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DRAINAGE AND NITROGEN DYNAMICS IN AN AGRICULTURAL FIELD

by

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A Thesis Submitted to the Faculty of Graduate
Studies and Research, in Partial Fulfilment
of the Requirements for the Degree of
Master of Science

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ABSTRACT

M.Sc. Agricultural and Biosystems Engineering

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Drainage and Nitrogen Dynamics in an Agricultural Field

A two year field study was carried out in western Québec to investigate methods of predicting and reducing NO_3^--N leaching. Corn (*Zea mays* L.) was planted on the experimental site and there were four treatments: water table controlled at 600 mm and 120 kg/ha of N fertilizer (WT120), water table controlled at 600 mm and 200 kg/ha of N fertilizer (WT200), free drainage and 120 kg/ha of N fertilizer (FD120), and free drainage and 200 kg/ha of N fertilizer (FD200). Rainfall, and soil and air temperatures, were measured at the site. Drain flow was monitored and water samples were taken and analyzed for NO_3^--N. Soil NO_3^- levels were measured along with leaf chlorophyll and denitrification throughout the two growing seasons.

Drain flow was dependent on both rainfall and the soil moisture content. In 1996, water table control decreased drain flow. However, in 1997 (a drier year), the drain flows for all treatments were similar. NO_3^--N was reduced significantly in the controlled water table plots. In 1996, there was 59.2 % less NO_3^--N in the controlled water table plots than in the free drainage plots and in 1997 this increased to 75.9 % less NO_3^--N in the controlled water table compared to the free drainage plots. In 1996, denitrification was enhanced by the controlled water table plots, with 72.2 % more denitrification occurring in the controlled water table plots than in the free drainage plots. In 1997, there was a 93.2 % increase in denitrification occurring in the water table plots than in the free drainage plots.

The controlled water table plots had no effect on plant chlorophyll levels. Chlorophyll contents of the corn plants were higher where fertilizer was applied at 200 kg/ha. Four equations were developed relating the N in the soil, in the plant, in the drainage water and denitrification. Overall, it was shown that water table management can significantly decrease NO_3^--N pollution in drainage water.

RESUMÉ

M.Sc. **Génie de l'agriculture et des biosystèmes**

Craig Dockeray

Drainage et dynamique de l'azote au niveau du champ

Une étude au champ d'une durée de deux ans, visant à étudier des méthodes de prévision et de réduction du lessivage des nitrates, fut entreprise dans l'ouest du Québec. Le site de recherche fut en monoculture de maïs (*Zea mays* L.). Quatre traitements furent imposés: nappe phréatique contrôllée à 60 cm avec 120 kg N/ha d'engrais azoté (WT120); nappe contrôllée à 60 cm avec 200 kg N/ha d'engrais azoté (WT200); drainage libre avec 120 kg N/ha d'engrais azoté (F120); drainage libre avec 200 kg N/ha d'engrais azoté (FD200). Le niveau de précipitation et les températures du sol et de l'air, furent mesurés au site. Le taux d'écoulement par les drains souterrains fut suivi et des échantillons prélevés et analysés pour le NO_3^--N. Les niveaux de NO_3^--N dans le sol, la teneur en chlorophylle des feuilles et le taux de dénitrification du sol furent mesurées pendant deux saisons de culture.

Le taux d'écoulement par les drains souterrains fut dépendant du niveau de précipitation et de la teneur en eau du sol. En 1996, la gestion de la nappe réduisa l'écoulement. Cependant, en 1997, une année plus sèche, l'écoulement fut semblable pour tous les traitements. Le niveau de NO_3^--N fut réduit de façon significative dans les parcelles avec gestion de la nappe. En 1996, il y eut 59.2% moins de NO_3^--N dans les parcelles avec gestion de la nappe que dans celles avec un drainage libre, et en 1997 ce chiffre augmenta à 75.9%. En 1996, le taux de dénitrification fut amélioré par la gestion de la nappe, avec 72.2% plus de dénitrification dans les parcelles avec gestion de la nappe que dans les parcelles avec drainage libre. En 1997, le taux de dénitrification dans les parcelles avec gestion de la nappe fut 93.2% plus élevé que dans les parcelles avec drainage libre.

La gestion de la nappe n'eut aucun effet sur la teneur en chlorophylle des plantes. La teneur en chlorophylle des plants de maïs fut plus élevé dans les parcelles recevant 200 kg N/ha que dans celles recevant 120 kg N/ha. Une corrélation significative fut trouvée entre la teneur en N des feuilles et le niveau de NO_3^--N dans les eaux d'écoulement souterrain, et une équation reliant ceux-ci fut développée. Dans l'ensemble, il fut démontré que la gestion de la nappe peut réduire la pollution par le NO_3^--N de façon significative.

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Nomenclature

BD : Bulk density

BMP : Best management practice

CD : Controlled drainage

cm : centimeter

E_h : Redox potential

ET : Evapotranspiration

FD : Free drainage

g : gram

GLM : General linear model

ha : hectare

HCl : Hydrochloric acid

i.d. : inside diameter

k : hydraulic conductivity

kg : kilogram

l : litre

m : meter

mg : milligram

mm : millimeter

mv : millivolt

N : Nitrogen

N_2 : Nitrogen gas

NH_3 : Ammonia

NH_4 : Ammonium

N_2O : Nitrous oxide

NO_2^- : Nitrite

NO_3^- : Nitrate

NO_3^--N: Nitrate nitrogen

ppm : parts per million

SPAD : Soil plant analysis development

vs. : versus

WT : Water table

WTM : Water table management

°C : degrees Celsius

% : percent

Table of Contents

List of Figures

List of Tables

1.0 INTRODUCTION

1.1 Problem Definition

Non-point source pollution is a major environmental concern with today's modern agricultural practices. Farms specializing in animal feedlots or high value crops may pollute water supplies from manure runoff, fertilizer applications, or pesticide applications. Some of the major agricultural pollutants have harmful effects on both the environment and human health. Such pollutants include nitrate (NO_3), phosphorus, biocides, heavy metals and salts. High yielding crops, grain corn (*Zea Mays L.*) as an example, require high amounts of fertilizer, particularly nitrogen, to obtain maximum yield. However, the capture rate by the crop of these fertilizers is relatively low. Nitrogen is found in various forms in the soil, for example, as nitrogen gas (N_2), nitrate (NO_3), nitrite (NO_2), ammonia (NH_3), and ammonium (NH_4). Excess N in the soil leads to NO_3^--N pollution of the water supply. NO_3^--N levels higher than 10 mg NO_3^--N have been found in drinking water (Hubbard et al., 1989). NO_3^--N, in excess of this concentration, is linked to methaemoglobinaemia (blue baby syndrome). Of the total amount of N in the soil, only a very small amount is converted to a form which is acceptable to the plant. The remainder is then subject to such processes as leaching. Leaching is dependent on various climatological, soil and agricultural management factors.

Drainage is an important part of agriculture. It helps in removing excess water from fields and aids in the aeration of the soil resulting in less compaction. Drainage helps lengthen the growing season as well as remove unwanted compounds such as salts. In the provinces of Ontario and Quebec, there are over 2,000,000 ha of today's agricultural crop lands that have received drainage improvement. It is for this reason that there is a lot of research focussing on the quality of water exiting the drain pipes. Due to the soluble nature of NO_3^--N, it is possible that increased NO_3^--N is lost to subsurface drains. However, agricultural management practices play a crucial role in the movement of NO_3^--N in surface and ground water.

Best management practices such as crop rotations, proper chemical management and water table management are being investigated to help reduce environmental pollution. Water management techniques, such as subirrigation, prove useful in reducing NO_3^--N leaching. Water table management is a practice which can be used to reduce environmental damage while enhancing crop productivity. By maintaining a water table at a shallow depth of approximately 60 cm, denitrification is enhanced as microorganisms use NO_3^--N as an alternate electron acceptor to the limiting oxygen. The use of redox potential (E_h) probes may prove useful in determining the relationship of the redox potential to denitrification and would allow for the real-time measurement of denitrification in the field.

The N available in the soil is a primary factor in determining the plant chlorophyll level. If this level is properly estimated it would help in predicting N fertilizer requirements for a specific crop. A Minolta SPAD chlorophyll meter is one tool which allows for the prediction of plant chlorophyll levels. The handheld meter gives dimensionless units called SPADS (Soil Plant Analysis Development) which are proportional to the chlorophyll level in the plant tissue.

1.2 Objectives

The purpose of this study is to investigate the N dynamics on agricultural drainage water quality. Specific objectives of this study were to:

1. Determine the effects of water table management on the leaching of NO_3^--N to tile drains.
2. Determine the effectiveness of predicting soil denitrification using redox potential probes and plant chlorophyll levels using a Minolta SPAD meter.
3. Develop simple tools to predict NO_3^--N leaching using primary N factors.

1.3 Scope

This thesis presents a two year (1996-1997) field study conducted in the humid climatic region of south western Québec under site specific conditions of monocropped corn with sandy loam top soil. Both conventional drainage and a water table controlled at 60 cm were investigated with fertilizer application rates of 120 kg/ha and 200 kg/ha. The results are limited to similar management techniques, soil and climatic conditions.

2.0 LITERATURE REVIEW

2.1 Nitrate Leaching and Water Table Management Practices

Agriculture contributes to soil and water pollution. Water, through rainfall or irrigation, is the main mechanism for the transport of pollutants. Fertilizers, pesticides and sediments enter the water supply from various agricultural practices. Major environmental concerns exist over N losses in the soil profile and to the atmosphere. Due to the fact that N is an important nutrient for plants, it is one of the most widely applied fertilizers (Brady, 1990). One of the major problems facing agriculture today is that of pollution due to NO_3^--N leaching into the ground water (Wright et al., 1992). In many areas, the NO_3^--N contaminant levels in the drainage water were much higher than the maximum permissible drinking water level of 10 mg NO_3^--N /l (Hubbard et al., 1989), resulting in public concern over the drainage water and it's effects on the environment (Evans et al., 1995). Inadequate agricultural management is the primary cause of this pollution and it is reasonable to assume that if ample control is practiced in this area then a reduction in pollution will result.

Nitrogen is easily transformed to NO_3^--N which is subject to leaching and denitrification (Stevenson, 1982). Of the total N available in the soil, only a very small percentage is actually converted to a form which can be used by the plant (NO_3^--N and NH_4^+ -N). In most crops, this amount is not enough and often requires the application of other N sources. These alternative sources vary from manure to different types of fertilizers

(Smith et al., 1990).

Corn (*Zea Mays L.*), for example, requires large amounts of N fertilizer to achieve adequate production rates. Higher fertilizer application rates as opposed to normal rates naturally increase the NO_3^--N concentration in the soil during the growing season (Liang et al., 1991). Unfortunately, a considerable amount is lost to either leaching or denitrification (Fausey et al., 1995; Madramootoo and Kaluli, 1994). In Maryland, sandy soil with irrigated corn are fertilized with typical N application rates. The N concentration in the groundwater has been found to be between 10 mg NO_3^--N/l and 20 mg NO_3^--N/l throughout the year (Weil et al., 1990). This is not common to only corn production. Milburn et al. (1990) discovered that NO_3^--N leaching occurs under current potato production methods in New Brunswick. However, in certain intensively cropped areas where fertilizer is not applied the leaching loss is considerably less, as there are lower concentrations of NO_3^--N throughout the soil (Stevenson, 1982).

The fate of most agricultural chemicals is affected by the surface-soil conditions found in the field (Levanon et al., 1993). The leaching of important nutrients is determined by climatic and soil-nutrient interactions along with soil properties. For instance, greater amounts of leaching occur in sandy soils rather than clay soils because of higher percolation rates and lower nutrient-adsorbing powers of sandy soils (Brady, 1990). Among different types of sandy soils it is those soils which contain less organic matter which lose the most NO_3^--N on a yearly basis. Differences in the soil NO_3^--N concentrations can be related to fluctuations in the soil water content (Brown et al., 1993). In order to accurately compare NO_3^--N leaching between different soil types, the tests should be done at the same site and at the same time (Bergstrom, 1991). Evans et al. (1994) stated that neither the landscape position nor the climatic zone play a large role in determining NO_3^--N leaching. Liang et al., (1991) found that irrigation significantly decreased the soil NO_3^--N concentrations during the growing season. Sandy soils which receive supplemental irrigation may use nitrification inhibitors to delay or even reduce NO_3^--N leaching (Timmons, 1984). The NO_3^--N left at the end of the growing season, however, may still leach below the root zone.

Agricultural drainage water plays a significant role in the quality of water entering the water supply, indicating that it is important to study the effects of drainage on water quality (Fausey et al., 1995). Although annual nutrient losses are highly variable (Baker et al., 1975), many studies have evaluated the effects of agricultural practices on chemical concentrations in drainage water, as high levels of N, P and other nutrients have been found in drainage discharge waters. However, most studies analyzing the discharge water have only been preliminary studies to examine leaching losses from the root zone of different nutrients and pesticides (Ritter et al., 1995). Large NO_3^--N reductions may be needed if the health of the water systems are to be conserved/restored (Evans et al., 1995).

As agricultural practices play a large role in the fate of N, proper management of these practices can minimize the N loss and still supply the crop with adequate amounts of N, through mineralization, when needed (Crozier et al., 1994).

Drainage plays a very important role in improving water quality while maintaining agricultural viability (Fausey et al., 1995). As summarized by Ritter et al. (1995), there is various research currently being conducted in the area of water quality and drainage. Studies to correlate land management systems and tile drainage on the basis of quality and quantity of drained water have been initiated. The severity of the migration of agricultural chemicals, being leached below the crop root zone, with the drain effluent moving into local streams, rivers and water supplies is also being examined along with investigations into pesticides and nutrient reductions from subsurface drainage discharge using water table management systems.

2.2 Results of Water Table Management Research

In Baton Rouge, Louisiana, Bengston et al. (1988) discovered that subsurface drainage was able to reduce N loss by 20% and increase total drainage by 35%. It has also been found that the closer the drain spacing, the more NO_3^--N will be leached into the drains (Kladivko et al., 1991). However, if the drains do not intercept all the subsurface flow, then the NO_3^--N concentrations found in the drains may not be an accurate indication of overall NO_3^--N losses from the field (Thomas et al., 1974).

Research has been set up to investigate Best Management Practices (BMP's) in order to protect the water resources and reduce the harmful effects of agricultural chemicals on the groundwater (Gilliam et al., 1986). These practices include crop rotations, chemical management and water table management (WTM) practices.

Water table management techniques, such as controlled drainage-subirrigation, are advantageous ways to help minimize the effect of dry summers on crop growth and reduce NO_3^--N losses from the soil profile by increasing denitrification (Drury et al., 1996; Wright et al., 1992). Subirrigation and controlled drainage are two systems where the water table below the root zone is controlled. Crop growth can be increased by using an optimum water table and the growth can be verified by monitoring different plant physiological parameters (Kalita et al., 1992). During drainage applications the water table is lowered to allow for increased trafficability on the field and to reduce the chance of waterlogging. During irrigation applications the water table is raised to allow the plant roots more access to needed water. Tan et al. (1996) conducted experiments with corn yields and various water table depths where the highest corn yields were found with a water table depth of 60 cm.

Lalonde (1993) and Kalita et al. (1992) measured the average NO_3^--N concentrations with respect to various water table depths and concluded that the NO_3^--N concentrations in the groundwater were reduced while maintaining a shallow water table depth. The average concentrations of NO_3^--N in the groundwater generally decreased with an increased depth and time during the growing season. Over the entire experiment the NO_3^--N concentrations in the unsaturated zone were usually greater than those in the saturated zone.

Madramootoo et al. (1994) stated that water table control with both intercropping and strip cropping could reduce NO_3^--N concentrations in drainage effluent significantly. Kaluli (1996) and Tan et al. (1993) mentioned that water table management/control with an intercrop is the best management system to abate NO_3^--N pollution of surface and drainage water, while Evans et al. (1995) state that reduction in N effluent is possible through controlled drainage practices and careful management of fertilizer application rates and timing.

Brown et al. (1993) stated that NO_3^--N is also significantly influenced by tillage practices, the N application rate, and various vetch treatments. For example, a legume cover crop may help in fixing N, becoming a useful tool in N management. Serem (1995) studied the effects of various tillage practices on the leaching of NO_3^--N and water movement through the soil profile.

Timing and rates of N fertilizer application can affect both the availability of N for crop growth and the amount of NO_3^--N remaining in the soil profile. Applications greater than the optimum nitrogen application rate can cause an accumulation of large amounts of NO_3^--N in the soil profile (Baker et al., 1981; Angle et al., 1993). While residual soil NO_3^--N is potentially available for the following year's crop, it is also susceptible to leaching or denitrification losses during the winter months (Jokela, 1992). Kanwar et al. (1988) found that a split N application reduced NO_3^--N concentrations rather than having a single, higher rate of application.

