EFFECTS OF WATER TABLE MANAGEMENT ON WATER QUALITY AND STRIP CROPPED CORN-SOYBEAN YIELDS

by

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ABSTRACT

MSc. **Agricultural and Biosystems Engineering**

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Effects of Water Table Management on Water Quality and Strip Cropped Corn-Soybean Yields

A two-year field study was carried out in eastern Ontario to investigate the effects of water table management (WTM) on water quality and crop yields. Corn (*Zea mays* L.) and soybean (*Glycine max* Merr.) were planted in alternate strips across the three treatments of 50 cm controlled water table (CWT), 75 cm CWT and free drainage (FD). Drainflow volume and nitrate-N concentration of the drainage water were measured. Soil samples were collected and analysed for total N,P,K, available N, soil moisture and organic matter levels. Chlorophyll-meter readings and plant harvest parameters were also measured. Rainfall, soil and air temperatures were recorded throughout the growing seasons.

The obtained data show that in 1995, the CWT plots significantly increased total drainflow, as compared to FD. Although nitrate concentrations in drainwater from the 50 cm CWT and 75 cm CWT plots, when compared to FD, were reduced by 84% and 77%, respectively, total nitrate loads were not statistically significantly different between treatments.

In 1996, overall drainflow and nitrate concentrations were significantly reduced. Nitrate concentrations were reduced by 61% and 52% by the 50 cm CWT and 75 cm CWT, respectively, compared to FD. The 50 cm CWT and 75 cm CWT reduced nitrate loadings by 94% and 30%, respectively, compared to FD. Rainfall distribution affected the amount of nitrate leached in both years. Dramatic improvements in water quality were attributed to both reduced drainage outflow and enhanced denitrification in the CWT plots.

Both the corn and soybean yields were higher with WTM than with FD for both years. In 1995, corn yield was increased by 13.8% and 2.8% by 50 cm CWT and 75 cm CWT, respectively, while soybean yield was increased by 8.5% and 12.9% by 50 cm CWT and 75 cm CWT, respectively. Similarly, corn yields in 1996 were higher in the 50 cm CWT and 75 cm CWT plots than in FD by 6.6% and 6.9%, respectively. 1996 soybean yield was increased by 37.3% in the 50 cm CWT and by 32.2% in the 75 cm CWT. Yield increases were most likely attributable to higher crop water and N-uptake as a result of shallower water tables. Overall, WTM proved to be a highly effective method for minimizing agricultural pollution, and improving crop yield.

RÉSUMÉ

MSc. Agricultural and Biosystems Engineering

Manuel Mejia

Effets de la nappe phréatique controlée sur la qualité de l'eau et la récolte en bande intercalaire des cultures de maïs et de fèves de soja

Une étude de deux ans fut conduite dans l'est de l'Ontario sur les effets de la culture en bandes avec nappe phréatique controlée sur la qualité de l'eau et le rendement des cultures de maïs (*Zea mays* L.) et de fève de soja (*Glycine max* Merr.). Des graines de maïs et fèves de soja furent plantées en bandes alternées sur trois parcelles. Les nappes phréatique de deux d'entre elles furent controlées à 50 cm et 75 cm, tandis que la troisième fut laissée en drainage libre. Des échantillons de sol furent prélevés afin de déterminer les concentrations totales de N, P, K, et de nitrates ainsi que leur teneur en eau et en matières organiques. Des mesures de chlorophylle ainsi que les paramètres de récoltes furent également analysés.

En 1995, les données recueillies montrèrent que l'écoulement de drainage total des parcelles à drainage contrôlé fut supérieur à celui obtenu par drainage libre. Les concentrations de nitrates dans les collecteurs de nappes phréatiques controlées à 50 cm et 75 cm furent réduites de 84% et 77%, respectivement par rapport à celles du drainage libre. Il n'en reste pas moins que les quantités totales de nitrates ne varièrent pas de façon significative d'un traitement à l'autre.

En 1996, l'écoulement des eaux de drainage et les concentrations de nitrates furent réduites de façon significative. Une réduction de concentration de l'ordre de 61% et 52% pour les nappes phréatiques controlées à 50 cm et 75 cm fut enregistrée. Ces deux niveaux de nappes phréatiques ont pu réduire les charges de nitrates de 94% et 30%, respectivement. La répartition des chutes de pluie affecta la quantité de nitrate lessivée durant ces deux années. L'amélioration dramatique de la qualité des eaux drainées fut attribuée à la fois à la réduction des eaux de drainage et à la denitrification des nappes phréatiques controlées.

Les résultats obtenus montrèrent un rendement plus élevé de maïs et de fève de soja grâce au contrôle de la nappe phréatique. En 1995, le maïs connu une hausse de rendement de 13.8% et 2.8% pour les nappes phréatiques controlées à 50 cm et 75 cm, respectivement. Le soja connu des augmentations de l'ordre de 8.5% et 12.9%, pour les mêmes conditions. De façon semblable, en 1996 le maïs connu une augmentation de rendement de 6.6% et 6.9% pour les niveaux de nappes phréatiques ci-dessus. Le rendement de soja augmenta de 37.3% et 32.2% respectivement pour les nappes controlées à 50 cm et 75 cm. L'amélioration du rendement des récoltes durant les deux années fut attribuée à une augmentation de la consommation à la fois d'eau et de nitrates par les plantes grâce à l'élévation du niveau de la nappe phréatique. En résumé, le contrôle de la nappe phréatique est une méthode efficace capable non seulement de réduire des effets de pollution agricole, mais aussi d'améliorer des rendements de récoltes.

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Nomenclature

BBS	: Blue baby syndrome
BMP	: Best management practice
CD	: Controlled drainage
CDN	: Canadian
CD/SI	: Controlled drainage/subsurface irrigation
CHU	: Corn heat units
cm	: centimeter
CWT	: Controlled water table
DAP	: Days after planting
EPA	: Environmental Protection Agency
ET	: Evapotranspiration
FD	: Free drainage
g	: gram
ha	: hectare
HCl	: Hydrochloric acid
HI	: Harvest index
in	: inch
K	: Potassium
kg	: kilogram
kW	: kilowatt
l	: liter
m	: meter
MFLP	: Matrix flux potential
mg	: milligram
mm	: millimeter
N	: Nitrogen

N_2	: Nitrogen gas
N_2O	: Nitrous oxide
NO_2^-	: Nitrite
NO_3^-	: Nitrate
NO_3^--N	: Nitrate nitrogen
OM	: Organic matter
OMAF	: Ontario Ministry of Food and Agriculture
Ortho-P	: Orthophosphate
P	: Phosphorous
ppm	: parts per million
PVC	: Polyvinyl chloride
s	: second
SI	: Subirrigation
SMC	: Soil moisture content
SPAD	: Soil Plant Analysis Development
t	: metric ton
UAN	: Urea ammonium nitrate
US	: United States of America
vs.	: versus
WTM	: Water table management
@	: at
^0C	: degrees Celsius
$	: dollar
%	: percent

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1.0 INTRODUCTION

1.1 Problem Definition

Non-point source pollution is a major problem associated with current intensive agricultural production methods. Surface and groundwater contamination from agricultural drainage water is of major environmental concern in the pursuit of sustainable agriculture. Major pollutants in drainage water include: salt, nitrate, phosphorus, sediment, heavy metals, trace elements, bacteria and pesticides. These pollutants destroy aquatic ecosystems and impair downstream water quality (Madramootoo, 1996). Nitrate-nitrogen (NO_3^--N) pollution, in particular, has received considerable attention in the last 25 years because of its adverse effects on human health and the environment. Blue baby syndrome and stomach cancer are two health problems associated with high levels of nitrate in drinking water (Addiscott et al., 1991). The accelerated eutrophication of lakes and rivers is also caused by excessive nitrate loadings from drainage waters.

In the lowland regions of the St. Lawrence Valley in Ontario and Quebec, drainage is an essential part of agriculture. Drainage is needed to remove excess water, since precipitation in the region exceeds evapotranspiration (ET) by 300 mm to 700 mm annually. Since much of the region was once submerged by the Champlain Sea, soils in the region are heavy clays or are underlain by lacustrine clay and thus, have low permeability and poor internal drainage. The topography of the region is also relatively flat with low hydraulic gradients to rivers and watercourses which further exacerbates the problem of drainage in the region. There are currently 750,000 ha of cropland which have been subsurface drained in Quebec. Most of this drained arable land is under extensive monocrop silage corn, grain corn and cereal cultivation. Soybeans are also increasingly occupying more drained agricultural land in both Ontario and Quebec. With drainage, the potential for nitrate leaching increases because nitrate is very soluble and easily lost via subsurface drains. However, the installation of subsurface drainage does not singularly lead to degradation of receiving aquatic ecosystems. Increased use of N-fertilizers has also caused deleterious nutrient loadings to watercourses. Modern intensive production methods require large inputs of N-fertilizers for profitability. Furthermore, a large proportion of subsurface drained land is given to corn monoculture. These corn producers are also the largest consumers of fertilizer, using almost 65,000 tonnes N per year (Lalonde et al., 1996). The excessive application of N-fertilizers has further worsened the problem of nitrate pollution from agriculture.

Because intensive agricultural production is dependent on agrochemicals, management practices which reduce leaching of these chemicals to subsurface drainage systems and lower the concentration of toxic chemicals in drainage effluent are urgently needed. There is now an increased emphasis on modifying irrigation and drainage practices as well as cropping systems to reduce the level of pollutants in drainage effluent. There are some agronomic and water management practices which may be implemented at the field and watershed scales, to reduce agricultural pollution. Water table management (WTM) and corn-soybean strip cropping are two such practices which have the potential to protect the environment by improving soil and water quality, while enhancing crop performance.

WTM is the control of the water table level by means of controlled drainage (CD) and subirrigation (SI). Controlled drainage has been identified as a best management practice (BMP) effective in reducing nitrate losses by increasing denitrification (Wright et al., 1990). Evans et al. (1989) reported that drainage control reduced the annual transport of total nitrogen by 46.5%. Similarly, Gilliam et al. (1979) reported that controlled drainage reduces nitrate concentration by as much as 50% when compared to uncontrolled drainage fields. Kalita and Kanwar (1993) have also shown that WTM can bring down groundwater NO_3^--N concentration levels to meet and even surpass the regulated drinking water standard of 10 mg/l for nitrogen.

This pollution abatement practice does not necessarily compromise crop yields. In fact, it has been shown that crop yield increases can be expected from subirrigation (Madramootoo, 1990). Soybeans grown under a 40 cm water table were reported to have a 43% increase in yield compared to non-irrigated systems (Cooper et al., 1992). Because WTM provides water to the plant in times of drought, crop yield losses can be minimized.

Farmers, water management specialists and environmentalists in eastern Canada have expressed interest in WTM as a method of reducing agricultural water pollution. There is a need to identify and document the benefits and limitations of WTM at the field scale, as well as to develop recommendations for WTM systems for corn and soybean production in the region. WTM and strip cropping are two BMPs which have the potential to protect the environment while sustaining high productivity. With both economic and environmental benefits, these practices will play a key role in the viability of the drainage industry, and in the sustainability of corn and soybean production in eastern Canada.

1.2 Objectives

The purpose of this study is to investigate the combined effects of WTM and corn-soybean strip cropping on crop yields and agricultural drainage water quality. The specific objectives of this study were to:

1) Determine the drainflow volume and nitrate-N concentrations in drainage water from WTM compared to free drainage (FD).

2) Determine the effects of WTM and corn-soybean strip cropping on soil nitrate levels.

3) Determine plant N-uptake and yield for corn and soybean under different water table depths.

1.3 Scope

This thesis presents results from a two-year field study (1995-1996) conducted in eastern Ontario. The study was carried out under the site-specific conditions of a silt loam soil type, with a ridge-till system of corn (*Zea mays* L.) and soybean (*Glycine max* (L.) Merr.) strip cropping. The control water tables were set 50 cm and 75 cm below the soil surface. Therefore, the results and recommendations obtained from this study are limited to crop, soil and climatic conditions similar to those found in the study area.

2.0 LITERATURE REVIEW

This chapter presents information found in the literature on the sources of agricultural nitrate pollution, and the research work that has been carried out to help abate it.

2.1 Drainage in eastern Canada

Artificial drainage has long been an important component of land management in humid regions (Evans et al., 1995). In eastern Canadian agriculture, drainage plays an essential role. Because of the prevailing climate, soils and topography, artificial drainage is often a necessity --particularly in the lowland regions of the St. Lawrence and Ottawa valleys in Ontario and Quebec. The soils in these regions are generally of a heavy clay type or, if lighter in texture, are underlain by lacustrine clay due to the fact that much of the region was submerged by the Champlain Sea and Gilbert Gulf during the last receding of the glaciers. Therefore, the soils have low permeability and consequently, poor internal drainage. In addition, the topography is flat with low hydraulic gradients to rivers and water courses which further hinders drainage of the region. Naturally occurring water tables are within 1 m of the soil surface, and during summer rains, can rise up to the crop root zone (Broughton 1972). Finally, precipitation exceeds ET in the region by 300 to 700 mm per year. Waterlogging clearly limits agricultural production in this otherwise fertile region. As a result, farmers use subsurface drainage to remove the excess water in order to optimize the short growing season of the area.

Agricultural drainage has been practiced for more than 150 years in Ontario. Of the 5,500,000 ha of farmland in Ontario, 61% is cultivated. Most of this land has benefitted from drainage improvements, with systematically spaced subsurface drains being the most common practice (Ritter et al. 1995). Ontario has the largest and most diverse agricultural industry in Canada, with total receipts of US$4.0 billion in 1991 (Ritter et al. 1995).

In Quebec, installation of subsurface drainage systems began around 1912. Although the spread of subsurface drainage was slow at first, its expansion during the 1970s was unequaled in any other Canadian province. This boom in drainage was initiated to make agricultural lands more productive. Prior to 1965, only about 17,000 ha of land in Quebec had subsurface drains installed (Broughton, 1972) and by 1965, the annual rate of installation was only 1,900 ha (Ritter et al., 1995). In 1967, it was estimated that 1,300,000 ha, or about 60% of the cultivable land in Quebec was in need of subsurface drainage in order to maximize yields (April et al., 1967; Jutras, 1967). By 1975, the installation rate jumped twelvefold to 22,000 ha/yr. Shady (1989) estimated that subsurface drainage systems were installed in over 600,000 ha of agricultural land by 1988. Today, nearly 750,000 ha of cropland have been drained in Quebec, leaving an additional 550,000 ha that could still benefit from drainage.

2.2 Drainage benefits

Many soils which have poor natural drainage, when properly drained, rate among the most productive soils in the world (Schwab et al., 1993). The main objectives of drainage are to: (1) increase the productivity of agricultural soils by removing the free water which is injurious to plant growth; and (2) create a soil surface dry enough to enable farm machinery to be used whenever it is needed (Irwin, 1991).

The benefits of drainage are manyfold. Firstly, lowering the water table in the spring aerates and heats the soil faster, allowing earlier seedbed preparation and planting. An earlier start broadens the selection of hybrids available to the farmer and allows him to take full advantage of the area's heat units (Irwin, 1991). Early planting advances the maturity of corn which promotes better crop quality and increases yields. Planting timeliness is important in areas where the growing season in short. In Ontario, for example, the penalty in yield reduction associated with planting corn after the optimum planting date is about 1% of the potential yield per day (Irwin, 1991).

Secondly, by removing excess water in the root zone, trafficability is improved and reduces the potential for soil compaction from machinery. This efficient use of machinery also leaves more time for other operations.

Thirdly, through better soil aeration, yield reductions from anaerobiosis can be minimized. For example, in a five year study in Ontario, corn and soybeans grown on tile drained fields had 35% and 26% higher yields, respectively, than those grown on undrained fields (Irwin, 1991). Better aeration also promotes plant vigor, which helps plants compete with weeds and resist infection by disease (Irwin, 1991).

Fourthly, subsurface drainage effectively reduces surface runoff and erosion. In a 10 year field study, subsurface drainage was shown to reduce losses in soil by 31%, phosphorous (P) by 31%, potassium (K) by 27%, nitrogen (N) by 17% and pesticides by 50% (Bengston et al., 1995). Similarly, plots which were subsurface drained experienced a 29% reduction in surface runoff, in addition to reduced soil, P and K losses (Bengston et al., 1988).

In summary, drainage enhances farm productivity by: (1) increasing productive land without extending farm boundaries, (2) increasing yield and quality of crops, (3) permitting good soil management, (4) ensuring that crops may be planted and harvested at optimum dates, and (5) eliminating inefficient machine operation and soil compaction by waterlogged areas in the field (Schwab et al., 1993). Overall, drainage helps maximize the net profit from the farming enterprises (Bouwer, 1965). The average benefit from subsurface drainage for Illinois soils range from US$37 to US$156 per ha (Wendte and Lembke, 1977). In Ontario, the net return from drained corn fields is about CDN $185 per ha (Irwin, 1991). Farmers have a good appreciation of the importance of drainage and there has been no question about its value in farm production (Irwin, 1991).

Yet, in spite of its many benefits, subsurface drainage increases the potential for nutrient and pesticide leaching since more water is able to pass through the soil. Today, there is an increasing concern that improved drainage of agricultural land is environmentally harmful and not in the public's best interest (Ritter et al., 1995). The following sections will describe the effects of drainage on water quality and outline the pathways by which nitrate is leached from agricultural soils and enters natural waters.

2.3 Pollution from agriculture

Agricultural drainage water is a form of non-point source pollution which has raised major environmental and health concerns. Major pollutants in drainage waters include: salt, nitrogen, phosphorus, sediment, heavy metals, trace elements, bacteria and pesticides (Madramootoo, 1996). Drainage effluent can therefore be an important source of contaminants which could diminish the water quality in eastern Canadian watercourses. Evans (1993) reported that subsurface drainage increases total outflow by 20% as compared to natural undrained conditions in North Carolina. Since more water is able to pass through the soil with subsurface drainage, the potential for nutrient leaching is higher. Furthermore, since most aritificially drained soils are adjacent to environmentally sensitive surface water systems that provide natural outlets, drainage often causes the deterioration of these waters by: (1) a reduction in salt concentration in saline estuarine systems due to freshwater dilution; and (2) direct contamination due to sediment, nutrients, and pesticides in the drainage water (Evans et al., 1995). In North Carolina and several other states, it is estimated that agriculture contributes over 50% of the sediment and nutrients reaching surface waters (Evans et al., 1995). Pesticide recovery in subsurface drainage outflow has typically accounted for less than 0.1% of amount applied, while sediment and P transport by subsurface drainage is 40% to 50% less than in surface drainage (Evans et al., 1995). Nitrogen in the nitrate form (NO_3^--N) is by far the most mobile and easily conveyed nutrient in drainage effluent and is therefore a major contributor to streamflow nutrient loads.

The main factors affecting nitrogen loss from agricultural fields by leaching include the flow of water through the soil profile, and the amount of NO_3^- available for leaching at the time of water movement (Blackmer, 1987). NO_3^- is the form of N most susceptible to leaching through subsurface drainage because it is an anion and, therefore, not attracted to soil particles. Thus, unless NO_3^- is removed from the soil solution by some process such as immobilization, plant uptake, or denitrification, it is free to percolate below the crop root zone (Blackmer, 1987) where it could enter streams, lakes and rivers via subsurface drain outlets (Füleky, 1991). Furthermore, nitrate ions in deeper layers are leached into the groundwater (Trentholm, 1995).

