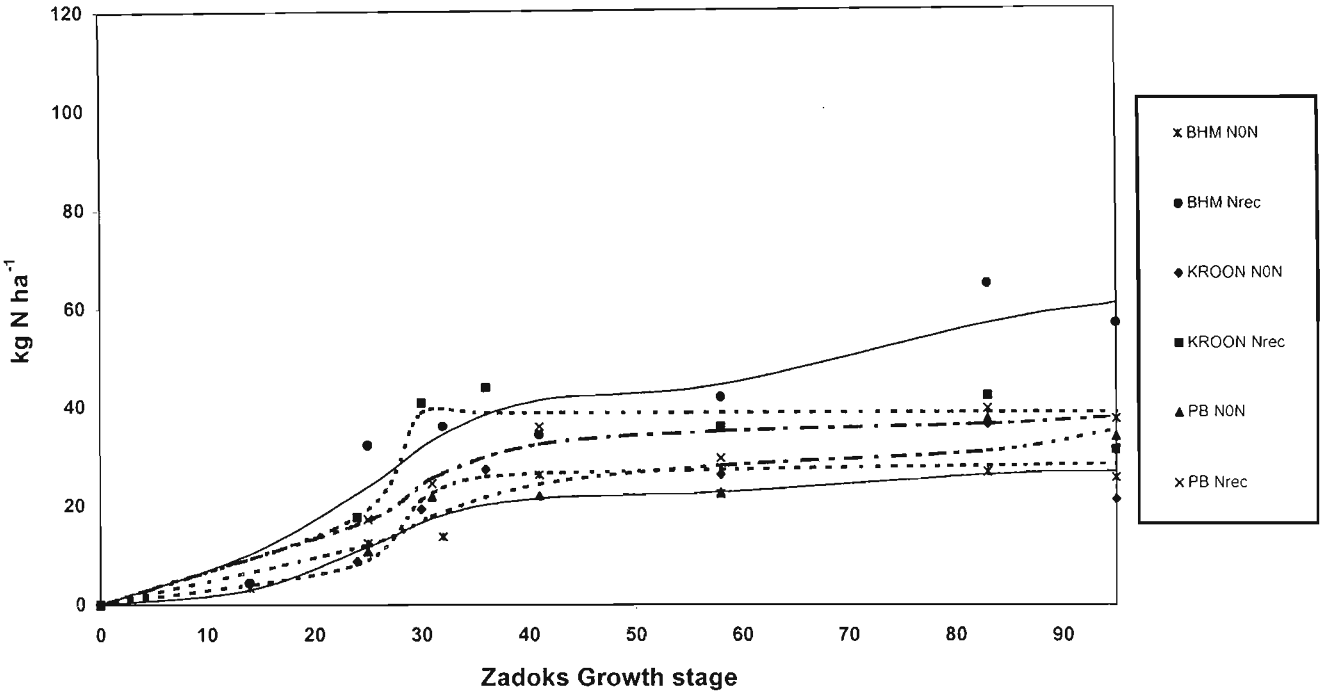

Figure 5.3 Cumulative N uptake and fitted curves (total N uptake) for the N_{0N} and N_{rec} treatments at Bethlehem (BHM), Kroonstad (KROON), and Petrusburg (PB) in 1998

Yield and grain protein percentage was significantly increased by N application at N_{rec} (11.43%), in comparison to 8.60% measured at N_{0N}. Grain N concentration was overall lower in 1998 compared to values in 1997.

The total N uptake was 25.55 kg N ha^{-1} (N_{0N}) and significantly higher for the N_{rec} treatment at 56.69 kg N ha^{-1} (Table 5.5; Appendix 5.4c). At maturity, the tiller N uptake for N_{0N} and N_{rec} were 10.91 and 24.73 kg N ha^{-1} (Table 5.4; Appendix 5.4b), with grain N uptake at 14.63 and 31.96 kg N ha^{-1} respectively (Fig. 5.3; Table 5.3; Appendix 5.4a).

5.1.2 Kroonstad

5.1.2.1 1997

The decreases in N concentration of leaves and tillers followed a similar pattern as at Bethlehem, with N application increasing N concentrations in leaves and tillers (Fig. 5.4; Appendix 5.6). Leaf N concentration decreased from 3.68% (N_{0N}) and 4.01% (N_{rec}) at Z30 to 0.61% and 0.58% respectively at senescence. Nitrogen concentration of tillers decreased from 2.25% (N_{0N}) and 2.57% (N_{rec}) during tillering to 0.48% and 0.46% respectively at maturity.

Tiller and leaf N uptakes declined during and after the grain filling stage, with no significant differences in tiller, leaf and ear N uptake at Z77. At this time 74.5% (N_{0N}) and 70.1% (N_{rec}) of total N uptake was found in the ears (Fig. 5.4). At maturity no differences were measured in tiller or grain N uptake, but the N_{rec} treatment showed higher total N uptake values in comparison to the N_{0N} treatment (Fig. 5.2; Table 5.5).

5.1.2.2 1998

Leaf N concentration decreased from 3.77% (N_{0N}) and 5.22% (N_{rec}) at Z30 to 3.25% and 3.06% respectively during Z70-80 (Fig. 5.4; Appendix 5.7). Nitrogen concentration of tillers decreased from 2.89% (N_{0N}) and 4.16% (N_{rec}) at Z30 to 0.315% and 0.415% respectively at maturity.

Measurements at Z24 - 36 showed increased tiller, leaf, and total N uptake for the N_{rec} treatment compared to N_{0N} (Fig. 5.3; Appendix 5.7). At maturity, tiller and ear N uptake differed significantly, with N_{rec} having higher values. Total N uptake was 31.02 at N_{rec} and 21.09 kg N ha^{-1} at N_{0N} respectively, with 19.27 and 14.42 kg N ha^{-1} being measured in the grain.

Measured N concentrations at Kroonstad were higher in 1997 than in 1998, also ending with higher tiller N and grain N values. Nitrogen application significantly increased N concentrations during the early part of the growing season in both years, but this response decreased to non-significance at maturity. Grain N percentage was lower in 1998 than in 1997.

5.1.3 Petrusburg

5.1.3.1 1997

Nitrogen application increased N concentration of leaves and tillers compared to N_{0N} (Fig. 5.5; Appendix 5.8). Leaf N concentration decreased during the growing season from 2.92% (N_{0N}) and 3.36% (N_{rec}) at Z30 to 0.84% and 0.67% respectively at senescence. Similarly, tiller N concentration decreased from 1.78% (N_{0N}) and 2.17% (N_{rec}) to 0.30% and 0.37% respectively at maturity. Nitrogen concentration of the ears increased initially, then levelled-out during grain filling, with values for the N_{0N} and N_{rec}

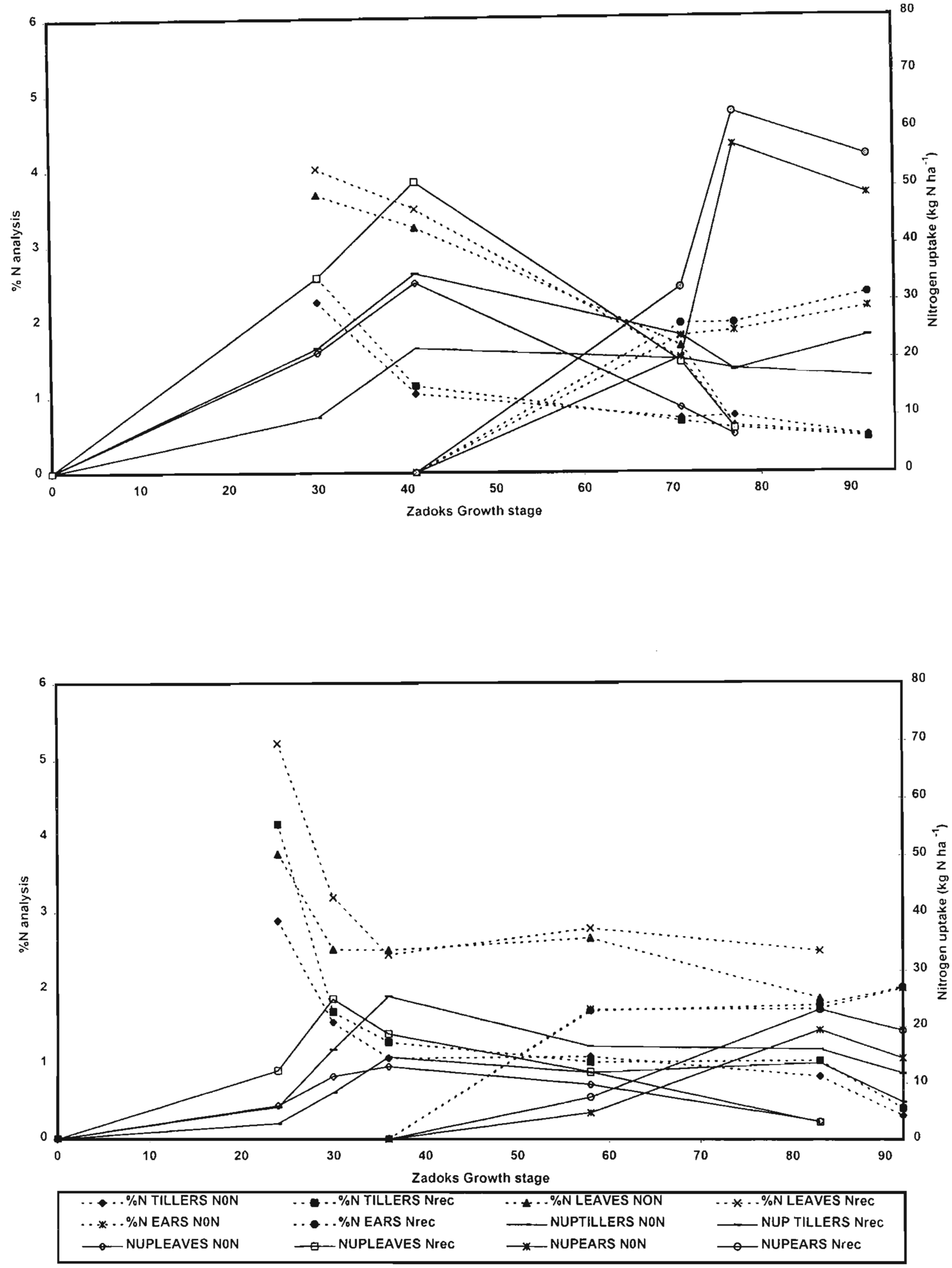

Figure 5.4 Nitrogen concentration (%N) and uptake of tillers, leaves, and ears at Kroonstad for the N treatments (N_{0N} and N_{rec}) for 1997 and 1998

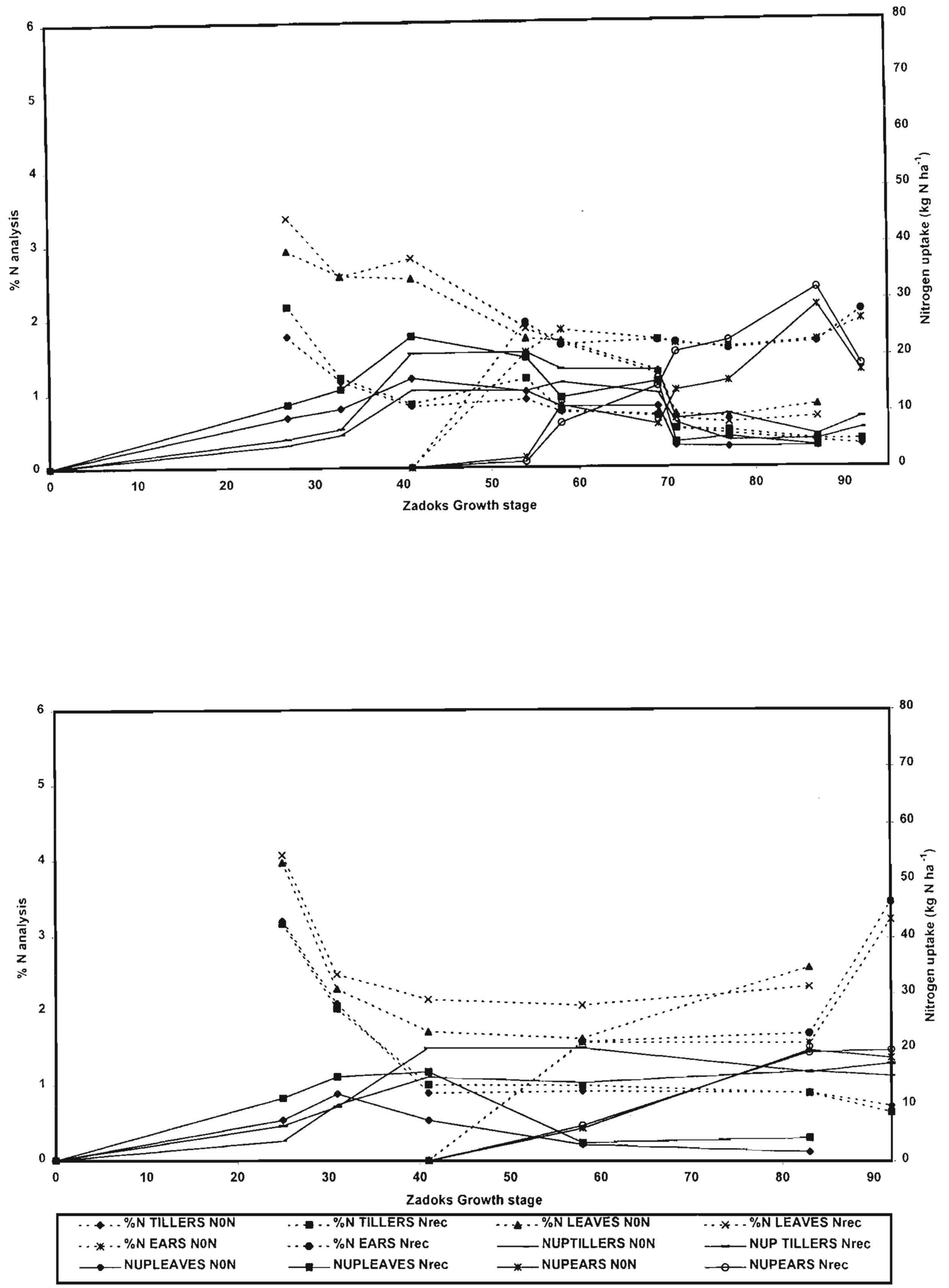

Figure 5.5 Nitrogen concentration (%N) and uptake of tillers, leaves, and ears at Petrusburg for the N treatments (N_{0N} and N_{rec}) for 1997 and 1998

treatments at maturity not significantly different. Grain protein percentage of N_{rec} was significantly higher than the N_{0N} treatment (Table 5.2).

5.1.3.2 1998

Nitrogen application increased N concentration in leaves and tillers compared to N_{0N} (Fig. 5.5; Appendix 5.9). Leaf N concentration decreased from 3.98% (N_{0N}) and 4.08% (N_{rec}) at Z25 to 1.63% and 2.08% respectively at Z60, but this was followed by an increase in values up to late grain filling. Nitrogen concentration of tillers decreased from 3.21% (N_{0N}) and 3.17% (N_{rec}) to 0.740% and 0.655% respectively at maturity. Values for tiller and leaf N concentrations at both treatments were higher than in 1997. Nitrogen concentration of the ears increased during grain filling to maturity, when values for N_{0N} and N_{rec} were not significantly different. This was as a result of enhanced uptake of N following rainfall during this period.

In 1997 at Petrusburg, no significant increases in N concentrations were measured during the early part of the season, but the N_{rec} treatment ended with a significantly higher tiller, leaf, and grain N concentration at maturity. During 1998, N concentration were of the crop residue were higher at maturity. Total N uptake at maturity (Fig. 5.3) showed no significant differences, with values of 33.67 (N_{0N}) and 37.18 kg N ha^{-1} (N_{rec}), and with 18.44 and 19.80 kg N ha^{-1} respectively being measured in the grain (Table 5.3).

5.2 Combined analysis

5.2.1 Tiller N concentration

The combined analysis of variance for N concentration of residue (tillers) at harvest for the three localities over the two year period is presented in Appendix 5.2 and Table 5.1. The N concentration in 1998 (0.51%) was significantly higher than in 1997 (0.41%) averaged over localities and N treatments. Of the locality main effects, Petrusburg showed on average the highest N concentration (0.52%), followed by Bethlehem (0.44%) and Kroonstad (0.42%).

The N_{rec} treatment resulted in a significantly higher N concentration of 0.49% in comparison to N_{0N} at 0.43%. The interaction Year X locality showed that at Bethlehem a non-significant higher N concentration was measured than at Kroonstad. At Petrusburg, a significantly higher N concentration was measured in 1998.

5.2.2 Protein percentage of the grain

The combined analysis of variance for grain protein percentage for the three localities over the two cropping years is presented in Table 5.2 and Appendix 5.3. From the Anova the Year main effect, Year X N treatment, Year X locality X N treatment interactions were not significant. The locality main effect showed that Petrusburg had the highest grain protein percentage (12.41%), followed by Kroonstad

Table 5.6 Calculated functions explaining variation in protein percentage of the grain measured in 1997 and 1998 at Bethlehem, Kroonstad, and Petrusburg (standard errors of coefficients in italics)

Intercept	In-season rainfall (mm)	Soil water content (mm)	Fertilizer (kg N ha^{-1})	Mineral soil N (kg N ha^{-1})	Yield (t ha^{-1})	R^2	F-value
13.0303 *(0.703)*	- 0.0047 *(0.0021)*					0.34	5.16 *
10.895 *(1.143)*	- 0.00914 *(0.00268)*	0.01289 *(0.00588)*				0.57	5.96 **
10.976 *(0.553)*	- 0.01093 *(0.00134)*	0.01191 *(0.00285)*	0.05601 *(0.01015)*			0.91	27.13 **
11.925 *(0.508)*	- 0.01040 *(0.00097)*	0.01173 *(0.00203)*	0.05714 *(0.00724)*	- 0.00516 *(0.0020)*		0.96	42.33 **
12.657 *(0.447)*	- 0.0092 *(0.00082)*	0.01003 *(0.00156)*	0.04379 *(0.00703)*	- 0.01426 *(0.00349)*	0.9479 *(0.3396)*	0.98	68.24 **

Example of calculated function: Soil mineral N- 200 kg N ha^{-1}, Fertilizer- 25 kg N ha^{-1}, Soil water content- 225mm, In–season rainfall- 200mm.

$y = 12.657 - 0.0092(200) + 0.01003(225) + 0.04379(25) - 0.01426(200) + 0.9479(1.4)$

$y = 12.644\%$

Table 5.7 Calculated functions explaining variation in protein content of the grain (%) measured in 1997 and 1998 at Bethlehem, Kroonstad, and Petrusburg (standard errors of coefficients in italics): Division of measured parameters

Intercept	In-season rainfall (mm) (flagleaf-harvest)	In-season rainfall (mm) (planting-flagleaf)	Fertilizer (kg N ha^{-1})	Mineral soil N (kg N ha^{-1}) (0-600mm)	Mineral soil N (kg N ha^{-1}) (600-1200mm)	Soil water content (mm) (0-600mm)	Soil water content (mm) (600-1200mm)	Yield (t ha^{-1})	R^2	F-value
12.95	-0.0062								0.30	4.25ns
(0.729)	*(0.0030)*									
13.03	-0.00469	-0.00471							0.34	2.32ns
(0.752)	*(0.0037)*	*(0.0062)*								
12.88	-0.0056	-0.00975	0.0611						0.73	7.23*
(0.512)	*(0.0025)*	*(0.0045)*	*(0.0179)*							
14.93	-0.0094	0.0032	0.064	-0.0203					0.77	5.82*
(1.97)	*(0.0043)*	*(0.013)*	*(0.017)*	*(0.0188)*						
19.74	-0.0183	0.0249	0.0553	-0.0305	-0.0411				0.86	7.43*
(2.92)	*(0.0058)*	*(0.015)*	*(0.0156)*	*(0.0165)*	*(0.0206)*					
15.78	-0.0164	0.0089	0.0574	-0.0271	–0.0228	0.0240			0.97	62.8**
(1.137)	*(0.002)*	*(0.0056)*	*(0.0052)*	*(0.0056)*	*(0.0074)*	*(0.0035)*				
15.90	-0.0164	0.0092	0.0572	-0.0276	-0.0238	0.0262	-0.0019		0.98	43.07**
(2.46)	*(0.0022)*	*(0.0076)*	*(0.0066)*	*(0.0113)*	*(0.0193)*	*(0.0400)*	*(0.0324)*			
23.02	-0.03343	0.04883	0.07116	-0.02817	-0.05536	0.01915	-0.00028	-2.589	0.99	59.32**
(4.406)	*(0.0096)*	*(0.0228)*	*(0.00935)*	*(0.0091)*	*(0.0233)*	*(0.0322)*	*(0.0259)*	*(1.436)*		

Example of calculated function: In–season rainfall (planting-flag leaf)- 100mm, In-season rainfall (flag leaf-harvest)- 100mm, Soil mineral N (0-600mm)- 100 kg N ha^{-1}, Soil mineral N (600-1200mm)- 100 kg N ha^{-1}, Fertilizer- 25 kg N ha^{-1}, Soil water content (0-600mm)- 125mm, Soil water content (600-1200mm)- 125mm, Yield- 1.4 ton ha^{-1}.

$y = 23.02 - 0.03343(100) + 0.04883(100) + 0.07116(25) - 0.02817(100) - 0.05536(100) + 0.01915(125) - 0.00028(125) - 2.589(1.4)$ $y = 16.72\%$

(12.16%) and Bethlehem (10.38%). The N_{rec} treatment also significantly increased grain protein percentage (12.34%) compared to N_{0N} (10.97%) averaged over years and localities. The interaction N treatment X locality showed that N_{rec} significantly increased grain protein percentage at all three localities. However, values for N_{0N} at Bethlehem were lower than at Kroonstad, with Petrusburg showing higher but non-significant values, the pattern following the inverse of the yield trend.

Grain protein percentages over the two growing seasons at the different localities were fitted by least-squares methods to identify the source of variation in the range of measured values. Analogue to fitted yield calculations, soil mineral N and soil water contents (0-1200 mm) at planting, N treatments, and in-season rainfall were included in the final analysis (Table 5.6).

The significance of calculated functions increased with additional variables included. In-season rainfall and soil water content at planting explained 57% of the change in grain protein, with the value increasing to 91% with the inclusion of the fertilizer treatments (Table 5.6). Inclusion of soil mineral N content at planting added another 5%, and measured yields improved the explanation to 98%. This indicates the major effect of soil water availability on yields and thereby grain N dilution (Smika & Greb, 1973), and also the positive effect of N fertilizer additions on grain protein percentage. The negative relation between yield level and grain protein percentage under N limiting conditions however, can be a contributing factor in rainfed wheat production, although it was not a major influence in this case.

Soil mineral N and soil water content at planting (divided into 0-600 mm and 600-1200 mm soil layers), and in-season rainfall (divided into planting-flag leaf and flag leaf-harvest periods), were included in the grain protein analysis (Table 5.7). In-season rainfall (both divisions) explained 34% of the variation in measured values, with the inclusion of fertilizer increasing this value to 73.1%. Soil mineral N content (0-600 and 600-1200 mm) added another 13%, and soil water content a further 12.6%. As with the previous analysis, measured yields explained just 0.7% of the variation in grain protein percentage.

5.2.3 Nitrogen uptake

From the combined analysis of variance for N uptake (kg N ha^{-1}) in harvested grain, the Year, locality, Year X locality, N treatment, and locality X N treatment main and interaction effects were significant (Appendix 5.4a, Table 5.3). Overall, significantly lower N was accumulated in the grain during 1998 compared to 1997. Kroonstad showed the highest value of 34.48 kg ha^{-1} followed by Bethlehem, with Petrusburg significantly lower on 17.91 kg ha^{-1}. This was also evident in the Year X locality interaction, where Kroonstad had the highest value in 1997, followed by Bethlehem, and with Petrusburg significantly lower. Grain N uptake decreased significantly at Bethlehem and Kroonstad in 1998, but increased slightly at Petrusburg. The application of N (N_{rec}) significantly increased mean grain N uptake

Table 5.8 Calculated functions explaining variation in N uptake (kg N ha^{-1}) at harvest in 1997 and 1998 at Bethlehem, Kroonstad, and Petrusburg (standard errors of coefficients in italics)

Intercept	Yield ton ha^{-1}	Mineral soil N (kg N ha^{-1})	Fertilizer (kg N ha^{-1})	Soil water content (mm)	In-season rainfall (mm)	R^2	F-value
2.6097 *(5.1442)*	30.232 *(3.262)*					0.90	85.90 **
2.7916 *(3.677)*	27.0285 *(2.5306)*	0.3489 *(0.1073)*				0.95	89.38 **
5.2791 *(4.3264)*	27.0307 *(2.5107)*	0.3963 *(0.1153)*	- 0.01062 *(0.0099)*			0.96	60.92 **
12.1889 *(5.767)*	36.095 *(5.985)*	0.2681 *(0.1308)*	- 0.00297 *(0.0102)*	- 0.1.13 *(0.0618)*		0.97	55.98 **
2.555 *(7.464)*	32.335 *(5.674)*	0.3121 *(0.1175)*	- 0.0212 *(0.0137)*	- 0.0639 *(0.0583)*	0.0458 *(0.0261)*	0.98	58.73 **

Example of calculated function: Soil mineral N- 200 kg N ha^{-1}, Fertilizer- 25 kg N ha^{-1}, Soil water content- 225mm, In–season rainfall- 200mm. y =

2.555 + 32.335 (1.4) + 0.3121 (200) - 0.0212 (25) - 0.0639 (225) +0.0458 (200)

y = 104.496 kg N ha^{-1}

Table 5.9 Calculated functions explaining variation in N uptake at harvest (kg N ha^{-1}) in 1997 and 1998 at Bethlehem, Kroonstad, and Petrusburg (standard errors of coefficients in italics): Division of measured parameters

Intercept	Yield (t ha^{-1})	Mineral soil N (kg N ha^{-1}) (0-600mm)	In-season rainfall (mm) (planting-flagleaf)	Mineral soil N (kg N ha^{-1}) (600-1200mm)	Fertilizer (kg N ha^{-1})	Soil water content (mm) (0-600mm)	Soil water content (mm) (600-1200mm)	In-season rainfall (mm) (flagleaf-harvest)	R^2	F-value
2.6097	30.232								0.90	85.90 **
(5.1442)	*(3.262)*									
7.7366	37.693	-0.1338							0.91	44.36**
(6.933)	*(7.5658)*	*(0.1227)*								
11.9652	39.1312	-0.2183	0.0441						0.91	28.43**
(8.9711)	*(7.965)*	*(0.1667)*	*(0.0572)*							
17.457	42.159	-0.1893	0.0393	-0.1520					0.92	22.34**
(10.090)	*(8.287)*	*(0.1661)*	*(0.0565)*	*(0.1352)*						
9.643	35.643	-0.1364	0.00206	-0.0359	0.3327				0.97	33.58**
(8.101)	*(6.668)*	*(0.1253)*	*(0.0445)*	*(0.1103)*	*(0.1292)*					
-5.912	35.915	-0.1437	-0.0558	0.0289	0.3386	0.1249			0.98	40.87**
(10.593)	*(5.5609)*	*(0.1045)*	*(0.0479)*	*(0.09804)*	*(0.178)*	*(0.0655)*				
-24.782	35.364	-0.0523	-0.0892	0.1905	0.3700	-0.2617	0.3136		0.98	29.97**
(37.894)	*(6.107)*	*(0.208)*	*(0.082)*	*(0.327)*	*(0.131)*	*(0.743)*	*(0.600)*			
132.731	-18.968	-0.0978	0.7789	-0.5235	0.6564	-0.3747	0.3155	-0.3703	0.99	64.08**
(65.786)	*(21.437)*	*(0.135)*	*(0.3409)*	*(0.3478)*	*(0.140)*	*(0.481)*	*(0.387)*	*(0.144)*		

Example of calculated function: In–season rainfall (planting-flag leaf)- 100mm, In–season rainfall (flag leaf-harvest)- 100mm, Soil mineral N (0-600mm)- 100 kg N ha^{-1}, Soil mineral N(600-1200mm)- 100 kg N ha^{-1}, Fertilizer- 25 kg N ha^{-1}, Soil water content (0-600mm)- 125mm, Soil water content (600-1200mm)- 125mm, Yield- 1.4 t ha^{-1}.

y = 132.731 -18.968(1.4) -0.0978(100) 0.7789(100) -0.5235(100) 0.6564(25) -0.3747(125) 0.3155(125) -0.3703(100) y = 93.91 kg N ha^{-1}

compared to the N_{0N} treatment. This effect was significant at Bethlehem and Kroonstad, with only an insignificant increase between the N treatments measured at Petrusburg.