Many studies have been conducted which conclude that the average NO_3^--N concentrations found in drainage discharge waters are significantly lower in plots which have no-till tillage compared with those with conventional tillage (Kanwar et al. 1988 ; Carefoot et al. 1990 ; Angle et al., 1993). Drury et al. (1996) found that controlled drainage- subirrigation combined with conservation tillage practices was able to lower the annual NO_3^--N losses by 49% when compared with a plow tillage and free drainage treatment. The no-till form of tillage retains greater amounts of NO_3^--N originally near the soil surface and plant root zone when compared to using the mouldboard plow (Kanwar et al., 1985). However, no-till soils may reduce the crop recovery of the N from the fertilizer by immobilization at the soil surface (Rice et al., 1984). In conventional tillage practices there is a higher amount of leaching of NO_3^--N from the surface of the soil when compared to no-till. This can be associated with greater net N mineralization in conventional tillage practices. Also, higher amounts of organic matter in no-till plots can enhance the biodegradation of the fertilizer (Levanon et al., 1993).

Studies involving different agricultural practices on surface and groundwater have been limited due to the high costs involved. The solution to minimizing agricultural N losses to the environment is to increase the fertilizer N efficiency (Stevenson, 1982). However, experiments to examine pesticide and NO_3^--N leaching, to improve this efficiency, depend on numerous variables from the environment which make it considerably expensive and difficult to study (Fermanich et al., 1991). Tools to predict how much N may be lost would be very helpful in minimizing these losses to the environment (Liang et al., 1991).

2.3 Denitrification and Redox Potential

Denitrification is an important aspect of N leaching. NO_3^--N that is denitrified cannot be leached into the soil profile and therefore, does not contribute to water quality problems. Meek et al. (1969) found that denitrification was able to reduce the amount of NO_3^--N leached to the drainage system. Denitrification is due to the soil's microbial population's need for oxygen. These microorganisms use inorganic redox substances as electron acceptors, to decompose organic matter, with oxygen being the most important with it's large supply in the atmosphere (Brady, 1990). However, if the soil is flooded, oxygen becomes limited, and NO_3^--N is used as an alternate electron acceptor to produce carbon dioxide in place of the oxygen from the air (Addiscott et al., 1991). In anaerobic conditions, Schipper et al. (1994), discovered that there are two main pathways for microorganisms where NO_3^--N is used as a terminal electron acceptor; denitrification and dissimilatory NO_3^--N reduction to ammonium. Patrick and Jugsujinda (1992) found that there were, when required, three sequential, alternate electron acceptors; NO_3^- , Mn^{4+} compounds and Fe^{3+} compounds. When NO_3^- was completely reduced, Mn^{2+} first appeared in the soil solution at the critical redox potential of approximately 200 mv. Denitrification can then be classified as an anaerobic process where the end products

(N_2O or N_2 gases) become part of the atmosphere (Smith et al. 1983).

However, it has been said that N_2O is an ozone depleting gas (Stevenson, 1982). In order to properly assess the various environmental hazards associated with N_2O evolution, knowledge is important in determining the factors affecting the N_2O/N_2 evolution ratio from soils (Letey et al., 1981).

The water content of the soil is a very important environmental variable affecting denitrification. An increased denitrification rate can be observed by increasing the organic matter application at the highest water content (Meek et al., 1969). Denitrification is a very rapid process in waterlogged soils but quite slow in well-drained soils. These drained soils suffer from slow losses emanating from small anaerobic zones fastened within well-aerated soils (Craswell, 1978). Letey et al. (1981) suggested that the N_2O production rate may increase under oscillating redox potentials, saturated and unsaturated cycles, as compared to soils whose redox potential is continuously high or low.

Zausig et al. (1993) showed the existence of anoxic zones within different soil aggregates. Wet conditions in the soil limit the oxygen availability from the atmosphere helping to create the anoxic microsites. Letey et al. (1981) suggested that under continuous saturated conditions the soil may act as a sink for N_2O. Plant residues and other organic matter high in N, after being incorporated into the top layers of the soil, contain highly active hot spots, within soil aggregates, with respect to high rates of N_2O production (Fleesa and Beese, 1995 ; Hojberg et al. 1994).

Due to a higher population of denitrifying organisms, denitrification increases in no-till soils when compared to conventionally tilled soils (Angle et al., 1993). It is suggested by Rice and Smith (1983) that an increase in moisture content in no-till soils may also significantly influence the higher denitrifying activity. Doran (1980) stated that the higher denitrification rates with no-till soils are due to the different tillage and fertilizer management practices. This would account for the lower soil NO_3^--N concentrations and greater potential for immobilization of surface applied N when compared to conventional tillage practices. One of the primary advantages of no-till soils is the conservation of soil moisture. Although good for maintaining crop growth during dry periods, it may help in increasing denitrification losses to the atmosphere (Blevins et al., 1983). Although N_2O losses are lower from no-till cropped fields than from no-till fallow fields, more gaseous N is lost to the atmosphere with no-till practices when compared to conventional tillage.

The role the water table plays on the denitrification rate is important in water table management control practices. A shallow water table appears to allow the denitrification process to increase, by restricting O_2 diffusion in the topsoil or by transporting C and NO_3 from the surface to the subsoil with high denitrification potential, in order to remove the NO_3^--N before it is leached deep into the soil profile (Kliewer et al., 1995). In most systems the water table is never stable which may result in fluctuations of denitrification and N_2O evolution.

Nitrous oxide evolution seems to be highest under shallow water table conditions due to an increase in denitrification near the soil surface resulting in the N_2O escaping before it can be further reduced to N_2 . With deeper water tables, the low N_2O evolution corresponds to the low denitrification rate. It has been found that high NO_3^--N concentrations usually coincide with increased N_2O evolution (Letey et al., 1981). High NO_3^--N concentrations exist closer to the soil surface and decrease at depths approaching the water table. A small percentage of the NO_3^--N is reduced to N_2 before reaching the water table (Meek et al., 1969). Letey et al. (1981) suggested that even in the presence of higher NO_3^--N concentrations, N_2O can be reduced quicker than NO_3^-. There is a strong, positive relationship between N_2O evolution, the soil water content and soil temperature which may show that most N_2O evolved near the soil surface. If the temperature decreases, the minimum soil water content needed for denitrification to occur increases (Craswell, 1978). Sufficient NO_3^--N is produced, by mineralized organic N, to maintain the denitrification process. Therefore, although a shallow water table depth can result in decreasing the NO_3^--N concentrations leached into the groundwater, it also results in the highest N_2O evolution rate.

The redox potential, (E_h), usually measured in millivolts (mv), helps to determine whether a particular system will reduce or oxidize chemicals (Brady, 1990). Denitrification seems to occur approximately around redox potentials of 250 mv (Letey et al., 1981; Meek et al. 1969). There have been numerous studies conducted using redox potential. Volk (1939), investigated a satisfactory method for determining soil redox potentials. One study, (Jayaweera and Biggar, 1996), showed that soil E_h plays an important role in mobilizing the heavy metal, Se, into the water systems. Wang et al. (1993) discovered that soil redox potential was one of two important factors which help to control the microbiological process of methane formation in the soil. Grable and Sieman (1968) were able to correlate redox potentials with the oxygen status of the soil while Bell (1969) detected two stable E_h regimes after flooding, one of which was active denitrification at an E_h of 200 mv. Using both permanently and temporarily placed platinum electrodes, Bailey and Beauchamp (1971) studied the influence of NO_3^--N on the redox potential. Smith et al. (1983) studied the effects of pH and E_h on N_2O reduction and production while Meek et al. (1969) studied the decrease in soil NO_3^--N as related to redox potential. Kaluli (1996) investigated the use of using soil redox potential (E_h) and soil temperature to measure the real-time denitrification rate. It was concluded that for the majority of soils, E_h and soil temperature could adequately predict denitrification.

2.4 Plant Chlorophyll and the SPAD-502 Chlorophyll Meter

Few studies have been performed on the relationships between the demand for water and N by plants, and leaf senescence (Wolfe et al., 1988). Tyner and Webb (1945) studied the efficiency of applied N fertilizer within plant tissue as well as it's relationships with other nutrients. The demand for N by crops requires an understanding of the plant N requirements for efficient supplemental fertilizer applications. It is known that once the plant is resupplied with N, N deprived young leaves are able to regain their photosynthetic activity (Girardin et al., 1985).

Chlorophyll plays a very important role in plants and requires further research into it's estimation (Yadava, 1986). Although leaf greenness can be influenced by various factors, such as the type of plant hybrid, the stage of plant growth and different nutrients, it is the N availability which may be the most influential (Blackmer and Schepers, 1995). The leaf chlorophyll is directly related to the leaf N concentration and if estimated correctly can provide an excellent base to predict the N requirements for crops (Wood et al., 1992).

There are many methods used to determine the crop requirements for N including NO_3^--N testing, tissue N tests and calibrations from field trials. However, these tend to be rather expensive and tedious to perform (Kantety et al., 1996). A reliable and quick method for establishing the N content in plant tissues is important for proper N management practices in crop production (Dwyn et al., 1995). A lightweight, handheld chlorophyll meter (SPAD-502), produced by the Minolta company, now exists. This meter holds many advantages over traditional methods for determining the N status in the plant tissue. For example, the meter is extremely portable and is able to rapidly assess the N situation in the crop without destroying any part of the plant tissue in the field (Blackmer and Schepers, 1995). The chlorophyll meter gives dimensionless units called SPADS (Soil Plant Analysis Development) which are proportional to the amount of chlorophyll in the plant tissue (Reeves et al., 1993). The chlorophyll meter measures the transmittances of the leaf in the red and near-infrared region. The shorter wavelength deals with the measure of leaf chlorophyll content and the longer wavelength provides a reference and accounts for varieties in moisture and leaf thickness (Blackmer and Schepers, 1995). The SPAD values do not actually indicate how much N to apply to a crop, but rather indicates the need to do so (Turner and Jund, 1994). However, there have been few studies, conducted with the meter, to identify those areas where N levels are in excess (Wood et al., 1992).

Numerous studies have been performed using the SPAD-502/501 chlorophyll meters on corn and other important crops. Marquard and Tipton (1987) investigated the relationships between various crop SPAD readings. Using the chlorophyll meter on corn could provide farmers an excellent overview of their N fertilizer management plans for the growing season along with supplying valuable information for later years (Wood et al., 1992; Piekielek et al., 1995). Dwyer et al. (1995) were able to generate SPAD values to estimate corn leaf N concentrations from various soil and crop regimes. Blackmer and Schepers (1995) used the chlorophyll meter to predict when corn plants were in need of N, in order to supply them with N fertilizer through irrigation water. Reeves et al. (1993) used the chlorophyll meter on wheat to predict additional N fertilizer requirements from the N status at different growth stages of the crop. A study was performed (Nielson et al., 1995) to examine the applicability of using the meter to analyze the N status of apple trees, while Johnkutty and Palaniappan (1996), Peng et al. (1995) and Peng et al. (1996) studied various relationships between SPAD meter readings and the N concentrations in rice. Kantety et al. (1996) studied the possibility of using the SPAD-502 to determine the N status in tall fescue, and Westcott and Wraith (1995) studied the use of it for peppermint.

Chlorophyll levels of plants may have a tendency to vary, due to factors such as plant hybrid, planting dates, crop growth stage and the timing of fertilizer applications, regardless of the N status of the crop (Jemison and Lytle, 1996; Schepers et al., 1992). However, Dwyer et al. (1991) suggest that the calibration of corn is not significantly affected by variations in plant hybrid or growth stage.

Blackmer and Schepers (1995) suggested that the chlorophyll meter use may be limited early in the growing season unless the readings can be changed to take into account other environmental factors. Two of the most important factors would be the soil temperature and early season plant vigor (Piekielek et al., 1995). Dwyer et al. (1991) thought that caution should be taken when using the meter readings at very low chlorophyll concentrations, for instance when the plant is near senescence. The SPAD readings also seem to plateau later at higher leaf N levels suggesting that other plant nutrients other than N are limiting chlorophyll production (Dwyer et al., 1995; Blackmer and Schepers, 1995).

The chlorophyll SPAD-502 meter is extremely advantageous to those requiring to monitor the chlorophyll content of plants in the field. The readings are instantaneous and nondestructive and can save time and money in the lab (Kantety et al., 1996). However, this new technology should not replace the other N management practices but rather, should be used in conjunction with other N management tools to improve N fertilizer practices (Turner and Jund, 1995).

2.5 Summary

Agricultural fields are the primary source for both NO_3^--N leaching to groundwater and NO_3^-N in surface runoff, posing a major concern. Inadequate knowledge of proper agricultural management techniques is a significant part of the problem. Water table management and various agricultural practices have been found to reduce NO_3^--N leaching. Denitrification has also been suggested as a possibility to help minimize NO_3^--N leaching by reducing the amount of NO_3^--N in the soil. However, the process of associating soil redox potential with denitrification in the field is still a relatively fresh concept. The use of the SPAD meter to determine the leaf N percentage in the corn has been investigated quite intensively in the last decade and has been proven to be moderately reliable. The ability to predict, both rapidly and easily, different levels of NO_3^--N leaching in the field would be a definite asset to those involved in the agricultural sector.

3.0 MATERIALS AND METHODS

3.1 Experimental Setup

3.1.1 Soil Properties

During the 1996 and 1997 growing seasons, a field study was conducted on a 4.2 ha experimental site located in Soulanges County, Quebec, 30 km south-west of the Macdonald Campus of McGill University. The field is generally flat and the soil properties were measured in a previous study (Kaluli, 1996). The soil is classified as a sandy loam in the top 25 cm, gradually becoming a sandy clay loam between the 25-50 cm layer and turning to a clay between the 50-100 cm layer (Table 3.1).

Table 3.1: Soil properties at the site (Kaluli, 1996). Where θ_{sat} ,θ_{wp} , BD, K, are saturated soil water content, wilting point, bulk density and hydraulic conductivity, respectively.

Soil Properties									
Depth (cm)	Soil Type	θ_{sat} cm^3/cm^3	θ_{wp} cm^3/cm^3	BD g/cm^3	K m/day	% clay	% silt	% sand	% organic C
25-50	Sandy loam	0.36	0.26	1.6	0.451	10.1	30	55	5.0
50-75	Sandy clay loam	0.47	0.32	1.6	0.364	20.0	20.0	58	1.5
75-100	Clay	0.50	0.32	1.5	0.138	39.3	28.3	30	-

3.1.2 Field Layout

The field (Figure 3.1) has been established as a randomized complete block design, split into three blocks (block A, B, C). The blocks are 75 m long by 120 m wide with two undrained buffers, 30 m wide, separating the three blocks. Each block is separated into 8 plots, 15 m wide. A heated building with electricity (5m x 5m) is located between blocks A and B and another between blocks B and C. Situated in the middle, and running the length of each plot, at a mean depth of 1.0 m and a slope of 0.3% are 75 mm diameter subsurface drain pipes which enter one of the two buildings. A plastic curtain, at a 1.5 m depth, surrounds each plot to minimize the seepage of water and chemical flow. The blocks were planted with a monocrop of corn and there were four treatments: water table control at 60 cm and 120 kg/ha of N fertilizer (WT120), water table control at 60 cm and 200 kg/ha of N fertilizer (WT200), conventional drainage and 120 kg/ha of N fertilizer (FD120), and conventional drainage and 200 kg/ha of N fertilizer (FD200). Those plots with controlled water tables were surrounded on either side by a buffer plot with an identical water table level to minimize seepage between treatments. During the growing season, water is pumped from a 25 m deep well, located a few hundred meters away, to the water control tanks in order to maintain the specified water tables.