2.3.1 Nitrate pollution

Nitrate leaching from agricultural lands has become a major health, environmental (Milburn et al., 1990) and economic concern. As a result, many water quality studies were undertaken to understand and abate the problem. Many researchers have reported increasing levels of nitrate in ground and surface waters in Europe and North America (Addiscott, 1991 et al.; Skaggs and Gilliam, 1981). Hallberg (1986) has observed an almost linear increase in groundwater NO_3^--N concentration in the United States during the 1970s and 1980s. NO_3^--N levels in subsurface water samples from tile drains which were significantly higher than the water quality standard of 10 mg/l of NO_3^--N were reported by various researchers. For example, Logan et al., (1980) reported NO_3^--N concentration in the range of 0.5 mg/l to 120 mg/l in tile drainage water under corn in Iowa, Minnesota, and Ohio. In Iowa, Baker and Johnson (1981), observed NO_3^--N levels of 10 mg/l to 70 mg/l in subsurface water samples from tile lines under corn rotated with oats or soybeans. In Quebec, Madramootoo et al. (1992) measured nitrate concentrations as high as 45 mg/l in subsurface drain flow from a sandy loam field cropped to potato. Barry et al. (1993) reported NO_3^--N concentrations of 9 mg/l to 20 mg/l in tile effluent from continuous grain corn fields in Ontario. These high levels of NO_3^--N concentrations in both surface and ground waters have intensified the adverse environmental, health and economic effects of nitrate pollution.

2.3.2 Nitrogen losses

It has been estimated that between 30% and 60% of the N fertrilizer applied in Quebec is lost, and may make its way to groundwater and waterways via leaching and subsurface runoff (Neilson and MacKenzie, 1977). Apart from the fraction that is taken up by the crop, N can also be lost through volatilization, erosion, denitrification and leaching processes.

Loss of nitrate from agricultural lands can have a significant economic impact on producers. For example, in NO_3^- loss studies conducted in Quebec, average losses from conventionally drained fields was 21.9 kg/ha in 1992 to 1993 (Kaluli and Madramootoo, 1995). In Ontario, the amount of NO_3^--N lost observed in a conventionally drained field ranged from 10.62 kg/ha to 32.9 kg/ha during two growing seasons (Lalonde, 1993). These losses translate into fertilizer costs for producers. Yet, this leaching is not only a financial loss to farmers, but can also produce negative environmental impacts.

2.4 Environmental consequences of N pollution

Excessive nitrate loadings to surface waters can cause choking of ditches with weeds, blocked waterways and accelerated eutrophication. Nitrogen and phosphorus levels in many rivers, streams and estuaries strongly affect the very delicate balance that exists between undesirable species such as blue-green algae and other desirable flora (Paerl, 1987). Water bodies receiving excessive nutrient loads are typically more susceptible to undesirable blooms of blue-green algae (Addiscott et al., 1991). When the algal blooms die, the bacteria that degrade them consume oxygen and thereby lessen the supply of oxygen to other organisms such as fish, which often die as a result. An undesirable shift in the ecological balance and the filling up of a water body with sediment and plant matter is usually the end result of eutrophication. Ortho-P and ammonium-N are also detrimental nutrients which can cause eutrophication but because they bind more readily with clay particles, their concentrations in subsurface drainage effluent are relatively low compared to NO_3^--N. Eutrophication and other surface water problems may occur at nutrient concentrations much lower than drinking water standards (Thomas et al., 1991). Eel grass survival, for example, is significantly depressed when NO_3^- concentrations exceeded values as low as 0.1 ppm (Evans et al., 1995).

2.5 Health hazards of N pollution

In addition to degrading water resources, nitrate pollution can pose serious human health hazards. Nitrate itself is not toxic. It only becomes a problem when it is converted to nitrite (NO_2^-). Methemoglobinaemia (also known as cyanosis or blue-baby syndrome-BBS), and stomach cancer are two health problems associated with high levels of nitrate in drinking water (Addiscott et al., 1991). BBS can occur when infants consume too much nitrate. Microbes in the stomach convert nitrate to nitrite and when it reaches the bloodstream it reacts with the hemoglobin. This interaction lessens the oxygen-carrying capacity of the blood and the transport of oxygen around the body can be reduced to a fatal point.

Stomach cancer is the other health problem associated with nitrate in potable water. It is hypothesized that nitrite produced from nitrate reacts with an organic compound called a secondary amine coming from the breakdown of meat. The resulting compound would be an N-nitroso compound which can cause cancer because of its ability to modify DNA components (Addiscott et al., 1991).

Americans obtain 50% of their drinking water from groundwater sources (Laws, 1993). About 95% of the US rural population depends on groundwater for drinking water, and according to Laws (1993), 75% of the major cities in the US depend upon well water for most of their supplies. Hubbard and Sheridan (1989) reported that in many agricultural areas, NO_3^--N levels in drinking water were significantly higher than the maximum contaminant level of 10 mg/l set by the U.S. Environmental Protection Agency (EPA). Continued contamination of groundwater may mean that many of the sources may no longer be appropriate for domestic uses. In the corn-growing state of Nebraska, for example, there are presently 38 towns where concentrations of nitrates in domestic water supply are so high that babies below the age of six months must be given bottled water for health reasons (Biswas, 1996).

In Canada, 26% of all Canadians rely on groundwater for domestic use; over 3 million Canadians living in urban areas rely on groundwater for their domestic water supply and at least another 3 million rural Canadians also use groundwater (Environment Canada, 1994). Asselin and Madramootoo (1992) reported several cases of nitrate-contaminated well water in Quebec. Although Canadians rely less on groundwater (90% of water used in Canadian municipalities across Canada comes from surface waters), surface waters are also becoming unsuitable. Pollutants from agriculture are increasingly contaminating the surface waters from which municipalities draw upon.

2.6 Need for pollution reduction methods

The problem of nitrate pollution in ground and surface waters is especially serious in drained agricultural areas. The existing drainage systems act as conduits for mobile nitrate which enrich surface waters and accelerate eutrophication. However, the mere installation of drainage is not the sole cause of nitrate pollution. Increased fertilizer use, changing land use and production methods also play a large part in the nutrient enrichment of lakes and rivers. The observed linear increase in nitrate concentrations have been correlated with an increase in N fertilizers (Addiscott et al., 1991). Nearly 1.5 million ha of corn are grown in Canada; Ontario and Quebec account for 99% of the total Canadian corn production (Statistics Canada, 1993). In Quebec, up to 40% of the arable land in most southern agricultural watersheds is devoted to monocropped corn. Corn producers are also the largest consumers of fertilizer, using almost 65,000 tonnes N per year (Lalonde et al., 1996). Nitrate fertilizers boost yields at very little cost to farmers, but excessive applications excacerbate the nitrate problem.

In eastern Canada, both drainage and fertilizer inputs are often requirements for profitable corn production (Kaluli and Madramootoo, 1995). However, because of the resulting water quality problems, alternative production methods which do not harm the environment are needed in order to keep the agricultural and drainage industries viable. Countermeasures must be taken to reduce NO_3^- pollution while ensuring that crop production is both environmentally and economically sustainable.

At the present moment, there are no economically feasible ways to treat drainage water at the watershed scale (Madramootoo, 1996; Biswas, 1996). However, much research in the field is being conducted to minimize pollution and maximize N-use efficiency. Water table management and strip cropping are two methods which show great promise and potential in reducing agricultural pollution while boosting production.

2.7 Water table management

Water table management has been recognized as a BMP in North America (Wright et al., 1990). The most tangible benefits of WTM are nitrate pollution reduction and increased yields. Due to its many agronomic, environmental and economic benefits, WTM is becoming a more popular water management technique among crop growers in eastern Canada.

WTM is composed of two components: controlled drainage (CD) and subirrigation (SI) (see Figure 2.1). In CD, a control structure is used to manage the water table level in the drainage outlet. In the spring, CD can be used to lower the water table in order to allow planting operations. During the growing season, discharge is restricted from the tile drain outlet, resulting in a higher water table. The water table drops with time due to evaporation and deep seepage, and is only raised by rain or irrigation. CD may reduce total outflow by about 30% when managed all year and by 15% during the growing season when compared with uncontrolled conventional systems (Evans et al., 1995).

With SI, water is pumped continually into the drainage system to maintain a near constant water table during the growing season. When large rainfalls occur, causing the water table to rise above the desired level, the irrigation pump is stopped and the excess water is drained via an overflow pipe connected to the outlet. By supplying water to the crop's

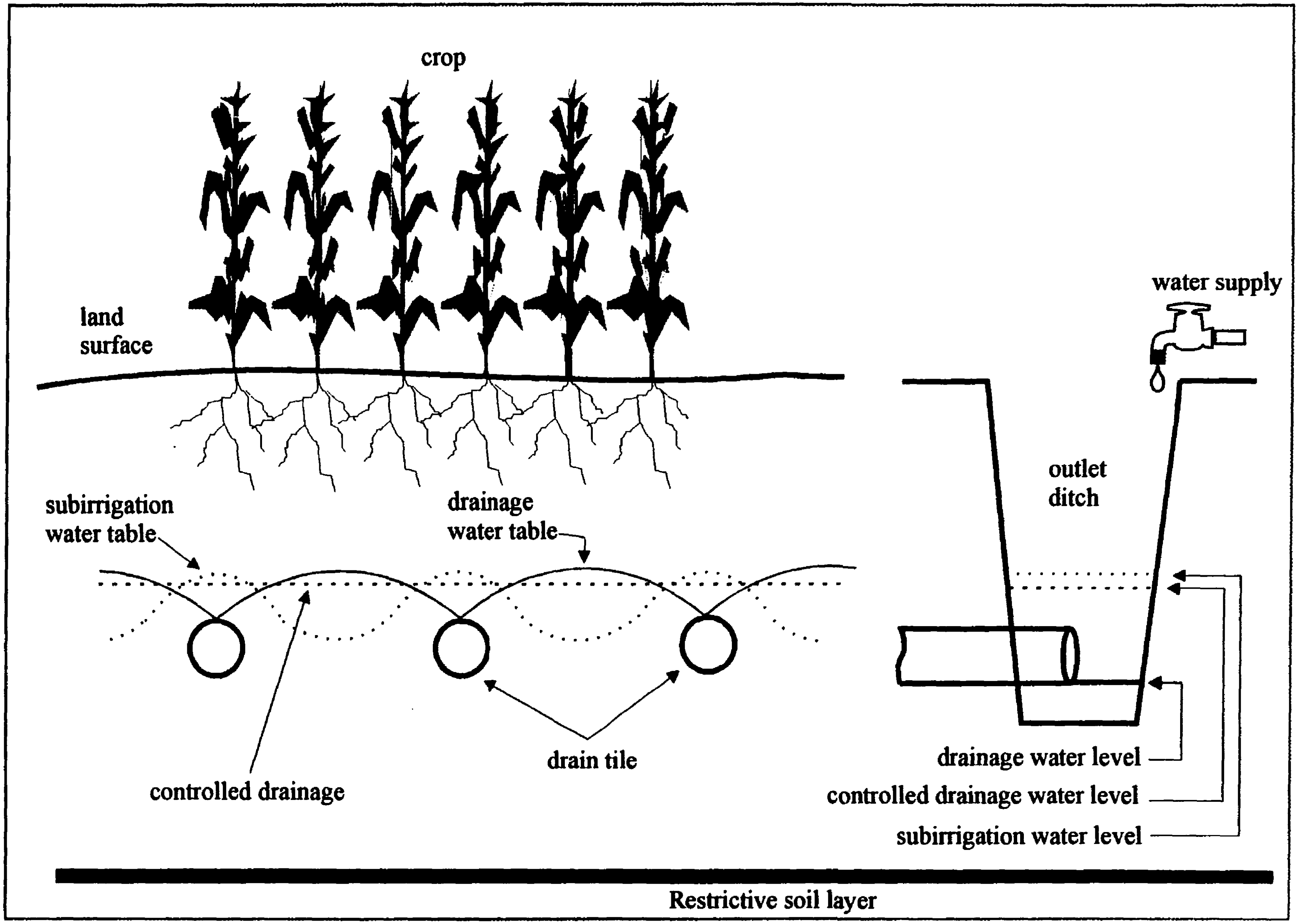


Figure 2.1 Water table management systems.

roots via the tile drains during dry spells, yield losses due to water stress is reduced.

The most tangible benefit of WTM on water quality has been its influence on the total nutrient loadings to drainage outflow (Evans et al., 1989). Thereduction of nitrate pollution is attributed to enhanced denitrification as well as restricted outflow under WTM (Wright et al., 1990; Evans et al., 1995).

Denitrification is the transformation of NO_3^- to N_2. It is an anaerobic process and is carried out by microorganisms which use NO_3^- as their primary electron acceptor for obtaining energy from organic compounds when low O_2 availability restricts their metabolism (Granli and Bøckman, 1994). Because higher water tables reduce aeration and diffusion, denitrification is enhanced under WTM and excess nitrate is converted to its gaseous form to be returned to the atmosphere, rather than being leached to drain water. It must be noted, however, that since heterotrophic denitrification occurs stepwise:

$$\mathbf{NO_3^- \rightarrow NO_2^- \rightarrow NO \rightarrow N_2O \rightarrow N_2}$$

and produces intermediate products such as N_2O which is a greenhouse gas, there is a chance that improved water quality is being bought at the price of the ozone layer. More modeling and field work is now being done to quantify the increase in denitrification rates which reduce the amount of NO_3^- lost by leaching and N_2O production (Skaggs and Gilliam, 1981).

Restricted drainage discharge is the other main explanation for the reduction of nitrate pollution. In North Carolina, it was reported that drainage control reduced the annual transport of total nitrogen and phosphorus by 30% to 50%, respectively, when compared with conventional drainage practices (Evans et al., 1995). Similarly, Gilliam et al. (1979) reported that controlled drainage reduces nitrate concentration by as much as 50% when compared to uncontrolled drainage fields. In Iowa, Kalita and Kanwar (1993) have also shown that WTM can bring down groundwater NO_3^--N concentration levels to meet and even surpass US EPA standards. In Michigan, a 58% to 64% reduction in NO_3^--N and a 16% reduction in dissolved phosphate-phosphorus was observed from WTM by subirrigation compared to conventional subsurface drainage (Fogiel and Belcher, 1991). In Quebec, Kaluli and Madramootoo (1995), showed that CD decreased nitrate losses by 64% when compared to conventional free drainage from 1993 to 1994. In Ontario, Lalonde (1993) found that a controlled water table at 75 cm and 50 cm from the soil surface reduced drainflow by 58.7% and 65.3%, respectively, when compared to FD. As for nitrate losses, the 75 cm CWT and 50 cm CWT reduced nitrate losses by 75.9% and 68.9%, respectively, compared to FD (Lalonde et al., 1996). The reduction in NO_3^- loss was attributed to the decreased drainflow. Gilliam et al. (1979) found that the total NO_3^--N lost through subsurface drainage was directly proportional to the volume of drain water. In addition to reduced nitrate levels in drainage effluent, WTM is also beneficial to the environment because decreased drainage volume reduces downstream flooding (Lalonde et al., 1996).

Substantial modeling work has also been done to understand NO_3^- leaching under different soils, climate and cropping systems. For example, a water quality model linking DRAINMOD and CREAMS using data from Louisiana showed that CD/SI decreased NO_3^- leaching by 35.1% (Wright et al., 1992). The model also predicted net nitrogen non-point-source pollution losses to surface and ground-water sources to be 17.8% less for the CD/SI system than for conventional subsurface drainage.

Another positive effect of WTM is increased yields. Because of the lack of soil moisture during the growing season when ET exceeds precipitation, crops in drained fields are usually water stressed. According to Drury and Tan (1995), the climatic factor most limiting to fertilized corn grain yields is insuficient rainfall during the growing season. The precipitation in July, in particular, had the greatest influence on the annual variability in grain yields. It is expected, therefore, that conservation of water by CD or the addition of water by SI should reduce this constraint and thus, increase water and nutrient uptake, thereby stabilizing crop yields. Hence, not only does WTM reduce pollution but also sustains crop productivity.

Several field studies were done to find the optimum water table depth with respect to maximizing pollution reduction and yield. In a 3-year study, Kalita and Kanwar (1993) compared the effects of three different water table depths (0.3 m, 0.6 m and 0.9 m) on yield and water quality. The 0.3 m water table depth (WTD) gave the least amount of pollution and the 0.9 m WTD gave the best yield for corn. They reccommended a WTD of 0.6 m to meet both environmental and economic objectives. In Quebec, Madramootoo et al. (1995b) reported that the optimum yield for soybean grown on a sandy loam soil was obtained when a constant watertable depth was maintained between 0.6 m and 0.8 m from the soil surface. Definite yield benefits of subirrigation for soybeans were also shown by Cooper et al. (1991) as well as for corn and sugarbeet (Fogiel and Belcher, 1991; Belcher, 1992).

Moisture from the water table moves up to the crop's roots by capillary rise. The capillary fringe not only provides water for the crops but also "locks" soluble minerals in the soil which can then be taken up by the plant. In addition, this process reduces the amount of leachable salts which diminish water quality. The governing equation for soil water movement from a water table is the Richards' equation. Numerical solutions to this equation have been used to estimate the steady upward flux from a water table. The Matric Flux Potential (MFLP) model is used for the design of water table management systems (Memon et al., 1986).

Not all fields and climates are suitable for WTM. WTM in arid areas is not recommended because of the risk of soil salinization. WTM systems require flat topography, coarser textured soils, an impermeable soil layer at 1-2 m depth and the presence of or installation of a pipe drainage system (Dodds et al., 1996). A WTM system is more economical than a sprinkler system (Doty et al., 1983; Broughton, 1995), and uses less energy, labor and water compared to other irrigation methods. In addition, WTM systems do not take up productive land, and many field crops such as corn and soybean are well-suited for subirrigation. In two counties in Quebec, Papineau (1988) estimated that 15,000 ha of land were suitable for subirrigation. In the United States, approximately 30% of the drained cropland in humid regions, or 8,500,000 ha, are suitable for controlled drainage (Evans et al., 1995). Furthermore, in the humid regions of the United States, the full implementation of CD to areas that are physically suited to the practice could potentially reduce nitrogen loading to surface water by nearly 100,000,000 kg annually (Evans et al., 1995). In summary, many researchers have shown that water table management conserves water, reduces nitrate leaching and increases crop yields.

2.8 Alternative best management practices

Apart from WTM, the cropping system practiced is another important factor which influences NO_3^- leaching and water quality. Strip cropping, for example, is an alternative systems to monoculture which has the potential to control leaching losses and reduce the amount of NO_3-N reaching surface waters via subsurface drainage effluent by optimizing N-use efficiency and increasing yields. Tools which improve N-management techniques also help minimize pollution and maximize efficiency.

2.8.1 Strip cropping

Strip cropping has many benefits. A strip cropping system, with the proper selection of crops, can improve economic return in several ways. Firstly, by reducing pest and allelopathic problems observed in monocultures (Francis and Clegg, 1990), strip cropping not only saves the farmer in pesticide application costs, but also favors the environment by reducing the amount of chemical used. Secondly, the ability of legumes to fix nitrogen reduces requirements for nitrogen fertilization (Voss and Shrader, 1984; Francis and Clegg, 1990). Although this is not unique to strip cropping, legumes are widely used in strip cropping for this purpose. Thirdly, diversifying crops temporally by crop rotation, and spatially by strip cropping, has been shown to increase total crop production as compared to monocultures (Ghaffarzadeh et al., 1994). Intercropping systems are regularly reported to be more productive than sole crops grown on the same area of land (Davis et al., 1981; Francis et al., 1982; Harris et al., 1987). Because corn and soybean are two economically important crops, a lot of attention has been given to the effect of strip-intercropping corn and soybean on yield and profit (West and Griffith, 1992).