A similar trend as found with grain N uptake was found in N uptake into residue at harvest. Overall, a significantly lower N uptake in the residue was measured in 1998 compared to 1997 (Table 5.4; Appendix 5.4b). Averaged over years and N treatments Bethlehem had the highest value, followed by Kroonstad and Petrusburg. The N_{rec} treatment significantly increased N uptake in residue. The Year X locality interaction showed that N uptake decreased significantly during 1998 at Bethlehem and Kroonstad, but increased at Petrusburg. The locality X N treatment interaction showed smaller significant increases at Bethlehem and Kroonstad, but insignificant changes in N uptake at Petrusburg.

The combined analysis of total N uptake by the crop at harvest is shown in Appendix 5.4c. Overall, lower values for total N uptake (Table 5.5) was measured in 1998 than 1997. Bethlehem showed the highest total N uptake, followed by Kroonstad and Petrusburg. Application of N increased total N uptake significantly from 38.15 kg ha^{-1} to 52.82 kg ha^{-1}. The N uptake values for Bethlehem and Kroonstad at the N_{0N} treatment did not differ significantly, but was higher than at Petrusburg.

Results of total N uptake at harvest at the three localities over the two cropping years were fitted by least-squares methods to identify the relative contribution of different variables to the range in values. Yields, N treatments, total in-season rainfall, soil mineral N and soil water contents at planting (0-1200mm) were included in the final analysis (Table 5.8).

Total in-season rainfall divided into the planting - flag leaf and flag leaf - harvest periods, and total soil mineral N and soil water content divided into the 0-600 mm and 600-1200 mm soil layers were also included in the analysis (Table 5.9). Yield, soil mineral N (0-600 mm), rainfall (planting - flag leaf), and soil mineral N (600-1200 mm) explained 92.7% of the variation in N uptake. Adding fertilizer N added another 3.9%, with soil water content and rainfall (flag leaf - harvest) only adding another 2.8%.

5.3 NITROGEN CONCENTRATION OF THE ROOTS AND ADDED CROP RESIDUE

The N and C concentrations, and C:N ratios of the above ground crop residue at harvest for the three localities are shown in Table 5.10 The root N concentration from the measurement depths at Petrusburg and Kroonstad showed lower values in 1998 than in 1997 (Appendix 5.10). This is linked to the dilution effect of the greater total root weight in 1998, and to overall lower total N content of biomass. At Bethlehem, comparable root N concentrations were measured. Decreases in root N concentration with an increase in measurement depth were evident at all three localities in both years.

Table 5.10 **Nitrogen analysis, total carbon concentration (Walkey-Black) and C:N ratio of crop residue at harvest in 1997 and 1998 at Bethlehem, Petrusburg, and Kroonstad**

Locality	Year	1997			1998		
		N_{0N}	N_{rec}	se ±	N_{0N}	N_{rec}	se ±
Bethlehem							
%N		0.36	0.49	0.05	0.39	0.54	0.05
C (%)		37.2	36.4	0.79	38.4	41.6	0.75
C:N ratio		102.6	73.9	1.40	98.0	77.0	1.10
Kroonstad							
%N		0.48	0.46	0.05	0.32	0.42	0.05
C (%)		35.9	33.6	0.75	33.1	36.2	0.81
C:N ratio		74.8	73.5	0.80	105.1	87.2	1.10
Petrusburg							
%N		0.30	0.37	0.05	0.74	0.66	0.05
C (%)		32.9	33.5	0.55	31.7	33.8	0.65
C:N ratio		108.7	90.4	1.30	42.8	51.6	0.50

5.4 DISCUSSION

Available N increases plant N accumulation by increasing leaf area and leaf N concentration (Orphanos & Krentos, 1980; Bulman & Smith, 1993), and leaf area duration (Novoa & Loomis, 1981). Nitrogen application significantly increased leaf and tiller N concentration during the early growth stages, in particular at Bethlehem (1997). This was despite the high soil mineral N content (0-1200 mm) at planting. This apparent anomaly can be explained by the relative distribution of soil mineral N in the profile in combination with spatial root development during the growing season, with the close proximity of the banded fertilizer N favoring early growth and N uptake (Chapter 4.2.2).

Typically, the N concentration of leaves and tillers is high during the vegetative stages and decreases rapidly as N is redistributed to reproductive organs from ear emergence to maturity (Osaki *et al.*, 1991; Zhang *et al.*, 2000). This was observed as decreases in measured total biomass, tiller and leaf N contents in 1997 between ear emergence and maturity. The loss in biomass can be ascribed to losses due to leaf fall, translocation to grain, and increased respiration (Greenwood *et al.*, 1987; Herwaarden *et al.*, 1998a). Losses in tiller dry matter (as observed in this study) are commonly observed during anthesis/grain filling. This includes a sizable loss due to respiration, assimilate remobilization to the grain and premature senescence of tillers (Simmons, 1987; Austin *et al.*, 1987).

The N concentration of different plant biomass components decreased as the growing season progressed due to the dilution effect of growth and biomass accumulation on plant N concentration (Jarrell & Beverly, 1981; Olson & Kurtz, 1982; Cox *et al.*, 1985; Ellen, 1990; du Plessis & Agenbach, 1994). At all localities leaf and tiller N concentration decreased during both growing seasons, while ear N concentration and accumulation increased from the early stages of ear development until harvest (Baethgen & Alley (1989a). Ear N concentration generally followed a similar response pattern at all localities, with a slight decrease in N concentration towards maturity at Bethlehem in 1997 (N_{0N}). This was attributed to an extended grain filling period and delayed maturity, resulting in higher yields diluting grain protein. At Petrusburg in 1998 an increase in ear N concentration was measured towards maturity, which is attributed to favorable soil water conditions during grain filling delaying senescence and onset of maturity, and extending soil mineral N uptake.

Doyle & Holford (1993) found a more complete transfer of N from biomass to grain in dry years (on average lower in-season rainfall), than in wetter growing seasons (mean to above-mean rainfall in cropping season). They stated that translocation of N to developing grain is less retarded by relatively dry conditions than uptake into biomass. Thus, there was a relatively greater transfer of N from biomass to grain in dry years (Doyle & Holford, 1993). The same scenario can explain the lower values for grain N concentration in 1998. A relatively wetter part of the growing season occurred during grain filling to maturity resulting in incomplete and lower transfer of N from biomass to grain.

The onset of leaf senescence after anthesis resulted in transport of N to the grain as found by Herwaarden *et al.* (1998b). They also found a trend for reduced remobilization of N from leaves subjected to high temperatures, due to desiccation and sudden death of distal portions of green leaves making those areas of leaf inaccessible to catabolism by the plant. Thus, water stressed crops often have a high final leaf N concentration (Herwaarden *et al.*, 1998b; Clark, 1983). This trend was found in 1998 to some extent at Bethlehem and Kroonstad, with higher leaf N concentrations (>1% N) measured at senescence than in 1997. Tiller N content started contributing N to grain development from flag leaf to anthesis growth stages. At Bethlehem in 1997, tiller N concentration decreased during anthesis, but in 1998, this decline was already evident at the flag leaf stage. At Kroonstad, a similar trend was noticed in 1997 and 1998. At Petrusburg in 1997 and 1998, the decline in tiller N concentration was measured at ear emergence to anthesis growth stages.

The lower grain N concentration found in 1998 at Bethlehem and Kroonstad reflect a reduced supply of available mineral N in the second cropping season, in spite of lowered yields. Tiller and leaf N concentration indicated comparable tissue N concentrations compared to 1997, but this was the result of a reduction in biomass accumulation due to reduced soil water and soil mineral N availability. Therefore, reduced quantities of mineral N was assimilated and stored in the various plant tissues and translocated to developing grain in 1998.

Loss of N from the plant from anthesis to maturity has been found in several studies (Wetselaar & Farquhar, 1980; French & Schultz, 1984; Greenwood *et al.*, 1987), with losses within a range of 21 to 41% in winter wheat (Raun & Johnson, 1999). From calculated response functions (Figs. 5.2 and 5.3) there were marginal differences in N accumulation during the period anthesis to maturity at the three localities. Similar N concentrations were found in the residue at all three localities at maturity.

Low soil water availability during the 1998-growing season at Kroonstad (38 mm or 14% of total rainfall was measured from planting to flag leaf stage), combined with above mean temperatures, accelerated senescence of green tissues hastening the onset of physiological maturity (Chapter 3.4.6.2). Consequently, rainfall occurring late in the growing season did not have a similar positive influence on N accumulation and plant growth. Rainfall during this time probably aided N losses from plants before harvest, through N leaching from tissues and increased leaf fall (Greenwood *et al.*, 1987; Herwaarden *et al.*, 1998a). Kätterer & Andrén (1996) found significant losses through decomposition and consecutive N leaching from tissues of senescing plants under similar climatic circumstances.

Total plant N and grain N contents at maturity also responded positively to applied fertilizer N. The grain dry matter response to N addition often varies according to the growing season (Clark *et al.*, 1990; Bulman & Smith, 1993). Several authors have found that the proportion of grain N derived from post anthesis N uptake is highly related to dry matter accumulation during grain filling, which is in turn related to available soil water (Clark *et al.*, 1990; Bulman & Smith, 1993). Macduff & White (1984) and Echeverria *et al.* (1992) found reduced plant N accumulation of barley at harvest when compared to earlier samplings. They attributed this to a net translocation of N from the shoots to roots, or a loss of N from senescing tissues either through volatilization as NH_3, or leaching by rain of soluble N compounds within the tissues. Bänziger *et al.* (1992) found that total N accumulation in both the whole plant and grains are generally more related to biomass production than to tissue N concentration. In this study, increased biomass accumulation also increased N accumulation although measured N concentrations of the different plant components (leaves, tillers and ears) were comparable over the two growing seasons. The results also indicated that increases in N accumulation, biomass production, and potential yields depended on soil water and N availability.

The continued increase in N accumulation at Bethlehem and Petrusburg in 1998 was mainly the result of favorable soil water conditions during the anthesis - harvest period following significant rainfall (Chapter 3.4.6.1; 3.4.6.3). Nitrogen accumulation increased at Petrusburg by 44.8% for N_{0N} with 41.0% at N_{rec} in comparison to 1997 values, owed partly to increased soil water availability during grain development, resulting from above mean rainfall during this time (192.9 mm from flag leaf to harvest). This increased soil water availability delayed senescence of leaves resulting in a lengthened growing season. The rainfall distribution during the growing season influenced N uptake, with rainfall during the pre-flag leaf period resulting in higher soil water contents, hence increasing N availability and N uptake into biomass. Comparatively, rainfall during the post flag leaf growth stages tended to increase late uptake of soil mineral N, delay plant senescence, and increase grain protein percentage.

The crop also benefited from additional available soil mineral N from previously dry soil layers during this late part of the growing season to increase biomass, N uptake, and grain protein. Asseng *et al.* (1998) found in their studies significant differences in wheat tiller N concentration and accumulation at stem elongation and beginning of grain filling. Higher tiller N concentrations contributed to the delay of leaf senescence and probably improved photosynthetic activity, and these combined effects may have helped to extend the life of the root system (Van Keulen *et al.*, 1989), extending further growth and accumulation of N (Smith & Gooding, 1996).

The decreases in N accumulation values calculated at the N_{rec} treatment are within the range reported by Raun & Johnson (1999). This indicates that when there is a shortage of available N, the plant tends to conserve N. On the other hand, with sufficient N available, N can be lost from the plant (Novoa & Loomis, 1981). Therefore, as growth and biomass accumulation are limited by drought, continued assimilation and translocation of N are limited, and high concentrations of N accumulate in plant tissues (Olson & Kurtz, 1982).

However, there was a marginal decrease in cumulative N accumulation at Bethlehem from November to maturity in December 1997. Nitrogen accumulation measured at Bethlehem for N_{0N} and N_{rec} in 1998 expressed as a percentage of 1997 values, showed a 57.3 and 34.5% lower N accumulation respectively. This decrease in N accumulation was also evident from the lower values for grain protein percentage measured in 1998 at both N treatments. At Kroonstad in 1998 the total N accumulation was 67.8 and 60.8% lower for N_{0N} and N_{rec} respectively in comparison to 1997 values. Higher yields were recorded in 1997, with a resultant higher grain N accumulation, all combining to higher total N values in 1997 than 1998. The grain protein percentage also decreased at both N treatments in 1998. The reduced values in the second season are the combined result of decreased mineral N availability after the previous growing season (Chapter 6.2).

The differences in N uptake between the fertilizer treatments were also partly related to differences in biomass accumulation induced by the treatments, together with a N concentration effect associated with the N application and uptake by the plant (Soon, 1999). In addition, lower soil water availability due to the shortened fallow period, and a different rainfall distribution over the growing season (as discussed in

Chapter 3.4.6.2), lead to reduced growth due to increased water stress heightened by above long-term mean temperatures. This reduced biomass accumulation, and linked to the lowered soil mineral N availability, with smaller amounts of N available for uptake and subsequent translocation to the developing grain, resulted in low grain protein.

Greenwood *et al.* (1987) found that approximately 80% of the total aboveground N content of wheat plants were in the grain irrespective of cultivar or experiment. Wetselaar & Farquhar (1980) reported a range of 65-75% in research carried out on earlier released wheat cultivars. Values of 74.5% (N_{0N}) and 70.1% (N_{rec}) were found in 1997 at Kroonstad, with lower values of 68.4% and 62.1% respectively in 1998. At Bethlehem 62.8% and 60.8% was found at N_{0N} and N_{rec} respectively in 1997, with values of 57.3% and 56.4% in 1998. Likewise at Petrusburg, in 1997 values of 69.6% and 65.3% were measured at N_{0N} and N_{rec} respectively, but only 54.8% and 53.3% in 1998.

Yield results for Bethlehem in 1997 also indicated that although there was sufficient N available to increase growth and produce good yields utilizing the favorable climatic conditions, the N_{0N} treatment failed to produce an acceptable grain protein percentage. There was a significant reduction in grain protein percentage at Bethlehem and Kroonstad in 1998, but with the value at Petrusburg in 1998 significantly higher than in 1997. This high value at Petrusburg is the result of the extended uptake of soil mineral N towards the end of the growing season, resulting in higher total N uptake into the above ground biomass (Table 5.5). This increased the translocation of N to the developing grain, increasing the grain N content and hence protein percentage. Due to the limited sink size (lower yield potential because of lower grain number) the increased source of available N (total biomass N content) could not be completely transferred to the grain, resulting in high N concentrations in the residue (Table 5.4).

The lower grain protein at Bethlehem and Kroonstad are the results of relatively higher yield responses to N application in 1998. At Bethlehem, yield response was 64%, with 32.9% at Kroonstad compared to 1997, with an insignificant response at Petrusburg (Chapter 4.3.4). This resulted in the dilution of grain protein because of the reduced pool of available N (source) in relation to the increased yield (sink).

High hectoliter mass values were recorded in 1997 at Bethlehem, which can be ascribed to the favorable soil water situation during grain filling, favoring translocation of carbohydrates to the developing grain. This continued translocation favored grain yield but diluted the grain protein, especially in the N_{0N} treatment, resulting in low protein values for this treatment. Due to lower yield levels at Kroonstad and Petrusburg in 1998, the dilution effect on grain N content as expressed in lowered grain protein values was minimized.

Plant growth and N accumulation were also influenced by soil water availability and distribution. The N concentration of tillers and leaves were not significantly reduced, but because of lower biomass production, total N accumulation was decreased. The reduced soil mineral N availability especially at N_{0N} is linked to the removal of N by the previous crop, as well as uncompleted residue decomposition during the fallow period. The undecomposed crop residue is a result from erratic rainfall distribution during the fallow period, delaying effective soil cultivation and residue management. The decomposing residue furthermore immobilized available soil mineral N during the continuation of the decomposition process in the growing season reducing availability of soil mineral N (Chapter 6.2). This combination of factors decreased total N accumulation measured at maturity in 1998.

Except at Petrusburg in 1998, C:N ratios of crop residues were characteristically wide (e.g. 73 to 103). Residue at Petrusburg had a relatively narrow C:N ratio in 1998 due to a high N concentration, attributable to increased uptake of N during the period grain filling to senescence, after rainfall events during September and October (Chapter 3.4.6.3). This led to an uncompleted transfer of N to the grain and therefore a high crop residue N concentration. The variation in N concentration of crop residues, while the measured C concentration remained fairly constant caused the variation in C:N ratios measured. The N concentration of crop residue was typically below 1%. Organic materials with such low N concentrations and/or wide C:N ratios will generally result in net immobilization of soil mineral N for a longer period of time, than materials having a high N concentration and a narrower C:N ratio. Organic materials with C:N ratios of 25 or less, and N concentrations of above 1.5% are required for net mineralization to occur quickly (Campbell, 1978; Haynes, 1986b).

Significance of the calculated functions increased the explanation of differences in N uptake with inclusion of more variables (Table 5.8). Yield levels contributed significantly to total N uptake (90% of variation explained), and with the inclusion of soil mineral N and fertilizer N treatments (indicating N availability to the crop), increased this value to 96%. As was the case in the yield analysis, soil water content and total in-season rainfall contributed only 2%, playing a lesser role in explaining variation in total N uptake values in this case.

A slightly higher significance in the analysis of N uptake values were calculated when soil mineral N, soil water content and in-season rainfall were divided into relative depths and growth periods. The only change of interest was that rainfall (planting–flag leaf) increased in relative importance together with yield, soil mineral N content and fertilizer, with the latter factors adding 6.6%. Yield however, was still the major indicator emphasizing the magnitude of N accumulation related to biomass development and potential grain production. In contrast to expectations, the amount of undecomposed residue at planting did not influence N uptake at harvest significantly in this study, and only made a insignificant contribution in the multivariate analysis (0.002%). As discussed in the analysis of yields (Chapter 4.3) where a similar response was found, the impact of undecomposed residue was on soil mineral N availability via immobilization and subsequent mineralization during the growing season, and this parameter in turn contributed significantly to change in N uptake values.

The results over the two growing seasons indicate that in a fallow-wheat-wheat-fallow rotation system, initial growth of the second wheat crop was reduced by low available soil water in the cultivation zone. This in turn reduced subsequent plant and root development, N uptake, accumulation, and yield potential. In addition, the distribution of available soil mineral N also contributed to reduced growth, yield, and grain protein, therefore increased N fertilization was required (Chapter 6.2). Undecomposed residue in the cultivation soil layer at planting also affected the availability of soil mineral N to the growing crop mainly because of soil mineral N immobilization during continued decomposition of these residues. This scenario indicates the increased production risk of this cropping system to the second wheat crop. Soil cultivation and residue management, linked to soil water conservation during the shortened fallow period, affect soil mineral N availability to the crop, and becomes more important. The importance of available soil water (soil water content and rainfall) in rainfed cropping systems however, cannot be overlooked and their combined effect could be significant in other growing seasons with a wider variation in these factors as in the current analysis.

CHAPTER 6 SOIL MINERAL NITROGEN IN THE SOIL PROFILE OVER THE TRIAL PERIOD

Insufficient nitrogen (N) availability for maximum crop production is characteristic of soils all over the world. The problem is often acute in regions where soils typically have low organic matter contents. Any system designed to increase crop production must therefore include additional inputs of N and improved efficiency of N utilization (Broadbent, 1981). Optimal utilization of N in annual crop production requires a balance between the supply of N, both from fertilizer and mineralization of soil organic matter, and crop demand. However, in most cropping environments, availability of N may be out of phase with crop demand (Angus & Moncur, 1985). High efficiency of fertilizer N use by crops should be expected when N availability matches crop needs throughout the growing season. Understanding the N uptake pattern of wheat linked to N availability is therefore important for improving N fertilizer management (Baethgen & Alley, 1989a).

The use of soil mineral N content in humid regions has been reported to be too variable to be a good indicator of N availability to crops (Fox & Piekielek, 1978). Several efforts have been made to develop suitable soil testing procedures aiding optimum N fertilizer rate prediction. Residual soil mineral N and/or mineralizable organic N indices have been used in areas where leaching of NO_3^- from the root zone is minimal (Baethgen & Alley, 1989b). These authors also suggested that a potentially successful approach for assessing wheat N requirement should include plant N tissue testing during different stages of crop growth.

The cycling of N in growing plants and the recovery efficiency of N in the plant-soil system had been a topic of considerable interest over the years. Researchers have found that not all of the soil and fertilizer N measured at planting can be accounted for at the end of a growing season. Research has also suggested that N can be lost from soils in volatile forms as ammonia, dinitrogen, nitric oxide, nitrogen dioxide and nitrous oxide (Haynes, 1986a; Harper *et al.*, 1987). Losses from the plant may also occur and these have been shown to include gaseous NH_3 (Farquhar *et al.*, 1983). In addition to these direct losses of N, applied fertilizer N may also become unavailable to the plant due to microbial immobilization, particularly in management systems with high amounts of organic residue in the upper soil layers (Harper *et al.*, 1987).

Declining soil fertility due to poor crop management is a basic agricultural problem in many developing countries (FAO, 1997). Crop residue management is thus a promising alternative for nutrient cycling in these countries. It is a critical factor not only for increasing crop yields but also in sustaining long-term productivity through the use of renewable sources. Primarily, decomposing crop residue maintains soil fertility by recycling nutrients absorbed by the plant except for amounts translocated to the grain and removed in harvestable products. Furthermore, added residue builds up soil organic matter and water-holding capacity of soils over time (Gebrekidan *et al.*, 1999). These authors also found in their studies that a crop planted in residue of the previous crop without additional N application resulted in decreased yields.

Cultivation can also cause physical losses of residue by decreasing particle size, making it more susceptible to losses by wind, more accessible to microbial decomposition, but less detectable by the method used in measuring the amount of remaining residue in a soil. Addiscott & Dexter (1994); Stemmer *et al.* (1999), and Amstrong *et al.* (1998) stated that after soil cultivation and incorporation of crop residue, microbes responsible for residue decomposition use soil mineral N in the process, and this will lead to a period of immobilization of available soil mineral N. The main factor governing the release of N is the C:N ratio of the added residue. The wider this ratio, the more N is needed by the microbial biomass, and therefore the slower the decomposition rates if available N is limited (Mary *et al.*, 1996). Residue decomposition can be related to the change in soil mineral N content, especially the cultivation zone (0-400 mm) during the fallow period. Immobilization of N can have a positive effect during this time to prevent N losses through leaching, depending on the C:N ratio and chemical composition of the residue, the soil water content/rainfall situation, mineral N available in the cultivation zone, and soil temperature conditions (Schomberg *et al.*, 1996).

Researching N behavior under field conditions necessitates soil sampling at regular intervals throughout the growing season. These soil analysis results will indicate soil mineral N content, plus possible movement and losses of N from the soil by leaching or denitrification. The net accumulation of soil mineral N under field conditions in the absence of plant roots (fallow treatment) is thought to provide a good index of N availability to plants (Bundy & Meisinger, 1994). An accurate assessment of the N supplying capability of a soil requires the estimation of mineral N production under field conditions because of the strong effect of site environmental factors on soil N transformation rates (Binkley & Hart, 1989).

It has long been known that the method of preparation and especially drying can significantly alter residual NH_4^+ and NO_3^- contents of soil samples, and thus total residual mineral soil N. The objectives of soil sample drying and processing are to stop biological activity as soon as possible and to homogenize samples. Soil microbial activity can be stopped either by rapid air drying or low temperature oven drying. (Bundy & Meisinger, 1994). The most frequently observed and pronounced changes reported during air-drying are increases in exchangeable NH_4^+, and losses of NO_3^-. Drying of soil samples usually increases N mineralization on subsequent rewetting and incubation of these soils (Sereviratne & Wild, 1985; Wiltshire & du Preez, 1994).

If measurements of residual soil mineral N are to be used for fertilizer advisory services, analysis of field moist samples for analysis may not be practical (Wiltshire & du Preez, 1994). These authors also found that the estimation of soil mineral N in air-dried samples was not significantly smaller than in field moist samples. Although air-drying of samples takes time, acceptable soil mineral N contents of the respective soil layers were measured using this drying method. Sereviratne & Wild (1985) found that although there was an increase in mineralizable N at a drying temperature of 28°C compared to 18°C, no significant change in residual soil mineral N was measured. The decision to use air-dried samples in this study was further motivated by the practical difficulties in using field-moist samples for routine analysis of soil mineral N, plus the reality of possible delays due to distances of localities from the laboratory.

As discussed in Chapter 3.4.1, soil mineral N content of the different soil layers was measured during the period June 1997 to August 1999, during two growing seasons and subsequent fallow periods at three localities (Bethlehem, Kroonstad, and Petrusburg) at three N treatments (N_{rec}, N_{0N} and fallow). Determining N uptake of a field crop receiving no fertilizer N is accepted as a method of estimating soil mineral N supply in a given soil-climate-crop system because it integrates crop growth and soil N dynamics under natural conditions (Meisinger, 1984). The N_{rec}, N_{0N} and fallow treatments were compared to determine *in situ* soil N dynamics, relating it to plant N uptake (at N_{0N} and N_{rec}) during the measurement period.

6.1 SOIL MINERAL N DISTRIBUTION IN THE PROFILE (0-1200 mm) OF THE THREE LOCALITIES AT PLANTING (1997)

Results of the combined analysis of variance for NH_4^+, NO_3^-, and total mineral N (0-1200 mm) at planting in 1997 are presented in Appendices 6.1a, b and c, and Tables 6.1, 6.2 and 6.3. The distribution of averaged soil mineral N contents (NH_4^+ + NO_3^-) in the soil profile (planting 1997) at the localities differed (Fig. 6.1). Petrusburg had the lowest initial total soil mineral N content, and the deeper soil layers (600-900 and 900-1200 mm) at Bethlehem showed higher N contents, although Bethlehem and Kroonstad had similar N contents in the 400-1200 mm soil layers.

From the combined analysis for NH_4^+, NO_3^-, and total soil mineral N for the three localities at specific sampling points (planting 1997, harvest 1997, planting 1998, harvest 1998, end of fallow 1999), the main effects and interactions were significantly different. Bethlehem showed the highest values, followed by Kroonstad with Petrusburg significantly lower.