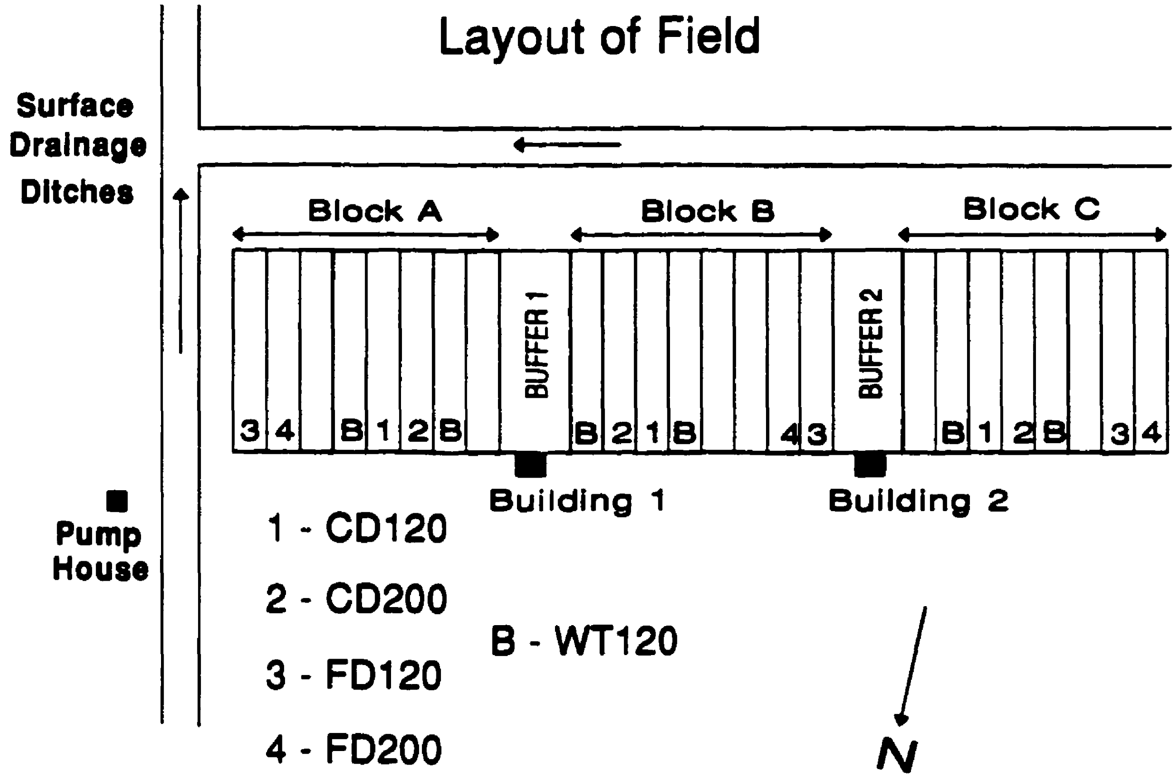


Figure 3.1 Field layout

3.1.3 Subirrigation

All the subsurface drains from block A and half of the drains from block B enter building #1. Building #2 houses the other half of the drains from block B and all the drains from block C. In the beginning of May, 1996, the field was staked and each plot was surveyed above each drain, along with the top of each drain outlet in each building. This enabled the repositioning of the water table control structures in each building to the desired level. Figure 3.2 shows a schematic drawing of the water table control structures found in the two buildings attached to each subsurface drain. This allows for both conventional free drainage and subirrigation to occur, depending on the time of year. When the ball valve is open, conventional drainage occurs and the drainage water flows freely to a tipping bucket. When the ball valve is closed, subirrigation can occur. During subirrigation, water is supplied from the well and pumped into the individual water table control chambers. The water flows into the subsurface drains to maintain the water table level at 60 cm. When this water table is reached, there is a float valve in the control chamber which shuts off the supply of water. During rainfall periods, water is infiltrated into the

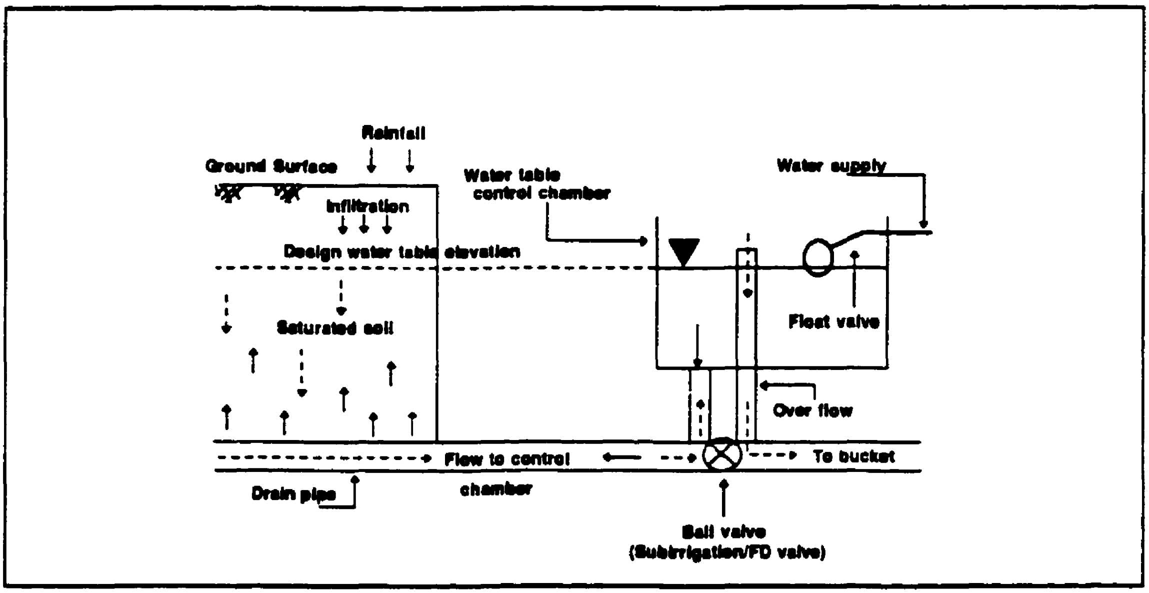


Figure 3.2 Schematic drawing of a water table control structure found in each building (redrawn from Kaluli, 1996).

soil and leached into the drain pipes. The water level in the water table control chamber is raised and the leached water flows into the over flow pipe and into the tipping buckets. Piezometers were placed in the middle of each treatment plot, to a depth of 1.5 m. The piezometers were capped to stop any rainfall from entering and a graduated rod with a water sensor at the end was lowered into the piezometer to monitor the water table levels over the growing season.

3.1.4 Drainage Flow Sampling

Tipping buckets were located at the outlet of each subsurface drain to monitor the drainage discharge during rainfall events. Automatic sampling valves were set up to take 500 ml samples of drain flow, after a known volume (250 l) of water had been discharged, into a 20 l bottle. Once a week sub-samples were collected into smaller 20 mL bottles and stored at 5^0 C. These sub-samples were filtered and then analyzed for NO_3^--N concentrations. Once the concentrations were known, they were linked with their respected drainflow and converted to total NO_3^--N in terms of kg/ha.

Two modem (one in each building) computer data acquisition and control systems were installed. They were able to monitor and store the tipping bucket discharge rates, rainfall data and control the operations of the water samplers.

3.2 Weather Observations

Rainfall was collected every minute and compiled on a daily basis using two tipping bucket rainguages, one on the top of each building. The rainfall was also monitored using a manual rainguage set up between the buildings. There was very minimal discrepenacies between the rainguages. The farm owner also operated a Québec Government weather station, approximately 100 meters NE of the experimental site. Rainfall, temperature and wind speed were measured by the farm owner on a daily basis. There was little difference between the farmer's rainguage, and those at the experimental site.

3.3 Agronomic Practices

During the two year study, the farm owner performed the spring disking and harrowing of the site, the harvesting and the fall ploughing. Seeding, fertilizer applications for the treatments and the spraying of the herbicides was performed by Macdonald Campus staff.

The field was seeded at a rate of 88,000 seeds/ha with Pioneer corn seed 3905 Hybrid. Insecticide Diazinon Lindane Capton was applied both years on May 23. Fertilizer (18-46-0) was applied with seeding and ammonium NO_3^--N was applied at later dates to obtain the treatment fertilizer levels. Tables 3.2 and 3.3 show the agronomic activity for 1996 and 1997, respectively.

Table 3.2 Agronomic activity at the field site (1996).

DATE	Agronomic Practices
May 23	Field Seeded, Fertilized and Sprayed
June 20	Field Fertilized (Ammonium Nitrate)
October 29	Corn harvested

Table 3.3 Agronomic activity at the field site (1997).

DATE	Agronomic Practices
May 23	Field Seeded, Fertilized and Sprayed
June 18	Field Fertilized (Ammonium Nitrate)
June 26	Field Sprayed
October 30	Corn Harvested

3.4 Soil Nitrate Sampling and Analysis

Soil samples were taken in both 1996 and 1997 to determine NO_3^--N levels. Pre-plant samples were taken in the spring (early May) and post harvest samples were taken in the fall (November). Using hand held augers, soil samples were taken in each treatment plot at three depths; 0-25 cm, 25-50 cm and 50-75 cm. Samples were then taken to the laboratory for NO_3^--N analysis. A KCl extraction was performed using the Keeney and

Nelson method (Keeney and Nelson, 1982).

Along with the spring and fall soil NO_3^--N samples, bi-monthly soil samples were taken at a depth of 15 cm each time denitrification was measured. Nitrate concentrations were again measured in the laboratory (Keeney and Nelson, 1982).

3.5 Redox Potential and Denitrification

The field study was conducted between June and October for both 1996 and 1997. In the middle of each of the four treatment plots, for all three blocks, platinum redox potential electrodes were placed at a soil depth of 15 cm. The top half of the probe was placed in a small section of 50 mm diameter perforated pipe and capped on top to protect it from animals and the environment. The bottom half of the electrode was placed securely into the ground. Before the electrodes were used, they were placed in a standard pH solution where both pH and E_h (mv) were measured, verifying similar readings from each probe. After installation, both the Eh and soil temperature were measured, using a 9025C Hanna Portable pH/Orp meter with an attached soil temperature probe, on a weekly basis.

The denitrification rate was estimated by using a C_2H_2 inhibition method (Aulakh et al. 1982). Within 2 m of each electrode, in each block, soil samples were taken bi-monthly. The samples were taken using aluminum cylinders, 0.028 m i.d x 0.15 m long. Before being taken to the laboratory, the cylinders were incubated for a 24 hour period in an open environment, in 2 litre plastic jars with 10% C_2H_2. In the laboratory, the N_2O concentration was determined using a 5870 series-II Hewlet-Packard gas chromatograph containing a Tracor electron capture linearizer which operated a Tracor ^{63}Ni electron-capture detector (Liang and Mackenzie, 1997). Once the N_2O concentrations were determined, they were correlated with E_h and soil temperature using the Proc CORR and REG procedures from SAS. An equation relating the redox potential and soil temperature with the N_2O rate was then established.

3.6 Plant Nitrogen Uptake

In the middle of each central corn row of each treatment plot, above the subsurface drain, ten corn plants were tagged. These plants were used throughout the summer for SPAD (Soil Plant Analysis Development) readings. The SPAD reading was taken using a hand held chlorophyll meter (Minolta-SPAD-502 meter) . Before silking of the corn plant, readings were taken on the uppermost extended leaf and after silking from the cob-ear leaf. Three readings were taken on each leaf and then averaged. Likewise, the ten plants' readings were averaged to represent the treatment plot's overall SPAD reading. SPAD readings were discontinued at the end of August when the plants had stopped growing and were beginning to senesce.

Corn leaf samples were taken from each plot twice in each summer; before silking and after silking. SPAD readings were taken on the leaves and then they were removed from the plant and taken to the laboratory to be analyzed for total N. The leaves were dried for two days at a temperature of 80 ^{0}C and then were shredded into minute pieces. A Kjeldahl digestion, distillation, and acid titration with 0.05 *M* HCl was used in order to determine the leaf-N content (Bremer and Mulvaney, 1982). Once the leaf-N content was known, it was correlated with the SPAD readings, taken on the leaves before digestion, using the program CURVE EXPERT. Two equations were developed linking the SPAD readings to the leaf-N content; one for before silking and one for after silking.

3.7 Statistical Analysis

Statistical analysis was performed on all collected data. Using SAS and the GLM procedure, an f-test was conducted to see if there was significance at the $p \leq 0.5$ level. SAS was used to determine the significance of time, treatment and block and their relationships to each other. A t-test was conducted to compare the individual treatments with each other.

The significance of certain N parameters were also investigated; the relationship between the % N in the plant, the denitrification rate and the soil NO_3^--N levels to the leached NO_3^--N in the drain waters was determined using SAS and the Pearson Correlation procedure. If any of the N parameters were found to be related significantly to NO_3^--N levels in the drainage waters, equations were developed linking the two factors using CURVE EXPERT. If more than two of the N parameters were related significantly to the NO_3^--N levels in the drainage waters then more complex relationships could be derived.

4.0 RESULTS AND DISCUSSION

4.1 Rainfall and Air Temperature Data

Figures 4.1 and 4.2 show the hyetographs for the 1996 and 1997 growing seasons, respectively. The monthly rainfall averages, during the growing season, are shown with the historic monthly averages in Table 4.1. Throughout Canada, 1996 proved to be the wettest year in recorded history. Most of the precipitation which occured came in the form of intense events. Comparing Figures 4.1 and 4.2 it is seen that there were not necessarily more rainy days in 1996 but rather greater amounts of precipitation when it did rain. In Table 4.1, the 1996 growing season had a 21.1% increase in precipitation when compared to the average over the last 30 years. In comparison, the 1997 growing season had only a 2.1% increase in precipitation when compared to the average over the last 30 years.

Daily air temperatures for 1996 and 1997 are presented in Table 4.2 in terms of the average temperature for each month between April and October along with historical air temperatures from the last 30 years from the Environment Canada station at the Dorval International Airport. When compared to the Environment Canada temperatures from the past, the growing seasons of 1996 and 1997 were slightly lower than normal temperatures. The average temperature in 1996 was 14.0 ^{0}C, compared to the norm of 14.2 ^{0}C, a -1.4% difference. Similarly, in 1997, there was a -2.8% difference, with the average temperature being 13.8 ^{0}C.

Table 4.1 - Monthly growing season rainfall data, from the building rain guages at the field site, for 1996 & 1997, and historic data.

MONTH	1961-1990†	1996		1997	
	Rainfall (mm)	Rainfall (mm)	Difference (%)	Rainfall (mm)	Difference (%)
April	73.5	122.6	+66.8	91.3	+24.2
May	68.3	103.8	+52.0	66.2	-3.1
June	82.5	81.8	-0.85	98.0	+18.8
July	85.6	133.9	+56.4	97.0	+13.3
August	100.3	40.8	-59.3	96.3	-4.0
September	86.5	140.6	+62.5	91.4	+5.7
October	72.8	66.0	-9.3	41.4	-43.1
Total	569.5	689.5	+21.1	581.6	+2.1

† (Environment Canada, 1994)

Table 4.2 - Monthly growing season air temperature data, from the field site, for 1996 & 1997, and historic data.