The usual explanation for increased yields in corn-soybean strip cropping systems is that different crop species make partially complementary use of resources, in both time and space, and thus, use resources more efficiently (Pilbeam et al., 1994). An alternative explanation for the increased yields is that the two species exploit different forms of nitrogen, since beans have the potential to fix atmospheric nitrogen, while corn relies on previously fixed nitrogen in the soil (Pilbeam et al., 1994). There has been some debate about whether the yield advantage gained from corn-soybean strip cropping derives from a sparing use of the soil mineral nitrogen by the beans, leaving more to be exploited by the corn (Vallis et al., 1967), or from a direct transfer of fixed nitrogen to the corn (Giller et al., 1991). Pilbeam et al. (1994), however, suggest that both may indeed occur at the same time. Crop interactions at corn and soybean strip edges with respect to light and shading, as well as competition in adjacent rows are important and can affect yields. Because they have similar planting times and crop maturity dates, adjacent corn and soybean strips compete throughout their life cycles (Ghaffarzadeh et al., 1994). Soybean rows bordering corn rows, for example, generally yield less than monocrop soybean because of less sunlight and soil moisture (West and Griffith, 1992). Corn rows at the edge, on the other hand, consistently yield more than the average in a corn-soybean strip cropping system (Francis et al., 1986). The consensus is that with corn-soybean strip cropping, the soybean yield averaged across all rows is lower than with monocropping (Francis et al., 1986). Overall, however, strip cropping of corn and soybean has been found to yield a greater harvest of total grain protein than a sole crop of corn in northern temperate regions (Carr et al., 1992). Therefore, "combining diversity in time and space may be the most feasible approach for developing an economically sound and environmentally friendly system" (Ghaffarzadeh et al., 1994).

2.8.2 Soil Plant Analysis Development (SPAD)

Methods which can accurately, quickly and inexpensively estimate N status in plants and soils are needed to improve N-management. The Minolta SPAD-502 chlorophyll meter has been found to be effective in estimating leaf chlorophyll content (Dwyer et al., 1994). Between 50% and 70% of total N in corn leaves is associated with the chloroplast (Hageman, 1986). Therefore, the amount of chlorophyll measured by the SPAD meter can be used as an index for leaf-N status. This information is useful in pinpointing areas in the field where there is insufficient soil-N. Likewise, leaf-N status can also indicate where there is adequate N in the soil and thereby indicating that any ammendments would be unnecessary. Thus, the management of N fertilizer can be applied on a need basis and prevent potential nitrate losses.

2.9 Summary

Drainage is a necessary soil management technique in eastern Canada. Agricultural production depends on it. The expansion of subsurface drainage, increased area of corn monocropping and high N fertilizer use have intensified the problem of nitrate pollution. Nitrate losses from agricultural soils are an economic burden to producers, and have caused serious environmental and health problems. Alternative production methods which ensure the environmental and economic viability of agriculture are urgently needed. Water table management in combination with other BMPs such as strip cropping, as well as N-status tools, have the potential to help reduce nitrate pollution and increase increase fertilizer efficiency and crop yields in eastern Canada.

3.0 MATERIALS AND METHODS

3.1 Field site and layout

The field experiments were carried out on the McRae Farm in Bainsville, eastern Ontario (45°11'N, 74°23'W). The farm is located on the north shore of the St. Lawrence River, 6.5 kilometers west of the Quebec border (Figure 3.1). The field is located in the McRae Creek watershed, north of Ontario Highway 401. The experimental plots are bounded to the east by a drainage ditch and to the south by Rural Road No. 2. The experimental plots extend 125 meters to the west from the ditch and 275 m to the north (Figure 3.2). The field site is 3.5 ha in size, with an average southward slope of 0.06%.

3.2 Drainage system

The drainage system was installed under the ideal conditions of dry weather and low water tables by Linscott Drainage of Alexandria, Ontario during the week of October 23-30, 1991. A Wolfe trenchless plough was used to lay the pipes. It consists of 15 subsurface lateral drains which discharge individually into a drainage ditch. Each lateral is 125 m in length; the first 10 m section from the outlet is a 75 mm diameter non-perforated polyethylene pipe to minimize water table drawdown by the ditch, and the other 115 m which extend beneath the field is a 100-mm perforated polyethylene drainage pipe with a filter sock. The average drain depth is 1 m and the laterals are sloped at 0.10%. The drain spacing between outlets is 18.3 m. Lateral drains are centrally located beneath each plot. Therefore, each lateral drains an area 18.3 m wide by 115 m long, for a total of about 0.21 ha.

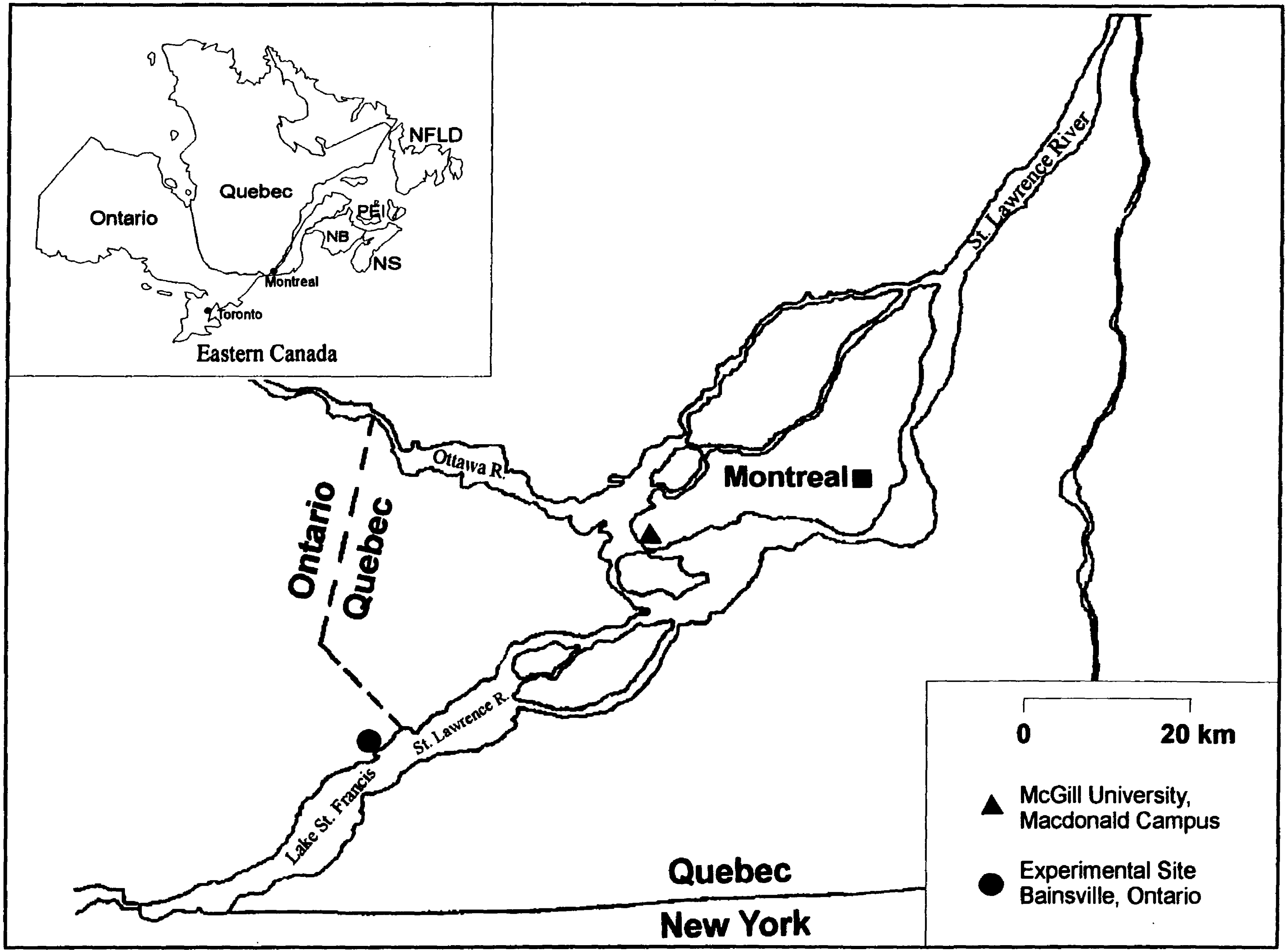


Figure 3.1 Field site location.

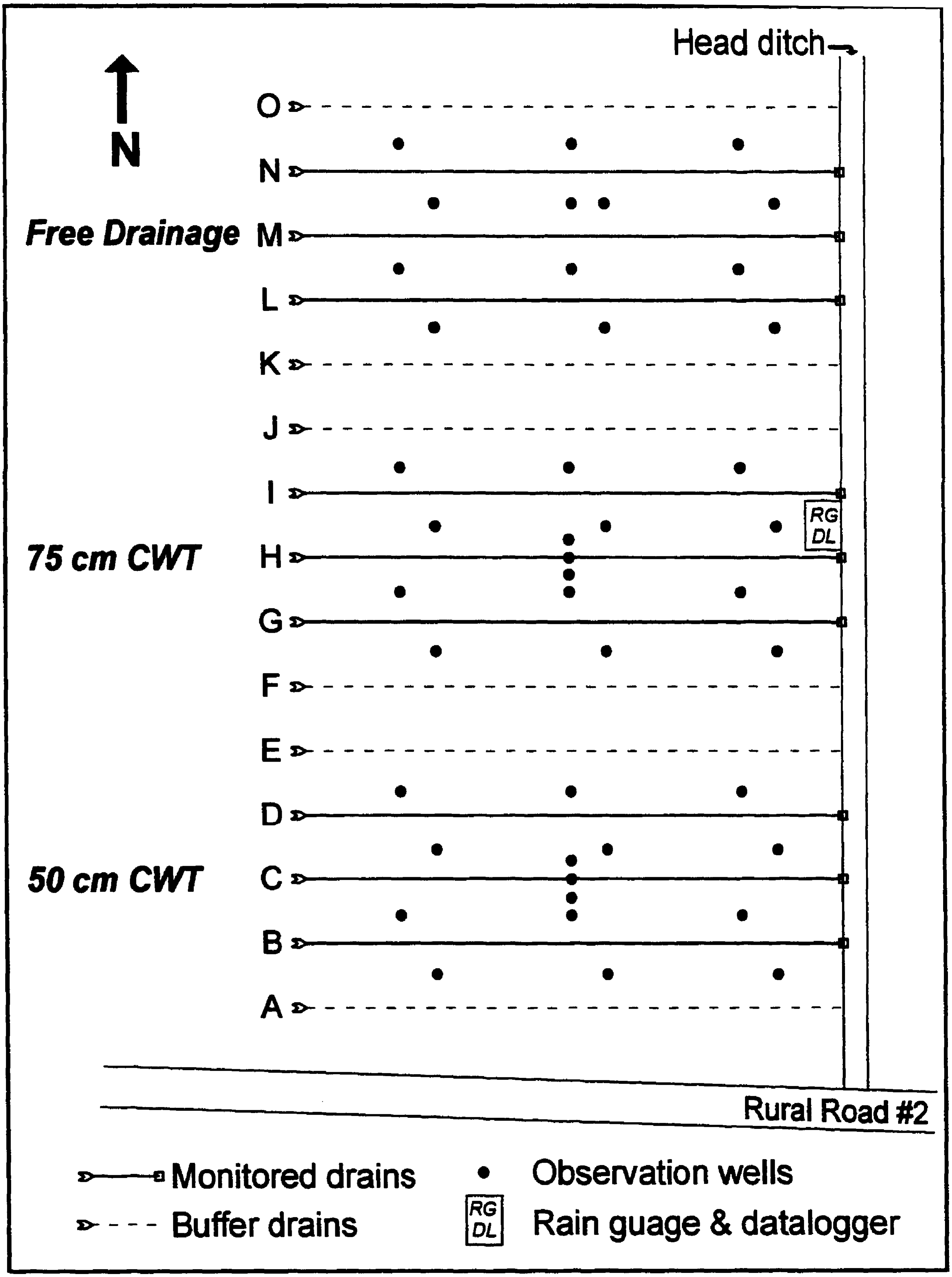


Figure 3.2 Experimental field layout.

3.3 Water table treatments

The three treatments were: controlled water tables (CWT) at 50 cm and 75 cm below the soil surface, and conventional free drainage (FD). Of the 15 drain laterals, 9 were monitored for drainflow and water quality (3 per treatment), while 6 served as buffer drains which isolated flows between treatments (Figure 3.2). There were three replicates per treatment. The water tables were kept up by means of controlled drainage and subirrigation.

Drains B, C, D in the 50 cm CWT plots, drains G, H, I in the 75 cm CWT plots, and drains L, M, N in the free drainage plots were all monitored for drainage outflow with tipping buckets. Drains A, E, F, J, K and O were unmonitored buffer drains.

Drains A through J had water table control structures at the outlets and subirrigation pipes leading into the risers to maintain the water table treatments, while drains K through O drained freely into the ditch (Figure 3.3).

3.3.1 Control structures

The controlled drainage structures attached to the outlets were made from 50 mm diameter ABS pipes. They were designed to restrict discharge by plugging the original outlet and forcing the water to back up in the field to a specified level. Drainage outflow through the control outlet occurred only when the water table level exceeded the pre-set control level (Figure 3.4). This control structure raises the water table level by holding back irrigation and rainwater in the soil instead of draining it. Over time, however, lateral and deep seepage losses, along with evapotranspiration, will lower the water table below the drain pipe. Thus, subirrigation was used in order to maintain the water table levels.

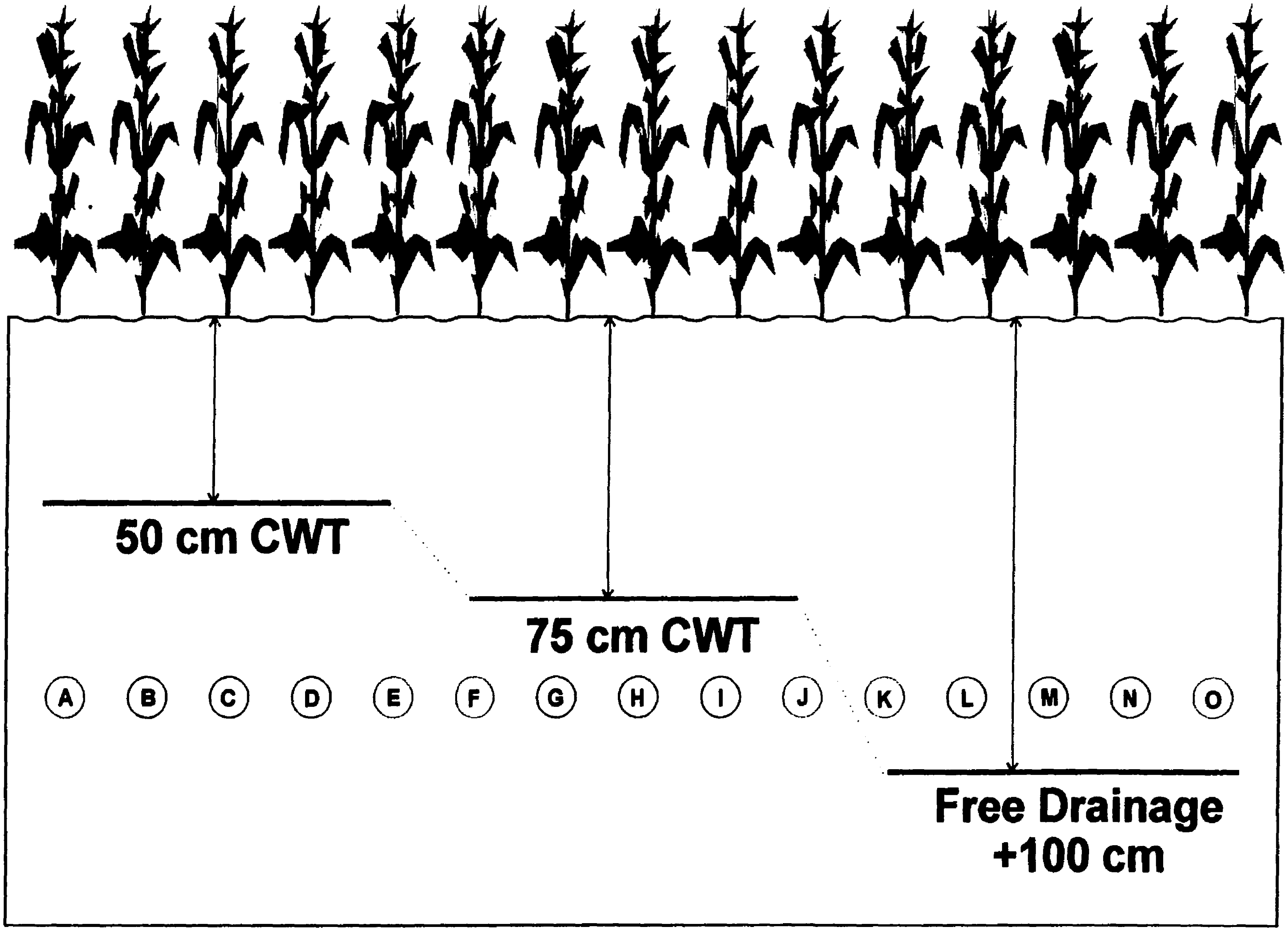


Figure 3.3 Water table treatments.

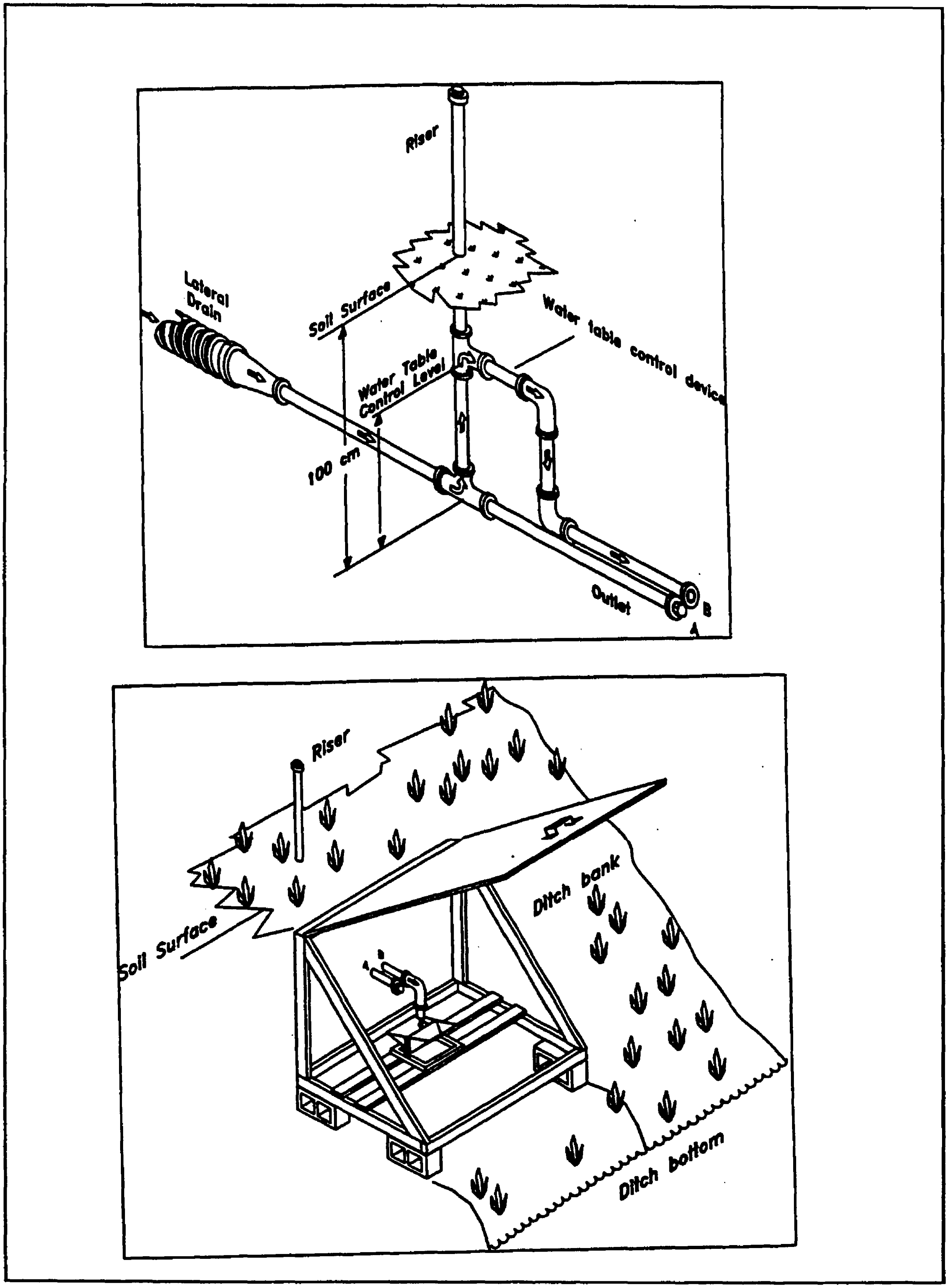


Figure 3.4 Control structure and tipping bucket hut at outlet (adapted from Lalonde, 1993).