Table 6.1 NH_4^+ content (kg ha^{-1}; 0-1200mm) at three localities (Bethlehem, Kroonstad, and Petrusburg) for three treatments (fallow, N_{0N} and N_{rec}) in 1997-1999

Locality	N Treatment	Time of sampling					Locality/ N treatment mean
		Planting 1997	Harvest 1997	Planting 1998	Harvest 1998	End 1999	
Bethlehem	N_{0N}	205.21	153.68	124.12	87.00	74.15	128.83
	N_{rec}	166.54	114.57	76.78	112.20	70.66	108.15
	Fallow	207.53	190.92	90.70	103.00	67.52	131.93
Locality/sampling mean		193.09	153.06	97.20	100.73	70.78	122.97
Kroonstad	N_{0N}	181.00	134.50	61.95	63.85	41.88	96.64
	N_{rec}	168.76	101.99	62.49	84.45	48.30	93.20
	Fallow	183.63	142.59	63.07	105.34	66.87	112.30
Locality/sampling mean		177.79	126.36	62.58	84.55	52.35	100.71
Petrusburg	N_{0N}	144.65	47.55	102.55	58.16	23.04	75.19
	N_{rec}	160.41	23.25	96.72	81.01	31.51	78.58
	Fallow	141.65	74.19	118.20	94.35	65.59	98.80
Locality/sampling mean		148.90	48.33	105.82	77.84	40.05	84.19

N treatment and time of sampling response in NH_4^+ content

N Treatment	Time of sampling					N treatment mean
	Planting 1997	Harvest 1997	Planting 1998	Harvest 1998	End 1999	
N_{0N}	176.95	111.91	96.21	69.67	46.36	100.22
N_{rec}	165.24	79.94	78.66	92.55	50.16	93.31
Fallow	177.60	135.90	90.66	100.90	66.60	114.33
N treatment/sampling mean	173.26	109.25	88.51	87.71	54.37	102.62

LSD (P0.05) for time of sampling : 3.90
LSD (P0.05) for locality : 3.02
LSD (P0.05) for N treatment : 3.61
LSD (P0.05) for time of sampling x locality : 6.75
LSD (P0.05) for time of sampling X N treatment : 7.66
LSD (P0.05) for N treatment x locality : 5.93
LSD (P0.05) for time of sampling x locality x N treatment : 13.27

Table 6.2 NO_3^- content (kg ha^{-1}; 0-1200mm) at three localities (Bethlehem, Kroonstad, and Petrusburg) for three treatments (fallow, N_{0N} and N_{rec}) in 1997-1999

Locality	**Treatment**	**Time of sampling**					**Locality/ N treatment mean**
		Planting 1997	**Harvest 1997**	**Planting 1998**	**Harvest 1998**	**End 1999**	
Bethlehem	N_{0N}	116.01	7.02	92.80	4.49	84.65	60.99
	N_{rec}	98.21	9.04	121.85	23.86	122.46	75.08
	Fallow	114.47	26.04	83.40	43.70	101.23	73.77
Locality/sampling mean		109.56	14.03	99.35	24.01	102.78	69.95
Kroonstad	N_{0N}	87.25	23.04	64.62	27.31	54.34	51.31
	N_{rec}	91.84	15.63	74.44	38.53	95.37	63.16
	Fallow	86.12	131.89	90.37	45.11	66.03	83.90
Locality/sampling mean		88.40	56.85	76.48	36.98	71.91	66.12
Petrusburg	N_{0N}	39.08	2.83	22.12	17.68	51.15	26.57
	N_{rec}	35.52	1.33	27.51	28.80	57.06	30.04
	Fallow	43.05	21.40	37.69	51.92	77.76	46.36
Locality/sampling mean		39.22	8.52	29.11	32.80	61.99	34.33

N treatment and time of sampling response in NO_3^- content

Treatment	**Time of sampling**					**N treatment**
	Planting 1997	**Harvest 1997**	**Planting 1998**	**Harvest 1998**	**End 1999**	**mean**
N_{0N}	80.78	10.96	59.85	16.49	63.38	46.29
N_{rec}	75.19	8.67	74.60	30.39	91.63	56.10
Fallow	81.21	59.78	70.89	46.91	81.67	68.09
N treatment/sampling mean	79.06	26.47	68.45	31.27	78.89	56.83

LSD (P0.05) for time of sampling	:	5.52
LSD (P0.05) for locality	:	4.27
LSD (P0.05) for N treatment	:	3.36
LSD (P0.05) for time of sampling x locality	:	9.56
LSD (P0.05) for time of sampling X N treatment	:	8.25
LSD (P0.05) for N treatment x locality	:	6.39
LSD (P0.05) for time of sampling x locality x N treatment	:	14.29

Table 6.3 Total mineral N content (kg ha^{-1}; 0-1200mm) at three localities (Bethlehem, Kroonstad, and Petrusburg) for three treatments (fallow, N_{0N} and N_{rec}) in 1997-1999

Locality	Treatment	Time of sampling					Locality/ N treatment mean
		Planting 1997	Harvest 1997	Planting 1998	Harvest 1998	End 1999	
Bethlehem	N_{0N}	321.0	160.7	216.90	91.5	158.8	189.78
	N_{rec}	261.9	123.6	198.58	136.0	193.1	182.64
	Fallow	322.0	217.0	173.40	146.7	168.8	205.58
Locality/sampling mean		301.6	167.1	196.29	124.73	173.58	192.66
Kroonstad	N_{0N}	256.5	157.54	126.6	91.20	96.2	145.61
	N_{rec}	271.2	117.62	136.9	122.98	143.7	158.48
	Fallow	274.4	274.48	153.4	150.45	132.9	197.13
Locality/sampling mean		267.4	183.21	138.97	121.54	124.27	167.08
Petrusburg	N_{0N}	183.8	50.4	124.7	75.8	74.19	101.78
	N_{rec}	192.6	24.6	124.3	109.8	88.57	107.98
	Fallow	184.7	95.6	155.9	146.3	143.35	145.17
Locality/sampling mean		187.0	56.87	134.9	110.64	102.04	118.29

N treatment and time of sampling response in total N content

Treatment	Time of sampling					N treatment mean
	Planting 1997	Harvest 1997	Planting 1998	Harvest 1998	End 1999	
N_{0N}	253.8	122.88	156.1	86.17	109.73	145.73
N_{rec}	241.9	88.61	157.0	122.90	141.80	150.45
Fallow	260.4	153.26	206.3	147.82	148.36	183.23
N treatment mean	252.0	121.58	173.12	136.80	133.30	159.79

LSD (P0.05) for time of sampling	:	7.66
LSD (P0.05) for locality	:	5.92
LSD (P0.05) for N treatment	:	5.05
LSD (P0.05) for time of sampling x locality	:	13.24
LSD (P0.05) for time of sampling X N treatment	:	11.98
LSD (P0.05) for N treatment x locality	:	9.29
LSD (P0.05) for time of sampling x locality x N treatment	:	20.76

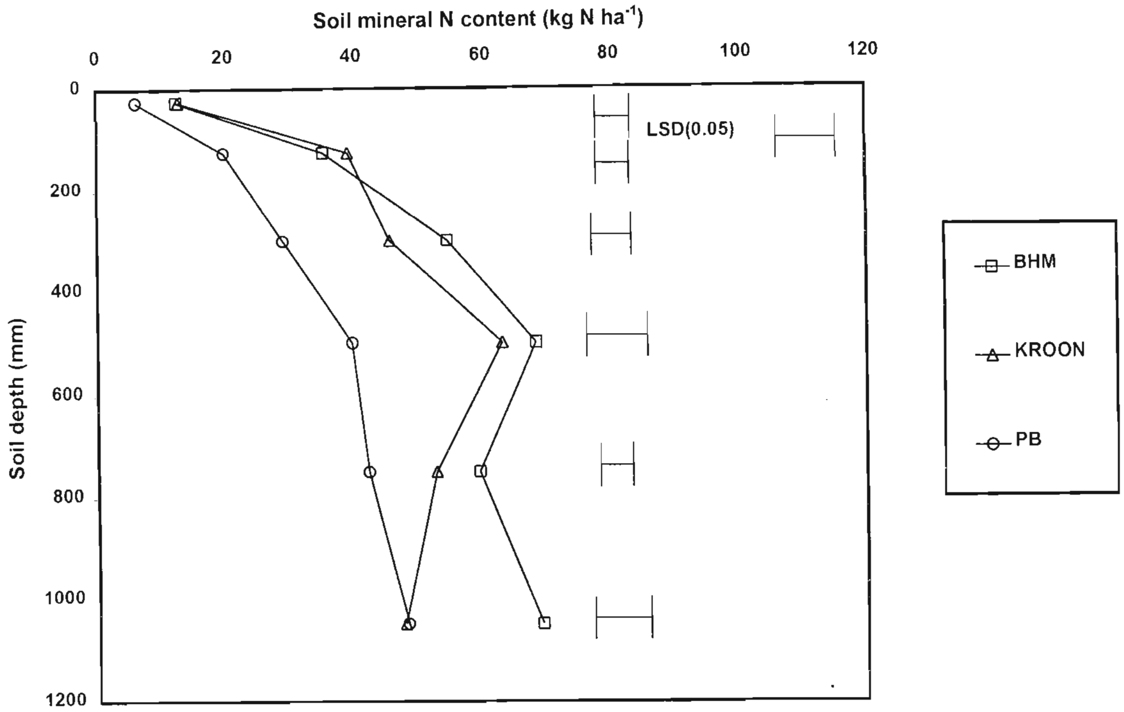

Figure 6.1 Distribution of soil mineral N content (kg N ha^{-1}) at Bethlehem (BHM), Kroonstad (KROON), and Petrusburg (PB) at planting in 1997

The fallow treatment had the highest values averaged over localities and sampling periods. Total soil mineral N, NO_3^- and NH_4^+ contents decreased from planting to harvest in 1997 at all localities and N treatments. Soil mineral N content increased during the fallow period in 1997/98 up to planting in 1998, likely due to increased NO_3^- content with a decrease in NH_4^+ resulting from nitrification (Haynes, 1986c). The total mineral N content at Bethlehem was marginally lower for the fallow treatment. At Kroonstad the N_{rec} showed increased values, with a decrease at N_{0N} that can be ascribed to immobilization of available N during residue decomposition. A large decrease was measured at the fallow treatment, which indicate losses of N during the fallow period, related to the amount of rainfall received during this period. At Petrusburg, all the treatments showed increased values during this period, mainly because of lower residue additions resulting in shorter and lower levels of immobilization of mineral N, and more remineralization during the fallow period.

Values for soil mineral N contents were generally lower at planting in 1998 compared to 1997. Similar decreasing responses in measured N values were measured at harvest in 1998. Total soil mineral N and NO_3^- generally increased during the fallow period in 1999, but with decreased NH_4^+ values. This indicate that because of the generally mean rainfall measured during this period at Bethlehem and Petrusburg, and lower rainfall at Kroonstad residue decomposition, mineralization and nitrification continued during this period.

6.2 TOTAL MINERAL N, NH_4^+, AND NO_3^- (0-1200 mm) FROM PLANTING (1997) TO END OF FALLOW PERIOD (1999)

6.2.1 Bethlehem

The NH_4^+, NO_3^-, and total mineral N contents (0-1200 mm) measured during the trial period showed several distinct responses (Fig. 6.2a). There was a decrease in NH_4^+ content at all three treatments during July to November. This decrease at N_{rec} and N_{0N} coincided with uptake of available soil mineral N by the growing crop (Fig. 6.2c). Available NH_4^+ was nitrified to NO_3^- subsequently taken up by the crop, hence the decrease in measured NO_3^- values (Fig.6.2b).

Although plant uptake accounted for a major part of the decline in measured mineral N content, the total difference could not be ascribed to plant uptake alone. With the similar decrease in mineral N content at the fallow in mind, immobilization via microbial action in response to increased soil temperatures may be another factor. Similarly the NO_3^- content at the fallow treatment increased during October to November. This increase could also be linked to warmer soil and air temperatures and rainfall during this period (Chapter 3.4.6.1), resulting in enhanced N mineralization and subsequent nitrification via an increase in microbial activity in response to increased temperatures. However, the NO_3^- content of the N_{rec} treatment showed higher levels during July to October, which was due to applied fertilizer N at planting.

In response to rainfall favouring soil water content together with higher soil temperatures during December (at physiological maturity), increases in NH_4^+ and total mineral N were measured due to mineralization, with the higher measured response at the fallow treatment. However, NO_3^- content remained at similar levels. The soil mineral N content (0-1200 mm) of the fallow treatment at harvest decreased to a total mineral N level of 217 kg N ha^{-1} (Table 6.3, Appendix 6.1), which was significantly higher than at the other two treatments. Furthermore, N_{0N} had a significantly higher value (160.7 kg N ha^{-1}) than the N_{rec} treatment (123.6 kg N ha^{-1}).

Because of higher yield levels at Bethlehem in 1997, 6194 and 6956.2 kg ha^{-1} of crop residue at harvest was added to the cultivation zone at the N_{0N} and N_{rec} treatments respectively. Residue remaining in the cultivation zone at harvest 1998 was 499 kg ha^{-1} for both treatments. Following disc cultivations during January a small response in NO_3^- was measured due to nitrification of available NH_4^+ and the initial mixing of crop residue into the cultivation zone. Ploughing of the site at the beginning of March was followed by an increase in NH_4^+ during April to May. This again was followed by a decrease in NH_4^+ contents during May to July, with an accompanying increase in NO_3^-, especially at the N_{rec} and N_{0N} treatments.

Mineralization and nitrification occurred earlier at the fallow treatment compared to the other treatments, mainly because of the delaying immobilization effect of the added crop residue in the other treatments.

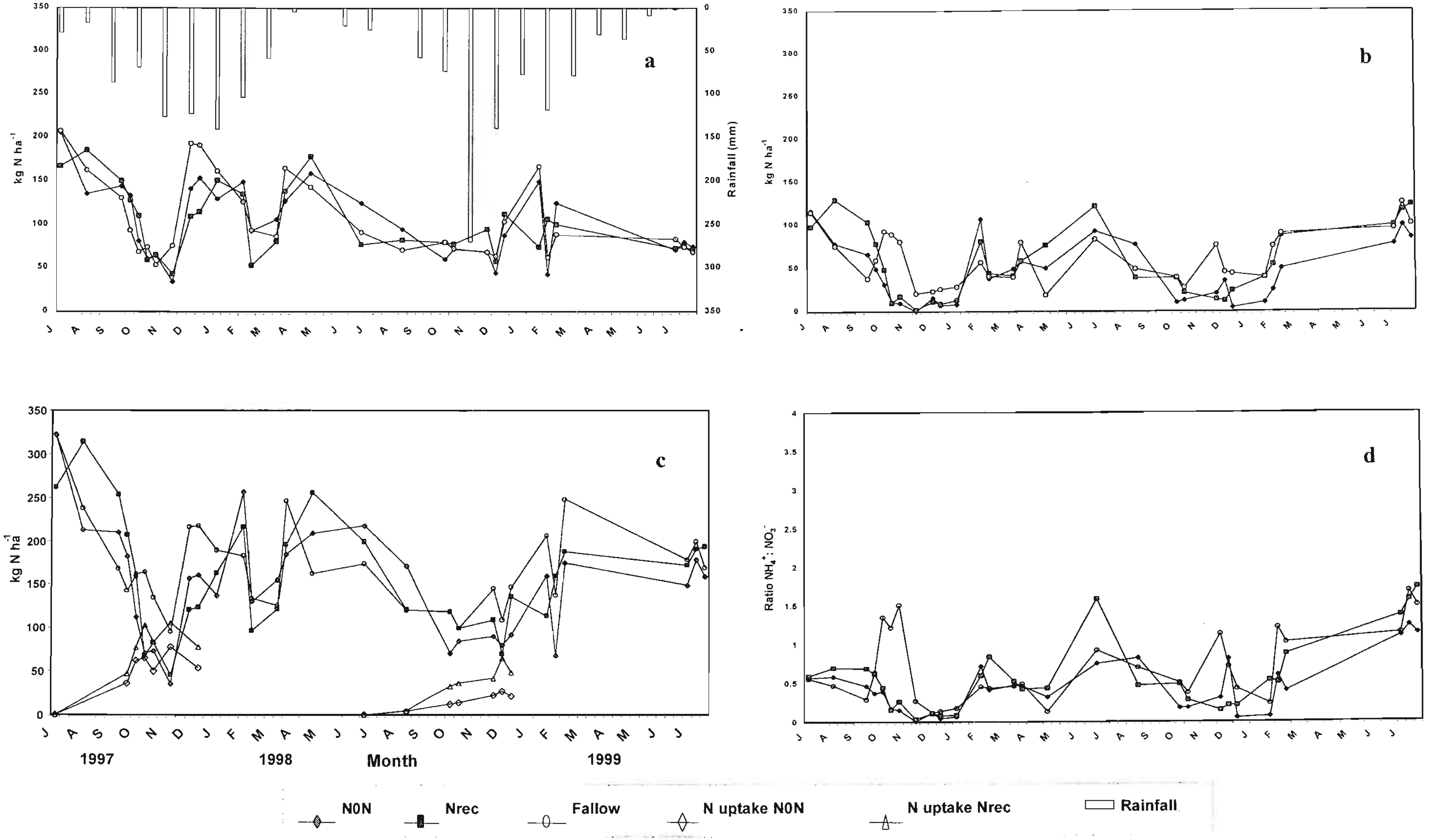

Figure 6.2 Soil mineral NH_4^+ and rainfall (a), NO_3^- (b), total soil mineral N (NO_3^- + NH_4^+) and plant uptake (c), and calculated NH_4^+: NO_3^- ratio (d) in the 0-1200 mm soil profile measured at the N_{0N}, N_{rec}, and fallow treatments at Bethlehem (1997 – 1999)

Rainfall (20 mm) in June resulted in a flush of available soil mineral N (increased NO_3^-) measured in July, with an accompanying decrease in the NH_4^+ content. Subsequent seedbed preparation cultivations also contributed to increased levels of available soil mineral N at planting in 1998.

During the fallow period (harvest 1997 to planting 1998), the total soil mineral N content of the fallow treatment decreased to 173.4 kg N ha^{-1}, but the increase in NO_3^- was mainly from nitrification of the high amounts of NH_4^+ present in the soil profile at harvest. A similar pattern was found at the N_{ON} and N_{rec} treatments. The mineral N content of the N_{ON} treatment during this period increased to a total of 216.9 kg N ha^{-1}, with the N_{rec} treatment at198.28 kg N ha^{-1} (Tables 6.1, 6.2 and 6.3). The distribution of soil mineral N in the soil profile at planting in 1998 at Bethlehem is presented in Fig. 6.3.

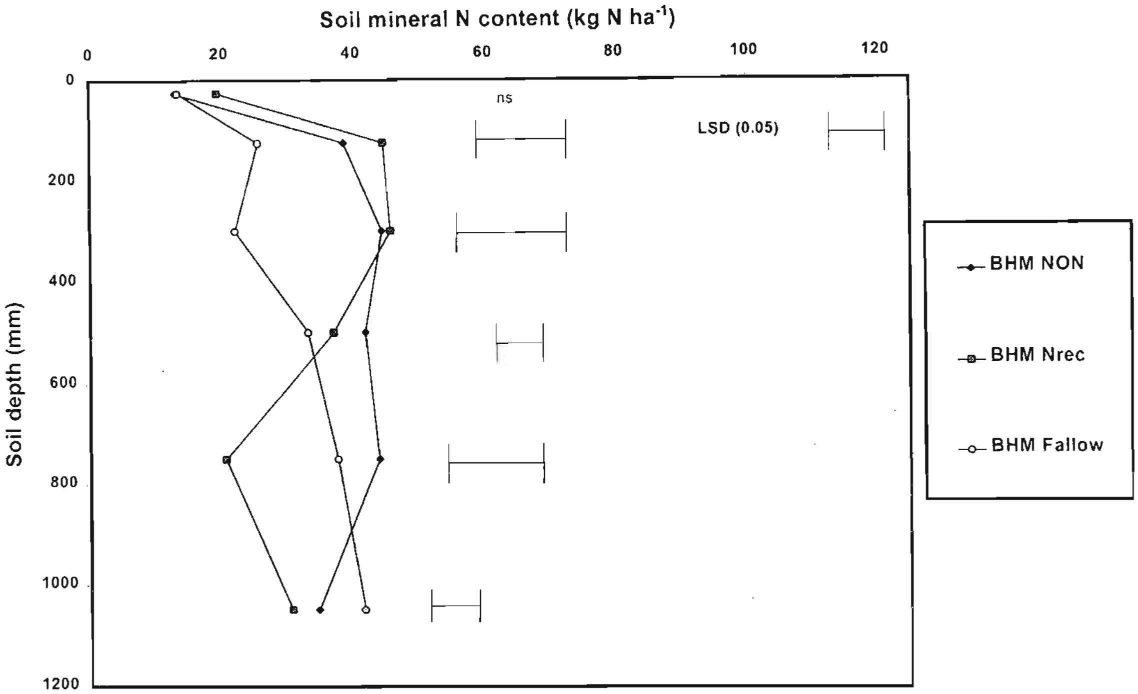

Figure 6.3 Distribution of soil mineral N content (kg N ha^{-1}) at Bethlehem (planting 1998)

There were significant differences in soil mineral N distribution, especially in the 0-50, 50-200 and 200-400 mm soil layers, where the N_{rec} treatment had a significantly higher mineral N content. The soil mineral N content measured in the 400-600 mm did not differ between the treatments, but with the fallow significantly higher than at the N_{rec} in 600-900 mm. In the 900-1200 mm soil layer the fallow had the highest mineral N content. This indicates the extent of the immobilization effect of the added crop residue stratifying soil mineral N in the upper soil layers, especially in the cultivation zone.

A similar pattern of a decrease in measured NO_3^-, NH_4^+ and total mineral N from planting (middle of July 1998) to harvest in December was observed, although of smaller magnitude compared to 1997. Plant uptake of mineral N was also lower than in 1997, but again the decrease in measured mineral N at the fallow treatment indicate immobilization via microbial action in response to increased soil temperatures aided by rainfall. The occurrence of rain late in the growing season (November to middle of December;

234.1 mm) resulted in renewed mineralization and subsequent nitrification of available NH_4^+ leading to increased levels of NO_3^- at harvest.

At harvest, the N_{rec} treatment had decreased to 136.0 kg N ha^{-1} since planting. The fallow treatment showed a decrease in N content of 26.7 kg N ha^{-1}, the N_{0N} a decrease of 125.4 kg N ha^{-1}, and the N_{rec} treatment a decrease of 62.58 kg N ha^{-1} compared to values measured at planting in 1998. At this time, the N_{0N} treatment had a total soil mineral N content of 91.5 kg N ha^{-1} with the fallow treatment measured at 146.7 kg N ha^{-1}. As measured in the previous season, soil cultivation resulted in the flush of mineralization measured as increased NH_4^+ levels in early January (discing) and early February (ploughing). This was followed by a decrease in NH_4^+ during the period of late February in 1998. This is due to immobilization of available soil mineral N during the decomposition process of added crop residue. This was followed by nitrification showing an increased NO_3^- level with decreasing NH_4^+ levels.

The total amount of crop residue added to the cultivation zone after harvest in 1998 were measured at 3370.9 and 5195.7 kg ha^{-1} for the N_{0N} and N_{rec} treatments respectively. Following the same trend as in 1997/1998, low amounts of residue were left at the end of July in 1999, when 352.5 and 502.5 kg ha^{-1} were measured at the N_{0N} and N_{rec} treatments respectively.

At the end of the fallow period (end of July 1999) the soil mineral N content of the fallow treatment totalled 168.82 kg N ha^{-1} (67.52 kg N ha^{-1} as NH_4^+, 101.23 kg N ha^{-1} as NO_3^-) (Tables 6.1, 6.2 and 6.3). The mineral N content of the N_{0N} treatment was 158.8 kg N ha^{-1} (74.15 kg N ha^{-1} as NH_4^+, 84.65 kg N ha^{-1} as NO_3^-), not significantly different from the fallow treatment. The mineral N content at the N_{rec} treatment was significantly higher, where 70.66 kg N ha^{-1} as NH_4^+, 122.46 kg N ha^{-1} as NO_3^-, and a total of 193.13 kg N ha^{-1} was measured.

6.2.1.1 Relative distribution of soil mineral N

The relative distribution of soil mineral N in the soil profile at Bethlehem at specific sampling times is shown in Table 6.4. Soil analysis at planting (1997) showed that on average 57.05% of the total soil mineral N content was found in the 0-600 mm soil layers. Values in the 0-400 mm soil layers at the N treatments decreased marginally from harvest (1997) to planting (1998), with values at the fallow treatment generally remaining similar. Values calculated at planting (1998) showed an increase in relative distribution in the 0-600 mm soil layers at both N treatments, but with higher values at N_{rec}.

The ratios of NH_4^+: NO_3^- (respective total soil mineral N content: 0-1200 mm) for the N treatments indicate decreases in calculated ratios during the growing season in 1997, which indicate uptake of NO_3^- by the crop during biomass and N accumulation, but with NH_4^+ being nitrified to NO_3^- (Fig. 6.2d).

However, the fallow treatment showed marked increases during this period, increased NO_3^- content resulting from nitrification during the early summer in response to increased soil and air temperatures, followed by a decrease in ratio during December. All treatments showed an increase in ratio following soil cultivation during February to March indicating the relative effects of mineralization and nitrification. A similar pattern was found during the growing season in 1998 as in 1997, with a decrease in ratio due to plant uptake of NO_3^-.

Table 6.4 Total mineral N distribution per soil layer (%) at Bethlehem for three treatments (fallow, N_{0N} and N_{rec}) in 1997-1998

Time of sampling	Treatment	Soil layer (mm) 0-50	50-200	200-400	400-600	600-900	900-1200
Plant 1997	Mean	4.20	11.83	18.22	22.80	24.84	18.12
Harvest 1997	N_{0N}	4.24	12.86	12.17	25.67	20.44	24.62
	N_{rec}	5.16	12.51	15.69	25.38	20.14	21.12
	Fallow	4.13	12.83	16.55	23.73	26.92	15.84
Planting 1998	N_{0N}	6.05	17.85	20.51	19.32	20.28	16.00
	N_{rec}	9.86	22.52	23.06	18.68	10.42	15.46
	Fallow	7.80	14.78	12.75	19.07	21.65	23.95
Harvest 1998	N_{0N}	4.47	13.74	18.86	19.05	20.52	23.36
	N_{rec}	6.73	11.39	12.72	20.96	25.65	22.54
	Fallow	2.30	11.44	16.70	24.21	22.12	23.24

6.2.2 Kroonstad

Measurements during the growing season (1997) showed a decrease in NH_4^+ and NO_3^- at both N_{0N} and N_{rec}, and a generally marginal decrease in NH_4^+ at the fallow treatment (Fig. 6.4 a, b) a similar pattern as found at Bethlehem in 1997. During the period July to December the measured soil NO_3^- of the fallow increased marginally, with decreases at N_{0N} and N_{rec} due to plant N uptake during the growing season. At harvest in 1997, the soil mineral N content (0-1200 mm) of the fallow treatment was significantly higher than the other treatments, with the N_{0N} higher than N_{rec} (Tables 6.1, 6.2, 6.3; Fig. 6.4c).

Crop residue at harvest in 1997 was measured at 3620 and 5272.1 kg ha^{-1} at N_{0N} and N_{rec} respectively. Following cultivation in January (discing), increased soil NH_4^+ was measured due to mineralization during December to March (1998), with the NO_3^- content decreasing up to April. This was followed by a decrease in available soil NH_4^+ content from April to June because of immobilization of available mineral N during the decomposition process, followed by nitrification.