MONTH	1961-1990†	1996		1997	
	Temperature (° C)	Temperature (° C)	Difference (%)	Temperature (° C)	Difference (%)
April	5.7	4.9	-14.0	4.7	-17.5
May	12.9	11.7	-9.3	10.3	-20.2
June	18.0	18.6	+3.3	19.3	+7.2
July	20.8	19.5	-6.3	20.6	-0.96
August	19.4	19.5	+0.5	19.0	-2.1
September	14.5	15.7	+8.3	14.6	+0.69
October	8.3	7.8	-6.0	8.0	-3.6
Average	14.2	14.0	-1.4	13.8	-2.8

† (Environment Canada, 1994)

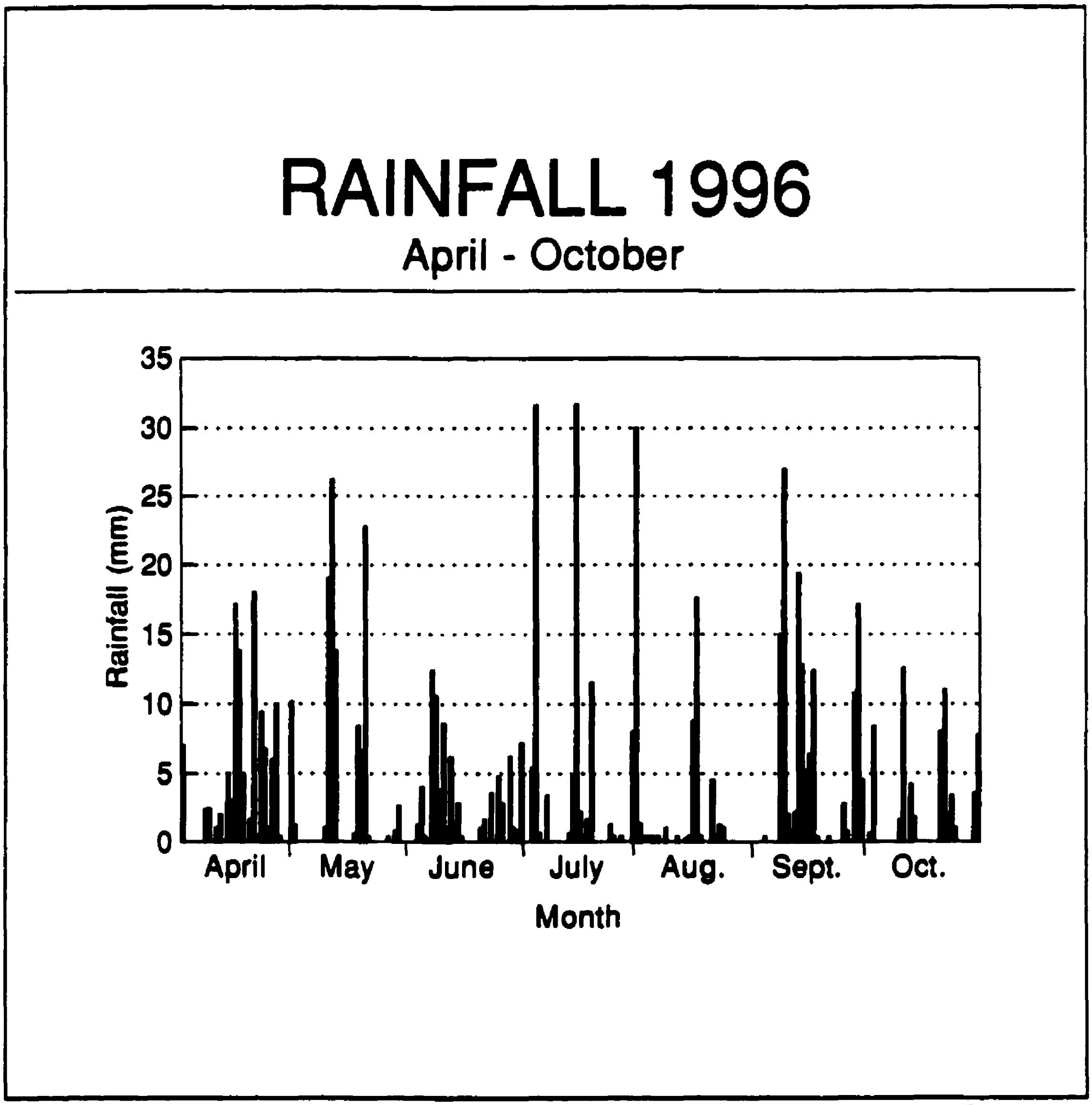


Figure 4.1 **Rainfall hyetograph for the 1996 growing season, from the rain guages on each building at the field site.**

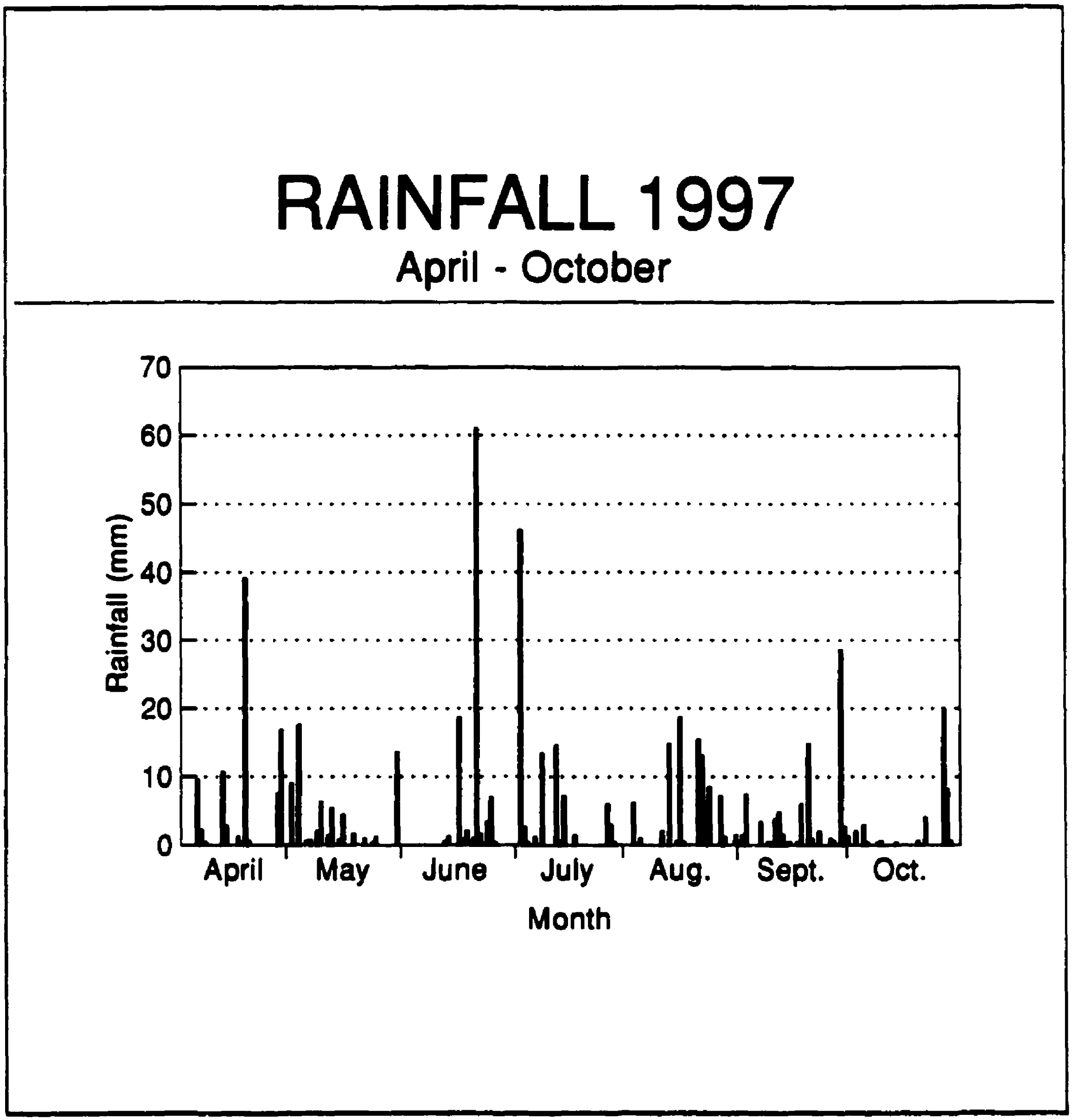


Figure 4.2 **Rainfall hyetograph for the 1997 growing season, from the rain guages on each building at the field site.**

4.2 Water Table Depth

The water table depths were monitored in each of the treatment plots for each block. It was difficult to sustain a continuous water table in the 60 cm water table plots. Although buffer plots were set up, with identical water table heights on either side of the WT200 and WT120 treatment plots, and there was also a 1.5 m deep plastic curtain around each plot, it was found that seepage still occured. During those months when the soil was saturated from frequent rainfall events, the water table was closer to the target mark. When the soil was drier, the water table was closer to the drain level at 1.0 m. A steady rainfall was required over a period of time to saturate the soil so that the required water tables could be maintained.

During the 1996 growing season (Figure 4.3), the target water table heights were met during the months of July and October. In July, there was a large amount of rain (133.9 mm), saturating the soil and helping to maintain the desired water table height. August was an extremely dry month where water table heights were closer to the drain depth at 1.0 m. In September, there were 140.6 mm of rain, but because of the initial dry conditions in August, it was only possible to maintain water tables midway to the target levels. In October, the desired water table levels were reached, due to the wetter soil conditions.

In the 1997 growing season (Figure 4.4), the water table heights were continually maintained at the midway point between the target levels and the free drainage level of

1.0 m. This was due to less precipitation than 1996, with the soil not becoming saturated at any one time.

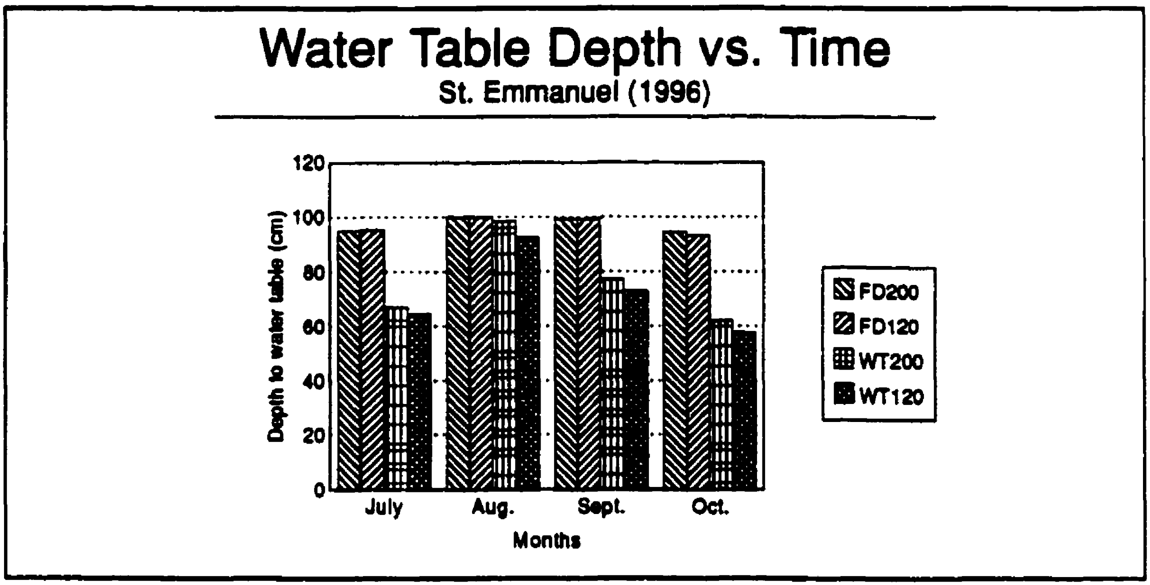


Figure 4.3 Water table depths for the 1996 growing season, from the field site measured with piezometers.

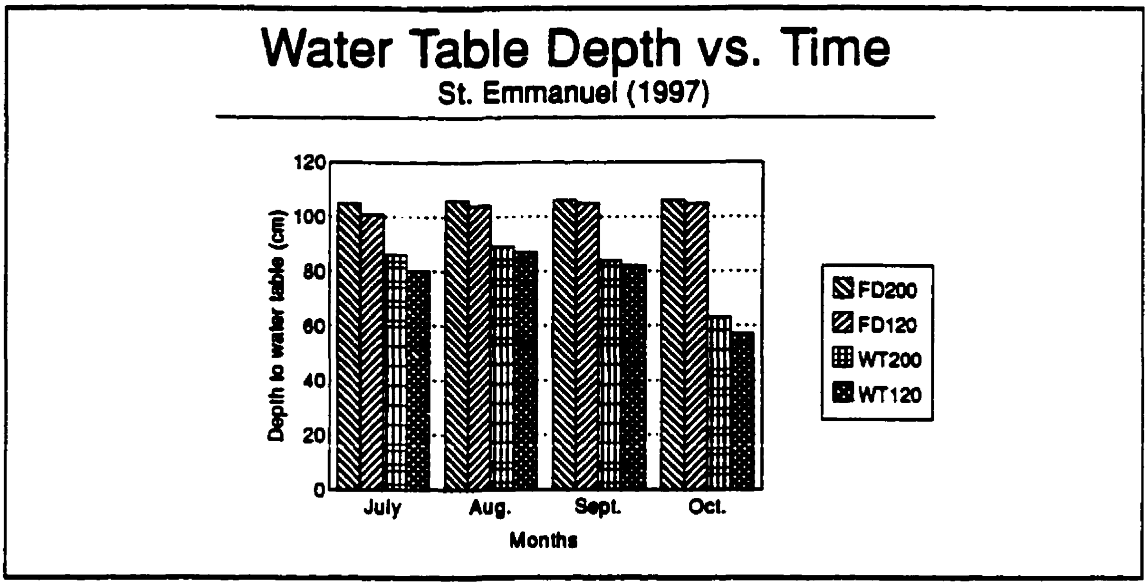


Figure 4.4 Water table depths for the 1997 growing season, from the field site measured with piezometers.

4.3 Drainage Flow

Drain flow for 1996 and 1997 is prsented in Figures 4.5 and 4.6. Subirrigation was turned on in mid June and turned off at the end of October. The total drain flow for the months between April and October for both 1996 and 1997 can be observed in Table 4.3. As can be expected there were approximately 100 mm more drainflow in each treatment plot in 1996 than in 1997 due to the higher rainfall.

Table 4.3 Total drain flow (April-Oct.) for 1996 and 1997 from the field site.

Treatment	Total Drain Flow 1996 (mm)	Total Drain Flow 1997 (mm)
FD200	249.9	96.4
FD120	256.0	146.0
WT200	223.8	135.2
WT120	238.5	145.4

In 1996, during the growing season, the water table control plots showed lower drain flow compared to the conventional drainage plots. Under ideal conditions of subirrigation, water table control plots should have less drain flow when compared to plots with conventional drainage. More water is made available to the crop in controlled water tables, by maintaining a desired amount of water in the root zone. Only when the water table exceeds the "desired" level will drain flow result. The month of August was dry (40.8 mm total rainfall) and the controlled water table levels were just slightly under the conventional drainage levels of 1.0 m.

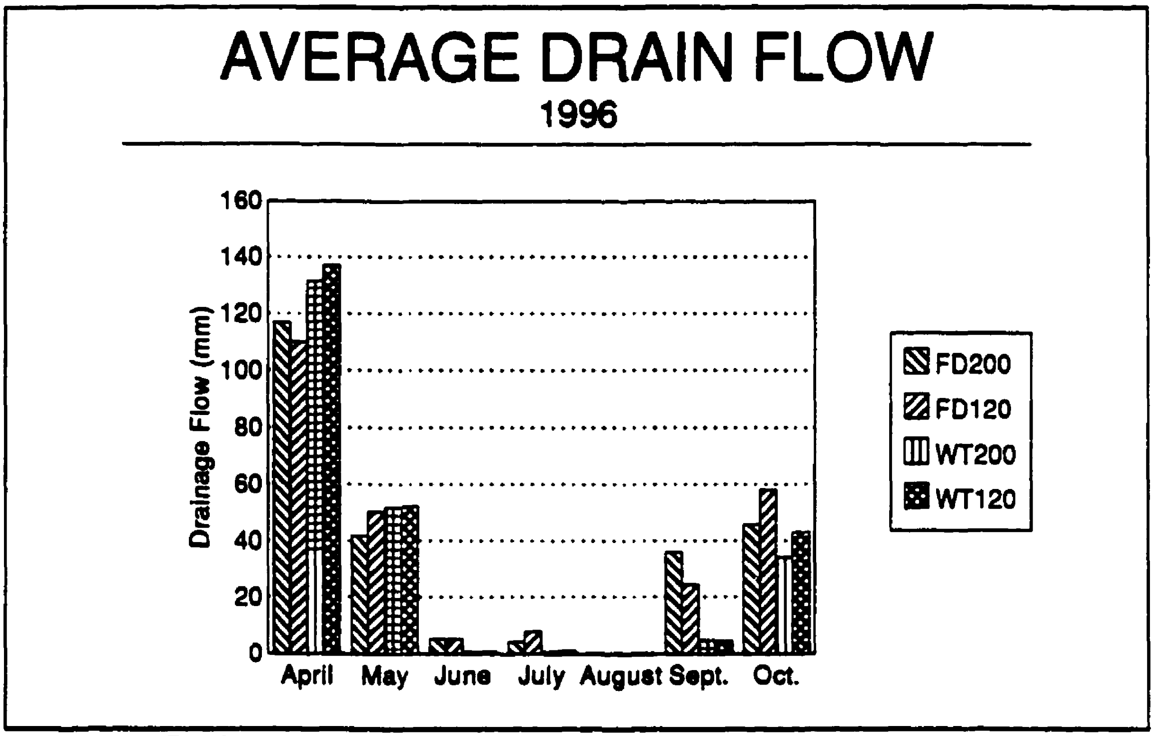


Figure 4.5 Drain flow for 1996, from the field site.