3.3.2 Subirrigation

A subirrigation system was installed to supplement rainwater in order to maintain the water table levels. Water for subsurface irrigation was pumped from a ditch which connects to Lake St. Francis, located 560 m south of the field experiment. A 0.75 kW Myers pump was used to bring the lake water to the drain laterals. The pump site was chosen for its proximity to the lake and power source. NO_3^--N analysis of the pumped water showed that the lake water was of good quality (0.26 mg/l NO_3^--N).

Polyethylene piping was used to convey the water to the field. The first 168.3 m section from the pump was made of 38-mm diameter pipe. For the remaining 392 m section leading to the field, two 25-mm diameter pipes were used. At the field, the water lines rejoined at a flowmeter which recorded the total volume of water supplied. The subirrigation system had a peak delivery rate of approximately 0.95 l/s or 3.7 mm/day.

3.4 Soil properties

A soil survey of Glengarry County describes the soil in the area as a stone-free Bainsville silt loam with good organic matter content (Matthews et al., 1990). There are also pockets of Allendale sandy loam with elevated deposits of Eamer loam interspersed with the Bainsville silt loam. The Bainsville silt loam exhibits characteristics of the Dark Grey Glysolic soil group (Matthews et al., 1990). According to Lalonde (1993), the soil profile has three distinct layers: the upper zone at 0-0.30 m is a sandy loam, the 0.30-0.60 m zone is a loam, and a clay loam at 0.6-1.0 m overlying a marine clay.

Soil samples were collected in the spring of 1995, prior to planting to analyse the initial levels of total nitrogen, phosphorus, and potassium as well as organic matter (OM) content and available N (NO_3^--N and ammonium-N or NH^+_4-N) at three depths: 0-30 cm, 30-60 cm and 60-90 cm.

The soil samples were analyzed for total N by the standard Kjeldahl digestion and colorimetric determination method (Bremmer and Mulvaney, 1982). This method involves digestion in concentrated sulphuric acid for 1.5 hours, using a 3.9 g Kjeldahl tablet containing 89.7% potassium sulphate and 10.3% cupric sulphate. Total P and K were determined by the Mehlich III extraction method (Mehlich, 1984). The LECO combustion method was used for the determination of organic carbon content (Allison, 1965).

Throughout the growing seasons, soil samples were collected at drain-midspacing (12 per treatment) to determine soil moisture content (SMC) after at least one week when rainfall was less than 10 mm. SMC was determined gravimetrically by weighing the samples before and after oven-drying them (Gardner, 1965). Mean bulk density and saturated hydraulic conductivity had been measured previously by Lalonde (1993) and are shown in Table 3.1.

Table 3.1 Soil physical characteristics.

Depth (m)	Soil texture	Bulk density (g/cm^3)	Saturated K (m/day)
0-0.3	Sandy loam	1.56	0.56-1.74 (top 1.2 m) 0.45-0.72 (below 1.2 m)
0.3-0.6	Loam	1.45	
0.6-1.0	Clay Loam	1.23	

Pressure plate tests had also been performed by Lalonde (1993) to derive soil moisture retention and upward flux curves to show capillary rise from a water table with the site's soil type . These data were useful for determining irrigation requirements in 1995 and 1996.

3.5 Agronomic practices

The farm owners performed all the seeding and field operations. During this study, their management practices consisted of ridge tillage with corn and soybean strip cropping. Each strip had six 0.75 m-wide rows. The cropping history of the field is shown in Table 3.2. The rotational patterns for the corn and soybean strips are shown in Figure 3.5.

Table 3.2 Rotational cropping history of the experimental field.

Year	Crop
1992	Monocropped corn
1993	Monocropped soybean
1994	Strip cropped corn and soybean
1995	Strip cropped corn and soybean
1996	Strip cropped corn and soybean

In 1995, a burnoff application of glyphosate herbicide (Roundup @ 0.28 l/ha) was performed before seeding. The seeding rates were 72,000 seeds/ha for corn and 432,000 seeds/ha for soybean. The pre-emergent herbicides used in 1995 were Primextra light (0.35 l/ha) and Banvel (0.07 l/ha) for corn, and Pursuit (0.02 l/ha) and Sencor (0.07 l/ha) for soybean, both applied over a 25-cm band during planting to control weeds within the rows. In 1996, the pre-emergent herbicides used were Fieldstar/Dual for corn and Broadstrike/Dual for soybean, both applied at 0.15 l/ha over a 25-cm band during planting. The corn and soybean rows were cultivated twice. An aqueous solution of urea/ammonium nitrate (UAN 28-0-0) was side banded to the corn rows at a rate of 140 kg/ha during the second cultivation. No fertilizer or *Rhizobium* inoculant were applied to the soybean strips. During the first soybean cultivation, a wick wiper containing glyphosate was mounted in front

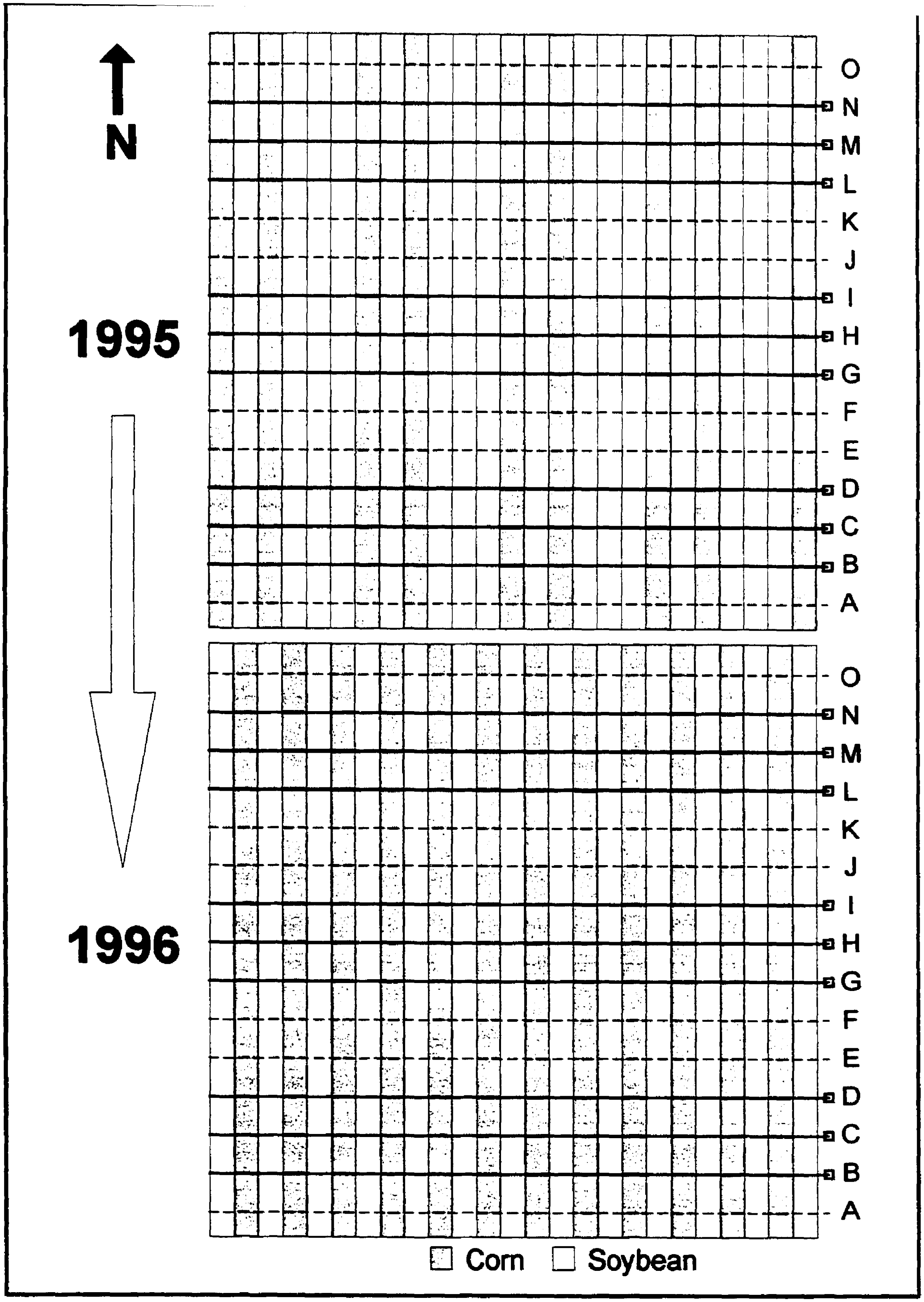


Figure 3.5 Change in location of corn and soybean strips from 1995 to 1996.

of the tractor to control milkweed (*Asclepias syriaca*) and other tall weeds (McRae, 1996). The operations schedules for both years are shown in Tables 3.3 and 3.4.

Table 3.3 Agronomic schedule for 1995.

Date	Operation
May 9	Weed burndown
May 11	Seeded corn, herbicide application
May 21	Seeded soybeans, herbicide application
June 9	1st Cultivation of corn
June 13	1st cultivation of soybeans
June 21	Cultivated and fertilized corn (28% UAN @ 130 kg/ha)
June 27	2nd cultivation of soybeans
October 3	Harvested soybeans
October 8	Harvested corn

Table 3.4 Agronomic schedule for 1996.

Date	Operation
May 25-26	Disked-up fields, and straightened rows
May 27-28	Seeded corn and soybean
June 20	Cultivated and fertilized corn (28% UAN @140kg/ha)
July 3	Formed corn ridges, herbicide application Soybean rows were left flat
June 27	1st cultivation of soybeans
July 5	2nd corn cultivation
July 12	2nd cultivation of soybean
October 19	Harvested soybean
November 2-3	Harvested corn

3.6 Weather observations

An on-site Campbell 21X datalogger (Campbell Scientific Inc., Edmonton) collected rainfall, air tempetrature, soil temperature and drainflow measurements every 15 minutes.

Daily rainfall at the site was monitored and compiled on a monthly basis for the 1995 and 1996 growing seasons. Rainfall was measured with a tipping bucket rainguage and was verified with a manual rainguage and vice-versa. Both measuring devices agreed closely with negligible discrepancies. Rainfall measurements were also compared with another rain guage site about 1.6 km away and the differences were minor.

Air temperature was the ambient temperature in the shade. Soil temperatures were measured by a thermal probe at 1 cm (surface), 5 cm, 20 cm and 50 cm depths. Because the probe was at the grassy edge of the field next to the datalogger box, rather than in the bare-soiled field, the readings for May and June may be lower than the actual temperatures. However, by July and August when the crop canopy was fully formed, it was assumed that the readings were representative of the actual field plot soil temperatures.

The data were stored in a SM-192 memory module (Campbell Scientific Inc., Edmonton) and downloaded to a computer twice a month. The datalogger was solar powered with a backup battery. A copper grounding rod and a spark-gap unit protected the instrumentation from lightning damage.

3.7 Growing conditions

Using the on-site weather data, growing conditions such as evapotranspiration (ET) and corn heat units (CHU) were calculated for both years. The Blaney-Criddle equation was used to calculate ET:

$$u=k*p(0.46T+8.13) \quad \textbf{(1)}$$

where:

u = Monthly evapotranspiration (mm)

k = Crop coefficient for corn (0.42 for May; 0.8 for June; 1.15 for July; 0.87 for August; 0.55 for September) (FAO, 1977).

p = Monthly percent of total daylight hours (Environment Canada Climatic Normals,1960-1990 at McGill University Weather Station, Montreal, Quebec).

T = Average monthly temperature (°C)

The corn heat units (CHU) were calculated using the following equation:

$$CHU=(1.80(T_{min}-4.4)+3.33(T_{max}-10)-0.084(T_{max}-10)^2)0.5 \quad \textbf{(2)}$$

where:

T_{min} = Minimum air temperature (°C)

T_{max} = Maximum air temperature (°C) (Brown and Boutsma, 1993).

The CHU were accumulated from the date of seeding until the date of grain physiological maturity. The dates of seeding were May 11 for 1995 and May 27 for 1996. The grain maturity dates were assumed to be 60 days after tasseling (Hanway, 1963). This date was September 17 in 1995, and September 28 in 1996.

3.8 Water table level

Water table depth from the ground surface was determined by lowering a graduated rod with a water sensor into observation wells placed in the field. The observation wells were 1.6 m long and made of 1 inch PVC pipes which were cut and plugged at the bottom with drainage tape (Broughton, 1972). The pipes had drilled holes of 6 mm in diamter along their lengths to let soil water in and were covered with geotextile to keep silt out. The wells were installed to a depth of 1.5 m at midspacing and protruded at the surface and capped to prevent surface runoff and rain from entering. There were 43 wells in total, 12 observation wells per treatment, 6 additional wells placed to monitor water table shape, and one 2 m well used to monitor the water table level when it dropped below 1.5 m in the FD plot. The top of each observation well was surveyed relative to a benchmark, to the drain outlet bottoms and to the tops of the risers of the water table control structures.

3.9 Drainflow and water quality

The volume of drainflow was measured by tipping buckets at each of the monitored lateral drain outlets and was recorded by the datalogger. Using a third order equation obtained from the calibration of the tipping buckets, drainflow volume was converted to drainage depth in mm/day (Lalonde, 1993). Grab samples were collected during flow events into Nalgene sample bottles and analyzed for nitrate-N. The samples were stored at 5°C before analysis. Nitrate-N concentrations were determined using a QUIK CHEM AE autoanalyser (Lachat Instruments, Milwaukee, WI). Nitrate-N concentrations from the outlets were matched with their respective drainflow volumes and were converted to nitrate loadings on a kg/ha basis.

3.10 Plant parameters

3.10.1 Soil Plant Analysis Development (SPAD)

SPAD-meter readings were taken at different growth stages in both years to compare plant N-status between treatments. In 1995, readings were taken from 30 plants (1 reading per leaf) in the central corn and soybean rows, above the central drain lateral. In 1996, the number of plants was decreased to 20 but the number of readings per plant was increased to 6 readings per leaf. The leaves measured were the last fully developed leaf with ligules before silking, and the subtending ear leaf after silking. The same plants were measured throughout the growing season. Leaf samples were taken from adjacent corn plants, dried, ground, weighed and analyzed for leaf-N content by Kjeldahl digestion and acid titration with 0.05 *M* HCl. The SPAD readings were then compared with the leaf-N levels and a linear fit was obtained by regression.

3.10.2 Crop harvest

The harvesting of corn and soybean was done by hand. Corn cobs were removed from plants 2.5 m on either side of the laterals. This was done 6 times for a total of 30 m per treatment. Additionally, 60 corn plants were taken from each treatment to determine the harvest index or the ratio between total biomass versus grain produced. The soybean plants were cut and shelled manually in 1995, but shelled by a combine harvester in 1996.

The cobs and corn plants were oven dried for 48 hours. The cobs were shelled using a corn sheller, dried and weighed. The soybeans were already field-dried. Subsamples from the shelled corn and soybean grains were taken to determine the treatment mean grain sizes by weighing out 100-kernels or seeds. The number of pods per plant was also assessed for soybean.

3.11 Statistical analysis

Due to the drainage layout and limited number of drains, the placement of the treatments was constrained. The change in water table control height between two adjacent plots necessitated two buffer drains between them to maintain the water table at a constant level within each of the monitored plots (Lalonde, 1993). Thus, this restriction forced similar water table treatments to be situated adjacent to each other.

Conventional statistical tests for significance were therefore not applied due to lack of complete randomization. Therefore, a two-tailed Student's *t*-test was used to determine if treatments were significantly different from each other (Agriculture Canada, 1989; Lalonde, 1993). The treatments were compared in pairs: 50 cm CWT vs. 75 cm CWT, 75 cm CWT vs. FD, and 50 cm CWT vs. FD. In cases where a certain outcome was expected, an upper-tailed, or directional *t*-test was applied to test the hypotheses.

The compared samples were homoscedastic (from populations with the same variance), were independent and normally distributed. The *t*-test is considered an appropriate statistical method to test hypotheses under such conditions (Agriculture Canada, 1989; Howell, 1989; Devore and Peck, 1990).

4.0 RESULTS AND DISCUSSION

4.1 Climatic data

The climatic data collected (rainfall, soil temperature and air temperature) were key to interpreting the results since all other parameters measured were weather dependent. For instance, the water table levels, drainflow volume and water quality were all functions of rainfall and ET. Moreover, parameters such as crop yields and soil microbial processes which control mineralization and denitrification rates, and consequently soil and water quality, are largely dependent on climatic conditions. Therefore, the climatic data are central to the interpretation of the results of this study.

4.1.1 Rainfall

A comparison between the recorded monthly rainfalls with the long-term (30-year) average from 1951 to 1980 obtained from the nearby Environment Canada Weather Station in nearby Lancaster, Ontario is shown in Table 4.1. Because of the high spatial variability of rainfall events during the summer, the proximity of the weather station where the long-term average was recorded is important when comparing rainfall to the long-term average. The Lancaster weather station was selected for comparison due to its proximity.

Rainfall is important since it affects the amount of water in the soil, and hence the soil moisture available for plant uptake, and the rates of N mineralization and denitrification. These processes, in turn, influence the amount of potentially leachable nitrate in the soil, total drainflow volume and crop yield.

The 1995 growing season was relatively dry as indicated by the total deviation from the long-term monthly average (Table 4.1). However, although the growing season was 13.7% drier than normal, the precipitation for the month of July was 68.9% above average. The month of July is critical because it is usually during this time that crops are drought-stressed. Furthermore, the growth intervals for corn and soybean in which irrigation produces the greatest benefits occur in July to August (James, 1988). Most of the rain fell at the end of July (Figure 4.1), just when the crops were about to wilt. This timely rainfall event replenished soil moisture and provided adequate water to save the crop from wilting.

Table 4.1 Rainfall for the 1995 and 1996 growing seasons.

Month	30-year Average Rainfall (mm)	1995 Rainfall (mm)	Difference from average (%)	1996 Rainfall (mm)	Difference from average (%)
May	76.4	69	+9.7	67.3	+11.9
June	69.1	54.6	-21	57.4	-16.9
July	66.8	112.8	+68.9	158.9	+137.9
August	91.4	67.6	-26	34.5	-62.2
September	90.4	35.9	-60.3	155.1	-71.6
Total	394.1	339.9	-13.7	473.2	+20.1

In contrast, the 1996 growing season was relatively wet (+20.1%). For example, May and July were 11.9% and 137.9%, respectively, wetter than average. However, June, August and September were drier than normal. Figure 4.1 shows the monthly rainfall for both years. From May 1st through October 31st, 1996 had 133 mm more rainfall than for the same period in 1995. The differences in rainfall amount and distribution between the two years had a large influence on water table levels, drainflow volumes, crop yield increases and nitrate losses.