Ploughing in March did not result in a flush of mineralization as was expected. This was due to the low soil water condition prevailing especially in the cultivation zone during the fallow period in 1998, which delayed decomposition of added crop residue. This was also seen in the analysis results with only slight increases in measured NH_4^+ and NO_3^- contents up to planting in 1998. Distribution of soil mineral N in the soil layers at planting for the three treatments is shown in Fig. 6.5. Small differences in the distribution of soil mineral N in the soil layers between the treatments were measured. The fallow and N_{rec} treatments did show slightly higher values in the 400-1200 mm soil layers compared to N_{0N}.

The soil mineral N content at planting in late May (1998) showed a decrease of 121.1 kg N ha^{-1} for the fallow treatment compared to harvest in 1997. The soil mineral N content for the fallow was significantly higher than the N_{0N} treatment, but did not differ from the N_{rec} treatment. The N content at N_{0N} also decreased by 30.9 kg N ha^{-1} but increased by 19.28 kg N ha^{-1} at the N_{rec} treatment. The dry soil conditions of the cultivation zone following cultivation practices during the fallow period reduced mineralization and nitrification resulting in lower mineral values at planting compared to values at planting in 1997.

During the early part of the growing season in 1998 (July to November) a general decrease in available soil mineral NO_3^- content was measured at N_{0N} and N_{rec} due to the uptake of N by the growing crop. Soil mineral NH_4^+ due to mineralization increased during October to November following rainfall during this period, but plant uptake of N did not increase significantly. The pattern of response was less evident in 1998 compared to that found in 1997, and also of a lower magnitude. Plant uptake at both treatments was also lower in 1998.

At harvest (1998) the soil mineral N content of the fallow treatment was significantly higher than at the N_{rec} and N_{0N} treatments, with the N_{rec} also significantly higher than the N_{0N} treatment (Fig. 6.4c). The mineral N content of the fallow treatment slightly decreased to 150.5 kg N ha^{-1} from 153.4 kg N ha^{-1} at planting (1998). The N_{0N} treatment showed a decrease during this period of 35.4 kg N ha^{-1} to 91.1 kg N ha^{-1} and N_{rec} decreased by 13.9 kg N ha^{-1} to 122.98 kg N ha^{-1}.

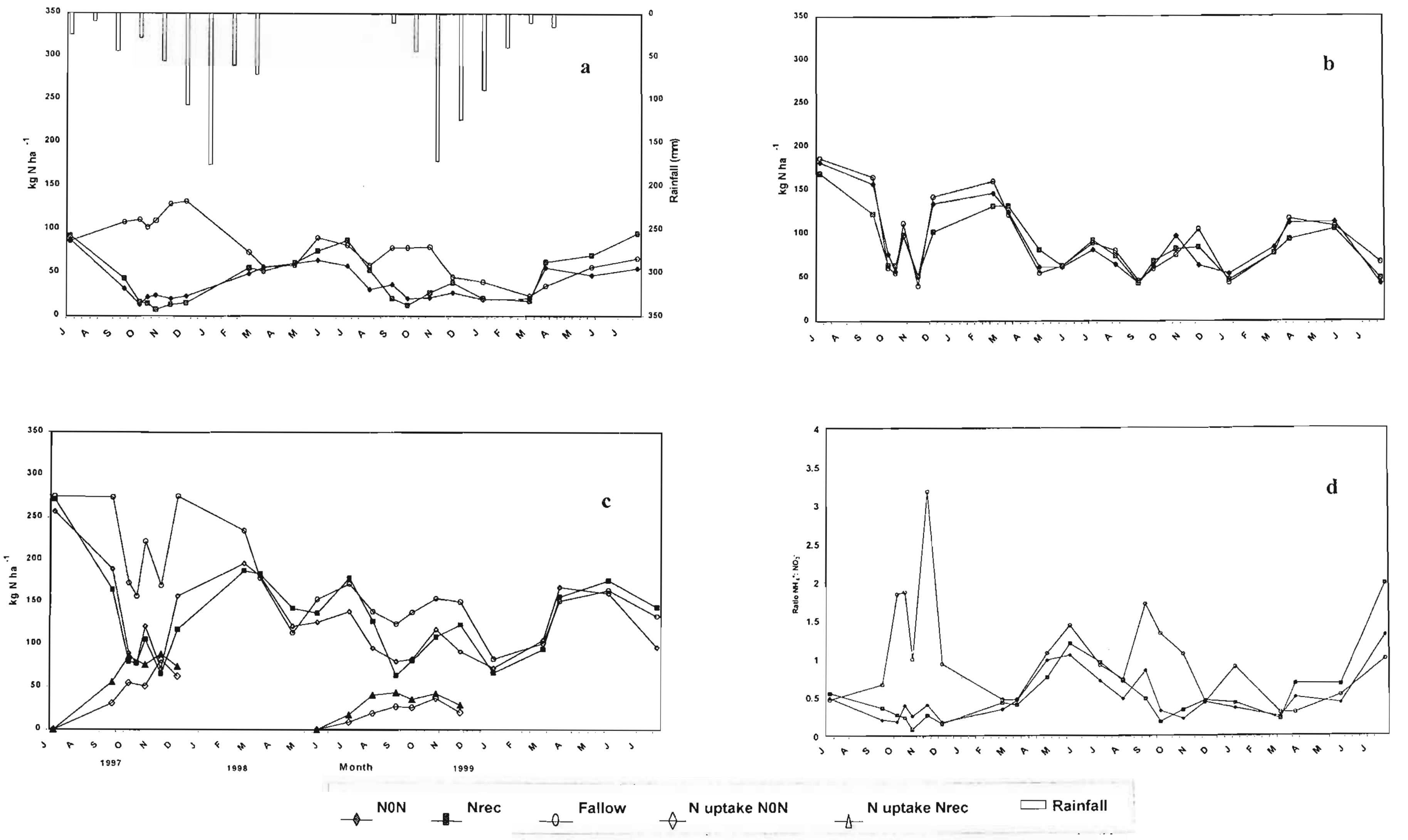

Figure 6.4 Soil mineral NO_3^- and rainfall (a), NH_4^+ (b), total soil mineral N ($NO_3^- + NH_4^+$) and plant uptake (c), and calculated NH_4^+: NO_3^- ratio (d) in the 0-1200 mm soil profile measured at the N_{0N}, N_{rec}, and fallow treatments at Kroonstad (1997 – 1999)

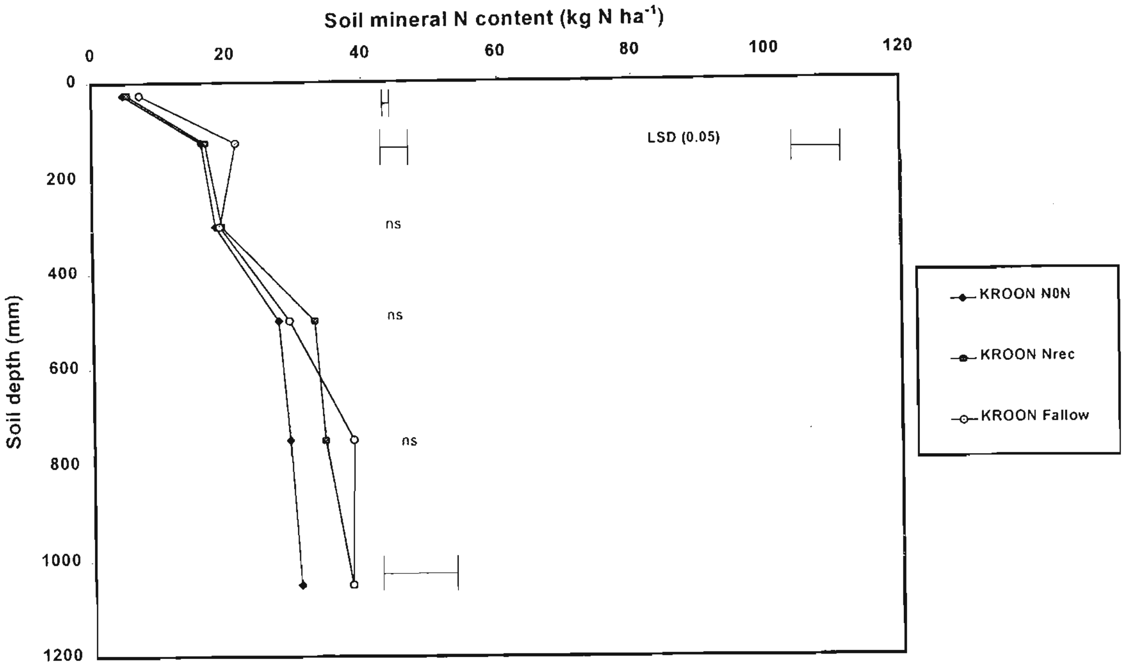

Figure 6.5 Distribution of soil mineral N content (kg N ha^{-1}) at Kroonstad at planting in 1998

Measured residue in the cultivation zone at harvest in 1998 was 638 and 950 kg ha^{-1} for the treatments and including added crop residue at harvest, it amounted to 2837.3 and 3871.5 kg ha^{-1} for the N_{ON} and N_{rec} treatments respectively. Cultivation combined with 157 mm of rainfall measured from January to August aided rapid decomposition and as a result only 142.5 and 675 kg ha^{-1} of residue remained at N_{ON} and N_{rec} respectively at the end of July in 1999.

The cultivation operations in 1999 resulted as expected in an increase in the measured NH_4^+ and NO_3^- contents. During the measurement period (late November 1998 to end of July 1999) a total of 327 mm rainfall was measured. This rainfall initially resulted in increased soil NH_4^+ and total mineral N contents from the middle of January to April (Fig. 6.4). From April to July an increase in soil mineral NO_3^- resulting from nitrification, together with a decrease in soil mineral NH_4^+ was measured. During the fallow period up to the end of July in 1999, the mineral N content of the fallow decreased by 17.55 kg N ha^{-1} to 132.90 kg N ha^{-1}, with N_{ON} showing an increase of 5.0 kg N ha^{-1} to 96.2 kg N ha^{-1}, and N_{rec} an increase by 20.72 kg N ha^{-1} to 143.7 kg N ha^{-1}.

6.2.2.1 Relative distribution of soil mineral N

The relative distribution of soil mineral N in the soil profile at Kroonstad over specific sampling times is shown in Table 6.5. Soil analysis at planting (1997) showed that on average 61.54% of the total soil mineral N content was found in the 0-600 mm soil layers. Calculated relative distribution at harvest in 1997 showed increased distribution in the 0-600 mm at the fallow treatment, with lower values at N_{ON} (0-200 mm and 0-400 mm) and higher values at N_{rec} (0-600 mm).

Table 6.5 Total mineral N distribution per soil layer (%) at Kroonstad for three treatments (fallow, N_{0N} and N_{rec}) in 1997-1998

Time of sampling	Treatment	Soil layer (mm) 0-50	50-200	200-400	400-600	600-900	900-1200
Plant 1997	Mean	4.93	15.01	17.47	24.13	20.18	18.28
Harvest 1997	N_{0N}	3.17	8.99	13.45	27.31	21.30	25.78
	N_{rec}	4.83	12.71	15.75	22.27	21.61	22.83
	Fallow	9.07	14.01	16.56	17.16	23.54	19.56
Planting 1998	N_{0N}	3.71	12.90	14.51	21.74	22.95	24.19
	N_{rec}	3.94	12.37	14.11	23.96	25.04	20.58
	Fallow	4.71	13.95	12.39	18.97	25.07	24.91
Harvest 1998	N_{0N}	2.92	11.29	11.22	18.89	23.25	32.43
	N_{rec}	3.17	8.82	17.60	20.41	24.60	25.40
	Fallow	2.79	11.23	13.89	23.52	24.04	24.53

Distribution remained generally similar at planting in 1998, with increased distribution for the fallow treatment in the 600-1200 mm soil layers. At harvest in 1998, the distribution in the 0-600 mm soil layers decreased at both N treatments indicating N uptake during the growing season, with the fallow treatment remaining similar to previous values. There were generally small changes in the relative distribution of mineral N in the 600-900 and 900-1200 mm soil layers. The calculated NH_4^+:NO_3^- ratios were generally stable in 1997 (Fig. 6.4d). The exception was the fallow treatment that showed variation during September to December, due to lower NH_4^+ and slightly increased NO_3^- contents. Ratios increased from May to August in 1998 mainly due to nitrification of NH_4^+, increasing the NO_3^- content. A similar sequence of N dynamics as seen at Bethlehem was responsible for the changes in calculated ratios.

6.2.3 Petrusburg

The soil mineral N content at planting in 1997 was lower compared to Bethlehem and Kroonstad. Soil mineral N analysis during early July showed increased NH_4^+ and NO_3^- and total mineral N contents related to the fertilizer N application at planting in the N_{rec} treatment. However from July to November, there was a decline in the NO_3^-, NH_4^+, and total mineral N contents at N_{0N} and N_{rec} treatments, with a decline in NH_4^+ and total mineral N but similar NO_3^- content for the fallow treatment (Fig. 6.6a, b, c). A similar response as observed at the other sites was found, where although plant uptake of mineral N increased during the growing season, it did not account for the decline in total mineral N. The major decrease was in NH_4^+ content, being nitrified to NO_3^- used by the plant, but also susceptible to immobilization via microbial action.

The increases in NH_4^+, total mineral N, and to a lesser extent NO_3^- during the period from late October to harvest in 1997 are mainly the result of 67.3 mm of rainfall. This increased the soil water content enabling renewed mineralization of organic matter in previously dry soil layers of the profile. This effect was more pronounced at the fallow treatment, with limited responses in NO_3^-, NH_4^+ and total mineral N contents at the N_{0N} and N_{rec} treatments. The lack of response in soil mineral N at the N_{0N} and N_{rec} treatments, is attributed to increased plant N uptake during this period (Chapter 5.1.3.1) thereby leading to similar soil mineral N contents at these treatments.

Plant N uptake declined towards the end of November, with total soil mineral N remaining at low levels. At harvest in 1997 the total soil mineral N (0-1200 mm) at N_{0N} had decreased to 50.4 kg N ha^{-1}, with a decrease in total mineral N of 168.4 kg N ha^{-1} measured at the N_{rec} treatment. A total mineral N of 95.6 kg N ha^{-1} was measured for the fallow (Tables 6.1, 6.2 and 6.3).

Cultivation of the trial site in December (discing) and in early January 1998 (ploughing) increased soil mineral N (NH_4^+ and NO_3^-) measured in February, with the measured content for the fallow remaining generally similar. There were increases in the measured NH_4^+ and total soil mineral N content during February to July in 1998 for the N treatments, with the response stabilising in August. Also, NO_3^- increased more rapidly from late May to June stabilising thereafter. These increases were related to rainfall of 90.4 mm and 73.8 mm respectively measured during these periods, enabling decomposition of added crop residues, mineralization and nitrification.

At planting in early May 1998, total soil mineral N content of the fallow treatment was 155.9 kg N ha^{-1}, an increase of 60.3 kg N ha^{-1} over values at harvest in 1997, and significantly higher than N_{rec} and N_{0N} that did not differ significantly. The N_{0N} treatment had 124.7 kg N ha^{-1} representing an increase of 74.3 kg N ha^{-1}over values at harvest. Likewise, at N_{rec} a total mineral N content of 124.3 kg N ha^{-1} represented an increase of 100.7 kg N ha^{-1} since harvest.

From the distribution of soil mineral N for the three treatments at planting in 1998 it is evident that the soil mineral content in all the soil layers (except 0-50 mm), were lower at the N_{rec} and N_{0N} compared to

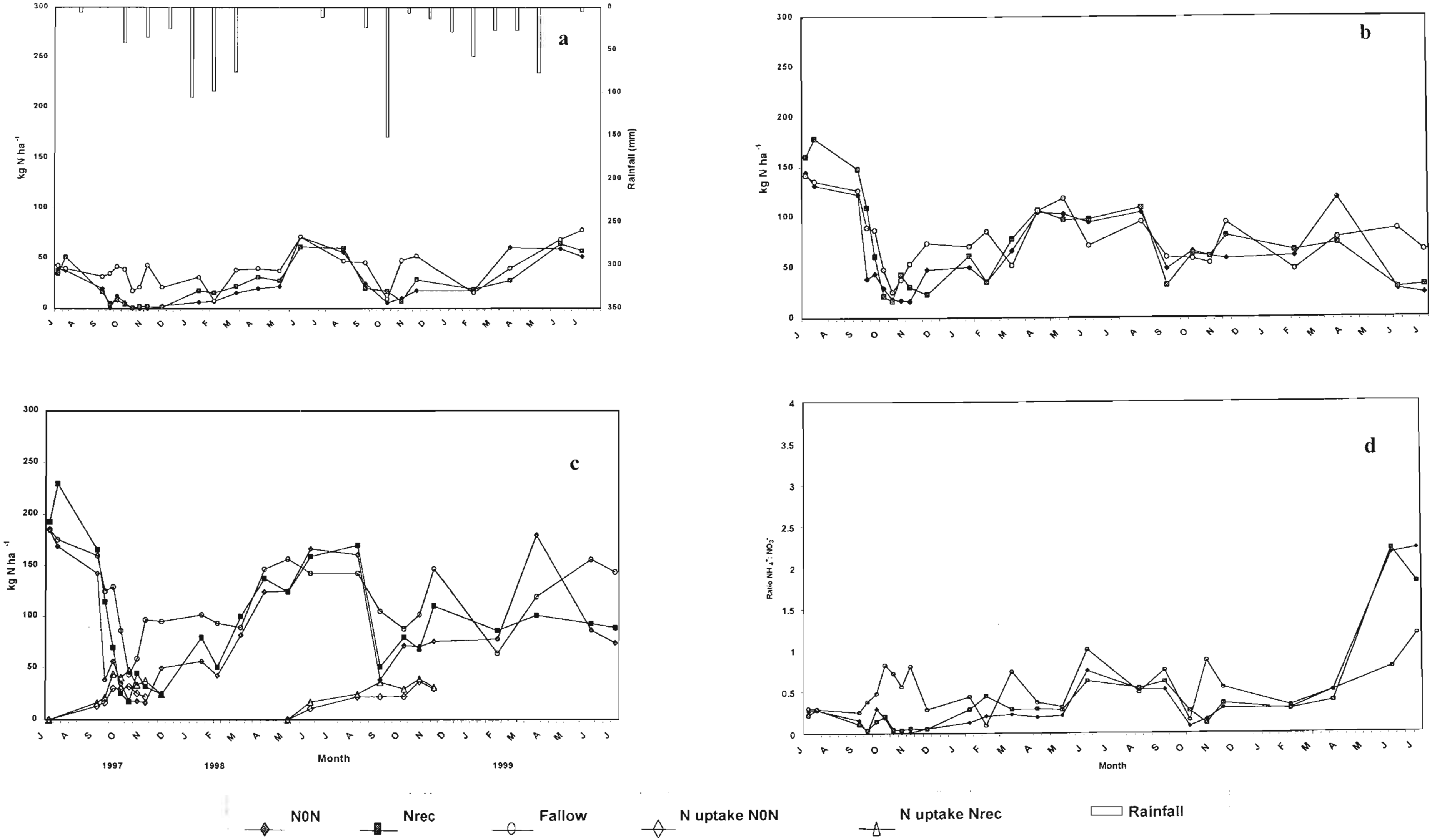

Figure 6.6 Soil mineral NO_3^- and rainfall (a), NH_4^+ (b), total soil mineral N (NO_3^- + NH_4^+) and plant uptake (c), and calculated NH_4^+: NO_3^- ratio (d) in the 0-1200 mm soil profile measured at the N_{0N}, N_{rec}, and fallow treatments at Petrusburg (1997 – 1999)

the fallow treatment (Fig. 6.7). The N_{ON} showed higher soil contents in the 50-600 mm soil layers than N_{rec}, with N_{rec} having higher contents in the 600-1200 mm soil layers.

During the growing season in 1998 there was a decrease in NO_3^- and NH_4^+ at the N_{ON} and N_{rec} treatments, linked to plant uptake of available soil mineral N. The decrease in mineral N followed the same pattern as in 1997 only smaller in magnitude. The increases in NH_4^+ measured from October to December can be linked to favourable soil water conditions occurring during this period (Fig. 6.6). Rainfall (151 mm) during this period enabled mineralization of N from crop residue and organic matter.

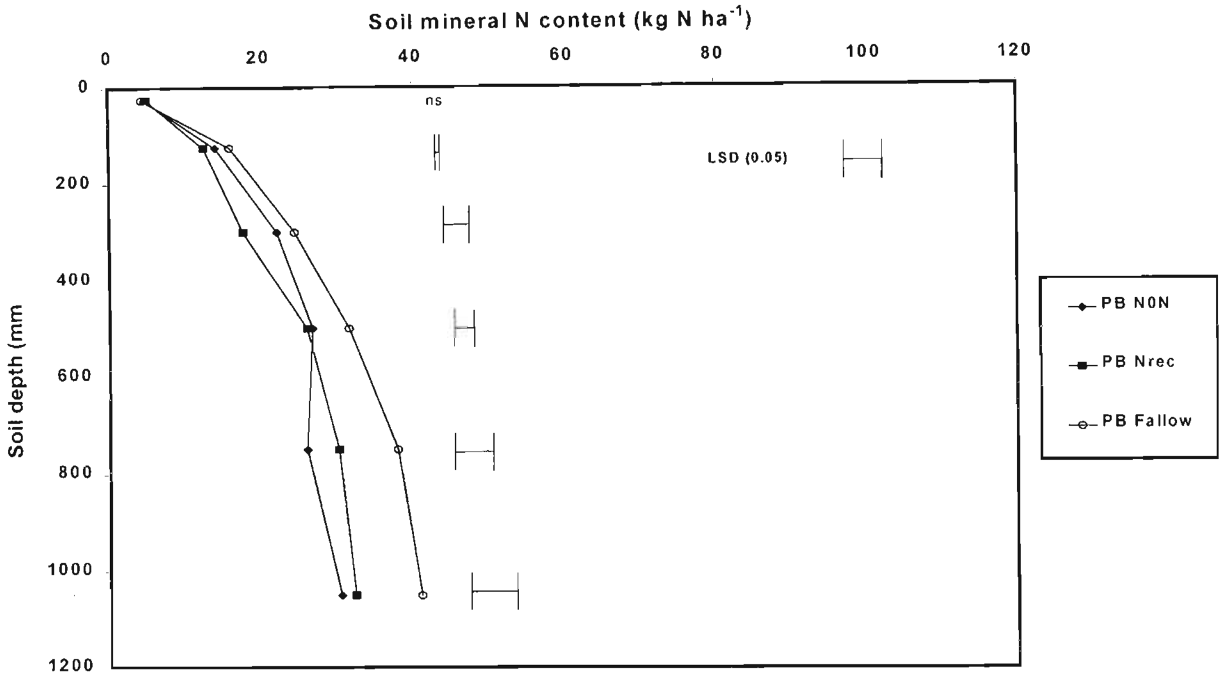

Figure 6.7 Distribution of soil mineral N content (kg N ha^{-1}) at planting in 1998 at Petrusburg

At harvest in 1998 significantly higher soil mineral N values were measured for the fallow and N_{rec} treatments, in comparison to N_{ON}. The fallow treatment had a total soil mineral N content of 146.3 kg N ha^{-1} representing a decrease of 9.6 kg N ha^{-1} since planting. The N_{ON} treatment showed the lowest values for total mineral N of 75.8 kg N ha^{-1} representing a decrease of 48.9 kg N ha^{-1}. At N_{rec} a total mineral N of 109.8 kg N ha^{-1} was measured, with a decrease of 14.49 kg N ha^{-1} over values measured at planting.

At harvest in 1997, crop residues of 2328 and 2447.5 kg ha^{-1} was measured for N_{ON} and N_{rec} respectively. Decomposition slowed down partly because of lower rainfall measured during August, November, and December, and in addition the soil water content of the cultivation layer decreased during the months up to planting, further inhibiting decomposition. At harvest in 1998, 416.7 and 535.8 kg ha^{-1} of undecomposed residue was measured in the cultivation zone (0-400 mm). Crop residues and roots amounted to 2463 and 3229.1 kg ha^{-1} for the N_{ON} and N_{rec} treatments respectively. Subsequent sampling of residues remaining at the end of July (1999) showed a decline to 668.75 and 442.5 kg ha^{-1} measured at N_{0N} and N_{rec} respectively.

Cultivation of the trial site in January 1999 resulted in a decline in soil NH_4^+, NO_3^- and total mineral N in late February that could be ascribed to immobilization of mineral N during residue decomposition. An increase in NO_3^-, NH_4^+ and total mineral N was measured up to April, followed by a declining NH_4^+ content due to nitrification increasing NO_3^- levels. Measured values for the fallow treatment remained generally at similar levels during this period.

Soil mineral N content (0-1200 mm) measured at the end of the fallow period (end of July, 1999) decreased by 2.95 kg N ha^{-1} for the fallow treatment to 143.35 kg N ha^{-1}. The mineral N content for the N_{0N} treatment was 74.19 kg N ha^{-1} representing a decrease of 1.61 kg N ha^{-1} in total mineral N. At the N_{rec} treatment 88.57 kg N ha^{-1} was measured, representing a decrease of 21.23 kg N ha^{-1} over values measured at harvest in 1998.

6.2.3.1 Relative distribution of soil mineral N

The relative distribution of soil mineral N in the soil profile at Petrusburg over specific sampling times, is shown in Table 6.6. Soil analysis at planting (1997) showed that on average 51.23% of the total soil mineral N content was found in the 0-600 mm soil layers. Distribution at harvest in 1998 showed decreases in values for the 600-1200 mm soil layers with values higher for the 0-600 mm layers at the N treatments, with values at the fallow remaining generally similar but and marginally higher in the 0-600 mm soil layers. Calculated distribution at planting in 1998 showed lower values in the 0-600 mm soil layers, accompanied by increased values in the 600-1200 mm soil layers at all treatments. The distribution at harvest in 1998 showed decreased distribution of N in the 600-1200 mm soil layers at N_{0N} and N_{rec}, but increased values in the 0-600 mm soil layers compared to values at planting. Distribution of N at the fallow treatment remained comparable to values at planting, although with slightly increased values in the 0-600 mm soil layers.

6.3 SOIL MINERAL N CONTENT AND PLANT N UPTAKE

The measurement of N uptake by a growing crop in the field is widely accepted as one of the methods for obtaining an index of the N supplying capacity of that soil. This value also has a predictive value, particularly with reduced input of fertilizer N (Broadbent, 1981).

The difference in soil mineral N (0-1200 mm) between the fallow and N_{0N} treatments at harvest (1997 and 1998) indicate that the uptake of soil mineral N by the crop in the absence of applied fertilizer N assuming all factors influencing the soil N dynamics were similar. This value was calculated as a decrease of 56.3 kg N ha^{-1} for N_{0N} in 1997 at Bethlehem (Table 6.5). The difference between the fallow and N_{rec} at harvest 1997 indicated a decrease of 93.4 kg N ha^{-1}. These values are comparable to the total plant uptake of N measured for the 1997-growing season. At Kroonstad greater differences between calculated soil mineral N values and measured plant N uptake was measured in 1997, indicating less efficient uptake of available soil mineral N.

Table 6.6 Total mineral N distribution per soil layer (%) at Petrusburg for three treatments (fallow, N_{0N} and N_{rec}) in 1997-1998

		Soil layer (mm)					
Time of sampling	**Treatment**	**0-50**	**50-200**	**200-400**	**400-600**	**600-900**	**900-1200**
Plant 1997	Mean	3.38	10.76	15.67	21.42	22.77	26.00
Harvest 1997	N_{0N}	6.25	20.76	16.67	20.72	15.96	19.65
	N_{rec}	5.82	17.98	25.26	19.12	11.19	20.63
	Fallow	5.53	13.77	15.12	22.95	19.37	23.27
Planting 1998	N_{0N}	3.86	11.35	17.82	21.54	20.93	24.51
	N_{rec}	4.11	10.16	14.30	21.02	24.36	26.01
	Fallow	2.87	10.30	15.75	20.33	24.40	26.35
Harvest 1998	N_{0N}	3.32	21.22	22.66	19.25	17.40	16.15
	N_{rec}	4.75	20.26	22.90	17.72	19.18	15.18
	Fallow	2.17	11.34	17.01	24.52	20.01	24.96

Larger differences in values were calculated than at Bethlehem, while calculated values for Petrusburg showed a similar response but of smaller magnitude. The picture changed in 1998 when smaller differences in soil mineral N values were calculated between the fallow and other treatments.