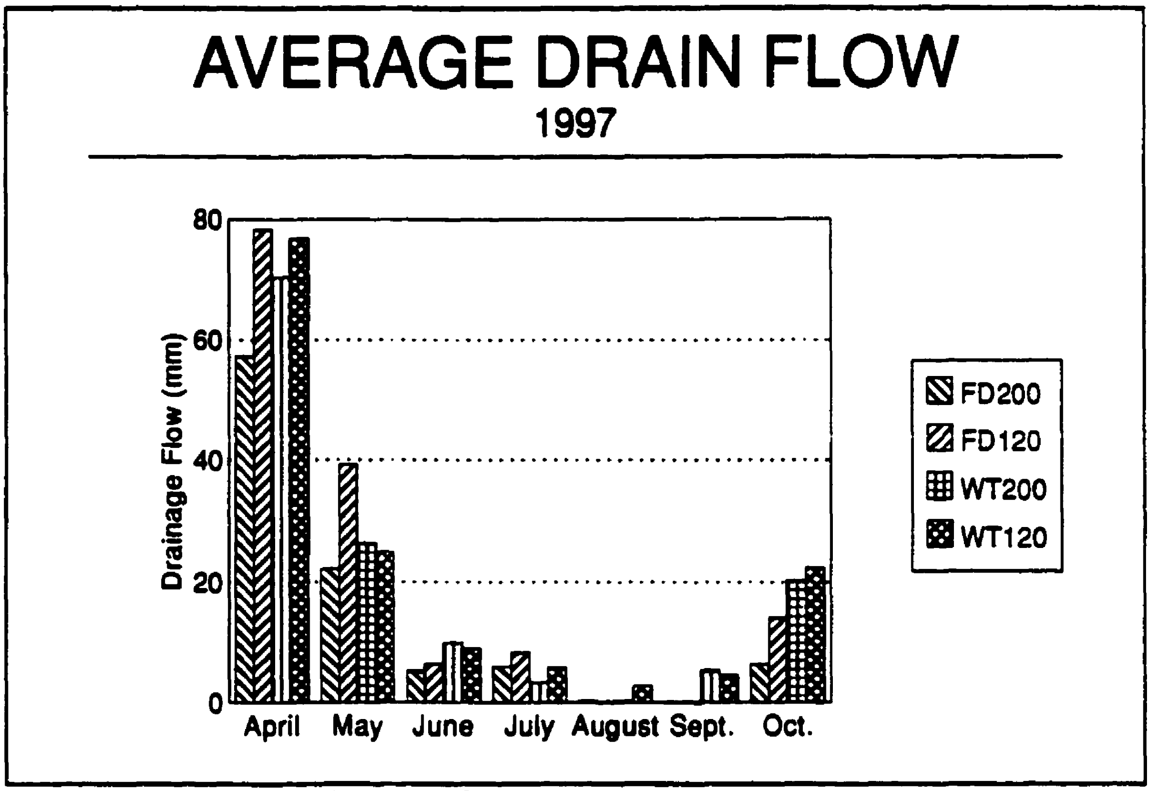


Figure 4.6 Drain flow for 1997, from the field site.

Although the summer months had little flow (no more than 8 mm per month), a difference between the treatments was still observed. For the two fall months (September and October), there were greater amounts of rainfall (140.6 mm and 66.0 mm, respectively) resulting in higher drain flow. In September, the contrast between the free drainage plots and the controlled water table plots was easy to distinguish, with 4.77 mm and 4.32 mm for the WT200 and WT120 plots, respectively and 36.04 mm and 24.37 mm for the FD200 and FD120 plots, respectively.

Drain flows during the 1997 growing season were, by contrast, quite different compared to 1996. July proved to be the only month where water table control plots had less drainage than the free drainage plots. In the other months during the growing season, the water table control plots had more flow than free drainage plots. In June, the water table control plots had slightly higher flows than the free drainage plots and in August and September, the free drainage plots recorded virtually no drainage flows, whereas the control plots recorded small amounts (0 mm and 5.19 mm for the WT200 plots in August and September, respectively; and 2.60 mm and 4.36 mm for the WT120 plots in August and September, respectively). This contradicts the results found in 1996. It is possible that controlled drainage plots had more flow than conventional drainage plots. In 1996, the months with higher rainfall alternated with the months with lower rainfall. This, coupled with the fact that there were 107.9 mm more rain throughout April to October in 1996 than in 1997, may have caused the soil in 1997 to be semi-saturated allowing for the water table controls to work properly. In 1997, there were roughly equal amounts of rainfall days in each month, with less intense events. The soil was consistently drier throughout the summer months. This would account for the fact that there was less drain flow in the free drainage plots. When water managed to percolate through the soil profile, it had a further distance to travel (1m) to reach the tile drains. With the soil being dry, the water was trapped in the pore space and never reached the drains. However, in the water table control plots, the water had to travel a shorter distance to the drains, due to the existence of the water table and heavy rainfalls. The soil pore space was also filled, not allowing the percolating water to be stored.

In 1996, analysis of repeated measures (Table 4.4) for drain flow found blocks to be significant, indicating possible field ambiguities such as moisture contents, bulk density or soil type. Time was also found to be significant, caused by different precipitation levels during the growing season. In 1997, from Tables 4.4 and 4.5, it is seen that treatment for drain flow was not significant, . Block and time, however, were both significant at the $p=0.05$ level again indicating possible field ambiguities, such as moisture content, in each of the three blocks and an indication of the different rainfall amounts during the various months.

Table 4.4 Repeated measures analysis of variance for drain flow and the error term for the data.

	Pr>F + (Error Term)	
Source	1996 Drain Flow	1997 Drain Flow
Time	0.0001* (0.263)	0.0001* (0.220)
Trt	0.1810^{NS} (0.103)	0.2000^{NS} (0.123)
Block	0.0001* (0.075)	0.0001* (0.090)
Time*Trt	0.0360*	0.6800^{NS}
Time*Block	0.0001*	0.0100*
Block*Trt	0.0200*	0.5180^{NS}

* Significant at 0.05 level
NS Not significant

Table 4.5 Repeated measures analysis of variance for drain flow between treatments.

	Pr>t	
Trt	1996 Drain Flow	1997 Drain Flow
WT120 vs WT200	0.1170^{NS}	0.6668^{NS}
WT120 vs FD200	0.8660^{NS}	0.0450*
WT120 vs FD120	0.0876^{NS}	0.2928^{NS}
WT200 vs FD120	0.8835^{NS}	0.5304^{NS}
WT200 vs FD200	0.1606^{NS}	0.1090^{NS}
FD120 vs FD200	0.1223^{NS}	0.3193^{NS}

* Significant at 0.05 level
NS Not significant

4.4 Water Quality from the Subsurface Drains

Figure 4.7 presents the NO_3^--N concentrations for both 1996 and 1997. As expected, free drainage plots with 200 kg/ha of fertilizer, gave the highest concentration of NO_3^--N in both years. Free drainage plots allow leaching to occur more easily than in controlled water table plots. This, along with the higher fertilizer rate, should result in higher NO_3^--N concentrations. In 1997, the WT200 treatment had the second highest concentration. The higher fertilizer rate of 200 kg/ha played a larger role in increasing the NO_3^--N concentration than the water table control had on decreasing it. More NO_3^--N in the field was available to leach through the soil and into the drains. This process, however, was slowed by the higher water table. As expected, the WT120 treatment had the lowest concentration as it had a combination of both a controlled water table and a low fertilizer rate of 120 kg N/ha.

Total NO_3^--N lost to subsurface drains, in 1996 and 1997, is presented in Figure 4.8. There was a higher amount of NO_3^--N pollution lost in 1996 compared to 1997. In fact, for the FD200, FD120, WT200 and WT120 treatments, there were 39.4%, 28.1%, 37.8% and 44.7%, respectively, greater amounts of NO_3^--N in 1996 than in 1997. The biggest contributing factor for such a large increase would be the higher rainfalls experienced in 1996. Since 1996 was a much wetter year than 1997, more leaching occured, and subsequently more NO_3^--N was lost, resulting in greater amounts of NO_3^--N pollution through the drains. This is an example of how important rainfall is to water pollution.

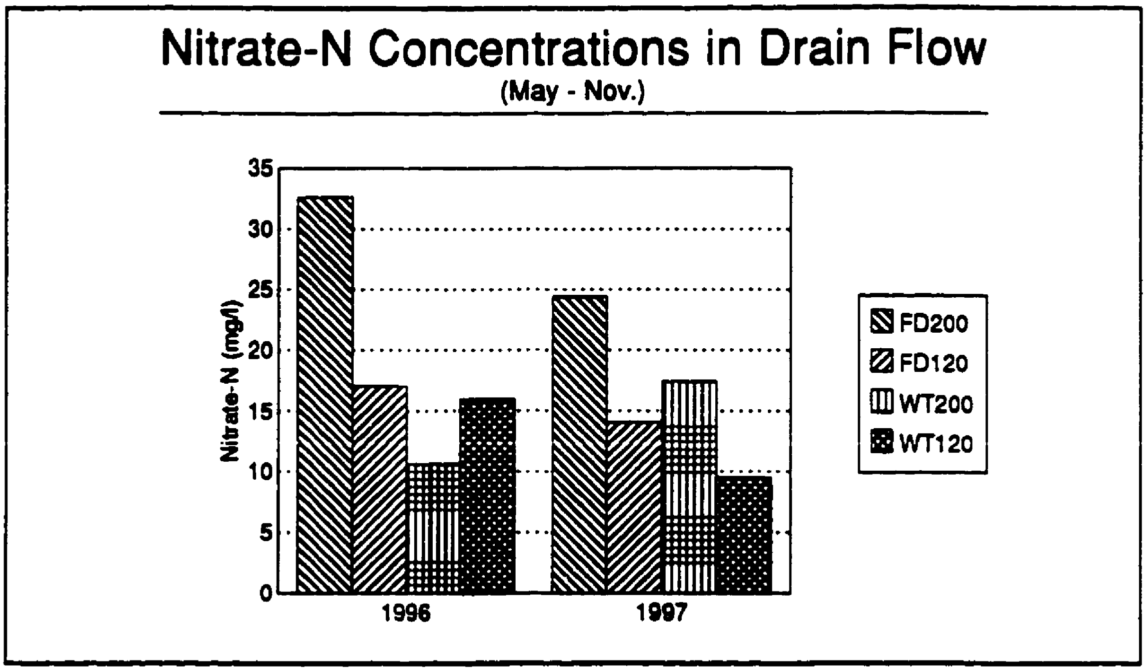


Figure 4.7 **Nitrate-N concentrations for 1996 and 1997, measured from the subsurface drains at the field site.**

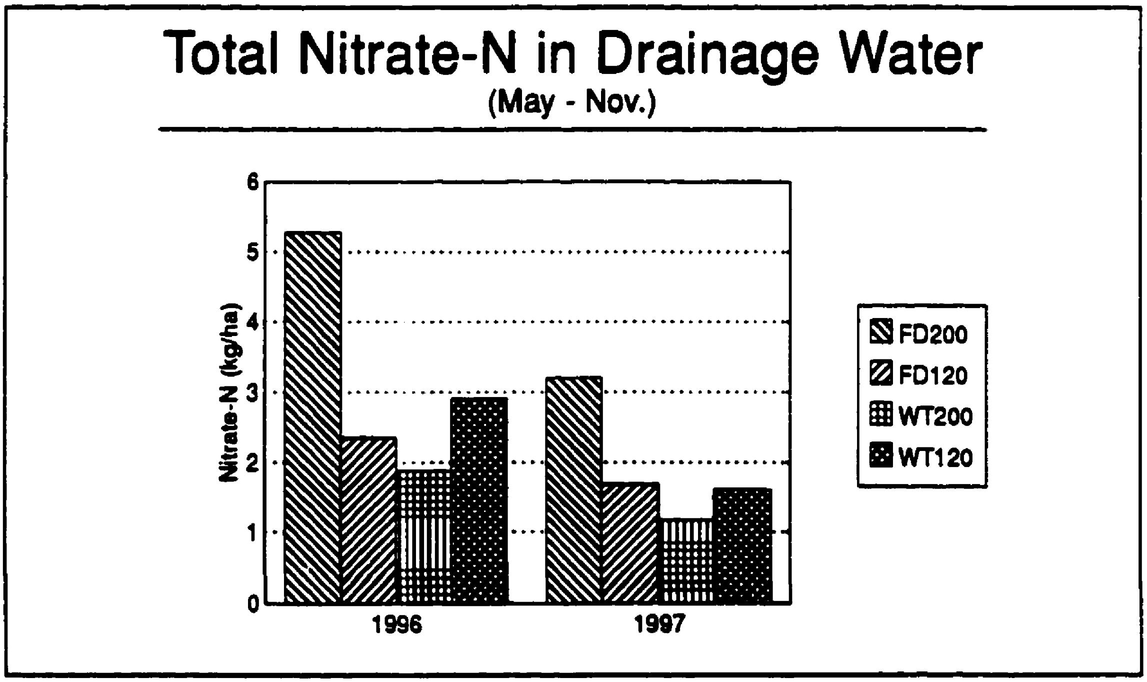


Figure 4.8 **Total nitrate-N lost to subsurface drains in 1996 and 1997, from the field site.**

When combining the two free drainage treatments, in terms of total NO_3^--N lost, and the two water table treatments, it can be seen that there is more NO_3^--N lost in free drainage plots compared to controlled water table plots. In 1996, there was a total of 7.63 kg/ha lost in free drainage plots and 4.79 kg/ha in controlled water table plots. Therefore, 59.2% more NO_3^--N was lost in free drainage plots compared to controlled water table plots. Similarly, in 1997, the free drainage and controlled water table plots lost 4.89 kg/ha and 2.78 kg/ha, respectively. Compared to the controlled water table plots, this is an increase of 75.9% NO_3^--N lost in the free drainage plots. Controlled water tables help in decreasing drainflow, unlike conventional drainage, as well as enhancing denitrification, resulting in less NO_3^--N lost. However, the treatment differences were not statistically significant implying that the treatments were neither statistically or agronomically significant. For 1996, the analysis of repeated measures showed that only time was significant (Table 4.6). In 1997, both time and block were significant. Time being significant because of the various amounts of drain flow throughout the growing season and block being significant due to field ambiguities such as moisture content and soil type which may impede the leaching of NO_3^--N to the drains.

Table 4.6 Repeated measures analysis of variance for NO_3^--N in the subsurface drains and the error term for the data.

	Pr>F + (Error Term)	
Source	[NO_3^--N] in 1996	[NO_3^--N] in 1997
Time	0.0001* (0.203)	0.0001* (0.203)
Trt	0.8830^{NS} (0.103)	0.1740^{NS} (0.133)
Block	0.5010^{NS} (0.097)	0.0060* (0.097)
Time*Trt	0.9230^{NS}	0.2200^{NS}
Time*Block	0.7340^{NS}	0.0180*
Block*Trt	0.8010^{NS}	0.3510^{NS}

* Significant at 0.05 level
NS Not significant

Table 4.7 Repeated measures analysis of variance for NO_3^--N in the subsurface drains between treatments.

	Pr>t	
Trt	[NO_3^--N] in 1996	[NO_3^--N] in 1997
WT120 vs WT200	0.2266^{NS}	0.5806^{NS}
WT120 vs FD200	0.4224^{NS}	0.1142^{NS}
WT120 vs FD120	0.7314^{NS}	0.9558^{NS}
WT200 vs FD120	0.4517^{NS}	0.5435^{NS}
WT200 vs FD200	0.7018^{NS}	0.0362*
FD120 vs FD200	0.7002^{NS}	0.1268^{NS}

* Significant at 0.05 level
NS Not significant

4.5 Soil Nitrate

The 1996 spring and fall NO_3^--N levels can be seen in Figure 4.9. The initial spring NO_3^--N levels were related to the previous year's field management and were not directly linked to the treatments applied in this experiment. When comparing the spring and fall levels, however, it is interesting to see that the fall NO_3^--N levels were much lower, ranging from 6.36 kg/ha in the WT120 treatment to 9.32 kg/ha in the FD120 treatment. This would be due to the increased leaching caused by the higher rainfalls experienced that year as well as crop uptake of N. The water table treatments had lower NO_3^--N levels compared to the free drainage treatments. Even though more drain flow was recorded in 1996 in the free drainage plots, the lower levels observed in the water table control plots are due to increased denitrification.

Figure 4.10 shows the soil NO_3^--N levels during the 1996 growing season. The graph starts in mid-July, because the soil samples were taken in conjunction with the denitrification samples. The two treatments with the higher NO_3^--N levels were the FD200 and WT200 because of their higher fertilizer application rate. Around Julian day 234 (Aug.23) the concentrations started to increase. There was a dry period during the summer and less denitrification occurred. On Julian day 248 (Sept.4) the concentrations started to decrease in unison with the higher rainfall events which occured in this period as denitrification increased with the saturated soil conditions.