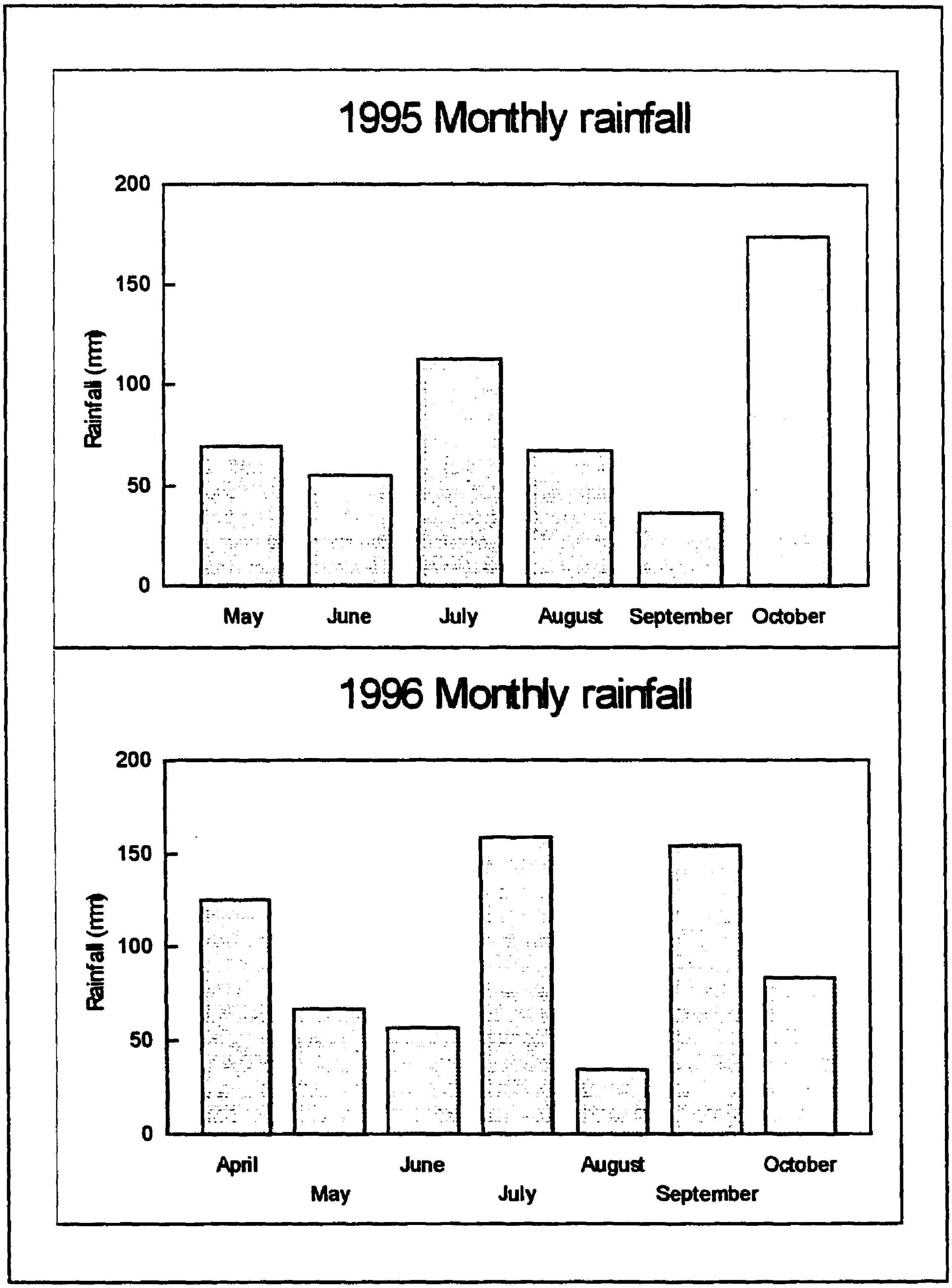


Figure 4.1 1995 and 1996 Monthly rainflall.

4.1.2 Temperature

Air and soil temperatures are important growth factors since they affect germination, ET and soil microbial activity, which in turn affect the processes of nitrification and denitrification.

The average air temperatures for the months of May through September are presented in Table 4.2. The 1995 growing season (May-September) was slightly warmer than that of 1996. The average air temperatures were compared to the long-term (1979-1995) temperature averages recorded at the Environment Canada Weather Station at Coteau du Lac, Quebec, which was the closest station with this data. Compared to the long-term average, 1995 and 1996 were warmer by 10.0% and 9.5%, respectively.

Table 4.2 Average air temperatures from May to September for 1995 and 1996.

Month	1995 Air temperature (°C)		1996 Air temperature (°C)	
	mean	standard deviaton	mean	standard deviation
May	13.67	5.15	12.9	5.87
June	20.8	6.15	19.38	4.54
July	22.02	5.05	20.65	4.1
August	20.67	5.9	20.81	5.71
September	13.56	6.69	16.65	5.51

The average monthly soil temperatures at five depths for both years are shown in Tables 4.3 and 4.4. The soil temperatures in 1995 were warmer than those in 1996 from May through August. September of 1996, however, had warmer soil temperatures than did September of 1995. The soil temperatures lagged behind the fluctuations in air temperature and were more stable due to the soil's thermal retention capacity, with standard deviations ranging only between 0.55°C and 2.16°C for 1995, and between 0.30°C and 2.46°C for 1996.

Table 4.3 Average soil temperatures from May to September for 1995 at five depths.

1995 Month	Soil temperature (°C)				
	Soil surface	5 cm depth	15 cm depth	20 cm depth	50 cm depth
May	11.72	11.19	10.6	10.09	8.35
June	16.86	16.32	15.74	15.21	13.28
July	19.43	19.01	18.53	18.07	16.3
August	19.08	18.92	18.73	18.54	17.63
September	13.15	13.35	13.6	13.79	14.27

Table 4.4 Average soil temperatures from May to September for 1996 at five depths.

1996 Month	Soil temperature (°C)				
	Soil surface	5 cm depth	15 cm depth	20 cm depth	50 cm depth
May	9.7	9.21	8.67	8.2	6.6
June	15.36	14.85	14.23	13.7	11.98
July	17.86	17.56	17.16	16.78	15.34
August	18.08	17.98	17.81	17.65	16.87
September	15.49	15.6	15.69	15.74	15.73

Soil temperature is an important factor which governs soil microbial processes. Denitrification proceeds at a progressively slower rate at temperatures below 20°C and practically ceases at 2°C (Stevenson, 1982). The optimal temperature range for denitrification is between 20°C and 35°C. Thus, the months of July and August probably had the highest denitrification rates, since this is when the soil was warmest.

4.1.3 Corn heat units

The amount of corn heat units (CHU) for each year is shown in Table 4.5. The starting date used for calculating CHU was the date of seeding, while the end date used was the date of grain physiological maturity.

Table 4.5 Corn heat units from seeding to maturity for 1995 and 1996.

Month	1995 CHU	1996 CHU
May	335	73
June	705	711
July	811	789
August	733	737
September	254	552
Total	2838	2862

The field site is located in a region which receives an average of 2700-2900 CHU during the growing season (Environment Canada, 1996). Compared to the 16-year average calculated from weather data taken from the Environment Canada Weather Station in nearby Coteau-du-Lac, Quebec, 1995 and 1996 were only slightly higher by 1.2% and 2.1%, respectively.

The crops in both years received approximately the same total CHU (1996 received 0.85% more than 1995). Thus, the difference in *total* CHU is probably negligible in its effect on the yield differences between both years. What may perhaps be more revealing is the temporal distribution of the total CHU. If compared on a *monthly* basis, May, June and July 1995 had a much higher cumulative CHU than the same months in 1996. These months are crucial since germination and most of the vegetative growth needed for establishing a good stand occur during these months and because "temperature effects are greater during canopy formation than during grain filling" (Treidl, 1977). In fact, "the environmental conditions prior to mid-June determine the number of leaves that will develop on the plants" (Hanway, 1963). Even though August and September of 1996 had higher CHU than in 1995, this amount was probably not as important as the earlier months' since vegetative growth had stopped, and plants had attained their full height by then. The fact that a wet spring in 1996 delayed seeding by 16 days when compared to 1995, caused lower CHU in 1996 during May, June and July. Thus, even though 1996 received more CHU in total than 1995, the lower CHU received in the critical growing months of 1996 may have partly caused the lower yields that year.

4.2 Water table levels

The water table controls were set at 50 cm and 75 cm below the soil surface. It is impossible to maintain a constant water table by controlled drainage alone due to the losses from ET, lateral and deep seepage. Therefore, subirrigation was used to help keep the water table above the drains in both years. Figures 4.2 and 4.3 show the fluctuations in water table level with rainfall. In 1995, the average water table level for the 50 cm CWT treatment plots was 91 cm, 103 cm for the 75 cm CWT treatment plots and 130 cm for the FD plots. In 1996, the average water table levels for the 50 cm CWT, 75 cm CWT, and FD plots were 75 cm, 85 cm and 121 cm, respectively.

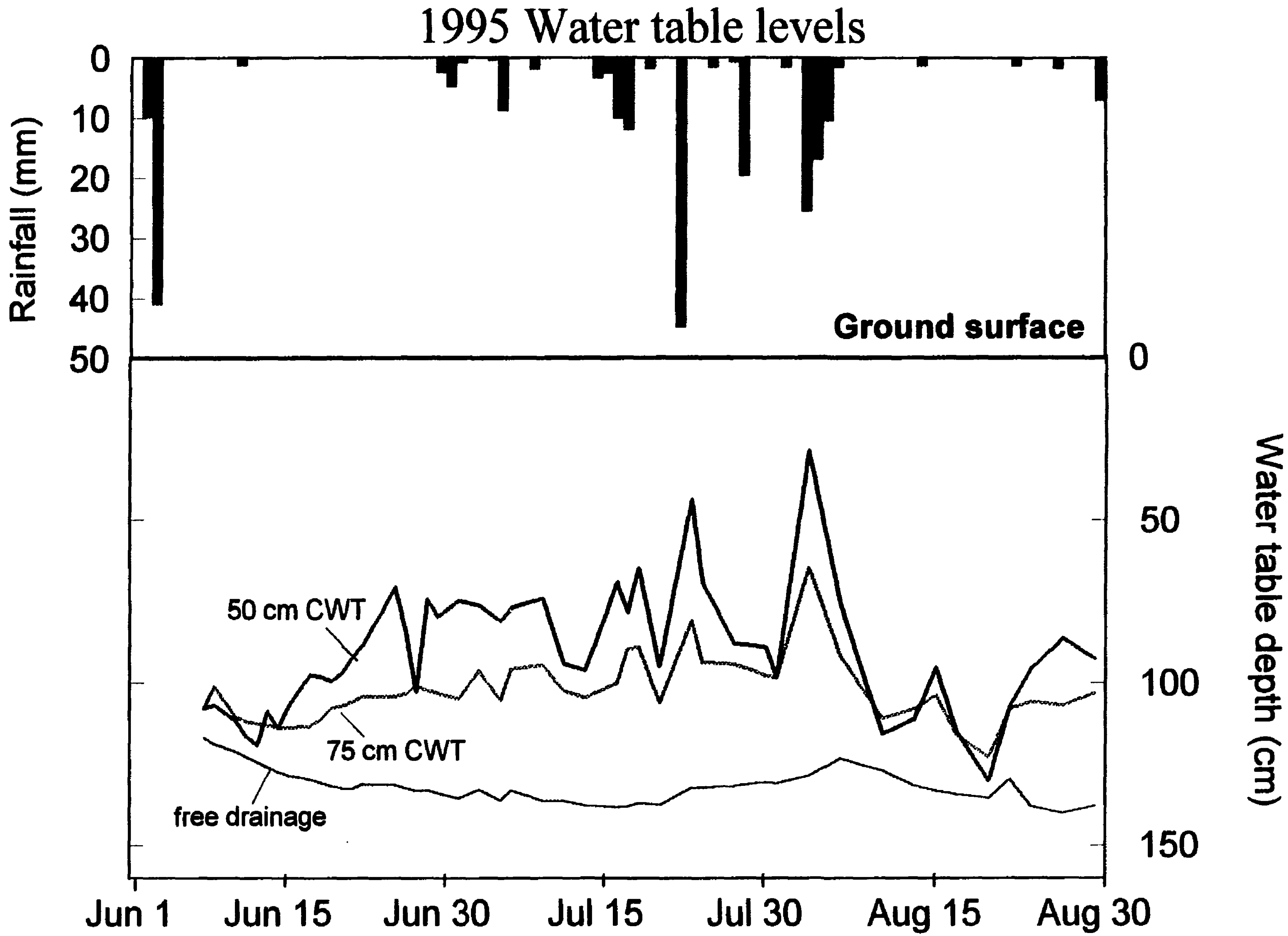


Figure 4.2 1995 Rainfall and water table levels

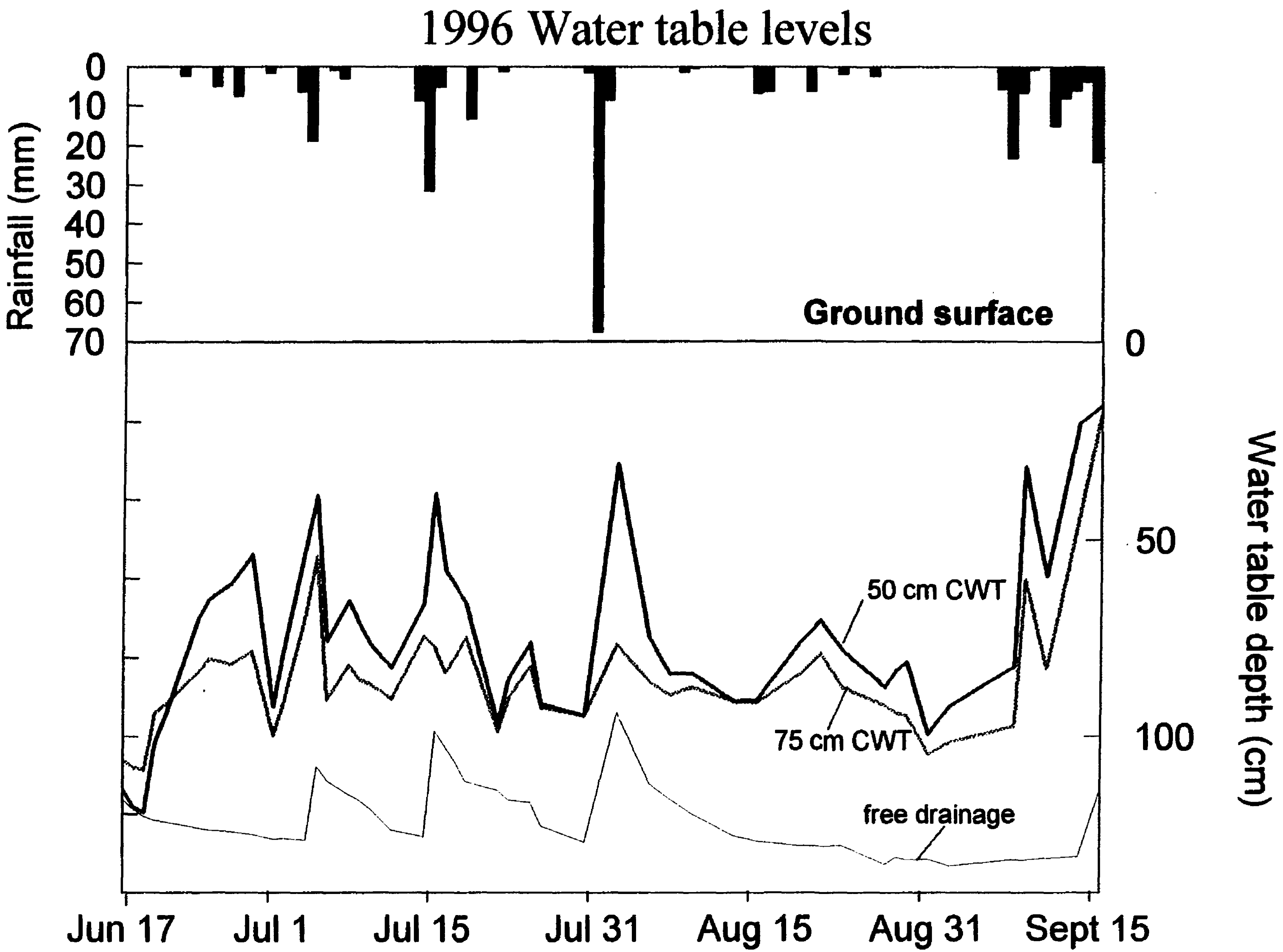


Figure 4.3 1996 Rainfall and water table levels.

Although the water tables could not be maintained constantly at 50 cm and 75 cm below the soil surface because the pump could not keep up with the seepage and ET losses, the water tables occasionally met the target levels and were consistently statistically different from each other at the 95% confidence level in both years. Because the raised water tables filled up the available pore space in the soil, the water table treatments would, in theory, greatly affect soil microbial processes, total drainage volumes and water quality, as well as grain yields. The following sections discuss the effects of the controlled water table treatments on these parameters.

4.3 Soil moisture

The shallower water tables in the CWT plots substantially increased soil moisture levels in both years. The differences in soil moisture content among treatments are presented in Figures 4.4 and 4.5. In July, when soil moisture is crucial for both crop growth and denitrification, the soil moisture in the CWT plots were significantly higher than in the FD plots at the 95% confidence level. This difference was due to the shallower water tables kept up by WTM. Figure 4.6 shows that WTM reduced soil moisture deficit by supplementing rainwater to meet crop and ET demands in both years.

Furthermore, as will be seen in the following sections, the wetter soil conditions experienced under WTM helped increase drainflow volumes and crop yields. In addition, since soil moisture is an important factor in soil microbial processes, the increases in soil moisture greatly affected denitrification, and consequently, the nitrate levels in both the soil and drainwater in both years. Figure 4.7 shows that the water table treatments did in fact affect soil redox potential and denitrification rates.