Table 6.7 Calculated soil mineral N changes (kg N ha^{-1}; 0-1200 mm) at harvest and differences in measured plant N uptake at Bethlehem, Kroonstad, and Petrusburg for the growing seasons 1997 and 1998 (standard errors in parenthesis)

Locality	Year		Soil mineral N Treatment – Fallow (kg N ha^{-1})	Plant N uptake (kg N ha^{-1})
Bethlehem	*1997*	N_{0N}	56.30 (±4.82)	59.84 (±4.04)
		N_{rec}	93.40 (±4.82)	86.59 (±4.04)
Kroonstad		N_{0N}	116.94 (±4.58)	65.51 (±1.76)
		N_{rec}	156.86 (±4.58)	79.09 (±1.76)
Petrusburg		N_{0N}	45.20 (±6.92)	23.26 (±0.63)
		N_{rec}	71.00 (±6.92)	26.37 (±0.63)
Bethlehem	*1998*	N_{0N}	55.20 (±2.90)	25.55 (±1.84)
		N_{rec}	10.70 (±2.90)	56.20 (±1.84)
Kroonstad		N_{0N}	59.25 (±4.48)	21.09 (±0.75)
		N_{rec}	27.47 (±4.48)	31.02 (±0.75)
Petrusburg		N_{0N}	70.50 (±10.56)	33.67 (±1.65)
		N_{rec}	36.49 (±10.56)	37.18 (±1.65)

6.4 DISCUSSION

Soil mineral N content has been shown to be an important but variable component of N management in modern agriculture. Soil mineral N variability is multidimensional and involves spatial components in vertical and horizontal directions, as well as temporal components (Meisinger, 1984). Difficulties in measurement of N in soils stem from the solubility and mobility of NO_3^-, non-uniform application of N fertilizer, natural spatial heterogeneity of soil organic matter and soil water, spatial and temporal heterogeneity of soil N transformations. Further difficulties also arise from sample collection and preparation (Meisinger, 1984). Holford & Doyle (1992) stated that the measurement of soil mineral N is notoriously unreliable as indices of available N for predicting fertilizer responsiveness and requirements of crops. This is mainly due to the variability in rates of mineralization of organic N, and vulnerability of NO_3^- to leaching and denitrification. The mineralization-immobilization sequence provides a natural safeguard against N losses, because of net immobilization during periods when the potential for leaching and denitrification will be the highest (Stevenson & Cole, 1999). Nitrogen losses from soil cannot be eliminated completely, but can be minimized by proper management practices.

In dryland agricultural systems with variable summer rainfall as generally found in the Free State, fallow periods are a necessity to accumulate soil water for the next crop in the rotation. Without this source of residual soil water, the risk of crop failure due to the unpredictable nature of rainfall would dramatically increase. This is also the scenario regarding the accumulation of soil mineral N, where the supply of N mineralized during the summer fallow period from crop residue and organic material, combined with summer rainfall and flushes of N mineralization of N after cultivation of fields, is out of phase/synchrony with crop demand. However, soil water conservation during this summer fallow period has traditionally been of more importance in South African wheat producing areas. Maximized soil water conservation will consequently also result in the accumulation of soil mineral N in the soil profile.

The measurement of soil mineral N is important in assessing the availability of N to the growing plant, where the need for additional fertilizer inputs can be linked to this availability. The impact of rainfall, soil water content, and residue decomposition on N mineralization and hence soil mineral N content is therefore important in explaining N behavior in soils, and quantify the different processes influencing soil mineral N availability. Care was taken during the study period to apply prescriptive soil sampling procedures. Standard analytical solutions and control soil samples were routinely included in laboratory analysis procedures. Variability in analysis results (mg kg^{-1}) was generally higher for the NO_3^- than NH_4^+, ranging from below 10% to 54.6% for individual soil layers in calculated N content (kg N ha^{-1}). However, total soil mineral N content (NO_3^- + NH_4^+; kg N ha^{-1}) for individual soil layers, as well as cumulative mineral N for the 0-1200 mm soil layers, showed reasonable levels of variation (<25%), with standard errors for NH_4^+, NO_3^- and total mineral N ranging from 5-20, 3-10 and 5-15 kg N ha^{-1} respectively. The conversion of analysis values (mg kg^{-1}) to N content (kg N ha^{-1}) further accentuated differences in the calculated N content of the soil layers. This indicated that unavoidable inconsistencies in sample handling (including time delays during transport and drying time) could have caused changes in the relative amounts of soil mineral NO_3^- and NH_4^+ in soil samples.

Furthermore, because of air-drying, the length of the actual drying period depended not only on room temperature but also on the soil water content of soil samples, and this could have caused changes. Higher soil mineral N contents for the higher clay content soil layers also occurred when relatively high soil water contents were also measured, as at planting in 1997, when in particular high standard errors were found (Bethlehem: 37.9, Kroonstad: 23.6 and Petrusburg: 12.3 kg N ha^{-1} respectively). The high soil water contents could have delayed the drying process thereby changing the relative values for soil mineral NO_3^- and NH_4^+ because of the extended period for mineralization in the soil samples. An indication of the possible magnitude of change in calculated N content with changes in detection limits of analysis values (mg kg^{-1}), is that if analysis values differ by 5 mg kg^{-1} for each soil layer, a change in total soil mineral N content of 96 kg N ha^{-1} (0-1200 mm) will result. Keeping this in mind, the differences in total soil mineral N between samplings may have been accentuated by this scenario, but the differences between treatments at a specific sampling will still indicate the relative treatment effect at that time.

High soil mineral N contents were measured at planting in 1997, especially at Bethlehem and Kroonstad, due to the long fallow periods (>12 months) preceding the study, but also with high standard errors probably due to measurement methods and calibration ranges used during analysis at that time. During this extended period, advanced decomposition of previously incorporated crop residue and hence accumulation of residual mineral N in the soil profile resulted. The accumulation of soil water during the fallow period aided in enhancing mineralization of N from organic N sources and from previously immobilized N during decomposition, resulting in the accumulation of mineral N.

The calibration range was adapted during subsequent analysis to accommodate lower soil N contents as soil mineral N measurements progressed. The large decline in measured mineral N values during July to October in 1997, in particular at Bethlehem, must be viewed with the previous discussion in mind. Plant uptake increased during this period, while immobilization of available N via microbial action in response to increasing soil temperatures also contributed to these declining values. Plant uptake and the decline in soil mineral N content followed similar patterns at the three localities, but varying in magnitude. At Petrusburg, lower amounts of soil mineral N in comparison to the other localities were accumulated. Due to generally lower levels of crop production with accompanying lower fertilizer inputs, lower amounts of crop residue are produced in this region. Lower levels of organic C and total N in the soil profile, also leads to reduced potential mineralization from these native sources, combining to produce low residual soil mineral N levels. The lower clay content of the soil layers, linked with an extended fallow period to accumulate soil water, could also result in losses/movement of soil mineral N beyond measurement depth.

This spatial distribution effect on soil mineral N utilization by the crop during the growing season was evident from the calculated relative distribution of soil mineral N in the profile (Table 6.4). Relatively small percentages of soil mineral N were found in the 0-50 mm soil layer, but values generally did not change to a large extent. This indicates limited use of soil mineral N from this layer, due to low soil water content and root development caused by temperature extremes and rapid drying cycles following rainfall events. Relative distribution values showed significant amounts of soil mineral N in the 600-1200 mm soil layers, and limited changes at Bethlehem (1997) and Petrusburg (1997 and 1998) in these layers. Part of the explanation for this limited use can be found in root distribution in the profile at physiological maturity (Chapter 4.5).

The significant amounts of mineral N in the 600-1200 mm soil layers indicate the importance that these reserves can play in N nutrition of the growing crop if effectively and timely utilized (Fiez *et al.*, 1994). From a technical point of view, soil mineral N may be less effective than fertilizer N because of differences in spatial distribution and subsequent use by the crop. Fertilizer N applied in surface soil layers increases availability of N to the plant early in the growing season. Conversely, the plant progressively utilizes available mineral N in the soil profile as the root system expands. Mineral N in deeper soil layers can thus have a relatively small effect on growth and grain yield, depending on the time of possible utilization by the plant (Habey *et al.*, 1983). The calculated relative root distribution showed that on average 90% of the total root length (mm cm^{-3}) at Bethlehem was found in the 0-600 mm soil layers, with 89% at Kroonstad and 85% at Petrusburg. At Petrusburg 15% of the root distribution was found in the 600-1200 mm soil layers, in comparison to 10% at Bethlehem and Kroonstad respectively, indicating the potential use of N from this part of the soil profile. However, in 1998 at Bethlehem (N_{ON}) lower root lengths was found in the 0-200 mm soil layer but higher values at the N_{rec} treatment compared to 1997. At Kroonstad and Petrusburg lower root lengths were found in the 0-200 mm soil layer in 1998, but comparable values in the 0-600 mm soil layers to 1997 at all localities. The lower root lengths in the 0-200 mm soil layer were attributable to the low soil water content of this layer at planting and during early development in 1998, not favouring extensive expansion of the root system in this layer (Chapter 3.4.2).

Significant amounts of NH_4^+ and NO_3^- were found in all soil layers of the profile, however, previous studies (Hadas *et al.*, 1989b) reported mostly low concentrations of NH_4^+ in measured soil samples in their studies. This difference can partly be linked to restrictions of soil chemical (soil acidity) and physical conditions combined with low soil water content on nitrification. Higher amounts of soil mineral N and soil water (0-1200 mm) were measured at Bethlehem and Kroonstad, in particular in the 400-600 mm soil layer. The soil layers 400-1200 mm at Bethlehem and Kroonstad have increasingly higher clay contents due to the duplex nature of these soils, slowing soil water infiltration, and thereby downward N movement in the soil profile, enabling accumulation of soil mineral N. This accumulation of soil mineral N was less evident at Petrusburg in a soil profile without a duplex soil nature, with measured soil mineral N more evenly distributed in the 400-1200 mm soil layers. Schepers (1988) stated that nitrate leaching is usually minimized in regions where fallowing is necessary to accumulate adequate soil water to support the next crop in the rotation.

From the multivariate analysis on yield, protein percentage of the grain and N uptake (Chapter 4.3, 5.2.2, and 5.2.3) soil mineral N content (0-1200 mm and 0-600 and 600-1200 mm soil layers), contributed significantly to the explanation of these measurements. This response shows promise that this measurement can contribute to improved N fertilization recommendations. Soil mineral N has been used worldwide in N fertilizer planning and high initial values can reduce the need for high N applications. The current N recommendation system for wheat production in South Africa does not include soil mineral N in calculating N fertilizer requirements. Based on the high residual soil mineral N content in 1997, reduced N fertilizer could have been applied. The small yield differences measured in 1997 supported this, but the protein content of the grain was significantly lowered without additional N (Chapter 5.2.2).

Because of the practical difficulties of N applications during the growing season effectively increasing grain protein percentage, linked to the variability of summer rainfall, the total N fertilization requirement is currently applied at planting (Anon, 1998). Banding of fertilizer also increased the response to N in this case, especially in 1998 when reduced soil water content in the cultivation zone limited early root development. The limited root development reduced crop growth at the N_{0N} treatment, although a high level of soil mineral N was available. This combination of factors led to the low use efficiency of soil mineral N content in particular during 1998 at Bethlehem and Kroonstad. The development of the root system during the growing season will also have an impact on the potential use efficiency of soil mineral N as the soil profile is explored, with soil water content affecting both root growth and nutrient uptake from the soil.

Total N uptake by the crop of available soil mineral N at planting (Tables 6.1, 6.2 and 6.3) at Bethlehem was calculated at 18.6% and 33.1% for N_{0N} and N_{rec} respectively in 1997. At Kroonstad, these values were 25.5% and 29.2%, while at Petrusburg 12.7% and 13.7% were calculated. The uptake percentages calculated for 1998 showed values at Bethlehem of 11.8% and 28.3%, and at Kroonstad (16.7% and 22.7%) for the N_{0N} and N_{rec} treatments respectively. At Bethlehem (N_{rec}) high soil mineral N values were measured at harvest leading to lower calculated values when compared to the fallow treatment. This does not fit the general response pattern found at the other localities, and results from rainfall during physiological maturity favouring mineralization of N from previously dry soil layers, but not increasing plant uptake. At Petrusburg (1998), higher values were calculated with 27.0% and 29.9% of available mineral N at planting taken up by the N_{0N} and N_{rec} treatments respectively. The positive response found at Petrusburg is due to increased availability of soil mineral N toward the end of the growing season, also found as a higher relative distribution of soil mineral N in the 0-600 mm soil layers. This resulted from rainfall following a substantial dry period, increasing soil N availability and resulting in increased uptake by the growing crop, in contrast to the lack of increase in measured values at Bethlehem in 1998.

These calculated values indicate that available soil mineral N was not utilized efficiently at the N_{ON} treatment, but more effectively at N_{rec}. This is related to increased growth, root development, and biomass and increased uptake of available mineral N induced by fertilizer N application at N_{rec}. In general, N uptake values and differences in soil mineral N were smaller in 1998 at Bethlehem and Kroonstad than in 1997, with the treatments at Petrusburg in 1998 showing higher N uptake and soil mineral N differences than in 1997.

Decreased soil mineral N was measured at planting in 1998 at all localities compared to 1997. The shorter fallow period and erratic rainfall distribution affected soil cultivation and residue management and subsequently, N mineralization, so that less residual soil mineral N accumulated at planting. At the N_{ON} treatment this reduced soil mineral N availability restricted plant growth and N uptake during 1998, in comparison to the N_{rec} treatment. Leaf and tiller N concentrations at the N_{ON} treatment (Chapter 5.1.3.2) were below generally accepted critical plant analysis values and the plants exhibited classical N deficiency symptoms (yellowing of older leaves, reduced tillering, lower leaf area indices and biomass accumulation) in comparison to N_{rec}. The growing crop can utilize mineralized N from crop residue and organic matter within a growing season, thus reducing the need for additional fertilizer N. However, it must be ensured that supply and demand of N and crop requirements are synchronized (Schepers, 1988).

Significant losses of NO_3^- can occur as a consequence of denitrification in soils. Under anaerobic conditions, such as frequently occur in soils following heavy rain, NO_3^- can be lost in a comparatively short time, particularly when energy sources are available in the form of organic residues. Losses are generally negligible at moisture levels below two-thirds of the waterholding capacity of the soil. Above this value, the magnitude of loss is correlated directly with moisture regime (Stevenson & Cole, 1999). Nitrate is the most mobile N form, and is susceptible to leaching and movement into water supplies. The magnitude of NO_3^- leaching is difficult to estimate, and will depend on a number of variables. These include; the quantity of NO_3^- available, amount and time of rainfall, infiltration and percolation rates, evapotranspiration, waterholding capacity of the soil, and the presence of growing plants (Stevenson & Cole, 1999).

The losses of mineral N via leaching and denitrification may have caused decreases in soil available mineral N during the study period. Losses through denitrification were probably the cause in most cases where surface layers were saturated following heavy rainfall during the summer fallow and growing season. Together with available carbon from decomposing residue in these soil layers, losses of N can occur in this way (Power & Doran, 1988). During the fallow periods in 1998 and 1999 at all three sites, the soil mineral N content of the fallow treatment decreased. The magnitude of change in NO_3^- content was greater at Bethlehem than measured at the other sites. This was evident in the fallow period of 1998 when there was a decrease in NO_3^- following rainfall. A similar but smaller response was measured at the

N_{0N} and N_{rec} treatments, indicating the benefit of soil mineral N immobilization by decomposing crop residue following soil cultivation. The responses measured at the other sites can also be due to lower rainfall, and generally lower soil mineral N contents. Schepers (1988) stated that lateral subsurface flow and perched water tables are common in areas where soils are shallow over consolidated rock, or where other materials retard downward water movement, as in the case of duplex soils. Under these conditions following rainfall, NO_3^- can be transported laterally, or be subjected to increased denitrification losses.

Sequences of mineralization and subsequent nitrification were measured at all three localities following cultivation and rainfall events, especially after dry periods. Ammonium can be important in soils in areas with a pronounced dry period because of accumulation of NH_4^+ (Wong & Northcliff, 1995). The conversion of NH_4^+ to NO_3^- (nitrification) is more sensitive to soil water deficits than mineralization (Wong & Northcliff, 1995). Dry conditions can thus lead to accumulation of NH_4^+ in soils, followed by rapid conversion of NH_4^+ to NO_3^- following rainfall sufficiently wetting these soil layers (Barrios *et al.*, 1998). This increased availability of soil mineral N following rainfall can increase N uptake late in the growing season (Petrusburg 1998), resulting in higher plant N contents and high grain protein percentages.

The ratio of NH_4^+: NO_3^- (respective total soil mineral N content: 0-1200 mm) for the N treatments were generally similar during the growing season in 1997, which indicate uptake of NO_3^- by the crop during biomass and N accumulation, but with NH_4^+ being nitrified to NO_3^- (Fig. 6.6d). However, the fallow treatment showed marked increases during October to December, indicating increased NO_3^- content resulting from nitrification during the early summer in response to increased soil temperatures.

All treatments showed an increase in the calculated ratio following soil cultivation during February to March indicating the effect of mineralization. A similar pattern was found during the growing season 1998 as in 1997, with a decrease in ratio due to plant uptake of N. Ratios increased towards the end of the fallow period in 1999 mainly due to nitrification of mineralized NH_4^+ and accumulation of NO_3^- in the soil profile. Although the general response patterns in calculated ratios were similar across localities, the magnitude of response was similar at Bethlehem and Kroonstad, but generally lower at Petrusburg. Increased calculated ratios are due to increased NO_3^- contents of the 0-50, 50-200 and 200-400 mm soil layers. Likewise, decreased ratios were the result of increased NH_4^+ contents of these soil layers. Generally, the calculated ratios indicated responses to cultivation, increases in soil temperatures, crop growth and rainfall that changed the relative amounts of NH_4^+ and NO_3^- depending on the specific process favoured by the action at that time.

The addition of crop residues to the cultivation zone has resulted in reduced soil mineral N availability at all three localities in 1998. This immobilization of soil mineral N will affect mineral N availability to the growing crop depending on conditions (soil water content and soil temperature). Hadas *et al.* (1992) stated that this immobilization effect was primarily due to the microbial biomass utilizing N from the inorganic pool in the soil, rather than directly from the decomposing soil organic matter. This will have an impact on the decomposition dynamics during the fallow period, the release and availability of soil mineral N through remineralization from previously immobilized mineral N sources. The quantities of fertilizer N fixed via immobilization may be considerable. Broadbent (1984) quoted that 30-40% of applied fertilizer N was fixed in soil organic matter in field experiments with cereals, with 21-39% found in oats, and up to 33% with wheat in other research.

Initial residue decomposition following harvest and cultivation was slow because of the lower soil water content, but loss of residue increased with time. Decomposition slowed during the winter months, because of lower air and soil temperatures. At planting in 1998 at Bethlehem, 21.7% of added crop residue at N_{rec} was lost by decomposition, with 71.1% at the N_{0N} treatment. This resulted in high amounts of crop residue still in the cultivation layer at planting. This undecomposed residue immobilized available soil mineral N and thereby depressed plant growth where no additional fertilizer N was applied (N_{0N}). The inclusion of residue at planting in the multivariate analysis did not contribute significantly (<1%) to the explanation of variation in values of yield, protein percentage of the grain or N uptake at harvest. The effect of undecomposed residue at planting must be on soil mineral N availability and recycling during the growing season.

The apparent lack of decomposition at the N_{rec} treatment at Bethlehem during the fallow period does not fit the overall trend measured at the other localities. The explanation for this lies partially with the cultivation practices followed in residue management, that initially did not incorporate large amounts of crop residue into the soil, thereby not enabling close soil-residue contact, slowing decomposition. In addition, measurement error cannot be excluded, because of a standard error of 772.8 kg ha^{-1} for the particular sampling, indicating variability in the measured data. Inclusion of this variability increased the possible decomposition value to 72.8% for this treatment.

On average 64.8% and 63.5% of added crop residue (0-400 mm) was decomposed (<0.5 mm) at N_{0N}, and 70.2% and 42.6% at the N_{rec} treatments respectively at Kroonstad and Petrusburg at planting (1998). On average 32.5% at Kroonstad, and 46.95% at Petrusburg of the added crop residue at harvest remained in the cultivation soil layer at planting in 1998. The uncompleted decomposition of added residue could be ascribed to the amount and variable distribution pattern of rainfall during the fallow period in 1997/1998. Effective soil cultivation practices and residue management relies largely on favourable soil water conditions, which were affected by the sub-optimal soil water conditions and irregular rainfall distribution during this fallow period.

Aita *et al.* (1997) has shown that decomposing plant residues rapidly accumulate in the fine soil fractions (<50 μm). The method of measuring undecomposed crop residue (>0.5 mm) in this study therefore only accounted for the larger fraction of remaining crop residue, while the smaller unmeasured fraction could still have had significant effects on soil mineral N availability. Broadbent (1984) described the relationship between N concentration of crop residues and N mineralization rate, with 1.5%N the threshold value for net mineralization of N from these residues. At above 2.5%N the rate of mineralization was sufficiently high to meet the N requirements of crops, depending on the total quantity of plant residues present. The N concentration of the added crop residue at harvest was generally below 1% at all localities, with the C:N ratio above 70:1, thus N immobilization following soil cultivation and residue incorporation could be expected. Furthermore, if appreciable amounts of undecomposed crop residue are present in these soil layers at time of planting, the immobilization effect of this residue on available soil mineral N will necessitate additional N applications. Tisdale *et al.* (1993) calculated a value of 26.9 kg N ha^{-1} per ton of crop residue (C:N ratio of 60:1) added. Westfall (1984) adapted the N fertilization guidelines for wheat fertilization in the mountain states of America by 17-22 kg N ha^{-1} per ton of nonlegume residue plowed down, aiming to prevent soil mineral N immobilization and aid in residue decomposition. This will ensure optimum growth of the crop by increasing mineral N availability early in the growing season (Stevenson & Cole, 1999). The beneficial effect of additional fertilizer N was illustrated in the N_{rec} treatment, that produced higher biomass, N uptake and yields than the N_{ON}, especially in the second cropping year when soil mineral N availability in the cultivation soil layer was also reduced.

Although the soil sampling intervals during the fallow period was fairly wide (± monthly) and did not pinpoint immobilization episodes following soil cultivation, immobilization measured as decreased soil mineral N content was found at the end of the fallow period. The undecomposed residue remaining in the cultivation zone at planting in 1998 limited the availability of residual mineral N, especially at the N_{ON} treatment. However, the banding of fertilizer N at planting at the N_{rec} treatment alleviated this potential lack of N availability to some extent, increasing N availability to the growing crop. Increased N application plus effective placement can therefore be a management option if similar cropping scenarios develop in a production system.

Burning of residues is another short-term option to prevent N immobilization and to aid soil cultivation and seeding practices. Burning of crop residues can result in nutrient losses as a result of convective transfer of ash, with subsequent losses increased by the action of wind and water (Kumar & Goh, 2000). Simultaneous losses of C, S, and N have been reported on residue burning. This practice may however show adverse effects on crop yields and soil quality (soil C and N) if continued indefinitely (Rasmussen & Parton, 1984). Thus, burning removes above ground crop residue, causes losses of nutrients contained in residue, returns less C and N to the soil, thereby limiting growth of microbial populations leading to a lower overall microbial activity in the soil (Biederbeck *et al.*, 1980). A significant amount of N can be returned to the soil by incorporation of crop residue. Burning of residue can lose a major part of this N, and the beneficial effect of adding organic residues to the soil is also lost.

Another alternative to prevent N immobilization of available soil mineral N is to leave crop residue at the soil surface without incorporation as in reduced and no-tillage systems. This provides a favourable environment for soil and surface dwelling microorganisms, because of reduced water loss, ameriolation of temperature extremes and fluctuations, and the presence of a relatively continuous substrate for decomposing organisms (Wells, 1984; Kumar & Goh, 2000).

Tillage influences soil organic matter through three major actions: the change in soil climate, the incorporation of organic matter, and the periodical disruption of soil structure (Balesdent *et al.*, 2000; Addiscott & Dexter, 1994). Tillage affects soil climate and thereby microbial activity in the soil. The presence or absence of mulch/organic matter is mainly involved, as well as the decrease in soil temperature, and increase in soil water content in no-tillage systems. Stemmer *et al.*, (1999) stated that cultivation (ploughing) decreases the organic matter content of surface soil layers by incorporating crop residues and accelerating decomposition by microbial attack as a result of aggregate breakdown. Soil cultivation in this study decreased measured crop residues at planting. The physical breakdown of the residue by the cultivation action, together with the aeration and mixing of the residue into the soil increased microbial activity, and hence increased immobilization of soil mineral N in the decomposition process (Addiscott & Dexter, 1994). Although different amounts of crop residue were added during the two growing seasons at the three sites, decomposition proceeded rapidly during the summer fallow period, and at the following harvest relatively small amounts of residue remained in the cultivation zone.

In addition to crop residues remaining, no-tillage systems also affects soil microbial populations, by promoting C accumulation at the soil surface due to a lack of incorporation of these residues (Wells, 1984; Kumar & Goh, 2000). Conventional cultivation systems incorporates crop residues, encourages the decomposition of native soil organic material, and thereby a reduction in available substrate (Tisdale *et al.*, 1993; Goh & Haynes, 1986). The balance between these two opposing occurrences will largely determine whether the microbial biomass aggregation stability would increase or decrease (Haynes & Francis, 1993). Stroo *et al.*, (1989) found that crop residues disappeared when little microbial activity could be expected because of low soil moisture and dry residues. These authors assumed that the losses must be non-microbial, with the most likely possibility being physical disintegration beyond removal by macrofauna and wind. This physical disintegration can be a factor during soil cultivations when the soil layers and crop residue are dry, and thus renders the residue more susceptible to removal by the wind.

Residual soil mineral N content increases in continuous no-tillage production systems, despite the increased potential for both leaching and denitrification of NO_3^-. This increased residual soil mineral N results from the increased concentration of organic residues near the soil surface. The mineralization of this pool of organic N is slower in no-tillage systems resulting in an increased residual soil mineral N content over time, although only gradually available to a crop in any one cropping year. Therefore as organic soil N resulting from the accumulation of residues due to the no-tillage system is built up, a new steady-state equilibrium between immobilization and mineralization of N is reached. This results in higher soil mineral N availability, thereby reducing fertilizer N inputs (Wells, 1984). In the short term, higher N requirements is however needed in no-tillage systems compared to conventional practices, because of the increased immobilization of soil mineral N due to the added organic residues in the surface soil layer. Potential losses are also higher from the no-tillage system because of higher soil water retention, that can result in higher denitrification losses because of the higher organic residue content in the surface soil layers (Tisdale *et al.*, 1993).

Farmers utilize fertilizer N mainly to increase wheat yields, improve grain quality and economic returns. Recommendations of optimal levels of fertilizer N are conditioned by the amount of available mineral N in the soil profile (Habey *et al.*, 1983), the result of N dynamics during the fallow period. The major problems in field balance studies of N are the uncertainty of determining small changes in the large pool of soil organic N, the difficulty of measuring leaching losses, and the unaccounted portion of the balance usually attributed to gas evolution (Broadbent, 1981).