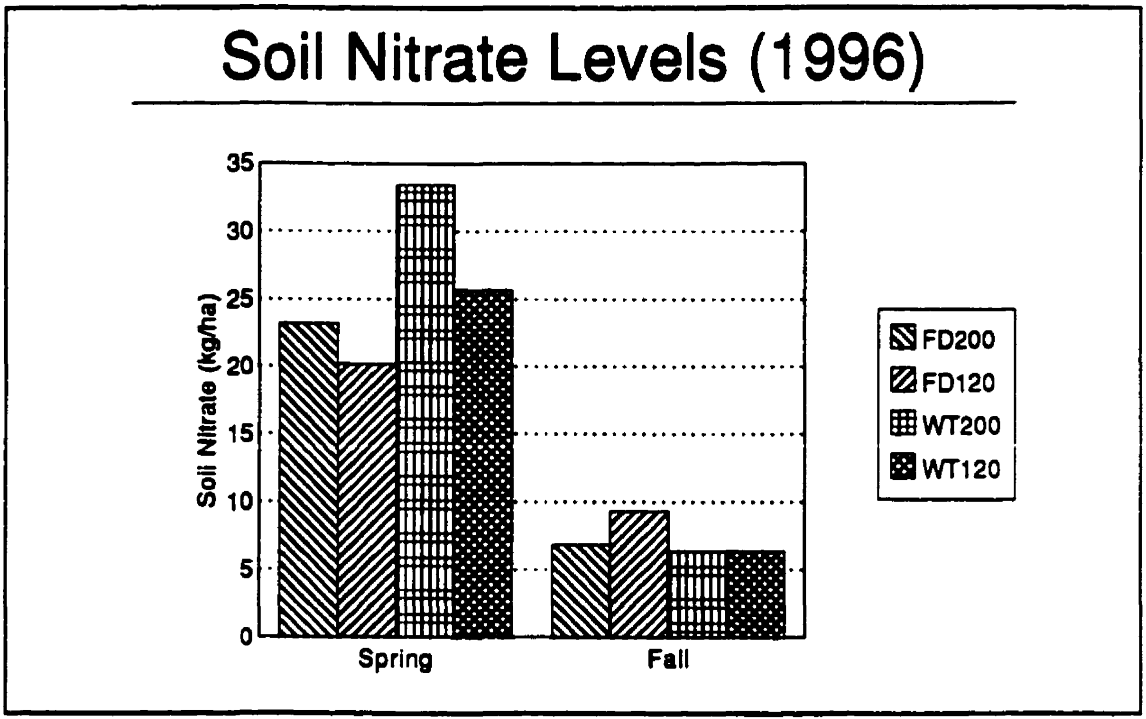
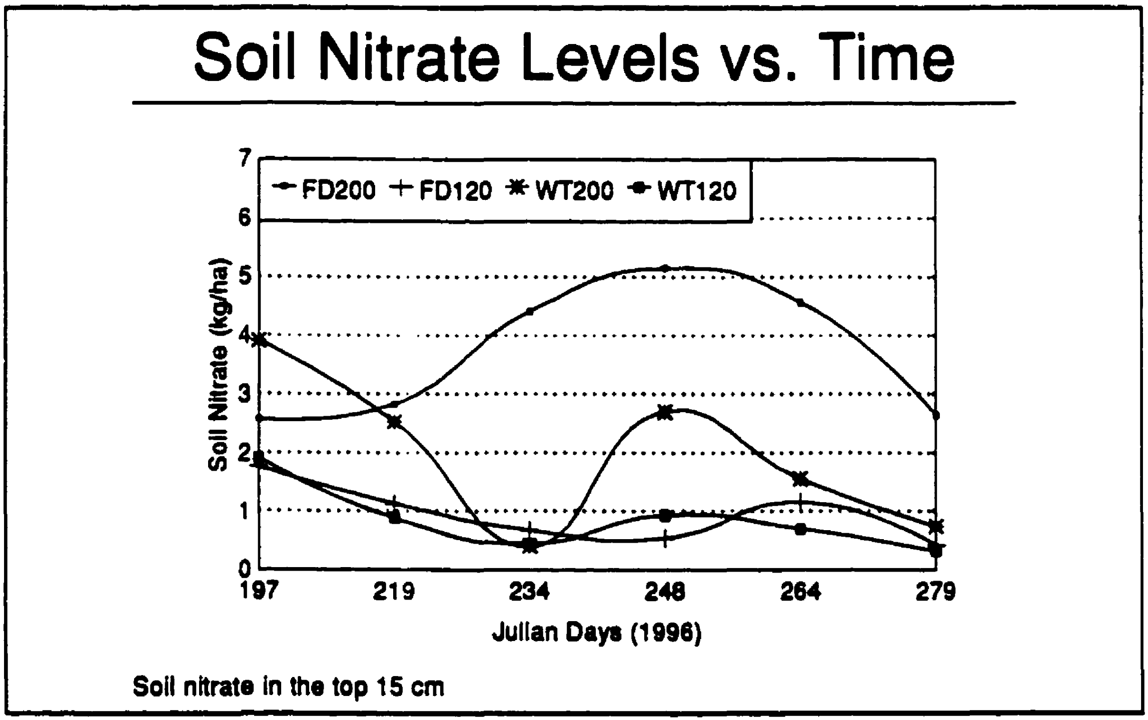


Figure 4.9 Soil nitrate levels, for spring & fall 1996, at the field site.



Soil nitrate in the top 15 cm

Figure 4.10 Soil nitrate levels, during the 1996 growing season, at the field site.

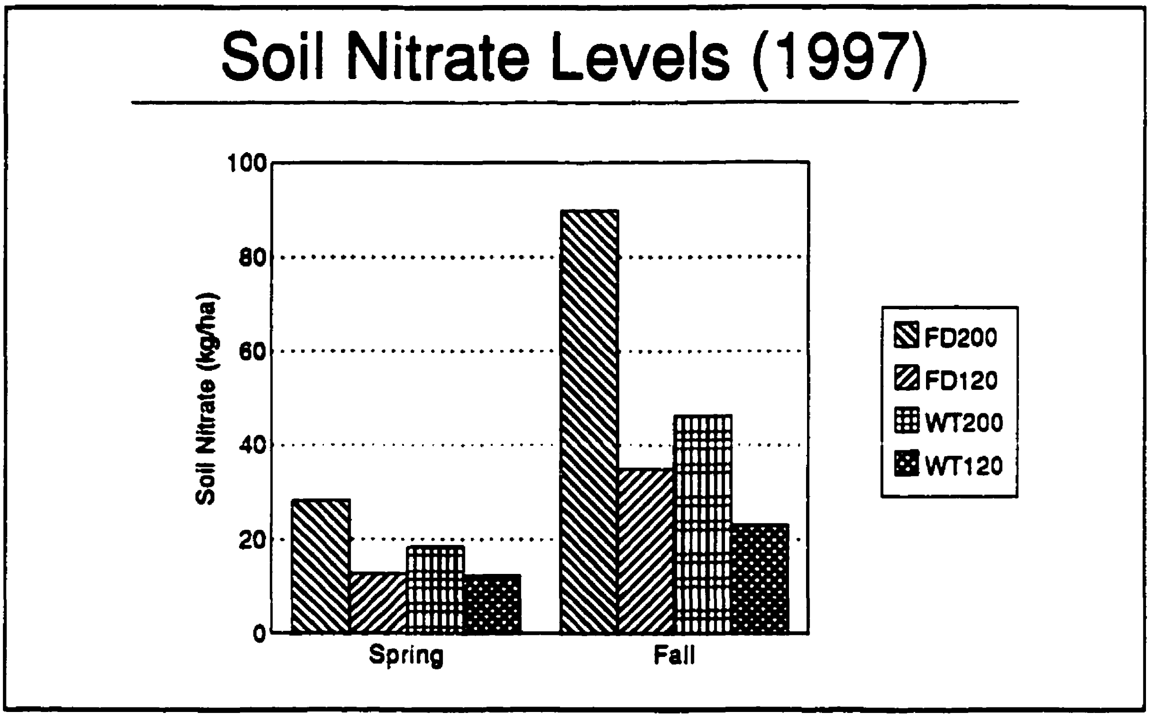


Figure 4.11 Soil nitrate levels, for spring & fall 1997, at the field site.

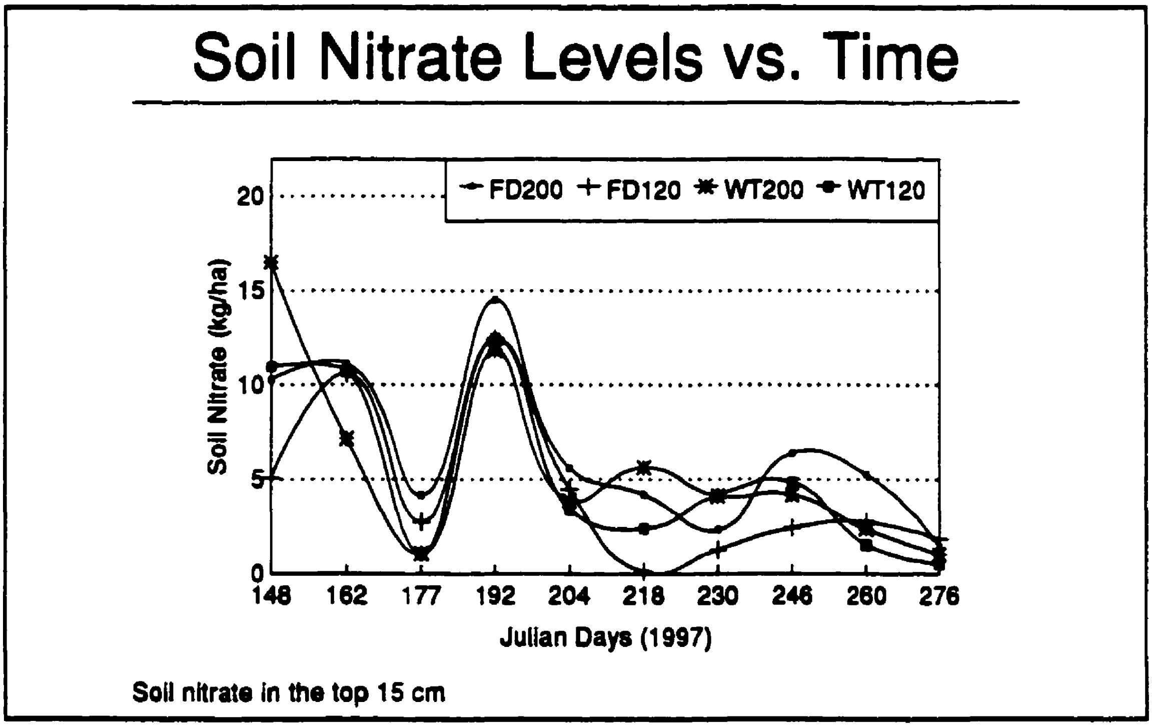


Figure 4.12 Soil nitrate levels, during the 1997 growing season, at the field site.

Figure 4.11 presents the 1997 spring and fall soil NO_3^--N concentrations. These concentrations increased tremendously compared to the 1996 fall values. This increase would be due to a significant increase of mineralization over the winter months (Liang et al., 1991) to replace and increase any lost NO_3^--N which may have occurred through leaching. The higher concentrations can be found in the two treatments which have the higher fertilizer rates. In the fall of 1997, the NO_3^--N concentrations increased. Although during the growing season, (Figure 4.12), the NO_3^--N concentrations fluctuate, after harvest there is no more crop to take up NO_3^--N, leaving more to accumulate in the soil. There were higher NO_3^--N concentrations in the FD200 and WT200 treatments than in the FD120 or WT120 treatments.

Figure 4.12 shows the soil NO_3^--N levels during the 1997 growing season. All four treatments share similar trends. Starting on Julian day 197, each of the four treatments decrease to lower NO_3^--N levels until Julian day 177. The low points on the graph indicate where higher denitrification is taking place. On Julian day 192 (July 11) the curves dramatically increased for all four treatments. On June 18, ammonium nitrate was applied on the field to complete the fertilizer application for the four treatments. Shortly after, soil NO_3^--N levels increase as NO_3^--N slowly leaches into the soil profile.

4.6 Soil Redox and Denitrification

Figure 4.13 presents the redox potential data for 1996. In theory, the higher the redox (mv), the higher the aeration in the soil. Therefore, the free drainage plots should have the highest redox potentials. It can be seen in Figure 4.13 that the natural trend is for the two higher fertilizer application treatments (WT200 and FD200) to have the higher redox potentials during the summer months.

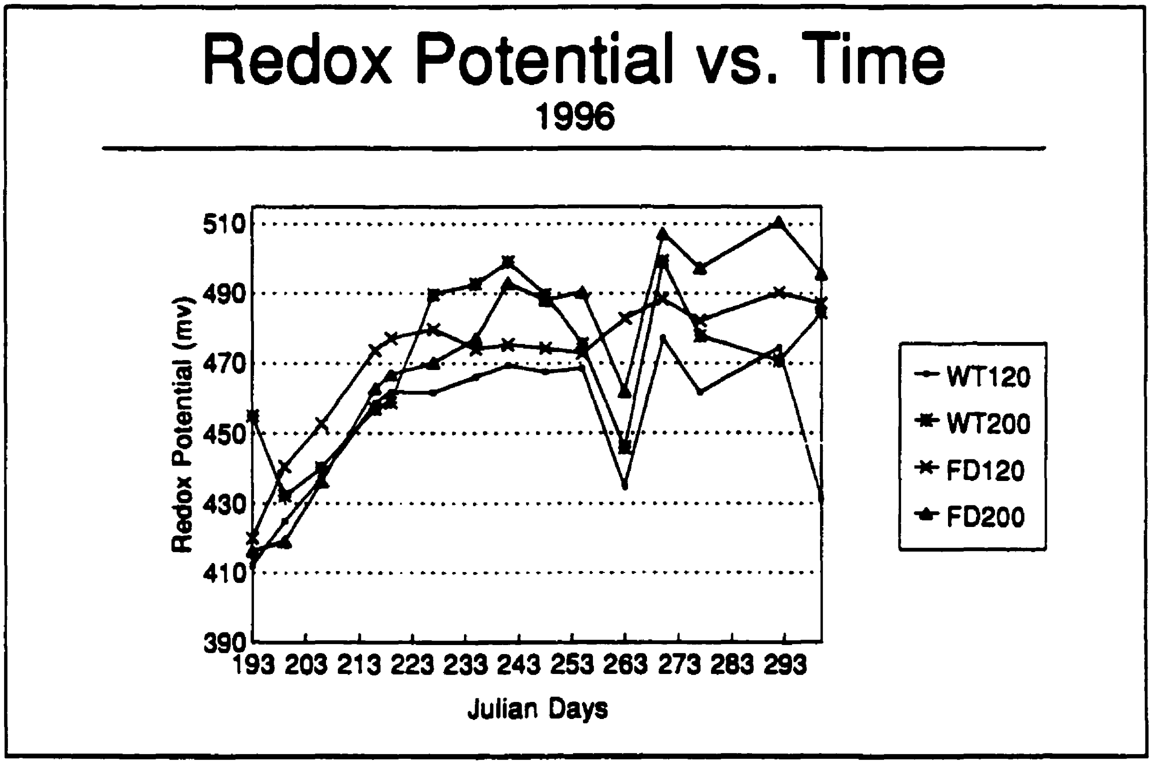


Figure 4.13 Redox Potential at the field site taken by an ORP meter, for 1996.

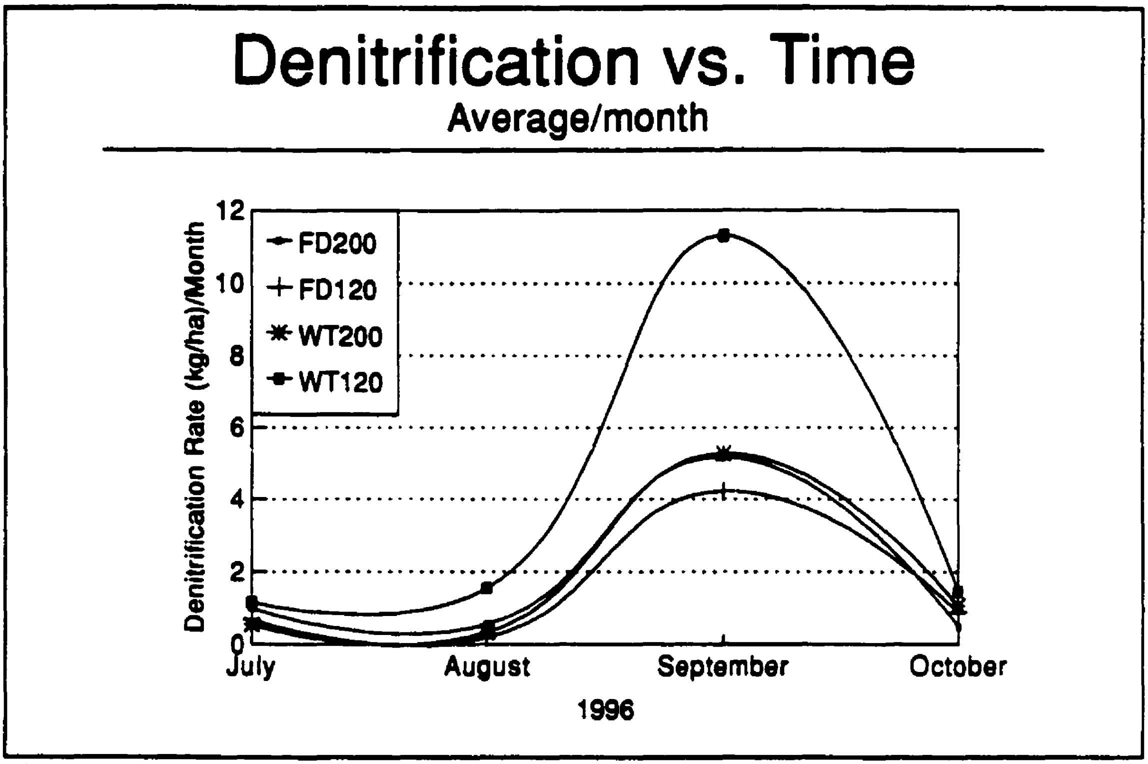


Figure 4.14 Denitrification in 1996 at the field site.