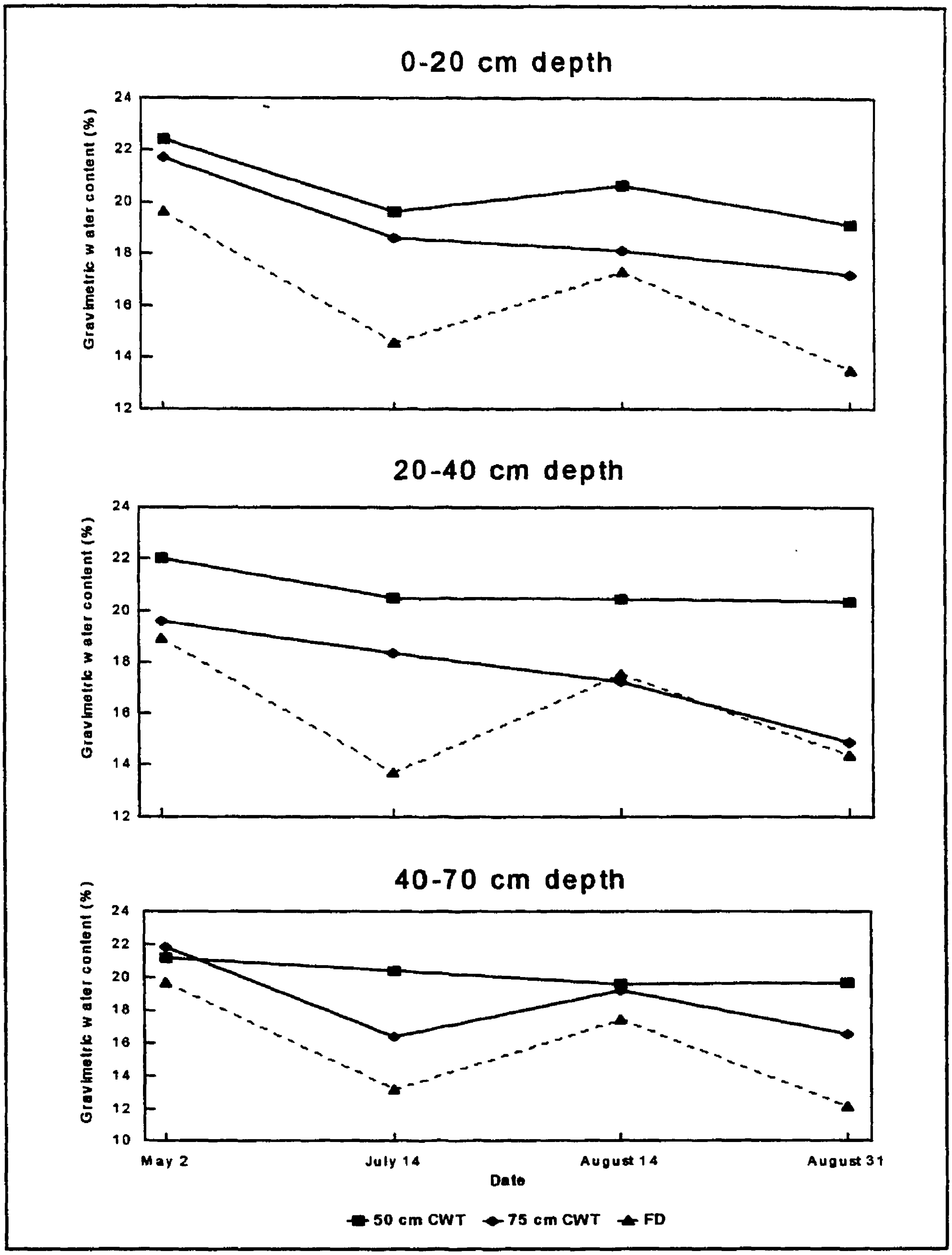


Figure 4.4 Soil gravimetric water content in the 1995 growing season (% by weight).

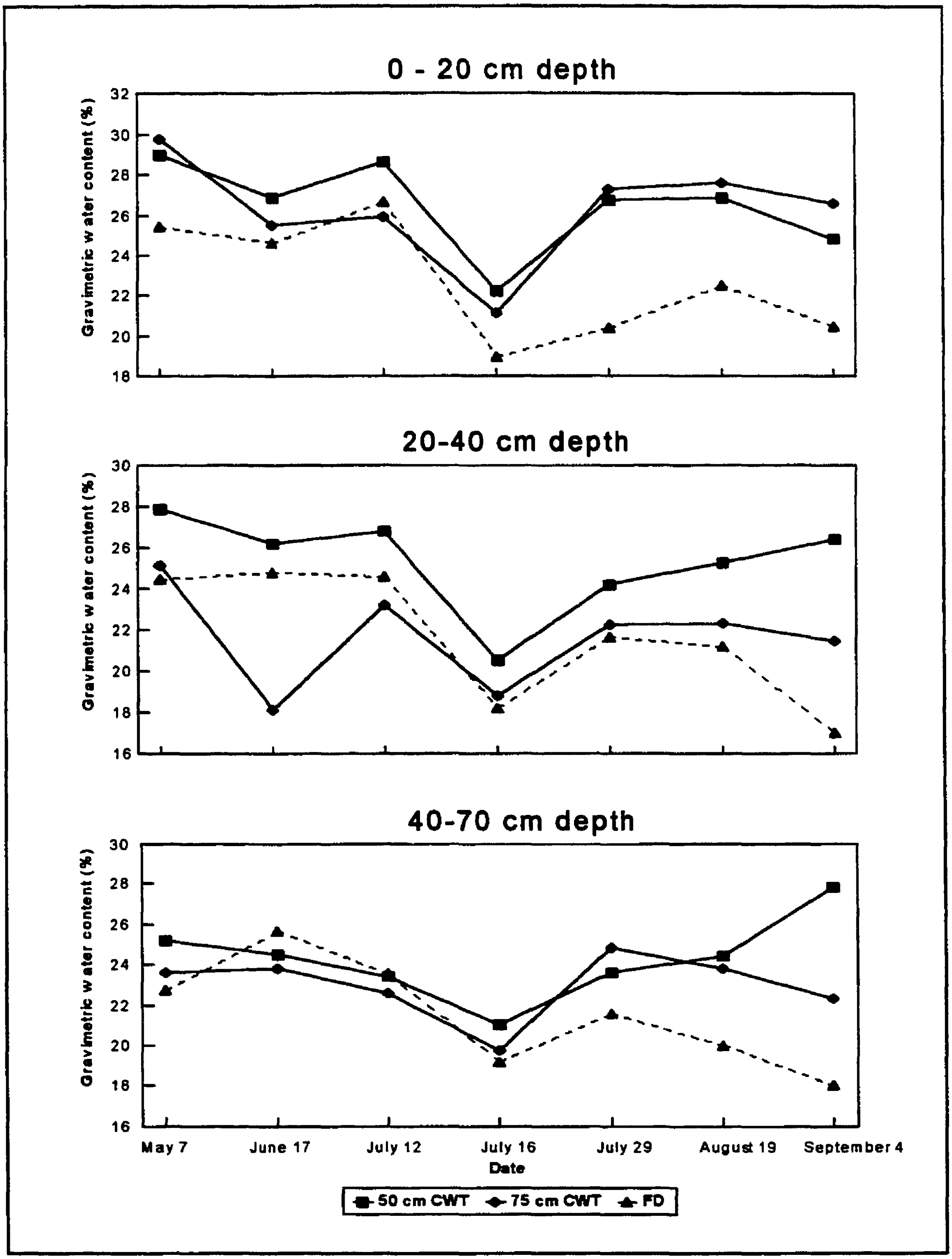


Figure 4.5 Soil gravimetric water content in the 1996 growing season (% by weight).

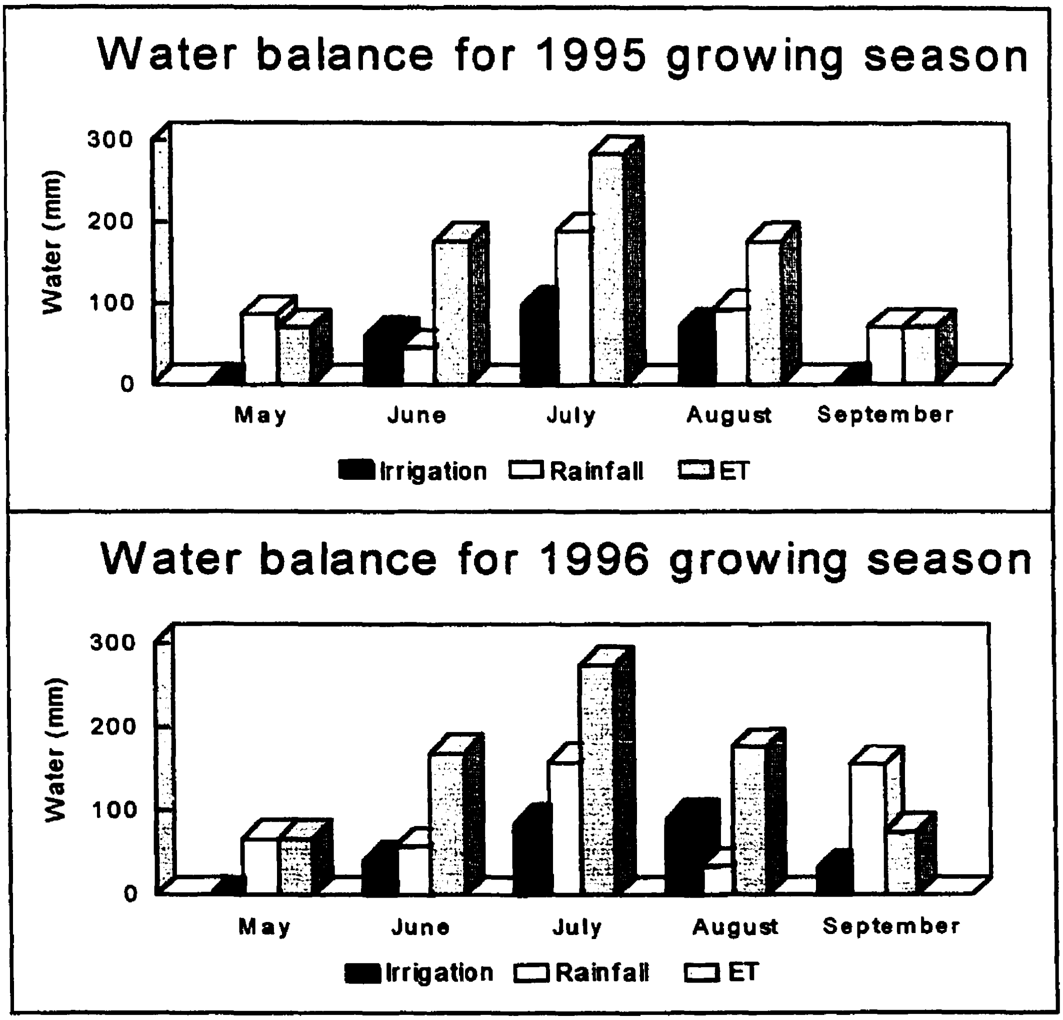


Figure 4.6 Water balance for 1995 and 1996.

The water table treatments (Figure 4.7) greatly affected both the soil redox potential in the soybean strips, as shown from measurements by Dockeray (forthcoming), and the denitrification rates in the corn and soybean strips, as shown from measurements from Elmi (forthcoming). Higher redox potentials indicate higher oxygen levels in the soil. Since denitrification occurs in "definitely wet soils" (Addiscott et al., 1991), the wetter, less-aerated CWT plots were more conducive to denitrification. Indeed, the denitrification in these plots were considerably greater than in FD as indicated by the greater losses of N_2O from the soil.

Nitrous oxide is an obligatory intermediate in the denitrification process. Therefore, N_2O emmission is an excellent indicator of denitrification. Furthermore, since N_2 is also a byproduct of denitrification, the amount of measured N_2O would give, at the very least, a baseline rate of denitrification. The highest N_2O production occurred in early August, when soil temperature was at its peak and soil moisture was high. Thus, most of the denitrification that occurred coincided with these ideal conditions.

More (+134%) N_2O was lost from the corn strips than the from the soybean strips. This difference was most likely due to the fact that the soybean strips were not fertilized and therefore, there was less nitrate to be convert to N_2O. Also, soybeans are leguminous, and therefore, capable of fixing atmospheric-N. Thus, the soybeans might possibly have fixed some of the evolved N_2O gas, whereas more N_2O was lost to the atmosphere in the corn strips.

Nitrous oxide evolution rates are clearly higher in the CWT plots as a result of the raised water tables. The probability levels at which they differed are shown in Table 4.6.

Table 4.6 Probability levels of comparisons for redox potential and denitrification.

1996	50 vs. 75 cm CWT		75 cm CWT vs. FD		50 cm CWT vs. FD	
Redox potential	0.00082**		0.12223^{ns}		0.00033**	
1996	corn	soybean	corn	soybean	corn	soybean
Denitrification	0.098*	0.302^{ns}	0.012**	0.054*	0.004**	0.010**

**means the comparison is significant at the 90% level, ** is significant at the 95% level, while ^{ns} is non-significant.*

Combined, both corn and soybean strips in the CWT plots increased denitrification by about 750%, compared to FD. In conclusion, WTM significantly enhanced denitrification compared to FD.

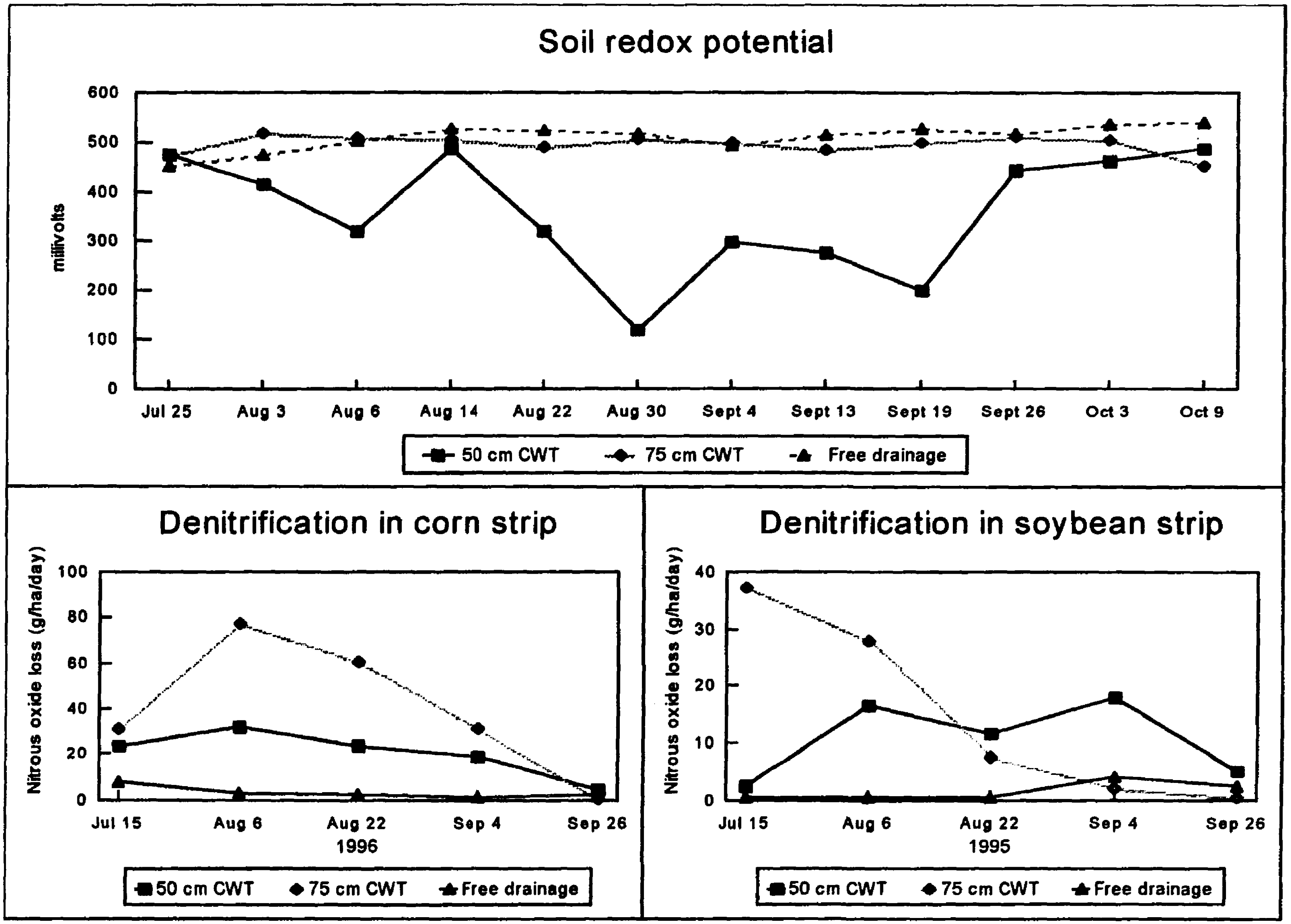


Figure 4.7 Soil redox potential and denitrification in 1996.

4.4 Drainage water quantity and quality

The water table treatments affected the amount of water drained due to their effect on the water holding capacity of the soil. Drain effluent quality was also affected by the water table treatments through their effect on soil moisture and microbial processes.

4.4.1 Drainflow volumes

Total drainflow volumes and distribution for 1995 and 1996 are shown in Figures 4.8 and 4.9. It was expected that CD in the CWT plots would reduce total drainflow volumes. However, the contrary was found in both years. In 1995 (May 1 to October 31) for example, 50 cm CWT and 75 cm CWT drained 555% (+97 m^3), and 583% (102 m^3) more than FD, respectively. In 1996, for the period of April 1 to October 31, the 75 cm CWT drained 70% (824 m^3) more water than FD. The only exception occurred in 1996 when the 50 cm CWT reduced total drainflow by 58% (+686 m^3) compared to FD.

This overall increase in drainflow for both years seems paradoxical. Evans et al. (1995) note that outflows from CD may vary widely depending on soil type, rainfall, type of drainage system and management intensity. Outflow may also vary seasonally. In wet years, for example, CD may have little or no effect on total outflow. During very wet periods, CD may even increase peak outflows. In contrast, CD may totally eliminate outflow in very dry years (Evans et al., 1995). This may explain the CWT drainflow increases in 1995 and 1996. The higher drainflows occurred in the CWT plots during July, August and October of 1995, and during April, June, July and September of 1996. These were periods when the water tables were near the controlled outlet levels due to subirrigation and heavy rainfalls.

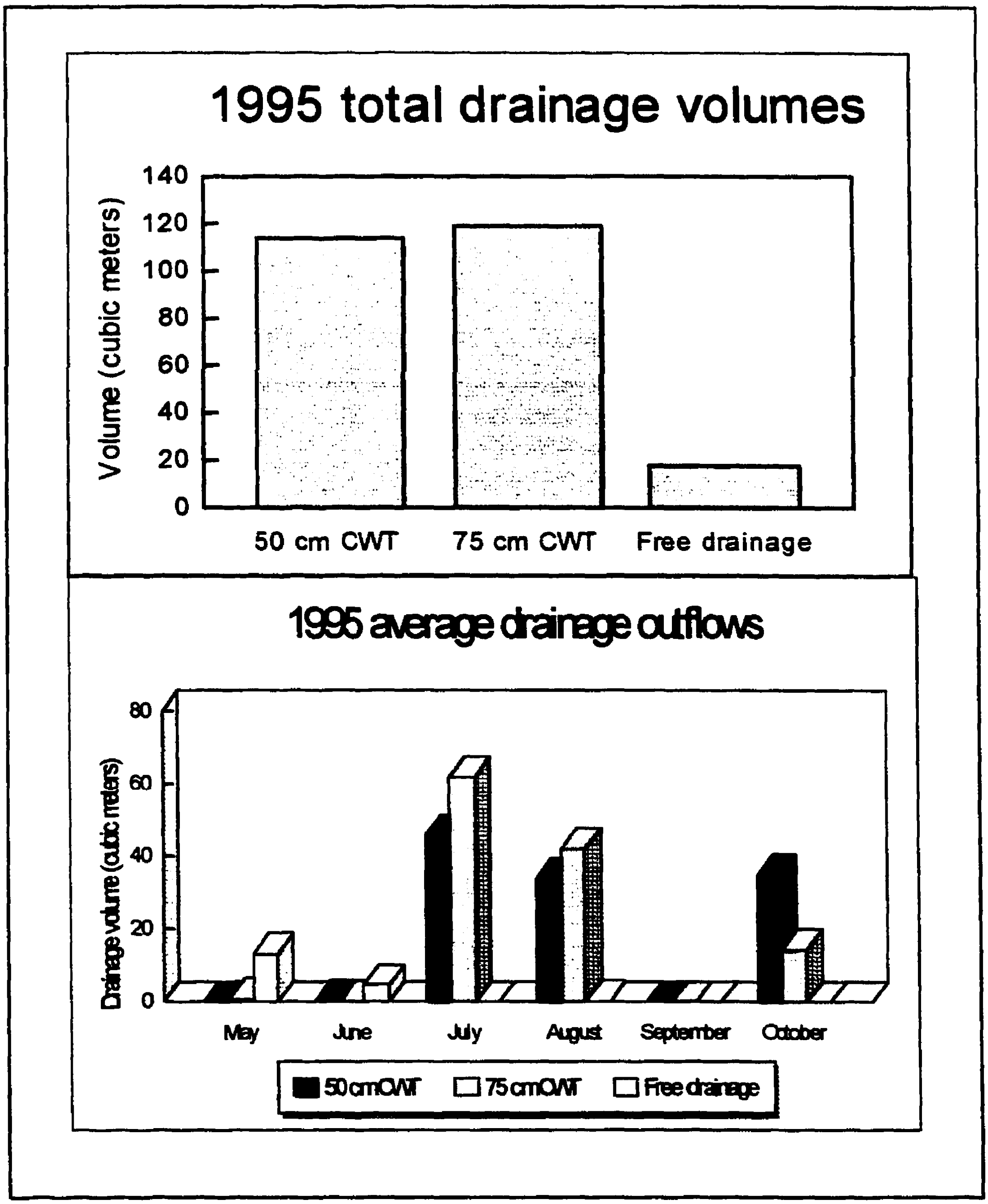


Figure 4.8 Total drainflow volumes for 1995.