SUMMARY AND CONCLUSIONS

Wheat production in summer rainfall production areas is potentially risky because of the fluctuating occurrence and distribution of annual and in-season rainfall. Temperature extremes also occur during the growing season influencing crop growth and subsequently yields. Excluding available soil water, N is the next most limiting factor in dryland production (Campbell *et al.*, 1993), but the ultimate response to applied N is modified by environmental conditions, in particular rainfall, temperature and soil N fertility. The majority of soils in South African wheat producing areas are inherently low in nitrogen (N) and need additional N for economically successful wheat production. This current scenario is mainly due to the long history of cultivation. Wheat yields have a tendency to fall with increasing periods of cultivation, particularly in monoculture cropping systems (Dalal & Meyer, 1986; Doyle & Holford, 1993).

The aim of this study was to investigate the effects of applied N on biomass development, N concentration of the relative plant tissues, calculated N uptake, yield and grain protein during two consecutive growing seasons in a fallow-wheat-wheat cropping system. The moderating effects of soil mineral N, soil water availability and environmental conditions on these growth parameters were also evaluated.

Trial sites in the major wheat production areas of the summer rainfall region differing in yield potential, due to differences in long-term average rainfall, were selected. Soil mineral N and soil water content were measured at planting, as well as representative above ground biomass measurements at agronomically important growth stages during the growing season. Total plant N uptake was calculated with the use of the N concentration values of the sampled biomass.

Climatic data for the localities indicated differences in total rainfall and its distribution and in temperatures during the study period which affected crop development, yield and grain protein. At Bethlehem, above average rainfall was measured in the 1997 growing season (459.1 mm compared to 332.6 mm long-term average), and 584.6 mm in 1998, although 270 mm occurred late in the growing season (November). At Kroonstad average rainfall was measured in-season in 1997 (108.6 mm compared to long-term average of 106 mm), but 269 mm occurred late in the growing season of 1998. At Petrusburg, below average in-season rainfall of 115.9 mm was measured in 1997 compared to the long-term value of 176.3 mm. Linked to above average aerial temperatures during the growing season, this depressed the yield potential. A total of 204.9 mm was measured in-season in 1998, but with 151 mm measured late in the growing season, this distribution pattern limited yields.

During the relatively long fallow period preceding the start of the trials, high levels of available soil water and mineral N were accumulated at all sites. Soil water content was 81.7% at Bethlehem, 69.6% at Kroonstad, and 78.2% of DUL at Petrusburg in 1997 respectively. Although comparable total soil profile water contents to 1997 were measured in 1998 at all three sites, the cultivation zone (0-400 mm) had a lower soil water content, posing the risk of reduced germination, emergence and early growth. This was attributed to the erratic rainfall distribution during the fallow period which did not allow effective soil cultivation management and subsequent soil water conservation.

The accumulation of soil water and mineral N was enhanced by the duplex soil nature of the soils found at Bethlehem and Kroonstad, where an initial soil mineral N of 301.6 and 267.4 kg N ha^{-1} respectively were measured. A lower level of 187 kg N ha^{-1} soil mineral N was measured at Petrusburg at planting in 1997, due to lower overall fertilizer and resultant crop residue inputs, linked to probable N losses via leaching beyond the measurement depth. Soil mineral N was lower at planting in 1998 compared to 1997, with 196.3 and 139.0 kg N ha^{-1} at Bethlehem and Kroonstad respectively, and 134.9 kg N ha^{-1} at Petrusburg. In addition to the overall lower N, there was a lower soil mineral N availability in the upper soil layers to the crop in 1998 due to undecomposed residue in the cultivation zone immobilizing soil mineral N during decomposition. The shortened fallow period between successive crops also decreased the time available for potential mineralization and accumulation of soil mineral N, further restricted by the low soil water content in the cultivation zone. Distribution of soil mineral N showed notable amounts in the 600-1200 mm soil layers, with limited changes during the trial period. This limited use of deep soil mineral N is linked to the low root exploration of these soil layers (10-15% of total root distribution). Measured soil mineral N during the two growing seasons indicated a general decrease in mineral N at all three sites on the cropped treatments, with the fallow treatment following a similar trend at Bethlehem, but with marginal changes measured at Kroonstad and Petrusburg.

The lower levels of soil mineral N availability at planting reduced initial growth, N accumulation, yield, and grain protein percentage without additional fertilizer N. With this cropping scenario in the second season, N fertilizer application overcame the effect of reduced N availability on crop growth and N accumulation to some extent. It should, however, be noted that this practice also increases the risk of crop failure because the enhanced growth due to N application results in increased soil water depletion early in the growing season.

The development pattern of plant components and cumulative biomass and thus the response to applied N, were relatively similar across sites in 1997, although the magnitude of the response varied. Response to applied N was depressed during 1998 owed to the lower soil water content in the cultivation zone at planting restricting early growth and development. Biomass accumulation at Petrusburg in 1997 reached a plateau earlier in the growing season than at Bethlehem and Kroonstad. Petrusburg and Kroonstad showed a lower but similar pattern of biomass development in 1998 to that in 1997. The amount and distribution of rainfall during the growing season affected growth and biomass accumulation, with rainfall late in the season either enhancing growth (Bethlehem 1998), increasing tiller N percentage at harvest (Petrusburg 1998), or having no significant effect (Kroonstad 1998) depending on the crop development stage at that time.

Nitrogen application significantly increased N concentrations in measured plant components compared to the control. Nitrogen concentrations of plants in control treatments were often in the deficiency range. Nitrogen concentrations of tillers and leaves decreased during the growing season due to a dilution effect of growth and biomass accumulation, while ear N concentration increased from ear emergence to maturity because of translocation of N from vegetative plant parts. Similarly, N application increased average grain protein percentage above that of the control, although mean values were lower in 1998 (11.58%) than in 1997 (11.72%). Bethlehem and Kroonstad showed lower values than Petrusburg. This was also linked to the lower percentage of total above ground N that was found in the grain in 1998, and reflected the reduced supply of soil mineral N.

Mean total N uptake by plants was on average lower in the control (38.15 kg N ha^{-1}) compared with N application (52.82 kg N ha^{-1}), with lower values being measured in 1998 (34.20 kg N ha^{-1}) than in 1997 (56.77 kg N ha^{-1}). Bethlehem and Kroonstad showed similar N uptake values in 1997, but at Petrusburg values were lower. Nitrogen uptake values were higher in 1998 at Petrusburg, but lower at Bethlehem and Kroonstad. Uptake of N continued during the late part of the growing season at Bethlehem and Petrusburg. This mirrored the pattern of biomass development and was attributed to favorable climatic and soil water conditions late in the growing season.

Higher grain yields were produced in 1997 (1.838 t ha^{-1}) compared to 1998 (0.980 t ha^{-1}). The greater grain yields in 1997 were attributed to accumulated soil water overcoming the negative effects of high temperatures and irregular rainfall within the growing season, and high soil mineral N accumulation favoring plant growth and yield potential development. There was a significant grain yield response to applied N at Bethlehem and Kroonstad in both cropping years, but no significant response at Petrusburg where low yields were produced. The relative response to applied N increased dramatically in 1998, although mean yield levels were lower, with the response being 64% at Bethlehem and 32.9% at Kroonstad compared to on average of 5.1% in 1997.

From the calculated response functions, soil water content at planting, soil mineral N content at planting, in-season rainfall, and added fertilizer N were the main variables that contributed significantly to the explanation of variation in grain protein percentage and plant N uptake at harvest. These variables contributed 98% to the explanation of grain protein percentage. This combined effect was also evident from multivariate analysis where soil mineral N, applied fertilizer, and soil water content explained 87% of variation in yields, with in-season rainfall only contributing 4%.

During the fallow period following the two cropping seasons, soil cultivation and to a lesser extent rainfall events, induced sequences of mineralization followed by nitrification. The incorporation of crop residue with a C:N ratio of above 73 in the cropped treatments resulted in immobilization of available soil mineral N. Rainfall distribution affected soil cultivation and crop residue decomposition during the fallow period. The ratios of NH_4^+:NO_3^- indicated similar values over the study period, with the relative ratios changed by crop N uptake, mineralization and nitrification as induced by rainfall and soil cultivation.

Undecomposed residue in the cultivation layer at planting appeared to affect the availability of soil mineral N to the growing crop, the response to applied N and therefore grain yields. At planting in 1998, undecomposed crop residue amounted to 53.6% at Bethlehem, 32.5% at Kroonstad and 46.9% at Petrusburg of the added residue at harvest in 1997. The progress of decomposition of added residue is linked to rainfall and cultivation practices during the fallow period. To decrease production risks for the second crop, soil water accumulation during the fallow period must be optimized and synchronized with effective soil cultivation practices. These practices will increase potential decomposition of crop residue, enabling recycling of nutrients, and accumulation of residual soil mineral N and soil water, and thus reduce extensive N immobilization during the growing season. Another alternative is to adapt the crop rotation system, lengthening the fallow period allowing extended time for effective residue and cultivation management and soil water conservation.

The current N fertilizer recommendations for dryland wheat production in the summer rainfall region were compiled using response curves calculated from fertilizer N calibration trials over time, and are based on approximations of the average yield potential for specific conditions and regions (Anon., 1998). In future the variables, soil water, soil mineral N content and rainfall should be included in N recommendation systems, aimed at increasing the accuracy of growth and yield predictions, and hence N fertilizer applications for specific target yields and grain quality requirements.

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Appendix 3.1: Soil analysis values for measured soil layers at Bethlehem (1997)

Soil layer (mm)	pH(KCl)	se ±	P(Bray1) (mg kg^{-1})	se ±	K (mg kg^{-1})	se ±	Ca (mg kg^{-1})	se ±
0-50	5.3	0.01	13.6	2.0	169.6	13.9	639	57
50-200	5.3	0.01	9.1	0.9	150.6	15.3	692	86
200-400	5.2	0.01	3.3	0.8	100.1	10.0	720	81
400-600	5.3	0.13	1.6	0.5	98.0	11.7	755	74
600-900	5.4	0.01	1.1	0.2	132.7	18.3	841	66
900-1200	5.4	0.01	1.5	0.9	147.9	18.0	844	103

Soil layer (mm)	Mg (mg kg^{-1})	se ±	Na (mg kg^{-1})	se ±	Total N (%)	se ±	Clay (%)	se ±
0-50	140.4	11.3	4.9	1.5	0.056	0.001	12.5	0.8
50-200	146.8	14.4	4.7	1.8	0.061	0.003	14.9	0.9
200-400	183.7	19.1	6.9	1.8	0.053	0.001	21.1	1.8
400-600	275.0	52.4	10.8	1.8	0.046	0.002	29.0	2.7
600-900	365.0	45.2	17.1	4.8	0.050	0.004	34.1	2.6
900-1200	347.0	36.0	18.8	5.7	0.055	0.002	35.8	1.3

Soil layer (mm)	Organic carbon (%)	se ±	CEC (cmol^{+} kg^{-1})	se ±
0-50	0.45	0.01	4.81	0.36
50-200	0.42	0.03	5.08	0.43
200-400	0.36	0.07	5.41	0.51
400-600	0.32	0.06	6.35	0.61
600-900	0.19	0.03	7.64	0.78
900-1200	0.26	0.02	7.55	0.85

Appendix 3.2: Soil water limits (drained upper limit – DUL, lower limit – LL, and plant extractable soil water – PESW in mm) and bulk density measurements at Bethlehem, Kroonstad, and Petrusburg

Bethlehem

Soil layer (mm)	DUL (mm)	LL (mm)	PESW (mm)	Bulkdensity (g cm^{-3})			
				1997	se ±	1998	se ±
0-50	12.5	3.2	9.3	1.60	0.01	1.59	0.02
50-200	38.9	9.9	29.0	1.65	0.01	1.71	0.01
200-400	58.2	26.7	31.5	1.63	0.02	1.74	0.02
400-600	72.2	37.9	34.3	1.50	0.03	1.62	0.02
600-900	93.8	75.6	18.2	1.57	0.01	1.76	0.02
900-1200	95.6	68.1	27.5	1.68	0.01	1.75	0.01
Total	371.2	221.4	149.8				

Kroonstad

Soil layer (mm)	DUL (mm)	LL (mm)	PESW (mm)	Bulkdensity (g cm^{-3})			
				1997	se ±	1998	se ±
0-50	8.8	3.8	5.0	1.50	0.03	1.51	0.01
50-200	39.9	17.2	22.7	1.55	0.01	1.78	0.03
200-400	43.4	22.2	21.2	1.60	0.01	1.74	0.03
400-600	63.8	42.4	21.4	1.65	0.01	1.63	0.01
600-900	97.4	48.0	49.4	1.70	0.08	1.74	0.04
900-1200	96.4	54.4	42.0	1.70	0.08	1.77	0.07
Total	349.7	188.0	161.7				

Appendix 3.2: continued

Petrusburg

Soil layer (mm)	DUL (mm)	LL (mm)	PESW (mm)	Bulkdensity (g cm^{-3}) 1997	se ±	1998	se ±
0-50	8.4	1.7	6.7	1.60	0.01	1.60	0.01
50-200	26.6	2.3	24.3	1.65	0.03	1.74	0.02
200-400	30.0	10.6	19.4	1.71	0.02	1.75	0.01
400-600	35.5	14.2	21.3	1.60	0.02	1.64	0.01
600-900	57.3	23.9	33.4	1.65	0.01	1.64	0.01
900-1200	58.6	24.4	34.2	1.65	0.02	1.69	0.03
Total	216.4	77.1	139.3				

Appendix 3.3: Soil analysis values for measured soil layers at Bethlehem (1998)

Soil layer (mm)	pH(KCl)	se ±	P(Bray 1) (mg kg^{-1})	se ±	K (mg kg^{-1})	se ±	Ca (mg kg^{-1})	se ±	Mg (mg kg^{-1})	se ±	Na (mg kg^{-1})	se ±	CEC (cmol^{+} kg^{-1})	se ±
0-50	5.33	0.033	14.3	0.5	169.2	14.5	552.3	4.5	138.6	5.9	16.3	3.5	4.41	0.43
50-200	5.23	0.034	8.3	1.1	143.0	21.7	583.8	40.0	146.7	13.2	10.3	0.4	4.54	0.40
200-400	5.17	0.030	2.8	0.5	82.1	4.5	663.8	27.0	198.8	54.3	13.8	2.4	5.23	0.49
400-600	5.20	0.058	1.8	0.3	86.3	15.4	672.3	9.5	196.1	62.6	17.7	3.8	5.28	0.48
600-900	5.32	0.017	1.5	0.3	99.1	16.7	703.8	11.0	350.2	63.1	25.2	4.8	6.78	0.61
900-1200	5.43	0.088	1.1	0.3	137.0	20.1	738.8	59.0	431.2	40.1	21.1	2.1	7.70	0.74

Appendix 3.4: Soil analysis values for measured soil layers at Kroonstad (1997)

Soil layer (mm)	pH(KCl) (mg kg^{-1})	se ±	P(Bray 1) (mg kg^{-1})	se ±	K (mg kg^{-1})	se ±	Ca (mg kg^{-1})	se ±	Mg (mg kg^{-1})	se ±	Na (mg kg^{-1})	se ±
0-50	4.7	0.3	17.1	2.1	163.1	20.5	227	45.8	85.2	8.9	5.1	2.6
50-200	4.5	0.2	14.8	2.4	151.8	22.8	219	32.1	75.2	8.5	4.1	1.9
200-400	4.6	0.1	3.8	0.8	167.9	68.6	364	91.7	190.0	54.8	13.0	5.3
400-600	4.9	0.2	2.1	0.9	306.0	46.7	856	197.0	394.0	73.7	53.7	13.6
600-900	5.5	0.2	1.2	0.4	411.0	50.6	1408	111.4	617.0	36.0	41.1	25.5
900-1200	5.8	0.7	3.1	1.2	494.0	73.7	2159	118.8	761.0	18.3	58.8	12.2

Soil layer (mm)	Acid saturation %	se ±	Total N (%)	se ±	Clay (%)	se ±	Organic carbon (%)	se ±	CEC (cmol^{+} kg^{-1})	se ±
0-50	1.35	1.08	0.035	0.001	7.4	0.6	0.16	0.02	2.31	0.22
50-200	2.84	1.24	0.037	0.002	7.3	0.7	0.28	0.04	2.18	0.22
200-400	1.02	0.73	0.036	0.002	9.1	1.3	0.29	0.07	3.92	0.37
400-600	0.09	0.16	0.049	0.004	25.5	0.6	0.23	0.03	8.56	0.88
600-900	0	0	0.057	0.002	29.1	2.8	0.21	0.01	13.81	1.20
900-1200	0	0	0.038	0.002	28.9	0.1	0.13	0.02	14.98	1.31

Appendix 3.5: Soil analysis values for measured soil layers at Kroonstad (1998)

Soil layer (mm)	pH(KCl) (mg kg^{-1})	se ±	P (Bray 1) (mg kg^{-1})	se ±	K (mg kg^{-1})	se ±	Ca (mg kg^{-1})	se ±	Mg (mg kg^{-1})	se ±
0-50	4.5	0.1	17.2	0.4	179.4	11.6	224.6	13.5	69.3	6.5
50-200	4.2	0.1	20.5	3.5	144.8	7.7	231.4	8.7	67.5	2.9
200-400	4.6	0.1	2.8	0.9	248.8	84.9	387.9	12.9	128.4	9.9
400-600	4.9	0.1	1.3	0.1	395.2	27.3	1106.6	53.6	442.9	37.6
600-900	5.7	0.1	1.4	0.1	347.6	96.4	1217.3	49.9	534.2	39.8
900-1200	5.8	0.1	1.2	0.1	361.0	81.4	1256.0	36.7	561.0	42.1

Soil layer (mm)	Na (mg kg^{-1})	se ±	Acid saturation (%)	se ±	CEC (cmol^{+} kg^{-1})	se ±
0-50	2.5	1.0	3.5	1.5	2.24	0.21
50-200	5.8	0.5	7.6	1.9	2.27	0.22
200-400	14.4	3.9	1.7	0.6	3.76	0.37
400-600	92.3	8.7	0	0	10.61	1.09
600-900	160.1	19.8	0	0	12.09	0.93
900-1200	161.2	21.2	0	0	12.54	0.99

Appendix 3.6: Soil analysis values for measured soil layers at Petrusburg (1997)

Soil layer (mm)	pH(KCl)	se ±	P (Bray1) (mg kg^{-1})	se ±	K (mg kg^{-1})	se ±	Ca (mg kg^{-1})	se ±	Mg (mg kg^{-1})	se ±	Na (mg kg^{-1})	se ±
0-50	4.3	0.1	13.6	3.4	143.5	14.8	284.7	27.3	94.2	15.4	5.6	1.7
50-200	4.2	0.1	14.7	2.4	155.5	14.9	307.0	29.6	101.9	17.9	5.0	1.4
200-400	4.6	0.2	6.5	1.9	192.3	14.7	424.0	56.4	173.0	39.3	5.8	1.6
400-600	4.9	0.2	1.9	0.7	208.5	19.6	557.0	7.5	280.0	36.6	5.8	1.2
600-900	5.3	0.2	0.9	0.4	161.1	27.4	595.0	54.7	333.7	27.6	6.2	1.6
900-1200	5.5	0.2	0.8	0.3	134.9	20.7	610.0	69.8	393.9	30.1	6.2	1.7

Soil layer (mm)	Acid saturation (%)	se ±	Total N %	se	Clay (%)	se ±	Organic carbon (%)	se ±	CEC (cmol^{+} kg^{-1})	se ±
0-50	5.38	2.08	0.026	0.001	6.91	0.228	0.20	0.03	2.73	0.270
50-200	5.61	2.13	0.023	0.002	7.00	0.262	0.19	0.03	2.96	0.286
200-400	1.43	0.87	0.028	0.002	10.23	0.664	0.18	0.02	4.13	0.399
400-600	0.14	0.26	0.032	0.002	14.75	0.795	0.20	0.03	5.74	0.588
600-900	0	0	0.031	0.001	14.63	0.538	0.21	0.01	6.17	0.604
900-1200	0	0	0.028	0.002	17.22	1.075	0.21	0.02	6.68	0.578

Appendix 3.7: Soil analysis values for measured soil layers at Petrusburg (1998)

Soil layer (mm)	pH(KCl)	se ±	P (Bray 1) (mg kg^{-1})	se ±	K (mg kg^{-1})	se ±	Ca (mg kg^{-1})	se ±	Mg (mg kg^{-1})	se ±
0-50	4.2	0.1	15.4	0.9	139.6	3.1	258.6	7.9	87.5	2.1
50-200	4.2	0.1	15.5	1.0	151.9	7.2	251.1	11.8	87.7	1.5
200-400	4.4	0.1	6.4	1.2	187.8	10.1	399.6	34.8	153.9	15.9
400-600	4.8	0.1	1.3	0.1	201.7	4.2	536.9	17.5	257.6	7.8
600-900	5.2	0.1	1.0	0.2	149.6	5.6	547.5	24.9	293.1	12.6
900-1200	5.3	0.1	0.8	0.1	122.3	3.9	562.3	15.1	307.5	11.9

Soil layer (mm)	Na (mg kg^{-1})	se ±	Acid saturation (%)	se ±	CEC (cmol^{+} kg^{-1})	se ±
0-50	9.3	3.1	6.5	0.6	2.41	0.23
50-200	5.1	1.9	6.6	0.2	2.39	0.21
200-400	7.6	2.5	3.8	1.5	3.78	0.32
400-600	10.4	3.9	0.6	0.6	5.38	0.43
600-900	6.6	2.2	0	0	5.57	0.47
900-1200	5.8	2.9	0	0	5.69	0.48

Appendix 3.8 Soil water content per designated layer (mm from surface) measured at Bethlehem, Kroonstad, and Petrusburg at planting in 1997

Locality	Soil depth (mm)	Soil water (mm)	se ±	% of DUL*
Bethlehem	0-50	6.80	1.15	54.4
	50-200	19.00	3.53	48.9
	200-400	56.71	12.19	97.4
	400-600	68.01	10.07	94.3
	600-900	61.31	14.35	65.3
	900-1200	91.25	16.24	96.2
Total	**0-1200**	**303.08**	**53.28**	**81.7**
Kroonstad	0-50	8.25	1.76	94.3
	50-200	25.29	74.27	63.5
	200-400	42.14	7.71	97.1
	400-600	44.68	9.87	70.0
	600-900	62.19	14.37	63.8
	900-1200	60.64	11.95	62.3
Total	**0-1200**	**243.19**	**36.14**	**69.6**
Petrusburg	0-50	2.64	0.39	31.4
	50-200	23.36	3.92	87.7
	200-400	27.33	3.71	91.0
	400-600	28.98	4.58	81.6
	600-900	44.03	8.72	76.8
	900-1200	43.21	8.07	73.8
Total	**0-1200**	**169.55**	**21.70**	**78.2**

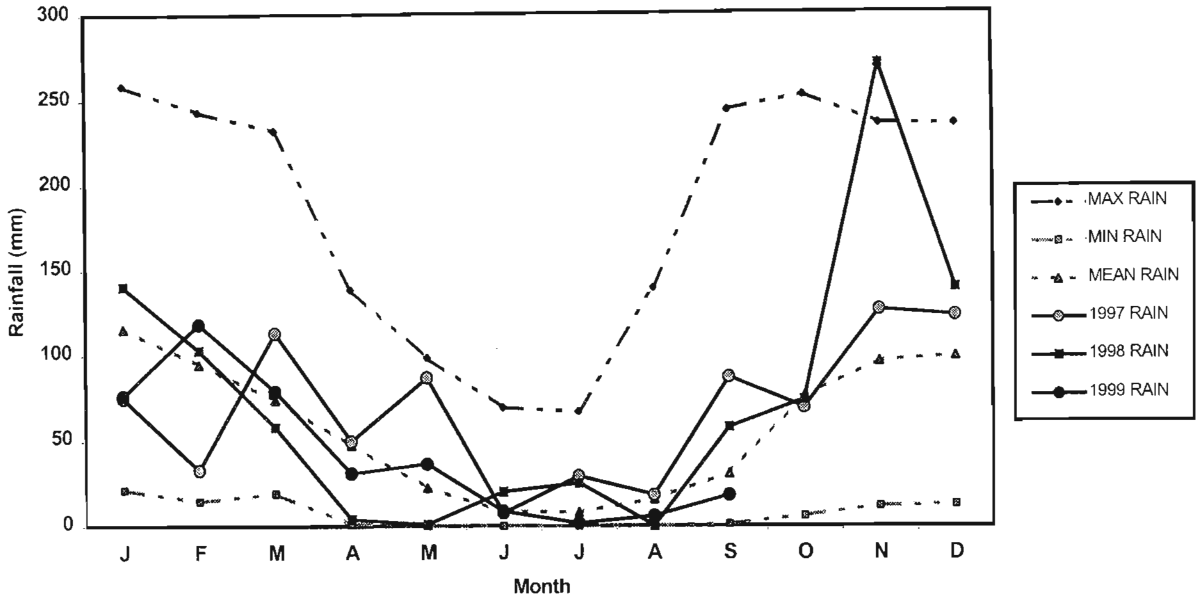
* DUL – drained upper limit

Appendix 3.9 Soil water content per designated layer (mm from surface) measured at Bethlehem, Kroonstad, and Petrusburg at planting in 1998

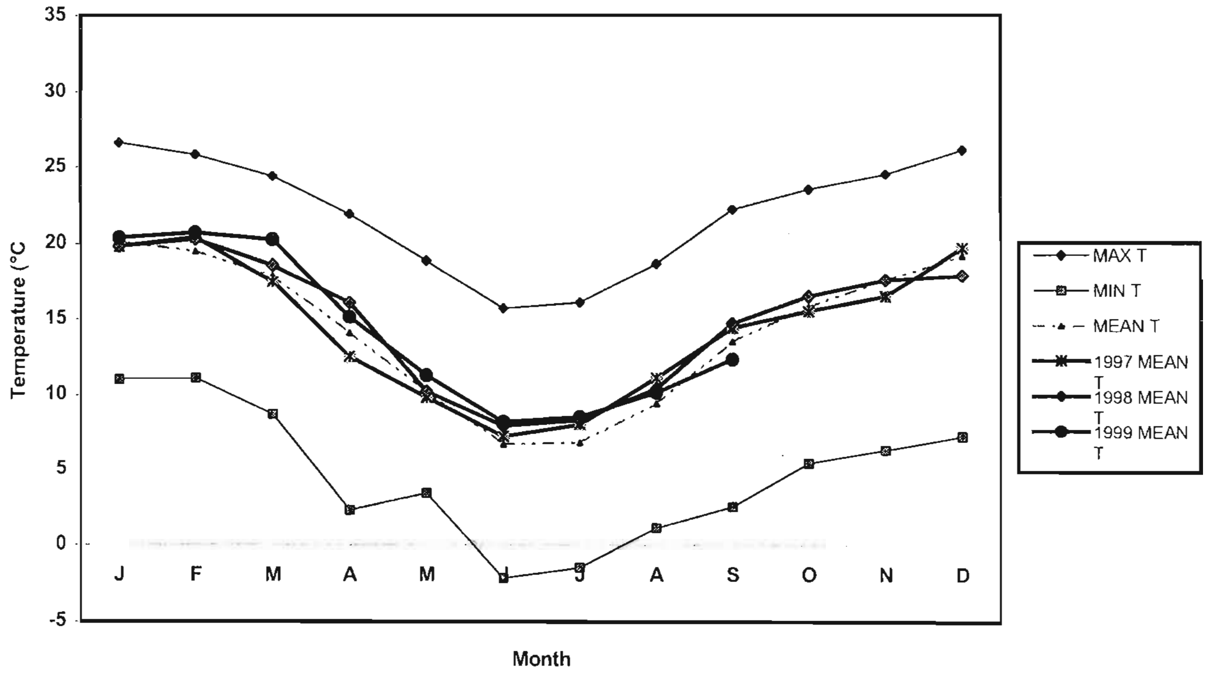
Locality	Soil depth (mm)	Soil water (mm)	se ±	% of DUL*
Bethlehem	0-50	8.74	2.05	69.9
	50-200	32.33	6.32	83.2
	200-400	61.23	13.94	105.2
	400-600	61.52	11.81	85.3
	600-900	105.34	25.49	112.2
	900-1200	98.74	22.22	103.3
Total	**0-1200**	**367.90**	**68.43**	**98.9**
Kroonstad	0-50	4.40	0.70	50.3
	50-200	24.43	4.13	61.3
	200-400	52.01	12.64	119.8
	400-600	69.42	15.56	108.8
	600-900	96.41	17.26	98.9
	900-1200	101.36	23.41	105.2
Total	**0-1200**	**348.03**	**72.39**	**99.5**
Petrusburg	0-50	1.65	0.34	19.6
	50-200	7.88	1.39	29.6
	200-400	27.63	4.61	92.0
	400-600	29.65	5.84	83.5
	600-900	45.65	9.31	79.6
	900-1200	50.69	11.20	86.6
Total	**0-1200**	**163.15**	**28.71**	**75.2**