Denitrification equations were developed for both years of research. In 1996, denitrification was positively correlated to soil temperature ($r^2=0.52$). Once the soil temperature and redox potential were known, using the REG procedure in SAS, a linear regression equation was established to equate the denitrification rate (DENIT-kg/ha) with both the redox potential (Eh -mv) and soil temperature (Temp-^{0}C) (Equation 4.1).

$$DENIT=364.3-0.7*Eh-2.4*Temp \qquad [r^2=0.57] \quad \ldots 4.1$$

From equation 4.1, monthly values of denitrification were generated and plotted in Figure 4.14. The treatments share the same trends as all four increase and peak in the month of September. The rainfall was greater in this month resulting in anaerobic conditions in the soil. The monthly denitrification rates were tabulated in Table 4.6 and totalled for July to October. The WT120 treatment had the highest amount of denitrification, in excess of 15 kg/ha. Consistently, throughout both 1996 and 1997, the water table in WT120 was shallower, compared to the other treatments, resulting in an environment favourable to denitrification. Both FD200 and WT200 treatments were similar, (7.21 kg/ha and 7.19 kg/ha, respectively), and the FD120 treatment had the lowest amount of denitrification with 5.96 kg/ha. FD200 and WT200 showed similar denitrification rates due to the higher fertilizer rate. The subirrigated plots produced generally higher denitrification, compared to the free drainage plots. The role of the water table on denitrification is important to achieve NO_3^--N reductions. During subirrigation, the soil profile contains more water when compared to conventional drainage. Therefore, a shallow water table allows the denitrification process to increase by restricting O_2 diffusion in the top soil, creating an anaerobic state.

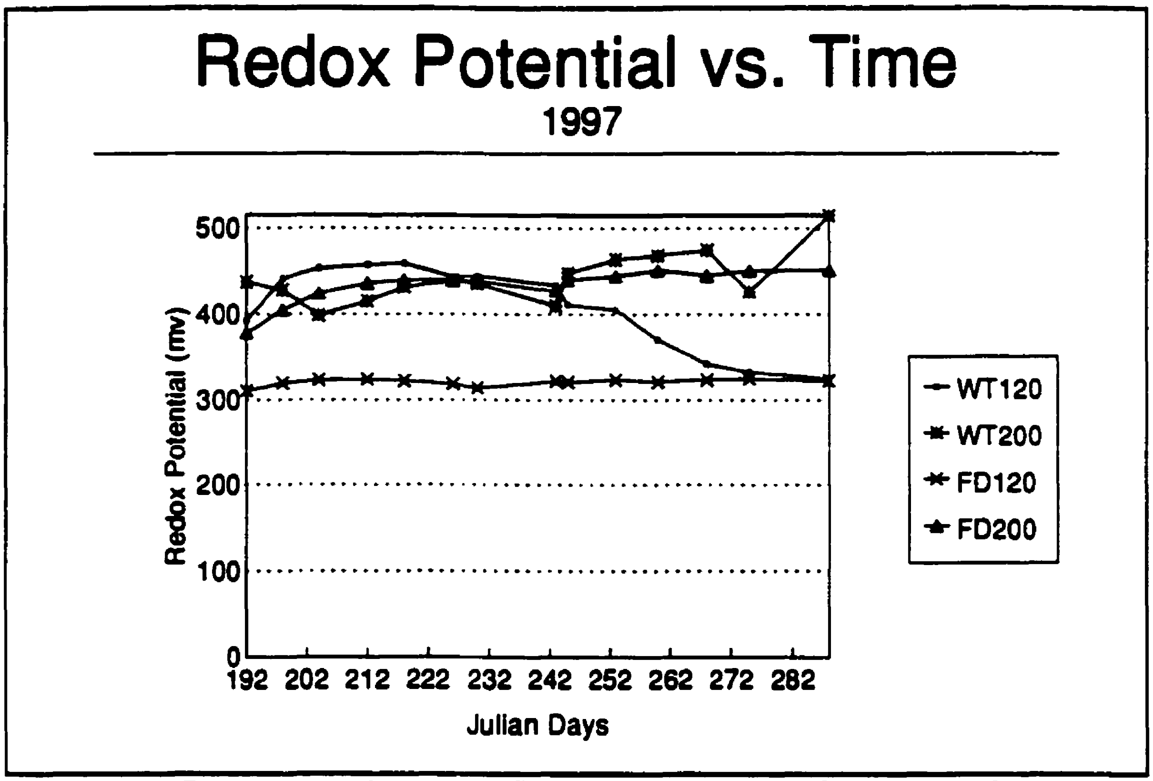


Figure 4.15 Redox Potential, at the field site taken by an ORP meter, for 1997.

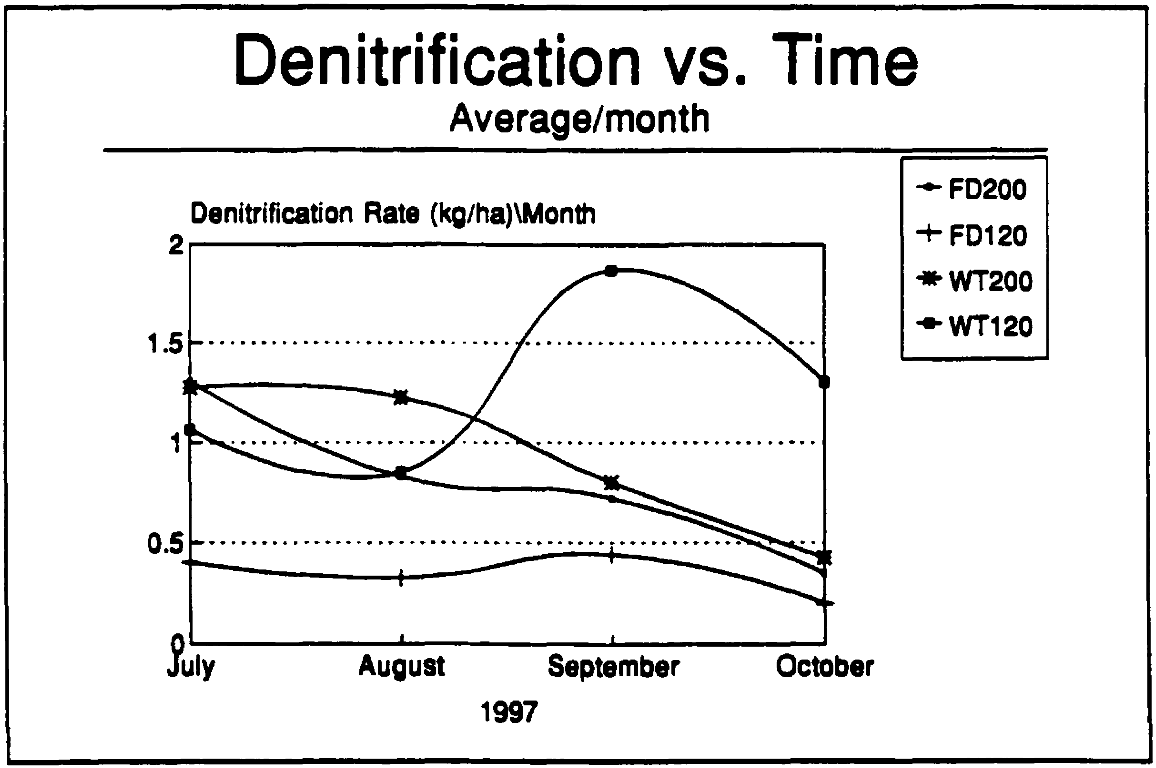


Figure 4.16 Denitrification, at the field site, for 1997.

Table 4.8 Total denitrification (kg/ha), at the field site, for 1996 and 1997 (July to October).

Treatment	Denit. (kg/ha) 1996	Denit. (kg/ha) 1997
FD200	7.21	3.20
FD120	5.96	1.36
WT200	7.19	3.72
WT120	15.49	5.09

Figure 4.15 shows the redox potential data for 1997. The FD200 and WT200 treatments had the highest redox potential, but only in the fall months. For 1997, equation 4.2 was developed to relate temperature and redox potential to denitrification.

$$DENIT = 177.5 - 0.4*Eh - 0.4*temp \qquad [r^2 = 0.32] \ \ldots 4.2$$

Figure 4.16 shows the monthly totals (July to October) of denitrification for 1997. The WT120 treatment increases in September while the other three treatments decrease. Referring to Table 4.8 it can be seen that denitrification in 1997 was considerably less than in 1996 (between July and October). There was 338.2% less denitrification in 1997 compared to 1996 for the FD120 treatment. This is attributed to the much higher rainfalls experienced in 1996. For the FD200, WT200, and WT120 treatments there was 125.3%, 93.3%, and 204.3% respectively, less denitrification in 1997 compared to 1996. Both water table control treatments had more denitrification compared to the free drainage treatments.

When combining the free drainage treatments and the water table control plots, it was found that, for both 1996 and 1997, there was considerably more denitrification in the water table control plots. In 1996, the plots with controlled water tables gave increased denitrification of 72.2% over free drainage plots and in 1997, by 93.2%. This demonstrates the enhanced denitrification due to water table control. In both 1996 and 1997, both the treatment and the blocks were significant ($p=0.05$) in terms of E_h and denitrification (Tables 4.9 and Tables 4.10, and Tables 4.11 and Tables 4.12, respectively).

Table 4.9 Repeated measures analysis of variance for redox potential and the error term for the data.

	Pr>F	+ (Error Term)
Source	E_h in 1996	E_h in 1997
Time	0.4849^{NS} (0.184)	0.0270* (0.220)
Trt	0.0015* (0.146)	0.0050* (0.126)
Block	0.050* (0.107)	0.0001* (0.092)
Time*Trt	0.4545^{NS}	0.5910^{NS}
Time*Block	0.2676^{NS}	0.0110*
Block*Trt	0.000*	0.0320*

* Significant at 0.05 level
NS Not significant

Table 4.10 Repeated measures analysis of variance for redox potential between treatments.

	Pr>t	
Trt	E_h in 1996	E_h in 1997
WT120 vs WT200	0.0010*	0.1526^{NS}
WT120 vs FD200	0.0016*	0.0088*
WT120 vs FD120	0.0007*	0.0001*
WT200 vs FD120	0.8846^{NS}	0.0029*
WT200 vs FD200	0.9894^{NS}	0.1943^{NS}
FD120 vs FD200	0.8786^{NS}	0.0678^{NS}

* Significant at 0.05 level
NS Not significant

Table 4.11 Repeated measures analysis of variance for denitrification and the error term for the data.

	Pr>F + (Error Term)	
Source	N_2O in 1996	N_2O in 1997
Time	0.0950^{NS} (0.327)	0.9780^{NS} (0.311)
Trt	0.0001* (0.084)	0.0001* (0.088)
Block	0.0001* (0.061)	0.0001* (0.064)
Time*Trt	0.5840^{NS}	0.1200^{NS}
Time*Block	0.0640^{NS}	0.0990^{NS}
Block*Trt	0.0001*	0.0001*

* Significant at 0.05 level
NS Not significant

Table 4.12 Repeated measures analysis of variance for denitrification between treatments.

	Pr>t	
Trt	N_2O in 1996	N_2O in 1997
WT120 vs WT200	0.0001*	0.0305*
WT120 vs FD200	0.0001*	0.0171*
WT120 vs FD120	0.0001*	0.0001*
WT200 vs FD120	0.3780^{NS}	0.0013*
WT200 vs FD200	0.2277^{NS}	0.8427^{NS}
FD120 vs FD200	0.6801^{NS}	0.0021*

* Significant at 0.05 level
NS Not significant

4.7 Plant Chlorophyll

Using a SPAD meter, leaf chlorophyll readings were taken every week in each treatment plot for both 1996 and 1997. In 1996, SPAD readings were measured from July 11 to August 28. Two equations were generated, transforming the unitless SPAD data into % leaf N, on a dry weight basis. Equation 4.3 describes the relationship before the corn began to silk and equation 4.4, after silking.

$$\%N = 4.7 - (70.6/SPAD) \qquad [r^2 = 0.80] \ldots 4.3$$

$$\%N = -11.3 + 0.5 * SPAD - 0.004 * SPAD^2 \qquad [r^2 = 0.66] \ldots 4.4$$

From equations 4.3 and 4.4, a graph was constructed in terms of leaf N content versus time, for 1996 (Figure 4.17). From this graph it is not clear as to the differences between the treatments. Before silking, the uppermost fully extended leaf was used for the SPAD readings. The leaf % N for all four treatments started under 3.5% and increased until July 26 (Julian day 206). Silking took place on August 5 (Julian day 216) and the SPAD readings were changed from the uppermost fully extended leaf to the ear leaf. After silking, leaf N dropped from approximately 3.5% to under 2.5%. Perhaps plants have a limit to the amount of N that can be taken up but theoretically, the treatments with the higher fertilizer application rates (200kg/ha) should have the highest N content in the plant as there would be higher uptake of NO_3^--N from the soil. However, this trend was not observed until the end of the summer (Julian day 236). On August 23 (Julian day

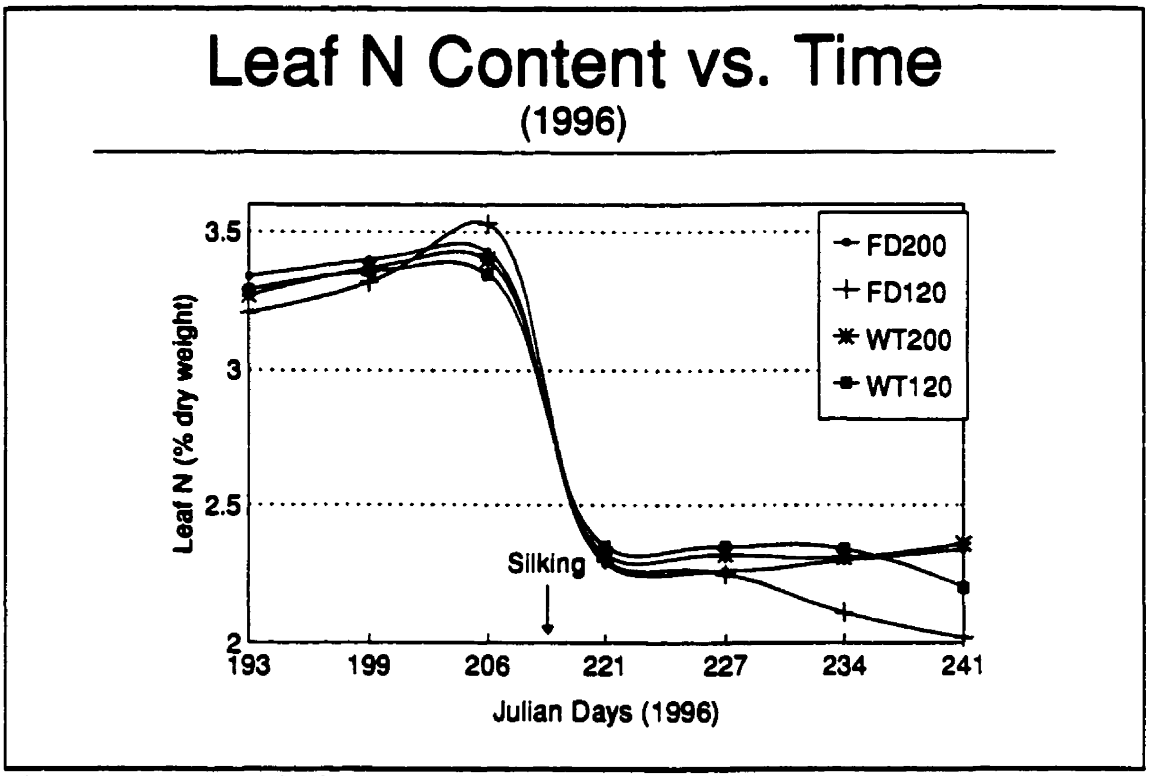


Figure 4.17 % Leaf Nitrogen, at the field site, for 1996.