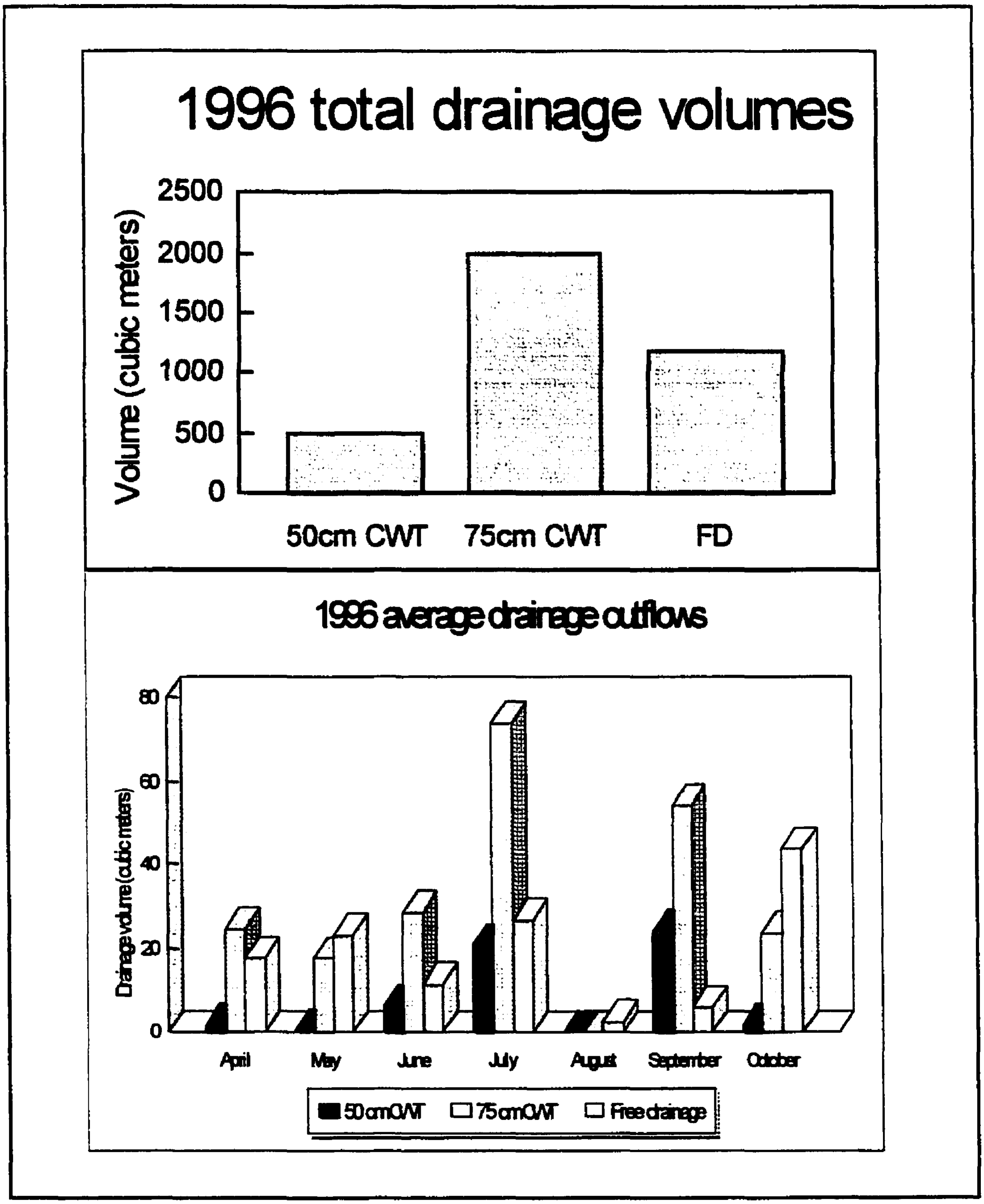


Figure 4.9 Total drainflow volumes for 1996.

Because the pore spaces were filled in the CWT plots during these months, the incoming water could not be absorbed. The drier FD plots, in contrast, had more available pore space or water storage capacity and absorbed the incoming water. There were also months in which the CWT plots reduced drainage when compared to FD--May and June in 1995, and May and August in 1996. When comparing total drainflow between years, 3410 m^3 or 1,358% more drainage occurred in 1996 than in 1995. This was because the period observed in 1996 included April and recorded some drainage from the spring thaw. In 1995, the datalogger was not installed until May. More importantly, 1996 received 133 mm more rain than 1995 which caused more drainflow. These differences in drainflows affected the total nitrate loadings to drainage water in both years.

4.4.2 Water quality

Effluent quality from the CWT plots was greatly improved by WTM. In spite of the fact that more drainage occurred in the CWT plots, nitrate pollution from the CWT plots was still lower than from FD. This is because the nitrate concentrations in the drain water samples from the CWT plots were much lower than those from the FD effluent in both years (Figure 4.10). As a result, when the mean concentrations were multiplied by the mean monthly discharge volumes for each treatment, the obtained total nitrate loadings from the CWT plots were still less than those from the FD plots. The amount of nitrate lost varied from drain to drain, even within treatments. These loadings were summed up for a treatment total and the mean was calculated for each treatment (3 drains per treatment). Tables 4.7 and 4.8 present the monthly treatment total and treatment average nitrate losses from both years.

Table 4.7 Treatment total and treatment mean nitrate-N losses in 1995 (kg/ha).

1995	50 cm CWT		75 cm CWT		Free drainage	
	Total	Mean	Total	Mean	Total	Mean
May	0	0	0.03	0.01	1.86	0.62
June	0	0	0	0	0.9	0.3
July	1.21	0.4	1.58	0.53	0	0
August	0.47	0.16	1.13	0.38	0	0
September	0	0	0	0	0	0
October	1.08	0.36	0.45	0.15	0	0
Sum	2.76	0.92	3.2	1.07	2.76	0.92

Table 4.8 Treatment total and treatment mean nitrate-N losses in 1996 (kg/ha).

1996	50 cm CWT		75 cm CWT		Free drainage	
	Total	Mean	Total	Mean	Total	Mean
April	0.44	0.15	7.51	2.5	2.66	0.89
May	0.02	0.01	1.9	0.63	3.2	1.07
June	0	0	0.02	0.01	2.17	0.72
July	0.44	0.15	2.81	0.94	4.7	1.57
August	0	0	0	0	0.55	0.18
September	0.32	0.11	2.14	0.71	0.93	0.31
October	0.14	0.05	1.74	0.58	8.82	2.94
Sum	1.36	0.46	16.12	5.37	23.03	7.68

In 1995, mean NO_3^--N concentrations were reduced by 84% and 77% by the 50 cm CWT and 75 cm CWT, respectively, as compared to FD (Figure 4.10). However, there was no appreciable difference in the mean nitrate loadings among the treatments in 1995 (Figure 4.11).

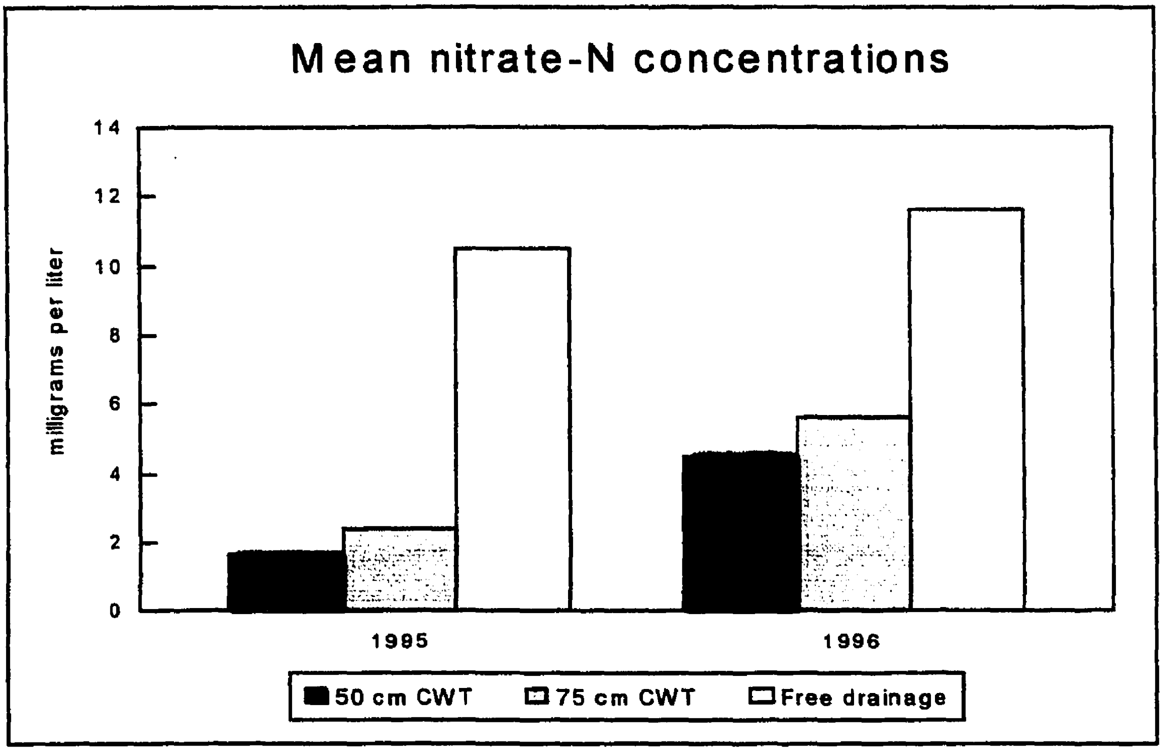
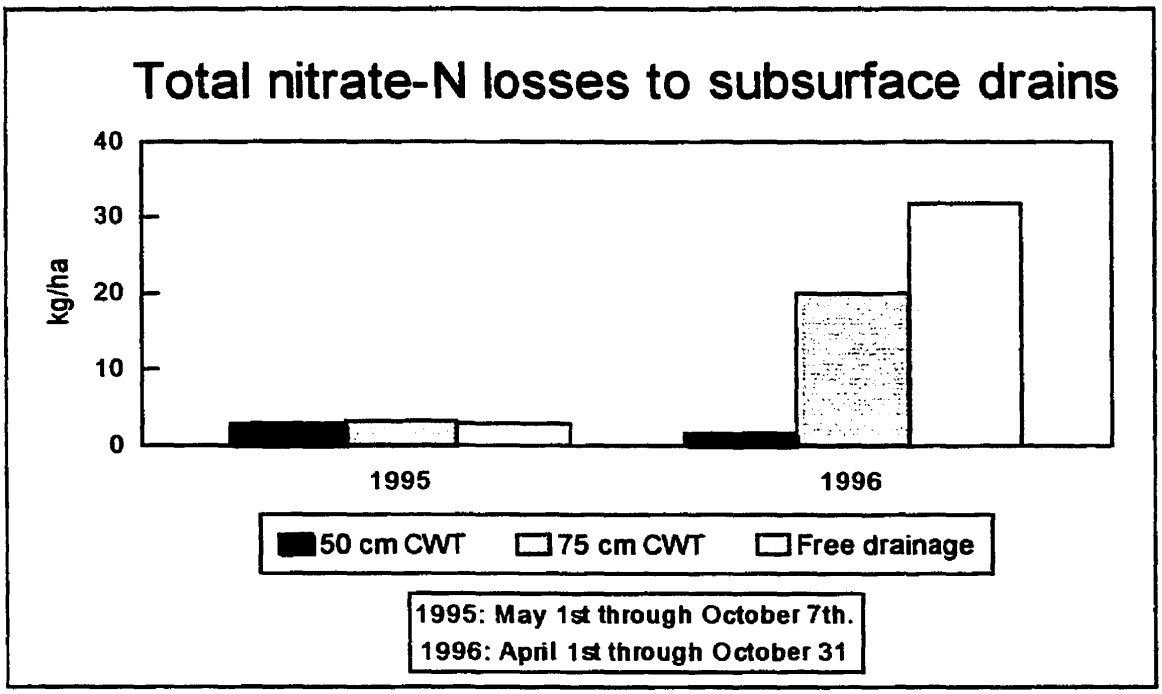


Figure 4.10 Mean nitrate-N concentrations in drainage water for 1995 and 1996.Figure



4.11 Total nitrate loadings for 1995 and 1996.

In spite of the lower nitrate concentrations found in the CWT drain effluent, the 75 cm CWT plots still lost the most nitrate in 1995 because of increased drainage outflow. The 75 cm CWT plots lost 16% more nitrate than FD, while the 50 cm CWT and FD plots lost the same amount. Combined, the CWT plots lost 8% more nitrate than FD. Overall, however, the difference in losses between treatments were not statistically significant at the 95% confidence level and were very low, with only approximately 1 kg/ha of NO_3^--N lost from each treatment.

In contrast, more nitrate loss, and consequently, more pollution occurred in 1996. 78% more (31.8 kg/ha) of nitrate was lost in 1996 than in 1995. This was due to the fact that the observed period in 1996 was longer than 1995. 1996 observations included some spring thaw drainage in April. More importantly, 1996 was wetter than 1995. 1996 had 133 mm more rainfall than 1995 which resulted in considerably more N-leaching. Total nitrate losses from the FD plots were 23.03 kg/ha, whereas the 50 and 75 cm CWT plots had losses of 1.36 kg/ha and 16.12 kg/ha, respectively. In 1996, the 50 and 75 cm CWT plots reduced nitrate pollution by 94% and 30%, respectively, when compared to FD (Figure 4.11). Combined, the CWT plots reduced nitrate pollution by 62% compared to FD. This reduction was attributed to a combination of decreased drainflow and enhanced denitrification. The drainage water quality and quantity results varied considerably between both years due to the difference in weather. The amount of rainfall greatly influenced the amount of nitrate leaching. Very little leaching occurred in 1995 due to the dry weather, while more leaching occurred in 1996 due to the wetter weather. It was fortunate that both a wet and a dry year occurred during the study since it showed how WTM affected nitrate leaching under these conditions.

In Onatrio, over 80% of total annual drainflow typically occurs from November to April, or during the non-growing season (Drury et al., 1996). Since the study was conducted only during the growing period, the obtained results represent only a fraction of the total amount of N that was lost or prevented from leaching by WTM. In conclusion, WTM proved to be highly effective in reducing nitrate losses and pollution during the growing season.

4.5 Soil properties

4.5.1 Initial N, P, K status

The average total N from the composite samples decreased with soil depth (Figure 4.12). This trend is probably attributable to the greater amount of organic matter in the upper soil layers and the fact that lower mineral horizons generally have less fixed N and smaller microbial populations. In comparing total N between plots, the CWT plots had higher total N than the FD plots in the top 0-30 cm layer. The 50 cm CWT plot had the highest amount of total N at all depths. Soil moisture promotes microbial processes such as nitrification which adds to the total N in the soil. In addition, in the upper 30 cm, total N was higher in the rows that had previously been planted with corn rather than with soybean, in spite of the nitrogen fixation by the soybeans. This is probably due to the higher amount of decomposing plant residue left by the corn. When averaged, the corn and soybean plots had similar total N levels in the upper 30 cm (Figure 4.12).

Total P and K levels in the top 30 cm of soil are presented in Tables 4.9 and 4.10. In all plots, P was higher in the rows previously planted with corn rather than soybean. Potassium, on the other hand, was higher in the soybean rows than in the corn rows for all plots. This runs counter to what was expected since soybeans generally take up more potassium than corn (OMAF, 1994). Corn and soybean have different nutrient demands and uptake rates. At maturity, for example, the beans contain about 60% of the potassium in the whole plant, whereas corn contains only 25% in the seed (OMAF, 1994). On the other hand, soybeans do not require as much phosphorus as corn in the early stages (OMAF, 1994). Some strips had been planted with either corn or soybean in two consecutive years and this may have lowered the N, P and K levels in the soybean rows.

Table 4.9 1995 Pre-planting soil-P status in corn and soybean strips.

Depth (cm)	Phosphorus (μg/g)					
	50 cm CWT		75 cm CWT		Free drainage	
	corn	soybean	corn	soybean	corn	soybean
0-30	35.52	15.84	22.71	19.95	34.68	27.62

Table 4.10 1995 Pre-planting soil-K status in corn and soybean strips.

Depth (cm)	Potassium (μg/g)					
	50 cm CWT		75 cm CWT		Free drainage	
	corn	soybean	corn	soybean	corn	soybean
0-30	69.48	77.68	61.01	66.31	71.30	76.69

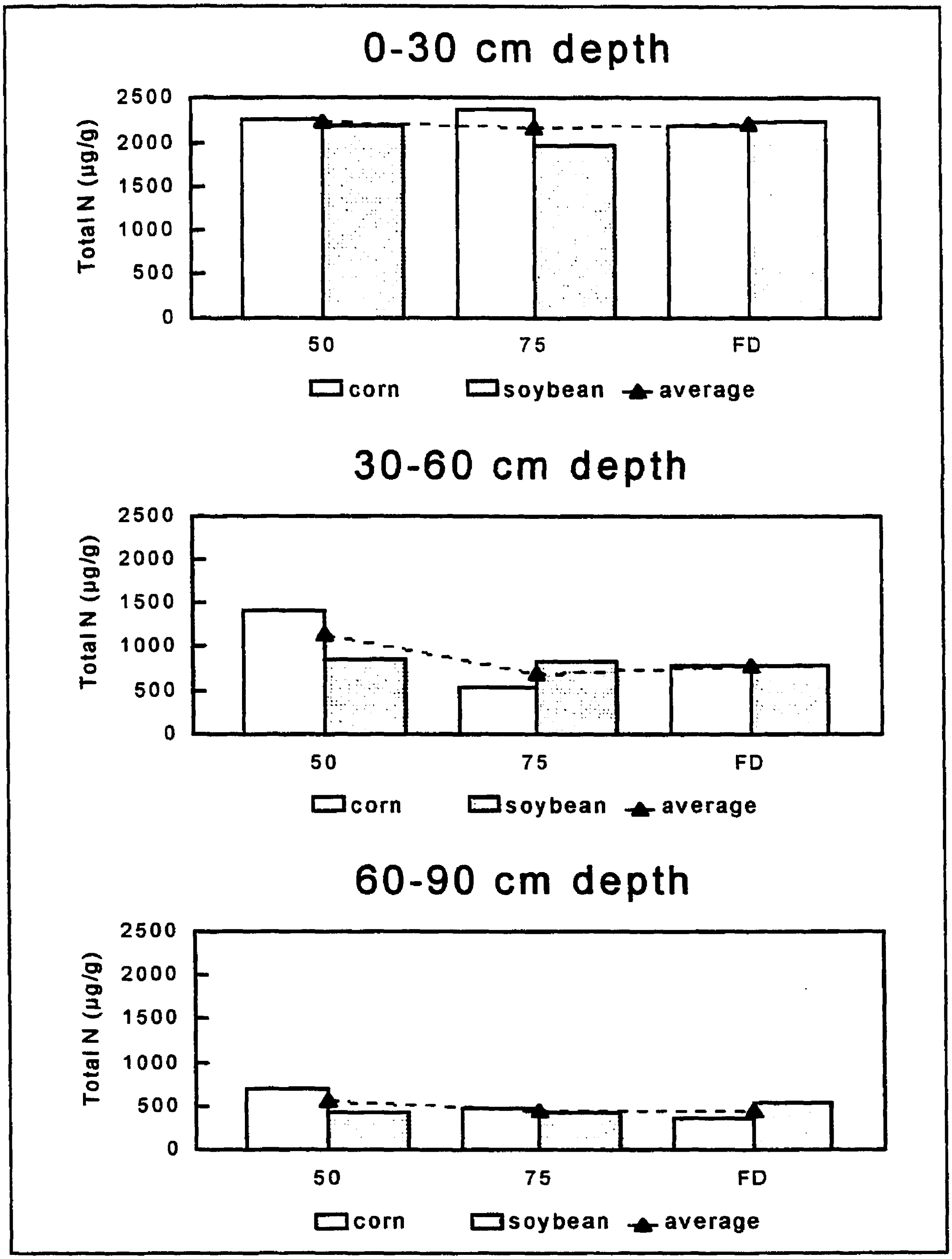


Figure 4.12 Total soil-N in all three plots before planting in 1995.