* DUL – drained upper limit

Appendix 3.10 Long-term and annual aerial temperatures (°C) and rainfall (mm)

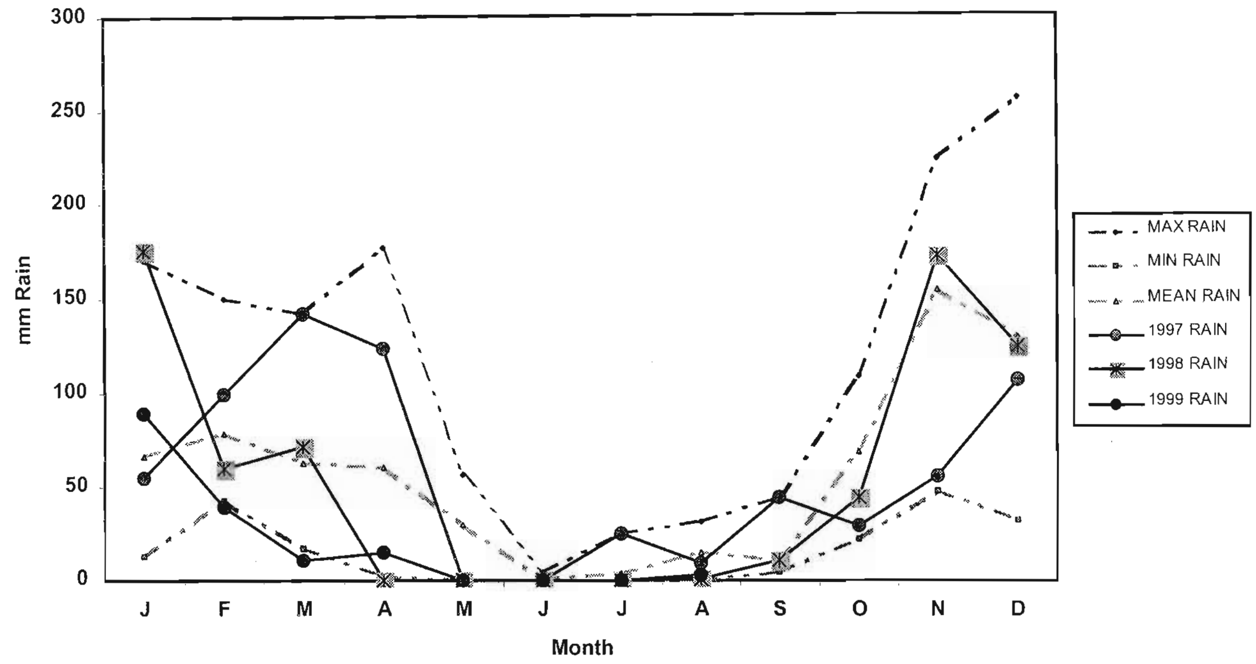


Rainfall measured at Bethlehem during 1997, 1998, and 1999

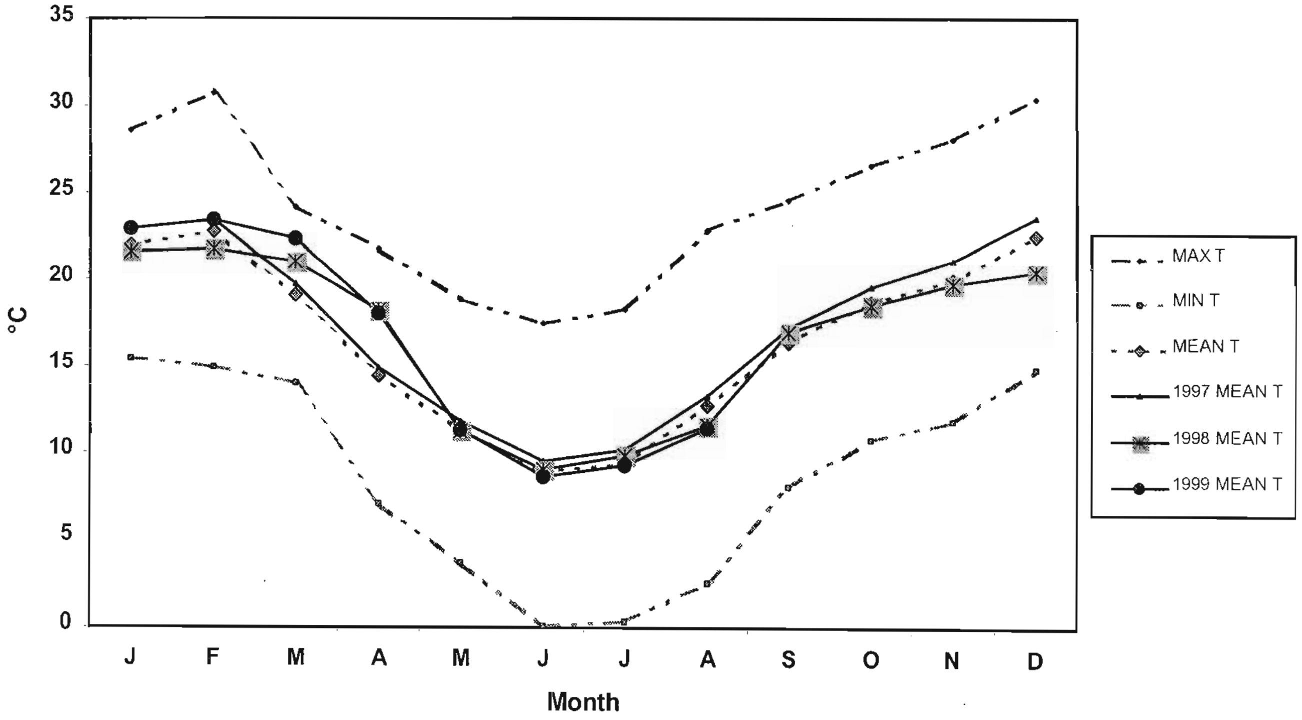


Mean aerial temperatures measured at Bethlehem during 1997, 1998, and 1999

Appendix 3.11 Long-term and annual aerial temperatures (°C) and rainfall (mm)

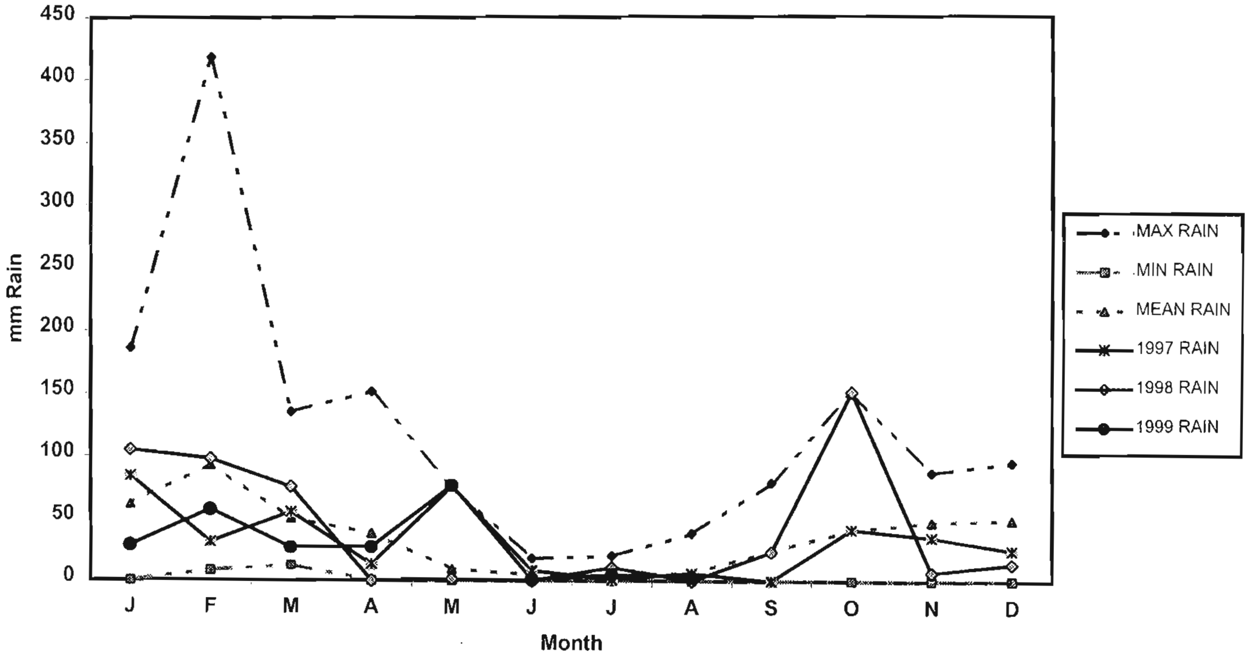


Rainfall measured at Kroonstad during 1997, 1998, and 1999

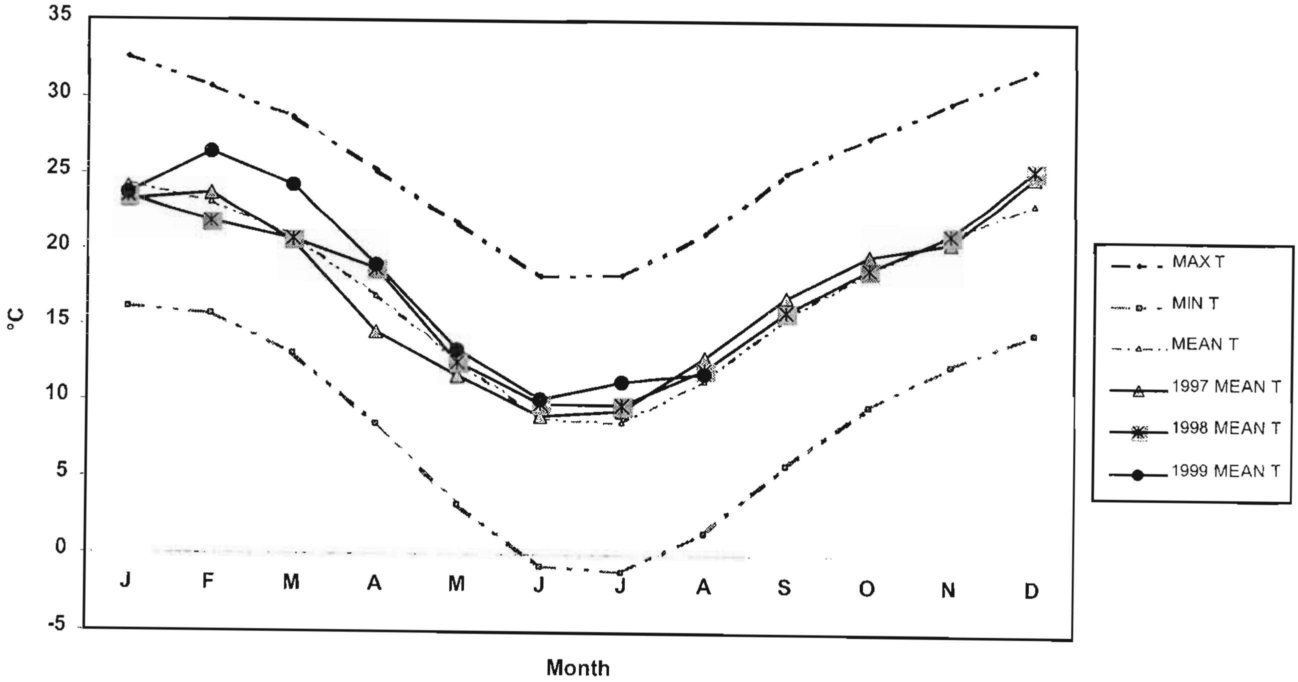


Mean aerial temperatures measured at Kroonstad during 1997, 1998, and 1999

Appendix 3.12 Long-term and annual aerial temperatures (°C) and rainfall (mm)

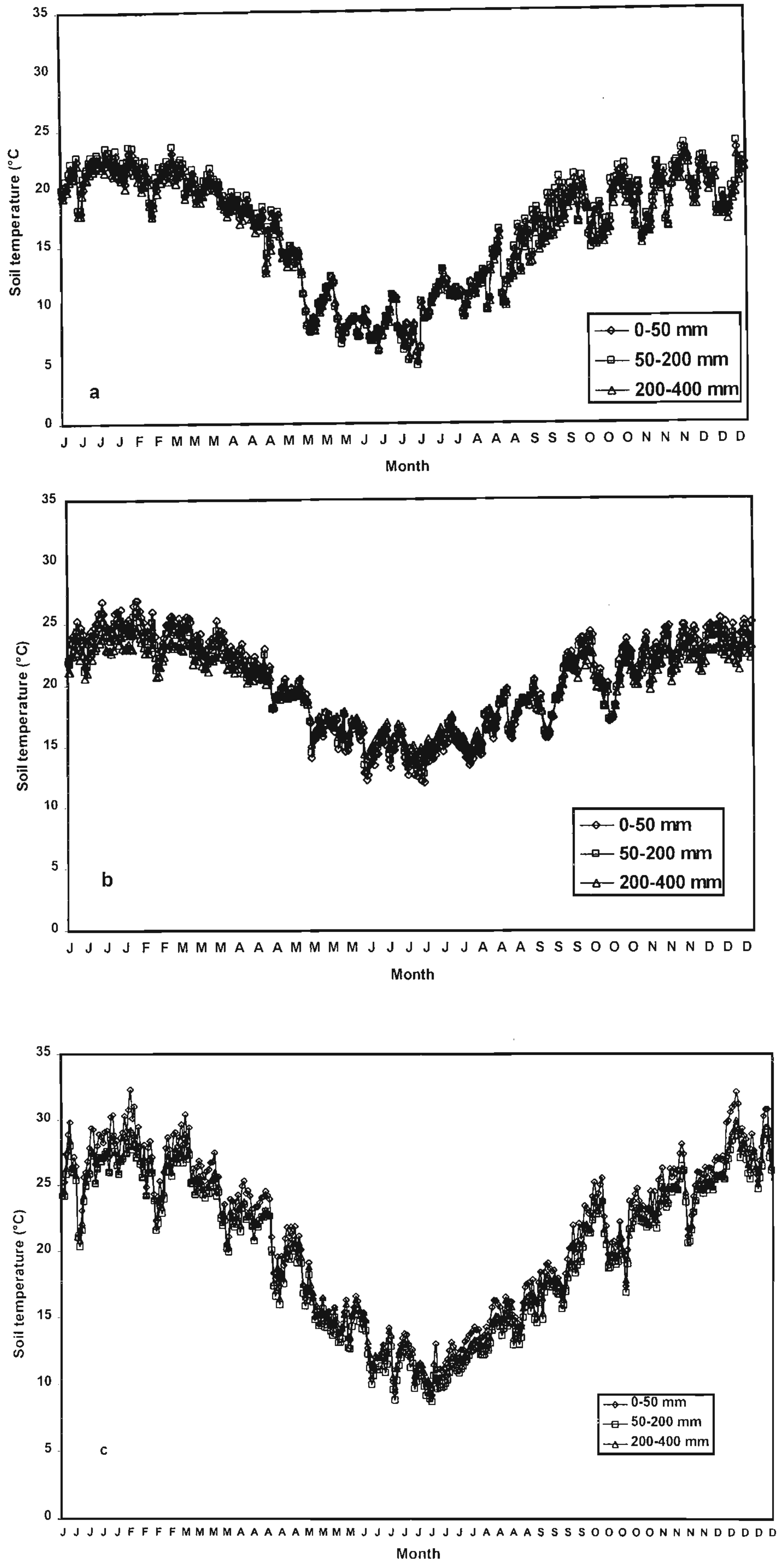


Rainfall measured at Petrusburg during 1997, 1998, and 1999



Mean aerial temperatures measured at Petrusburg during 1997, 1998, and 1999

Appendix 3.13 Mean soil temperatures (°C) measured at Bethlehem (a), Kroonstad (b) and Petrusburg (c)



Appendix 4.1 Regression coefficients and standard errors of fitted Gompertz* curves for cumulative biomass production at Bethlehem, Kroonstad, and Petrusburg in 1997 and 1998

Locality	Year	Treatment	R^2	*se* (observations)	Coefficients				F-value	F-probability
					B	M	C	A		
Bethlehem	1997	N_{ON}	97.1	52.6	0.02807*ns*	294.80*ns*	1065	12.3 *a*	78.31	<0.001
		se			*0.00847*	*7.49*	*206*	*50.2*		
		N_{rec}	91.1	114.0	0.04480*ns*	285.16*ns*	1016	28.0 *a*	24.81	0.005
		se			*0.02110*	*7.12*	*220*	*99.9*		
	1998	N_{ON}	99.6	9.32	0.01435*ns*	357.1*ns*	1167	2.56 *a*	538.72	<0.001
		se			*0.00493*	*35.8*	*648*	*7.50*		
		N_{rec}	98.9	24.5	0.01518*ns*	345.6*ns*	1626	5.4 *b*	213.86	<0.001
		se			*0.00743*	*44.2*	*1131*	*20.2*		
Kroonstad	1997	N_{ON}	98.5	39.6	0.06060*ns*	266.36*ns*	772.6	-1.3 *c*	109.32	0.009
		se			*0.01390*	*2.57*	*57.0*	*39.5*		
		N_{rec}	89.4	85.9	0.05700*ns*	269.99*ns*	618	-0.8 *d*	15.06	0.063
		se			*0.03500*	*7.70*	*134*	*85.2*		
	1998	N_{ON}	91.7	33.5	0.02000*ns*	236.9*ns*	347	0.1 *c*	23.03	0.014
		se			*0.01200*	*18.8*	*118*	*34.0*		
		N_{rec}	93.7	36.1	0.02040*ns*	218.9*ns*	404	-808 *cd*	28.62	0.010
		se			*0.01030*	*15.4*	*107*	*43.9*		

Appendix 4.1 continued

Locality	Year	Treatment	R^2	*se* (observations)	Coefficients				F-value	F-probability
					B	M	C	A		
Petrusburg	1997	N_{ON}	90.9	36.5	0.11850*ns*	264.39*ns*	284.7	27.4 *c*	34.37	<0.001
		se			*0.04500*	*3.07*	*32.2*	*25.8*		
		N_{rec}	88.7	51.8	0.12160*ns*	263.55*ns*	361.3	28.7 *c*	27.27	<0.001
		se			*0.05360*	*3.34*	*45.3*	*36.6*		
	1998	N_{ON}	93.4	30.7	0.02400*ns*	223.7*ns*	321.7	0.1 *c*	29.38	0.010
		se			*0.01150*	*14.1*	*76.4*	*30.0*		
		N_{rec}	95.4	29.3	0.02482*ns*	219.5*ns*	363.5	1.4 *c*	42.49	0.006
		se			*0.00965*	*11.1*	*66.6*	*28.8*		

* Gompertz curve: This curve is similar to a logistic curve, but is asymmetric about its point of inflection, i.e. the lower and upper halves are not mirror images (van Ark, 1995).

The general formulae: Y = A + C*EXP(-EXP(-B*(X-M))) where

Y = dependent variable
A + C = saturation value for y
M = inflection point
B = maximum growth rate at time M
-B*(X-M) = the growth function where x represents time

** Values followed by the same letter is not significantly different.

Appendix 4.2 Combined Analysis of variance

4.2a Combined Analysis of variance: Cumulative biomass production (g m^{-2}) at harvest

```
Source of variation     d.f.        s.s.        m.s.     v.r.   F pr.
YEAR.LOC.REP  stratum
YEAR                       1     723255.     723255.   425.42   <.001
LOC                        2    1130125.     565062.   332.37   <.001
YEAR.LOC                   2     342798.     171399.   100.82   <.001
Residual                  18      30602.       1700.     0.56

YEAR.LOC.REP .NLEVEL stratum
NLEVEL                     1     152117.     152117.    50.53   <.001
YEAR.NLEVEL                1       5310.       5310.     1.76   0.201
LOC.NLEVEL                 2      34239.      17119.     5.69   0.012
YEAR.LOC.NLEVEL            2      29247.      14624.     4.86   0.021
Residual                  18      54193.       3011.

Total                     47    2501886.
```

4.2b Combined Analysis of variance: Yield (t ha^{-1})

```
Source of variation     d.f.        s.s.        m.s.     v.r.   F pr.

YEAR.LOC.REP  stratum
YEAR                       1   8.842175    8.842175 1753.91   <.001
LOC                        2   8.801805    4.400903  872.95   <.001
YEAR.LOC                   2   4.729857    2.364929  469.10   <.001
Residual                  18   0.090745    0.005041    0.76

YEAR.LOC.REP .NLEVEL stratum
NLEVEL                     1   0.417002    0.417002    62.70   <.001
YEAR.NLEVEL                1   0.138071    0.138071    20.76   <.001
LOC.NLEVEL                 2   0.260590    0.130295    19.59   <.001
YEAR.LOC.NLEVEL            2   0.130270    0.065135     9.79   0.001
Residual                  18   0.119713    0.006651
Total                     47  23.530229
```

4.2c Combined Analysis of variance: Hectolitermass (kg hl^{-1})

```
Source of variation     d.f.        s.s.        m.s.     v.r.   F pr.

YEAR.LOC.REP  stratum
YEAR                       1     226.896     226.896   271.92   <.001
LOC                        2      60.070      30.035    35.99   <.001
YEAR.LOC                   2     164.110      82.055    98.34   <.001
Residual                  18      15.020       0.834     0.74

YEAR.LOC.REP .NLEVEL stratum
NLEVEL                     1       8.568       8.568     7.65   0.013
YEAR.NLEVEL                1       4.941       4.941     4.41   0.050
LOC.NLEVEL                 2       3.286       1.643     1.47   0.257
YEAR.LOC.NLEVEL            2       1.205       0.603     0.54   0.593
Residual                  18      20.165       1.120
Total                     47     504.261
```

Appendix 4.3a Calculated linear functions explaining variation in yields (t ha^{-1}) measured in 1997 and 1998 at Bethlehem, Kroonstad and Petrusburg (standard errors of coefficients in italics)

Intercept	Mineral soil N (kg N ha^{-1})	Fertilizer (kg N ha^{-1})	Soil water content (mm)	In-season rainfall (mm)	R^2	F-value
-0.5148	+ 0.00970				0.77	35.03 **
(0.03424)	*(0.00162)*					
-0.54747	0.009191	0.0115			0.85	25.41 **
(0.22985)	*(0.00142)*	*(0.0055)*				
-0.52637	+ 0.009221	+ 0.01183	- 0.00022		0.85	15.13 **
(0.41841)	*(0.001515)*	*(0.006217)*	*(0.00126)*			
-0.77257	+ 0.009607	+ 0.001408	+ 0.001735	- 0.001308	0.89	14.79 **
(0.4025)	*(0.00138)*	*(0.005738)*	*(0.00161)*	*(0.000766)*		

Example of calculated function: Soil mineral N- 200 kg N ha^{-1}, Fertilizer- 25 kg N ha^{-1}, Soil water content- 225mm, In–season rainfall- 200mm.

$y = -0.77257 +(0.009607*200) +(0.001408*25) +(0.001735*225) -(0.001308*200) = 1.312$ t ha^{-1}

Appendix 4.3b Calculated linear functions explaining variation in yields (t ha^{-1}) measured in 1997 and 1998 at Bethlehem, Kroonstad, and Petrusburg (standard errors of coefficients in italics) : division of parameters

Intercept	Mineral soil N (kg N ha^{-1})	In-season rainfall (mm) (planting-flagleaf)	Fertilizer (kg N ha^{-1})	Soil water content (mm)	In-season rainfall (mm) (flagleaf-harvest)	R^2	F-value
-0.5148	0.00961					0.78	35.03**
(0.3424)	*(0.0016)*						
-0.4241	0.00873	0.00103				0.79	16.29**
(0.4025)	*(0.00247)*	*(0.00213)*					
-0.6754	0.01002	-0.00105	0.0131			0.85	15.59**
(0.3733)	*(0.00225)*	*(0.00213)*	*(0.0067)*				
-0.8770	0.01055	-0.00182	0.0133	0.00059		0.86	10.37**
(0.8073)	*(0.00302)*	*(0.00351)*	*(0.00713)*	*(0.00204)*			
1.3950	-0.0000072	0.00983	0.00798	0.000261	-0.004618	0.96	30.21**
(0.7148)	*(0.00308)*	*(0.00346)*	*(0.00417)*	*(0.00114)*	*(0.00113)*		

Example of calculated function: Soil mineral N- 200 kg N ha^{-1}, Fertilizer- 25 kg N ha^{-1}, Soil water content- 225 mm, In–season rainfall (planting – flagleaf)-100 mm, In-season rainfall (flagleaf – harvest)- 100 mm.