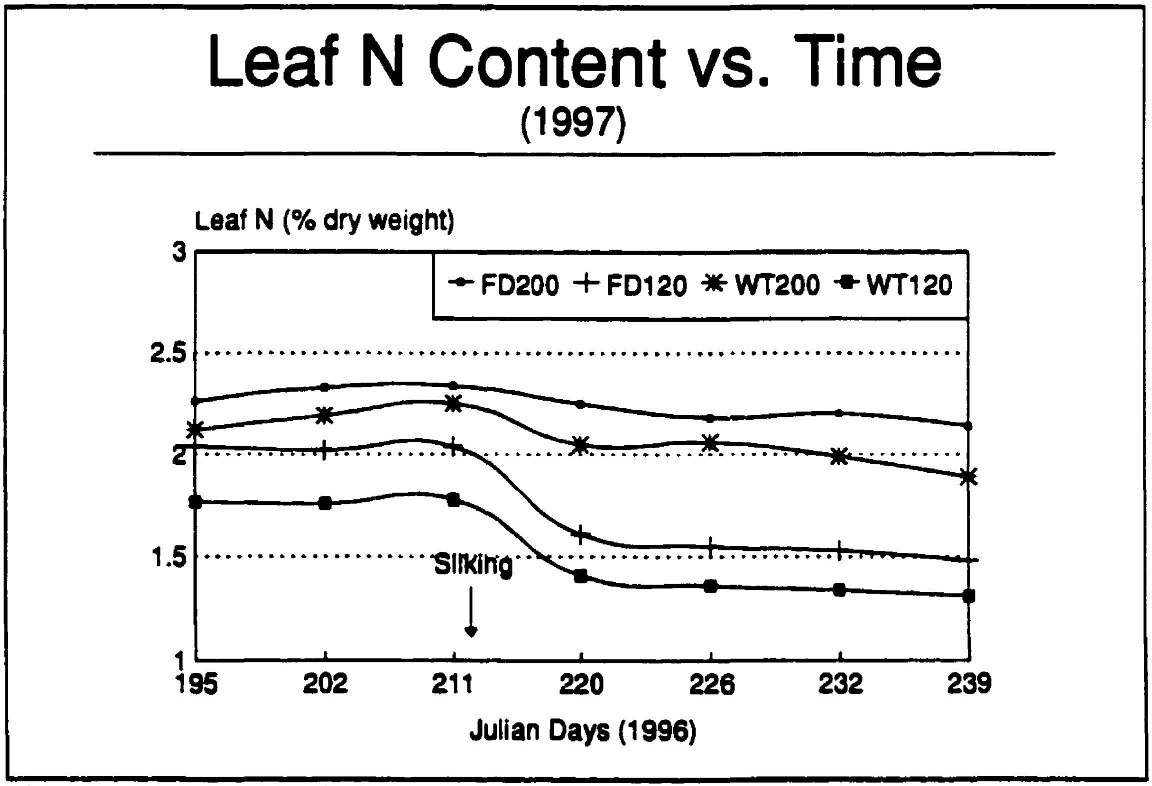


Figure 4.18 % Leaf Nitrogen, at the field site, for 1997.

236), both WT200 and FD200 exhibited greater % leaf N than the other two treatments with lower fertilizer rates. Corn has the ability to take up more N than it requires for growth. Therefore, in those plots with higher fertilizer rates, it would seem reasonable to assume that the corn plant consumed greater amounts of NO_3^--N than in plots with lower fertilizer rates. However, only 50-70% of the total N in the leaves is associated with chlorophyll. A large percentage of this total N is in the NO_3^--N form and not associated with the chlorophyll molecule (Dwyer, 1995). So there may be more N in the plant but not in the chlorophyll where the SPAD readings are taken. However, when looking at the averages of the % leaf N for both July and August (Table 4.13), both WT200 and FD200 had the highest percentages with 3.35% and 3.39%, respectively for the month of July. In August, WT200 and WT120 had the highest % leaf N with 2.33% and 2.31%, respectively. After silking, from August 8 (Julian day 221) to August 23 (Julian day 236), treatments with water table control had higher % leaf N.

Table 4.13 The average leaf N content, at the field site, for July and August in 1996 and 1997.

	1996		1997	
Treatments	July	August	July	August
FD200	3.39%	2.30%	2.31%	2.19%
FD120	3.35%	2.17%	2.03%	1.54%
WT200	3.35%	2.33%	2.19%	2.00%
WT120	3.33%	2.32%	1.77%	1.36%

In 1997, SPAD readings were taken between July 14 (Julian day 195) and August 27 (Julian day 239). Two equations were generated to describe the leaf N content. Equation 4.5 describes the leaf N content before silking and the leaf N content after silking is described by equation 4.6. The %N parameter is the leaf N content and the SPAD term is the SPAD number taken from the meter.

$$\%N=-0.9+0.09*SPAD-0.0006*SPAD^{2} \qquad [r^2=0.80) \ldots 4.5$$

$$\%N=1.4-0.03*SPAD+0.0008*SPAD^{2} \qquad [r^2=0.80] \ldots 4.6$$

From equations 4.5 and 4.6, a graph was constructed in terms of leaf N content versus time, for 1997 (Figure 4.18). As opposed to Figure 4.17, Figure 4.18 clearly demonstrates a distinct difference between treatments while maintaining the same trend. As in 1996, the four treatments start with a higher % N than at the end of the summer. On July 14 (Julian day 195), the % leaf N ranges from 1.77% (WT120) to 2.26% (FD200). After silking, this drops to a range between 1.31% (WT120) to 2.14% (FD200). It can be clearly seen that plants in the FD200 contain the highest % N and WT200 the second highest. Thus, plants in the two treatments with the highest fertilizer rates have the most % leaf N throughout the summer and the two treatments with the lowest fertilizer rates have the least. When looking at the averages of the %leaf N for both July and August, 1997 (Table 4.11), FD200 and WT200 had the highest leaf N content compared to FD120 and WT120. Plant vigour in August is considerably less than in July. This can be seen by the lower leaf N contents, for both 1996 and 1997, indicating the tendency of the corn plants to start to senesce.

Statistically, the analysis of repeated measures was conducted for both 1996 and 1997 (Table 4.14). It was found that for both years, time, treatments, and block were all significant at the p=0.05 level. Time was significant because as the growing season progressed into August and September, lower leaf N content were available in the plant. The two different fertilizer treatments were also an important factor in determining the leaf N content in the plant.

Table 4.14 Repeated measures analysis of variance for SPAD readings and the error term for the data.

	Pr>F + (Error Term)	
Source	%N 1996	%N 1997
Time	0.0001* (0.220)	0.0001* (0.220)
Trt	0.0001* (0.123)	0.0001* (0.123)
Block	0.0001* (0.090)	0.0001* (0.090)
Time*Trt	0.2460^{NS}	0.0060*
Time*Block	0.2950^{NS}	0.5090^{NS}
Block*Trt	0.0001*	0.0001*

* Significant at 0.05 level
NS Not significant

Table 4.15 Repeated measures analysis of variance for SPAD readings between treatments.

Pr>t		
Trt	%N 1996	%N 1997
WT120 vs WT200	0.0001*	0.0001*
WT120 vs FD200	0.0001*	0.0001*
WT120 vs FD120	0.2988^{NS}	0.0001*
WT200 vs FD120	0.0294*	0.0001*
WT200 vs FD200	0.0001*	0.0001*
FD120 vs FD200	0.0001*	0.0001*

*	Significant at 0.05 level
NS	Not significant

4.8 Nitrogen Relationships

Relationships between the N in the soil, plant and drainage water were investigated. SAS was used with the CORR procedure to determine the significance between denitrification and the leached NO_3^--N in the drainage water, leaf-N content and the leached NO_3^--N in the drainage water, and soil NO_3^--N levels and the leached NO_3^--N in the drainage water.

Table 4.16 Correlation factors for variable significance.

Relationship	Correlation Factor
N_2O and NO_3^--N in the drainage water	$r^2 = 0.13$
%Leaf-N and NO_3^--N in the drainage water	$r^2 = 0.44$
Soil NO_3^--N and NO_3^--N in the drainage water	$r^2 = -0.11$

Table 4.16 shows the correlation factors when determining the significance of the appropriate relationships. Both denitrification and leaf N content were found to be positively correlated, and soil NO_3^--N levels negatively correlated to the leached NO_3^--N levels in the drainage water. However, both the denitrification and the soil NO_3^--N levels were found to be insignificant when correlated to the leached NO_3^--N levels in the drain water. Leaf-N content, on the other hand was found to be significant, at the p=0.05 level, when correlated to the leached NO_3^--N levels in the drain.

Although only the leaf-N content was significantly correlated to drain NO_3^--N levels, equations were determined incorporating each variable. Since the controlling factor is not completely known, at this stage, four equations were developed for the N in the soil, plant and drainage water. However, it would be preferable for the equation to predict NO_3^--N leaching. The parameters in each equation are: NO_3^--N is the leached NO_3^--N levels found in the drain (kg/ha), %N is the percent leaf-N found in the plant leaf (%), SoilN is the amount of NO_3^--N in the soil (kg/ha) and N_2O is the amount of denitrification (kg/ha). Equation 4.7 predicts the leached NO_3^--N levels, equation 4.8 predicts the leaf-N content, equation 4.9 predicts the amount of NO_3^--N in the soil, and equation 4.10 predicts denitrification.

$$NO_3^- \text{-} N = 0.0063*(\%N) - 0.00018*(SoilN) + 0.1412*(N_2O) \qquad [r^2 = 0.061] \ldots 4.7$$

$$\%N = 0.534*(N_2O) - 0.0344*(SoilN) + 0.348*(NO_3^- \text{-} N) \qquad [r^2 = 0.044] \ldots 4.8$$

$$SoilN = 1.62*(N_2O) - 0.79*(\%N) - 0.23*(NO_3^- \text{-} N) \qquad [r^2 = 0.031] \ldots 4.9$$

$$N_2O = 0.027*(\%N) + 0.0035*(SoilN) + 0.39*(NO_3^- \text{-} N) \qquad [r^2 = 0.075] \ldots 4.10$$

As shown, each equation has an extremely low regression coefficient. However, the low coefficients were due to the fact that we had only two years of data. If data were available for a longer duration, the regression coefficients may have been increased. Seasonal versus annual effects were also not taken into account in the derivation of equations 4.7 to 4.10, and this could have led to higher r^2 values.

4.9 Summary of Results

Subirrigation, with a controlled water table height of 60 cm, was turned on in July and turned off in October. In 1996, the average water table heights were 97.2 cm for FD200, 97.0 cm for FD120, 76.2 cm for WT200 and 71.8 cm for WT120. In 1997, the average water table heights were 106.0 cm for FD200, 103.8 cm for FD120, 80.5 cm for WT200 and 76.5 cm for WT120.

More drain flow occured in 1996 than in 1997 due to the increased rainfall experienced in 1996. In 1996, the controlled water table plots showed lower amounts of drain flow compared to the free drainage plots. In 1997, there were similar drain flow for all treatments because of the drier nature, and lower moisture content, of the soil. However, NO_3^--N concentrations in the drains were lower in the plots with a controlled water table compared to the free drainage plots. In 1996, there was a 59.2 % increase in NO_3^--N lost in free drainage plots than in controlled water table plots, and in 1997, there was a 75.9 % increase. This decrease of NO_3^--N lost in the controlled water table plots can be attributed to an increase in denitrification.

In 1996, there was an overall increase of denitrification by 72.2 % in the controlled water table plots, compared to the free drainage plots. In 1997, there was an overall increase of denitrification by 93.2 % in the controlled water table plots, compared to the free drainage plots. In terms of plant chlorophyll, in both 1996 and 1997, the treatments with the higher fertilizer rates, FD200 and WT200, experienced higher leaf N content compared to the FD120 and WT120 plots. Leaf N content and drain NO_3^--N samples were found to be significantly correlated and an equation was developed linking these two variables.

5.0 SUMMARY AND CONCLUSIONS

5.1 Summary

In today's world of increased crop production and yield, the application of excess N fertilizer on agricultural fields leads to NO_3^--N pollution of the water supply. Methods to predict and decrease NO_3^--N leaching to the water supply are needed.

A field study was conducted on a 4.2 ha experimental site located in Soulanges county, Quebec during 1996 and 1997 to determine the effects of WTM on water quality and to investigate N dynamics at the experimental site. The site was split into 3 blocks, and each block contained 8 plots. Each block was planted with grain corn and there were four treatments: water table control at 60 cm and 120 kg/ha of N fertilizer (WT120), water table control at 60 cm and 200 kg/ha of N fertilizer (WT200), conventional drainage and 120 kg/ha of N fertilizer (FD120), and conventional drainage and 200 kg/ha of N fertilizer (FD200). Each plot had a subsurface drain running along it's center, at a depth of 1.0 m. Each drain had an outlet in one of two buildings on the site. In each building, there are water table control mechanisms and computer data acquisition systems. Drain flow from each plot was monitored and water samples were collected and analyzed for NO_3^--N. Soil NO_3^- levels were measured at three depths in the spring and fall and also at a depth of 15 cm throughout the growing system. Both denitrification and leaf N levels were also measured.

Difficulty arose trying to maintain the desired water table of 60 cm in both years. In 1996, the water tables were 76.2 cm and 71.8 cm for the WT200 and WT120 treatments, respectively. In 1997, the water tables were 80.5 cm and 76.5 cm for the WT200 and WT120 treatments, respectively. The drain flows varied between years depending on rainfall amounts. In 1996, the average drain flows were reduced in the controlled water table plots compared to the free drainage plots. In 1997, the average drain flows were similar for each treatment. NO_3^--N lost to the subsurface drains were greater in both 1996 and 1997. Denitrification was greatly increased in the controlled water table plots in both 1996 and 1997 and there was higher leaf N levels in those plots with higher fertilizer rates (FD200 and WT200). Four equations were developed linking the four parameters together.

5.2 Conclusions

1. Water table depths were difficult to maintain at the desired level of 60 cm. In 1996, the average water table heights were 76.2 cm and 71.8 cm for the WT200 and WT120 treatments, respectively. In 1997, the average water table heights were 80.5 cm and 76.5cm for the WT200 and WT120 treatments, respectively.
2. Drain flow for both 1996 and 1997 were dependent on the rainfall. In 1996, WTM plots showed decreased drainage flow. However, in 1997, there were similar drainflow for all treatments.

3. WTM greatly reduced NO_3^--N lost to the subsurface drains. In 1996, WTM lost

59.2 % less NO_3^--N than free drainage treatments. In 1997, WTM lost 75.9 % less NO_3^--N than free drainage treatments. Reduced NO_3^--N leaching with WTM is attributed to both decreased drain flow and increased denitrification.

4. WTM greatly increased denitrification compared to conventional drainage treatments. In 1996, controlled water table plots showed increased denitrification by 72.2 % over free drainage plots. In 1997, controlled water table plots showed increased denitrification by 93.2 %.
5. Plant chlorophyll levels were greatly increased in those plots with the higher fertilizer application rates of 200 kg/ha. WTM did not seem to play a large role in the leaf N content.
6. Leaf N content levels were significantly correlated to the drainage NO_3^--N levels. Four equations were developed linking leaching, soil N, denitrification and leaf-N.

Results from this field study show that WTM can significantly increase denitrification and reduce NO_3^--N leaching. Redox potential probes can be used effectively to estimate denitrification throughout the growing season and a SPAD meter can also be used to estimate the leaf N content of corn. Predicting NO_3^--N leaching was achieved by using leaf-N, soil N and denitrification data. In conclusion, WTM can significantly reduce NO_3^--N leaching. However, predicting the amount of leaching that will occur is difficult and depends on many soil and climatological processes.

6.0 RECOMMENDATIONS FOR FUTURE RESEARCH

1. Since it was difficult to maintain the desired water table of 60 cm in the soil, raise the water table control mechanisms higher in each building. Although, theoretically, the water tables would be set at a shallower level, in the field it would be at 60 cm.

2. Although NO_3^--N leaching at this site was not tremendously high, investigate the ideal fertilizer application rate to reduce further the amount of NO_3^--N leaching while maintaining high yields.

3. Study the relationship between the SPAD readings and the corn yield, under WTM.

4. SPAD data was highly correlated with the NO_3^--N in the drains. Investigate further the relationship between the leaf N content and the NO_3^--N lost in the drains and determine their relationship for different agricultural soils. Also, study the feasibility of predicting NO_3^--N leaching under large scale conditions.

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