$y = 1.3950 +(0.0000072*200) +(0.00984*100) +(0.00798*25) +(0.00026*225) –(0.00462*100) = 2.177$ t ha^{-1}

Appendix 4.4 Bethlehem: Root Measurements

Root length (mm cm^{-3})

	1997				1998			
Sampling depth (mm)	N_{0N}	N_{rec}	se	LSD	N_{0N}	N_{rec}	se	LSD
0-200	1.445	1.812	0.0609	0.274	1.39	2.11	0.246	ns
200-400	0.575	1.157	0.1217	0.548	0.96	1.10	0.202	ns
400-600	0.421	0.608	0.0340	0.153	0.75	1.01	0.240	ns
600-900	0.159	0.271	0.0275	ns	0.22	0.31	0.038	ns
900-1200	0.127	0.104	0.0113	ns	0.18	0.17	0.022	ns
Total	2.727	3.952	0.1114	0.511	3.50	5.02	0.298	ns

Root length (m ha^{-1})

	1997				1998			
Sampling depth (mm)	N_{0N}	N_{rec}	se	LSD	N_{0N}	N_{rec}	se	LSD
0-200	2890	3623	121.8	548.1	2772	4871	491.9	ns
200-400	1151	2313	243.4	1095.3	1921	2192	404.8	ns
400-600	841	1217	68.0	306.0	1499	2030	479.6	ns
600-900	477	813	82.5	ns	646	918	113.5	ns
900-1200	382	313	34.0	ns	550	511	66.5	ns
Total	5740	8279	243.3	1094.9	7393	10523	650.6	ns

Appendix 4.4 continued

Root weight (kg ha^{-1})

	1997				1998			
Sampling depth (mm)	N_{0N}	N_{rec}	se	LSD	N_{0N}	N_{rec}	se	LSD
0-200	32.7	46.5	4.54	ns	41.3	62.8	8.73	ns
200-400	12.3	30.7	2.61	11.75	20.6	26.9	3.87	ns
400-600	7.3	10.7	0.43	1.93	7.4	16.2	2.92	ns
600-900	3.9	9.4	1.49	ns	6.5	7.8	1.52	ns
900-1200	3.6	3.1	0.30	ns	7.4	8.2	1.60	ns
Total	59.7	100.2	7.10	31.95	83.3	121.9	7.39	33.26

Appendix 4.5 Kroonstad: Root Measurements

Root length (mm cm^{-3})

	1997				1998			
Sampling depth (mm)	N_{0N}	N_{rec}	se	LSD	N_{0N}	N_{rec}	se	LSD
0-200	1.110	1.830	0.1440	0.648	1.030	1.270	0.1700	ns
200-400	0.640	1.104	0.0719	0.324	0.479	0.787	0.0269	0.121
400-600	0.368	0.603	0.0499	0.225	0.438	0.405	0.0325	ns
600-900	0.144	0.250	0.0251	ns	0.146	0.204	0.0410	ns
900-1200	0.133	0.133	0.0088	ns	0.101	0.126	0.0322	ns
Total	2.39	3.92	0.1950	0.878	2.196	2.792	0.1203	0.541

Root length (m ha^{-1})

	1997				1998			
Sampling depth (mm)	N_{0N}	N_{rec}	se	LSD	N_{0N}	N_{rec}	se	LSD
0-200	2218	3666	287.9	1295.6	2064	2538	339.4	ns
200-400	1281	2209	143.7	646.7	958	1574	53.8	242.1
400-600	735	1205	99.8	449.1	876	811	64.9	ns
600-900	432	750	75.2	ns	438	613	123.0	ns
900-1200	400	399	26.3	ns	303	379	96.5	ns
Total	5065	8229	374.9	1687.1	4639	5914	21.0	94.5

Appendix 4.5 continued

Root weight (kg ha^{-1})

	1997				1998			
Sampling depth (mm)	N_{0N}	N_{rec}	se	LSD	N_{0N}	N_{rec}	se	LSD
0-200	56.0	68.0	16.80	ns	47.6	36.3	4.10	ns
200-400	16.3	25.5	3.07	ns	27.4	26.8	5.51	ns
400-600	9.08	11.71	0.179	0.806	16.8	19.5	1.95	ns
600-900	3.55	9.48	0.953	4.289	10.10	9.68	1.107	ns
900-1200	3.32	7.71	0.731	3.290	5.12	5.04	0.828	ns
Total	88	122	19.1	ns	107.1	97.4	6.68	ns

Appendix 4.6 Petrusburg: Root Measurements

Root length (mm cm^{-3})

	1997				1998			
Sampling depth (mm)	N_{0N}	N_{rec}	se	LSD	N_{0N}	N_{rec}	se	LSD
0-200	1.130	1.190	0.0477	ns	0.800	2.000	0.2440	1.098
200-400	0.774	0.714	0.1131	ns	0.531	0.969	0.0850	0.383
400-600	0.518	1.073	0.1337	ns	0.534	0.629	0.0601	ns
600-900	0.444	0.300	0.0489	ns	0.236	0.272	0.0438	ns
900-1200	0.0942	0.0881	0.0137	ns	0.167	0.189	0.0072	ns
Total	2.960	3.364	0.1030	ns	2.27	4.06	0.2370	1.067

Root length (m ha^{-1})

	1997				1998			
Sampling depth (mm)	N_{0N}	N_{rec}	se	LSD	N_{0N}	N_{rec}	se	LSD
0-200	2259	2381	95.3	ns	1605	4008	487.9	2195.60
200-400	1547	1428	226.2	ns	1061	1938	170.0	765.01
400-600	1035	2145	267.5	ns	1068	1258	120.2	ns
600-900	1333	899	146.7	ns	708	817	131.2	ns
900-1200	283	264	41.2	ns	501	567	21.5	ns
Total	6458	7117	183.0	ns	4943	8588	518.1	2331.51

Appendix 4.6 continued

Root weight (kg ha^{-1})

	1997				1998			
Sampling depth (mm)	N_{0N}	N_{rec}	se	LSD	N_{0N}	N_{rec}	se	LSD
0-200	28.4	31.6	4.56	ns	25.3	25.5	2.53	ns
200-400	14.6	12.9	1.52	ns	24.0	31.7	2.16	ns
400-600	6.13	9.03	1.204	ns	25.6	58.4	4.12	18.54
600-900	3.55	3.36	0.605	ns	14.8	15.5	1.48	ns
900-1200	1.712	2.598	0.0503	0.226	6.8	8.3	1.45	ns
Total	54.4	59.5	5.23	ns	96.5	134.5	3.58	16.11

Appendix 5.1 Nitrogen analysis and uptake measured at Bethlehem (1997)

Zadoks Growth stage 30

DOY 258	N_{0N}	N_{rec}	LSD (0.05)
%N			
Tillers	3.250	4.073	0.263
Leaves	4.180	5.290	1.031
N uptake (kg N ha^{-1})			
Tillers	18.6	24.6	ns
Leaves	17.4	22.3	ns
Total N uptake	36.1	47.0	ns

Zadoks Growth stage 36

DOY 275	N_{0N}	N_{rec}	LSD (0.05)
%N			
Tillers	2.063	2.638	0.454
Leaves	3.820	4.187	ns
N uptake (kg N ha^{-1})			
Tillers	15.68	23.51	4.41
Leaves	46.60	53.30	ns
Total N uptake	62.3	76.8	10.4

Zadoks Growth stage 41

DOY 288	N_{0N}	N_{rec}	LSD (0.05)
%N			
Tillers	1.197	1.153	ns
Leaves	3.290	3.500	ns
N uptake (kg N ha^{-1})			
Tillers	22.45	35.00	4.81
Leaves	42.30	68.30	17.1
Total N uptake	64.7	103.3	17.8

Appendix 5.1 continued

Zadoks Growth stage 52

DOY 300	N_{0N}	N_{rec}	LSD (0.05)
%N			
Tillers	0.720	0.915	0.145
Leaves	2.040	2.670	0.611
Ears	1.748	1.900	0.056
N uptake (kg N ha^{-1})			
Tillers	23.1	32.3	ns
Leaves	25.9	50.8	8.4
Ears	0.99	0.92	ns
Total N uptake	50.0	84.0	11.9

Zadoks Growth stage 65

DOY 314	N_{0N}	N_{rec}	LSD(0.05)
%N			
Tillers	0.673	0.948	0.187
Leaves	0.895	1.978	0.609
Ears	1.590	1.883	0.286
N uptake (kg N ha^{-1})			
Tillers	24.30	45.30	6.57
Leaves	19.70	32.00	ns
Ears	12.75	17.13	3.30
Total N uptake	56.75	94.40	18.1

Zadoks Growth stage 71

DOY 321	N_{0N}	N_{rec}	LSD (0.05)
%N			
Tillers	0.448	0.610	0.113
Leaves	0.818	0.935	ns
Ears	1.757	1.747	ns
N uptake (kg N ha^{-1})			
Tillers	12.7	31.2	9.05
Leaves	15.1	18.9	ns
Ears	50.3	55.8	ns
Total N uptake	78.1	105.9	15.8

Appendix 5.2 Combined Analysis of variance: Nitrogen concentration of residue (%)

```
Source of variation  d.f.  s.s.        m.s.      v.r.    F pr.


YEAR.LOC.REP  stratum

YEAR                   1   0.117019   0.117019   10.81  0.004

LOC                    2   0.084267   0.042133    3.89  0.039
YEAR.LOC               2   0.454050   0.227025   20.98  <.001
Residual              18   0.194812   0.010823    1.53

YEAR.LOC.REP .NLEVEL stratum
NLEVEL                 1   0.037969   0.037969    5.36  0.033
YEAR.NLEVEL            1   0.000052   0.000052    0.01  0.933
LOC.NLEVEL             2   0.045350   0.022675    3.20  0.065
YEAR.LOC.NLEVEL        2   0.038517   0.019258    2.72  0.093
Residual              18   0.127462   0.007081

Total                 47   1.099498
```

Appendix 5.3 Combined Analysis of variance: Grain protein percentage (%)

```
Source of variation     d.f.         s.s.         m.s.     v.r.  F pr.

YEAR.LOC.REP  stratum
YEAR                       1       0.2408       0.2408     1.67  0.213
LOC                        2      39.2908      19.6454   136.18  <.001
YEAR.LOC                   2      19.4347       9.7174    67.36  <.001
Residual                  18       2.5966       0.1443     0.98

YEAR.LOC.REP .NLEVEL stratum
NLEVEL                     1      22.5776      22.5776   152.64  <.001
YEAR.NLEVEL                1       0.5334       0.5334     3.61  0.074
LOC.NLEVEL                 2      14.6472       7.3236    49.51  <.001
YEAR.LOC.NLEVEL            2       0.4392       0.2196     1.48  0.253
Residual                  18       2.6624       0.1479

Total                     47     102.4229
```

Appendix 5.4 Combined Analysis of variance

Appendix 5.4a Combined Analysis of variance: Nitrogen uptake: Grain (kg N ha^{-1})

```
Source of variation      d.f.        s.s.         m.s.     v.r.   F pr.

YEAR.LOC.REP  stratum

YEAR                        1    3974.328    3974.328 1032.07   <.001
LOC                         2    2874.394    1437.197  373.22   <.001
YEAR.LOC                    2    2914.328    1457.164  378.40   <.001
Residual                   18      69.315       3.851    0.68

YEAR.LOC.REP .NLEVEL stratum
NLEVEL                      1     710.045     710.045  126.01   <.001
YEAR.NLEVEL                 1       0.268       0.268    0.05   0.830
LOC.NLEVEL                  2     466.838     233.419   41.42   <.001
YEAR.LOC.NLEVEL             2       9.163       4.581    0.81   0.459
Residual                   18     101.427       5.635

Total                      47   11120.107
```

Appendix 5.4b Combined Analysis of variance: Nitrogen uptake: Residue (kg N ha^{-1})

```
Source of variation      d.f.        s.s.         m.s.     v.r.   F pr.

YEAR.LOC.REP  stratum

YEAR                        1      229.60      229.60    12.55   0.002
LOC                         2     1021.74      510.87    27.92   <.001
YEAR.LOC                    2      949.39      474.69    25.94   <.001
Residual                   18      329.35       18.30     0.89

YEAR.LOC.REP .NLEVEL stratum
NLEVEL                      1      583.31      583.31    28.41   <.001
YEAR.NLEVEL                 1        0.02        0.02     0.00   0.974
LOC.NLEVEL                  2      236.04      118.02     5.75   0.012
YEAR.LOC.NLEVEL             2        7.03        3.51     0.17   0.844
Residual                   18      369.57       20.53

Total                      47     3726.04
```

Appendix 5.4c Combined Analysis of variance: Total Nitrogen uptake (kg N ha^{-1})

```
Source of variation      d.f.        s.s.         m.s.     v.r.   F pr.

YEAR.LOC.REP  stratum
YEAR                        1     6114.42     6114.42   271.55   <.001
LOC                         2     6177.18     3088.59   137.17   <.001
YEAR.LOC                    2     7006.85     3503.42   155.59   <.001
Residual                   18      405.31       22.52     0.96

YEAR.LOC.REP .NLEVEL stratum
NLEVEL                      1     2580.49     2580.49   110.54   <.001
YEAR.NLEVEL                 1        0.45        0.45     0.02   0.891
LOC.NLEVEL                  2     1365.54      682.77    29.25   <.001
YEAR.LOC.NLEVEL             2       32.24       16.12     0.69   0.514
Residual                   18      420.19       23.34

Total                      47    24102.66
```

Appendix 5.5 Nitrogen analysis and uptake measured at Bethlehem (1998)

Zadoks Growth stage 14

DOY 232	N_{0N}	N_{rec}	LSD (0.05)
%N			
Tillers + Leaves	4.060	4.460	ns
N uptake (kg N ha^{-1})			
Tillers	3.350	4.392	ns
Total N uptake	3.350	4.392	ns

Zadoks Growth stage 25

DOY 264	N_{0N}	N_{rec}	LSD (0.05)
%N			
Tillers	3.330	3.520	ns
Leaves	4.120	4.580	ns
N uptake (kg N ha^{-1})			
Tillers	4.56	10.95	2.71
Leaves	7.80	21.30	8.96
Total N uptake	12.4	32.2	11.39

Zadoks Growth stage 32

DOY 287	N_{0N}	N_{rec}	LSD (0.05)
%N			
Tillers	1.380	2.100	0.675
Leaves	2.630	3.460	ns
N uptake (kg N ha^{-1})			
Tillers	4.28	13.73	1.63
Leaves	9.50	22.20	7.92
Total N uptake	13.75	35.94	6.31

Appendix 5.5 continued

Zadoks Growth stage 41

DOY 302	N_{ON}	N_{rec}	LSD (0.05)
%N			
Tillers	1.280	1.317	ns
Leaves	3.427	2.690	0.281
N uptake (kg N ha^{-1})			
Tillers	13.91	22.19	6.14
Leaves	12.29	11.99	ns
Total N uptake	26.20	34.18	4.53

Zadoks Growth stage 58

DOY 309	N_{ON}	N_{rec}	LSD (0.05)
%N			
Tillers	0.980	0.813	0.011
Leaves	2.873	2.520	0.140
Ears	1.690	2.103	ns
N uptake (kg N ha^{-1})			
Tillers	10.20	16.90	ns
Leaves	6.80	11.82	ns
Ears	5.30	13.10	ns
Total N uptake	22.30	41.80	ns

Zadoks Growth stage 83

DOY 338	N_{ON}	N_{rec}	LSD (0.05)
%N			
Tillers	0.357	0.655	0.104
Ears	1.278	1.677	0.173
N uptake (kg N ha^{-1})			
Tillers	5.13	16.39	2.59
Ears	21.59	48.36	4.98
Total N uptake	26.70	64.70	7.47

Appendix 5.6 Nitrogen analysis and uptake measured at Kroonstad (1997)

Zadoks Growth stage 30

DOY 260	N_{0N}	N_{rec}	LSD (0.05)
%N			
Tillers	2.250	2.565	0.292
Leaves	3.675	4.012	0.285
N uptake *(kg N ha^{-1})*			
Tillers	9.79	21.94	5.54
Leaves	21.1	34.3	ns
Total N uptake	30.9	56.2	21.4

Zadoks Growth stage 41

DOY 276	N_{0N}	N_{rec}	LSD (0.05)
%N			
Tillers	1.038	1.145	ns
Leaves	3.235	3.480	0.208
N uptake (kg N ha^{-1})			
Tillers	21.9	35.0	11.0
Leaves	33.3	51.2	8.51
Total N uptake	55.1	86.2	13.9

Zadoks Growth stage 71

DOY 304	N_{0N}	N_{rec}	LSD (0.05)
%N			
Tillers	0.708	0.668	ns
Leaves	1.660	1.488	ns
Ears	1.787	1.952	ns
N uptake (kg N ha^{-1})			
Tillers	19.8	24.0	ns
Leaves	11.3	19.3	7.5
Ears	20.1	32.4	ns
Total N uptake	51.2	75.7	ns

Appendix 5.6 continued

Zadoks Growth stage 77

DOY 314	N_{0N}	N_{rec}	LSD (0.05)
%N			
Tillers	0.740	0.580	0.103
Leaves	0.610	0.583	ns
Ears	1.858	1.960	ns
N uptake (kg N ha^{-1})			
Tillers	18.11	17.95	ns
Leaves	6.57	7.62	ns
Total N uptake	82.1	88.8	ns

Appendix 5.7 Nitrogen analysis and uptake measured at Kroonstad (1998)

Zadoks Growth stage 24

DOY 188	N_{0N}	N_{rec}	LSD (0.05)
%N			
Tillers	2.89	4.16	0.619
Leaves	3.77	5.22	0.909
N uptake (kg N ha^{-1})			
Tillers	2.75	5.67	1.22
Leaves	5.92	12.10	1.38
Total N uptake	8.68	17.77	2.56

Zadoks Growth stage 30

DOY 225	N_{0N}	N_{rec}	LSD (0.05)
%N			
Tillers	1.550	1.687	0.324
Leaves	2.520	3.198	0.211
N uptake (kg N ha^{-1})			
Tillers	8.27	15.82	3.62
Leaves	11.1	24.8	7.16
Total N uptake	19.3	40.7	7.97

Zadoks Growth stage 36

DOY 254	N_{0N}	N_{rec}	LSD (0.05)
%N			
Tillers	1.070	1.285	0.059
Leaves	2.51	2.45	ns
N uptake (kg N ha^{-1})			
Tillers	14.47	25.28	4.54
Leaves	12.8	18.6	ns
Total N uptake	27.3	43.8	7.92

Appendix 5.7 continued

Zadoks Growth stage 58

DOY 273	N_{0N}	N_{rec}	LSD (0.05)
%N			
Tillers	1.097	1.025	ns
Leaves	2.670	2.795	ns
Ears	1.725	1.708	ns
N uptake (kg N ha^{-1})			
Tillers	11.82	16.44	ns
Leaves	9.68	11.91	ns
Ears	4.67	7.44	2.29
Total N uptake	26.2	35.8	ns

Zadoks Growth stage 83

DOY 296	N_{0N}	N_{rec}	LSD (0.05)
%N			
Tillers	0.840	1.048	ns
Leaves	1.88	2.51	ns
Ears	1.737	1.790	ns
N uptake (kg N ha^{-1})			
Tillers	13.57	15.99	ns
Leaves	3.25	3.06	ns
Ears	19.4	23.0	ns
Total N uptake	36.16	42.00	4.70

Appendix 5.8 Nitrogen analysis and uptake measured at Petrusburg (1997)

Zadoks Growth stage 27

DOY 244	N_{ON}	N_{rec}	LSD (0.05)
%N			
Tillers	1.775	2.170	ns
Leaves	2.923	3.360	0.353
N uptake (kg N ha^{-1})			
Tillers	4.12	5.23	ns
Leaves	9.07	11.42	1.61
Total N uptake	13.18	16.65	2.37

Zadoks Growth stage 33

DOY 261	N_{ON}	N_{rec}	LSD (0.05)
%N			
Tillers	1.167	1.220	ns
Leaves	2.583	2.575	ns
N uptake (kg N ha^{-1})			
Tillers	5.94	7.01	ns
Leaves	10.70	14.20	ns
Total N uptake	16.7	21.3	ns

Zadoks Growth stage 41

DOY 273	N_{ON}	N_{rec}	LSD (0.05)
%N			
Tillers	0.833	0.863	ns
Leaves	2.545	2.815	0.216
N uptake (kg N ha^{-1})			
Tillers	13.95	20.57	5.26
Leaves	16.10	23.60	ns
Total N uptake	30.1	44.2	ns

Appendix 5.8 continued

Zadoks Growth stage 54

DOY 279	N_{ON}	N_{rec}	LSD (0.05)
%N			
Tillers	0.920	1.203	ns
Leaves	1.740	1.873	ns
Ears	1.553	1.947	0.091
N uptake (kg N ha^{-1})			
Tillers	13.8	20.7	ns
Leaves	13.7	19.8	ns
Ears	1.86	1.08	ns
Total N uptake	29.3	41.5	ns

Zadoks Growth stage 58

DOY 286	N_{ON}	N_{rec}	LSD (0.05)
%N			
Tillers	0.747	0.770	ns
Leaves	1.703	1.673	ns
Ears	1.850	1.653	ns
N uptake (kg N ha^{-1})			
Tillers	15.32	17.67	ns
Leaves	10.97	12.58	1.56
Ears	11.18	8.04	ns
Total N uptake	37.5	38.3	ns

Zadoks Growth stage 69

DOY 293	N_{ON}	N_{rec}	LSD (0.05)
%N			
Tillers	0.710	0.690	ns
Leaves	1.300	1.257	ns
Ears	1.717	1.710	ns
N uptake (kg N ha^{-1})			
Tillers	13.28	17.48	ns
Leaves	10.90	15.40	ns
Ears	7.74	14.57	5.54
Total N uptake	32.0	47.4	12.78

Appendix 5.8 continued

Zadoks Growth stage 71

DOY 300	N_{0N}	N_{rec}	LSD (0.05)
%N			
Tillers	0.523	0.523	ns
Leaves	0.717	0.657	ns
Ears	1.663	1.680	ns
N uptake (kg N ha^{-1})			
Tillers	7.97	8.73	ns
Leaves	3.88	4.55	ns
Ears	13.8	20.6	ns
Total N uptake	25.63	33.91	6.07

Zadoks Growth stage 77

DOY 307	N_{0N}	N_{rec}	LSD (0.05)
%N			
Tillers	0.450	1.493	ns
Leaves	0.680	0.600	ns
Ears	1.607	1.593	ns
N uptake (kg N ha^{-1})			
Tillers	4.80	9.52	ns
Leaves	3.60	5.44	ns
Ears	15.5	22.6	ns
Total N uptake	23.9	37.5	ns

Zadoks Growth stage 87

DOY 314	N_{0N}	N_{rec}	LSD (0.05)
%N			
Tillers	0.350	0.370	ns
Leaves	0.843	0.673	0.160
Ears	1.700	1.677	ns
N uptake (kg N ha^{-1})			
Tillers	4.97	5.81	ns
Leaves	3.70	3.82	ns
Ears	28.8	31.9	ns
Total N uptake	37.5	41.5	ns

Appendix 5.9 Nitrogen analysis and uptake measured at Petrusburg (1998)

Zadoks Growth stage 25

DOY 187	N_{ON}	N_{rec}	LSD (0.05)
%N			
Tillers	3.210	3.170	ns
Leaves	3.980	4.080	ns
N uptake (kg N ha^{-1})			
Tillers	3.51	6.17	0.91
Leaves	7.18	11.14	ns
Total N uptake	10.69	17.31	6.39

Zadoks Growth stage 31

DOY 217	N_{ON}	N_{rec}	LSD (0.05)
%N			
Tillers	2.100	2.035	ns
Leaves	2.300	2.500	ns
N uptake (kg N ha^{-1})			
Tillers	9.98	9.62	ns
Leaves	11.89	14.92	ns
Total N uptake	21.90	24.50	ns

Zadoks Growth stage 41

DOY 253	N_{ON}	N_{rec}	LSD (0.05)
%N			
Tillers	0.903	1.013	ns
Leaves	1.723	2.155	ns
N uptake (kg N ha^{-1})			
Tillers	14.87	20.02	4.57
Leaves	7.17	15.78	4.21
Total N uptake	22.04	35.81	5.26

Appendix 5.9 continued

Zadoks Growth stage 58

DOY 275	N_{0N}	N_{rec}	LSD (0.05)
%N			
Tillers	0.930	1.005	ns
Leaves	1.630	2.080	ns
Ears	1.580	1.590	ns
N uptake (kg N ha^{-1})			
Tillers	13.91	20.04	ns
Leaves	2.87	3.19	ns
Ears	5.77	6.23	ns
Total N uptake	22.60	29.50	ns

Zadoks Growth stage 83

DOY 293	N_{0N}	N_{rec}	LSD (0.05)
%N			
Tillers	0.918	0.910	ns
Leaves	2.608	2.338	0.265
Ears	1.578	1.710	ns
N uptake (kg N ha^{-1})			
Tillers	16.0	15.9	ns
Leaves	1.63	4.13	1.60
Ears	19.7	19.4	ns
Total N uptake	37.3	39.4	ns

Appendix 5.10 Total N content (%) of roots

Locality	Year	1997		1998		
Bethlehem	N_{0N}	N_{rec}	se	N_{0N}	N_{rec}	se
0-200mm	0.832	0.979	0.0735	0.8785	0.8776	0.0005
200-600mm	0.822	0.987	0.0825	0.7850	0.9944	0.1047
600-1200mm	0.660	0.912	0.1260	0.7185	0.9129	0.0972
Kroonstad	N_{0N}	N_{rec}	se	N_{0N}	N_{rec}	se
0-200mm	0.881	0.860	0.0105	0.6494	0.7501	0.0504
200-600mm	0.754	0.719	0.0175	0.5906	0.6045	0.0070
600-1200mm	0.582	0.676	0.0470	0.4409	0.5202	0.0397
Petrusburg	N_{0N}	N_{rec}	se	N_{0N}	N_{rec}	se
0-200mm	0.824	0.801	0.0115	0.6206	0.6477	0.0136
200-600mm	0.702	0.674	0.0140	0.6404	0.5845	0.0280
600-1200mm	0.644	0.725	0.0405	0.4681	0.5508	0.0414

Appendix 6.1 Combined Analysis of variance: Soil mineral content

6.1a Combined Analysis of variance: NH_4^+ Total (kg N ha^{-1}; 0-1200 mm)

```
Source of variation      d.f.         s.s.         m.s.      v.r.   F pr.
SAMPLING.LOC.REP  stratum
SAMPLING                    4   459501.34   114875.33  1651.63   <.001
LOC                         2    28983.25    14491.63   208.35   <.001
SAMPLING.LOC                8   109669.58    13708.70   197.10   <.001
Residual                   45     3129.87       69.55     0.70

SAMPLING.LOC.REP .FERT  stratum
FERT                        2     7581.74     3790.87    38.15   <.001
SAMPLING.FERT               8    47466.10     5933.26    59.71   <.001
LOC.FERT                    4     1989.33      497.33     5.00   0.001
SAMPLING.LOC.FERT          16    33416.30     2088.52    21.02   <.001
Residual                   90     8943.79       99.38
Total                     179   700681.30
```

6.2b Combined Analysis of variance: NO_3^- Total (kg N ha^{-1}; 0-1200 mm)

```
Source of variation      d.f.         s.s.         m.s.      v.r.   F pr.
SAMPLING.LOC.REP  stratum
SAMPLING                    4   144358.04    36089.51   259.15   <.001
LOC                         2    78432.36    39216.18   281.61   <.001
SAMPLING.LOC                8    96280.02    12035.00    86.42   <.001
Residual                   45     6266.64      139.26     1.62

SAMPLING.LOC.REP .FERT  stratum
FERT                        2    27990.69    13995.35   162.84   <.001
SAMPLING.FERT               8    20731.39     2591.42    30.15   <.001
LOC.FERT                    4     1980.95      495.24     5.76   <.001
SAMPLING.LOC.FERT          16    33180.48     2073.78    24.13   <.001
Residual                   90     7735.04       85.94
Total                     179   416955.62
```

6.3c Combined Analysis of variance: Total mineral N (kg N ha^{-1}; 0-1200 mm)

```
Source of variation      d.f.         s.s.         m.s.      v.r.   F pr.
SAMPLING.LOC.REP  stratum
SAMPLING                    4    467720.7    116930.2   436.53   <.001
LOC                         2    200980.6    100490.3   375.15   <.001
SAMPLING.LOC                8     82038.3     10254.8    38.28   <.001
Residual                   45     12054.0       267.9     1.38

SAMPLING.LOC.REP .FERT  stratum
FERT                        2     67565.7     33782.9   173.55   <.001
SAMPLING.FERT               8     95928.6     11991.1    61.60   <.001
LOC.FERT                    4      3454.6       863.7     4.44   0.003
SAMPLING.LOC.FERT          16     67873.3      4242.1    21.79   <.001
Residual                   90     17518.8       194.7
Total                     179   1015134.6
```