4.5.2 1995 Nitrate-N and ammonium-N

Available soil-N in the forms of nitrate (NO_3^-) and ammonium (NH_4^+), were compared between treatments at three depths. In the spring of 1995, there was more NO_3^--N in both the CWT plots than in the FD plots at all three depths (Figure 4.13). At the 0-30 cm depth, the 50 cm CWT plot had statistically significantly more NO_3^--N than the FD plot. This indicates that more NO_3^--N was lost by leaching in the FD plots, while more was held in the soil in the 50 cm CWT plots. In the 30-60 cm and 60-90 cm depths, NH_4^+-N levels were statistically significantly different between all treatments, while NO_3^--N levels were not. The higher levels of available NO_3^--N in the CWT plots can give the CWT crops an advantage over the FD by retaining more readily available soil-N for crop use.

Ammonium-N levels were below 4 μg/g in all three treatments and depths. Because ammonium-N is not as soluble as nitrate, and because it stays fixed to soil particles, it does not pose as serious a pollution problem as does nitrate.

4.5.3 1996 Nitrate-N and ammonium-N

In 1996, the CWT plots showed higher levels than the FD plots in the spring indicating that more nitrate was leached out of the soil in the FD plots during snowmelt. Nitrate levels also decreased with depth. Among treatments, for the upper 30 cm of soil, the 75 cm CWT treatment plots showed the highest nitrate levels. This indicates that there was either more mineralization in the 75 cm CWT plots due to an ideal balance of aeration and moisture, or that the 50 cm CWT treatment plots had a higher denitrification rate due to anaerobic conditions and showed lower nitrate levels because some nitrate had been converted to N_2 and N_2O gases.

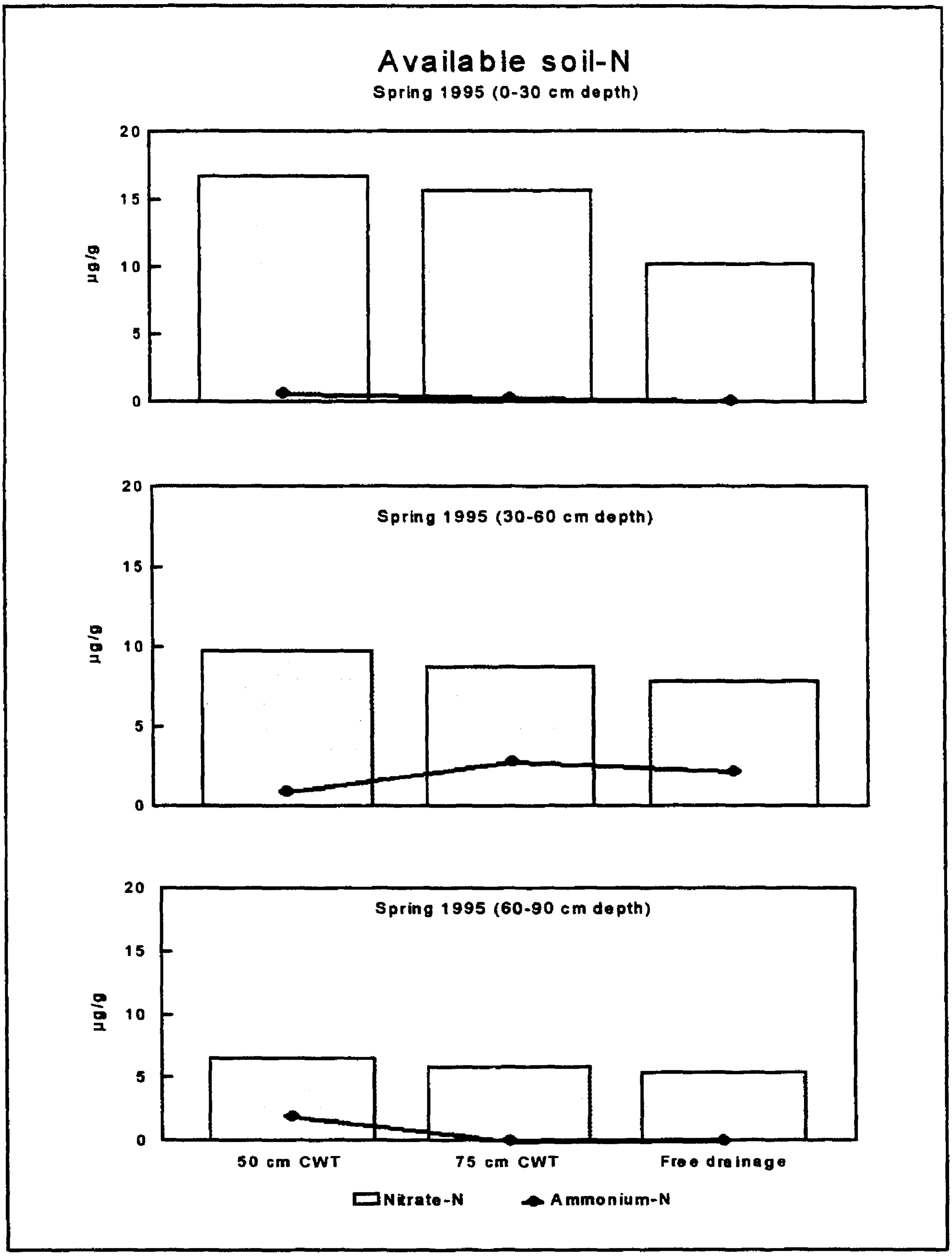


Figure 4.13 Available soil-N in 1995.

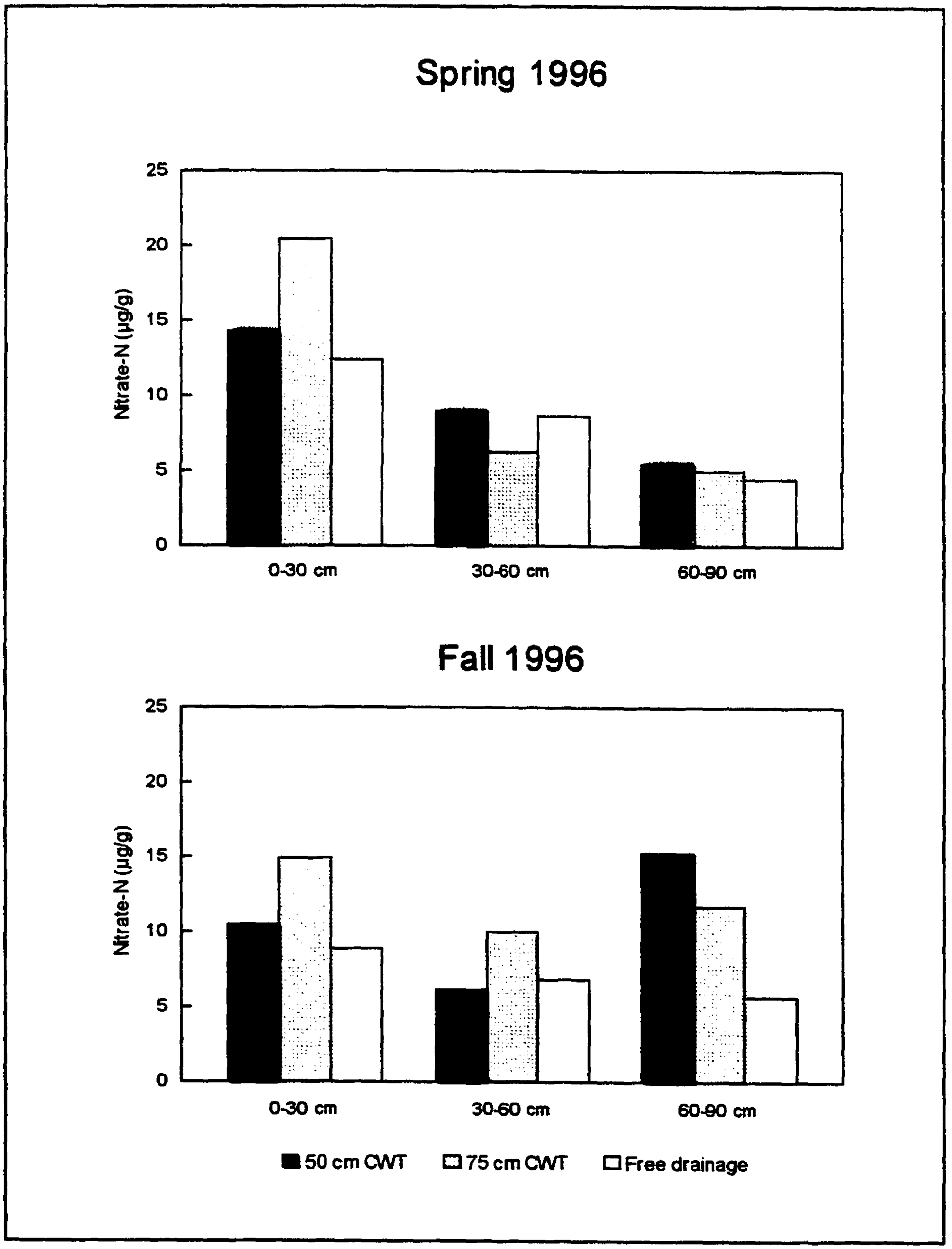


Figure 4.14 Soil nitrate-N in the spring and fall of 1996.

From spring to fall, nitrate levels decreased across all treatments. This reduction in nitrate could have been due to its removal by the crops and/or loss through leaching and denitrification. In the 50 and 75 cm CWT plots, for example, reductions of 5 µg/g from spring levels were observed in the upper 30 cm--the layer in which plants have the bulk of their roots and from which they extract most of their nutrients (Figure 4.14). Thus, much of the reduction can be attributed to plant uptake. However, since these plots were under CD/SI, some of the excess nitrate must have been lost, in part throught denitrification. Finally, the deeper horizons (60-90 cm) showed an increase from the nitrate spring levels. This indicates that most of the nitrate had also moved down the soil profile. This downward migration of nitrate is due to the large rainfalls of the 1996 growing season which caused some nitrate leaching as seen in the water samples collected from the FD drains. Figure 4.14 shows the effectiveness of CWT plots in holding more nitrates in the soil as compared to FD. Ammonium-N levels in the spring were low (<1.5 µg/g) and increased with depth (Fig. 4.15).

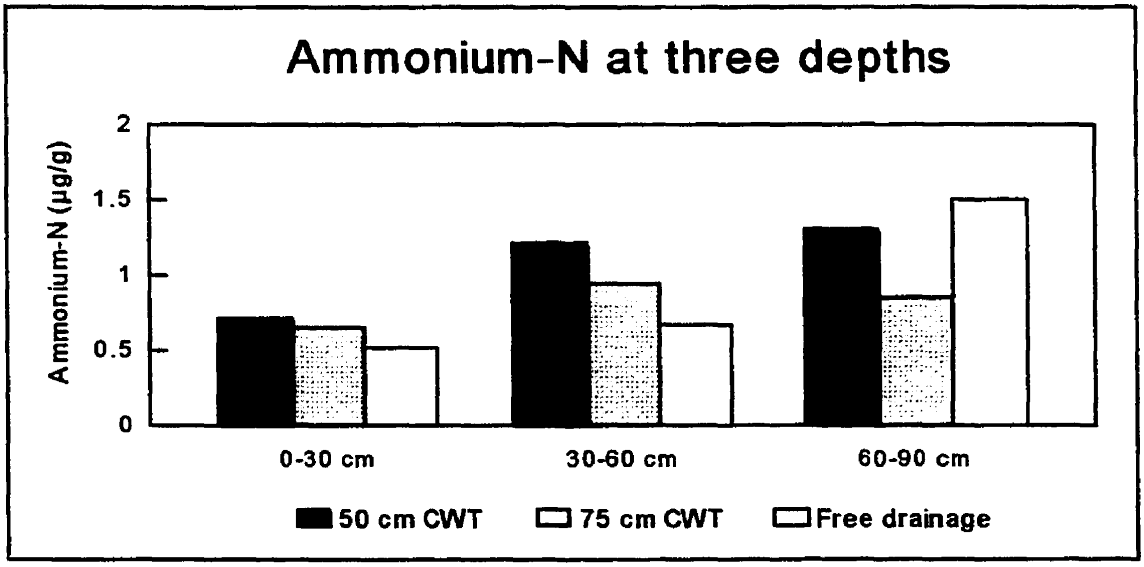


Figure 4.15 Ammonium-N in the spring of 1996.

4.5.4 Organic matter

Soil organic matter (OM) content is another important factor in the soil-N transformation processes. The lack of soluble carbon can be a limiting factor in denitrification even when moisture and temperature conditions are ideal. Organic matter content in all plots was considered relatively high for a mineral soil, and thus should not have been a limiting factor for denitrification.

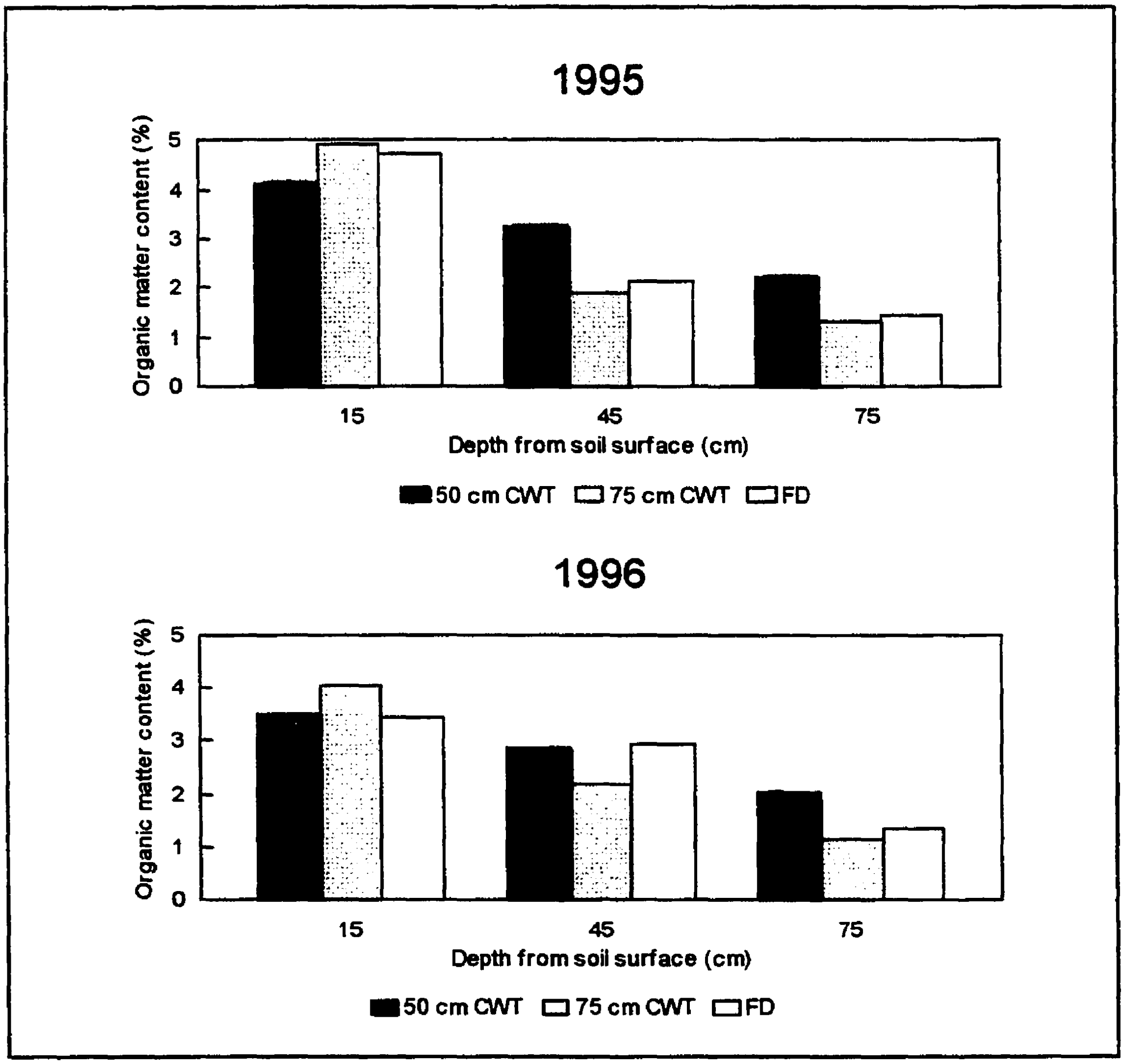


Figure 4.16 1995 and 1996 Soil organic matter contents at three depths and treatments.

4.6 Plant N-uptake and harvest parameters

Apart from reducing pollution, the higher water table levels in the CWT plots also enhanced crop performance. SPAD-meter readings and harvest analyses showed that WTM positively affected plant N-uptake and the subsequent grain yields.

4.6.1 Corn N-uptake

The SPAD-meter was able to detect differences in leaf-chlorophyll levels in the plants among the different water table treatments. The corn SPAD-meter values for 1995 and 1996 are plotted in Figure 4.17. In both years, the plants in the CWT plots had consistently higher chlorophyll levels than those in the FD plots throughout the growing season. The probability levels of the differences among treatments are shown in Table 4.11.

Table 4.11 Probability levels for corn SPAD value comparisons in 1995 and 1996.

	50 cm CWT vs. 75 cm CWT	75 cm CWT vs. FD	50 cm CWT vs. FD
1995	0.37217^{ns}	0.08505*	0.04806**
1996	0.14815^{ns}	0.27420^{ns}	0.05904*

**significant at the* $0.05 \leq P \leq 0.10$ *level,* ***significant at the 0.05 probability level, and* ^{ns} *is not significant.*

In 1995, there were no significant differences between the CWT plots: 50 cm CWT vs. FD was significant, while 75 cm CWT vs. FD was nearly or marginally significant.

In 1996, the difference in SPAD values between the 50 and 75 cm CWT, as well as between the 75 cm CWT and FD were not statistically significant, while the difference in values between 50 cm CWT and FD was nearly significant at the 95% confidence level (P=0.05904).

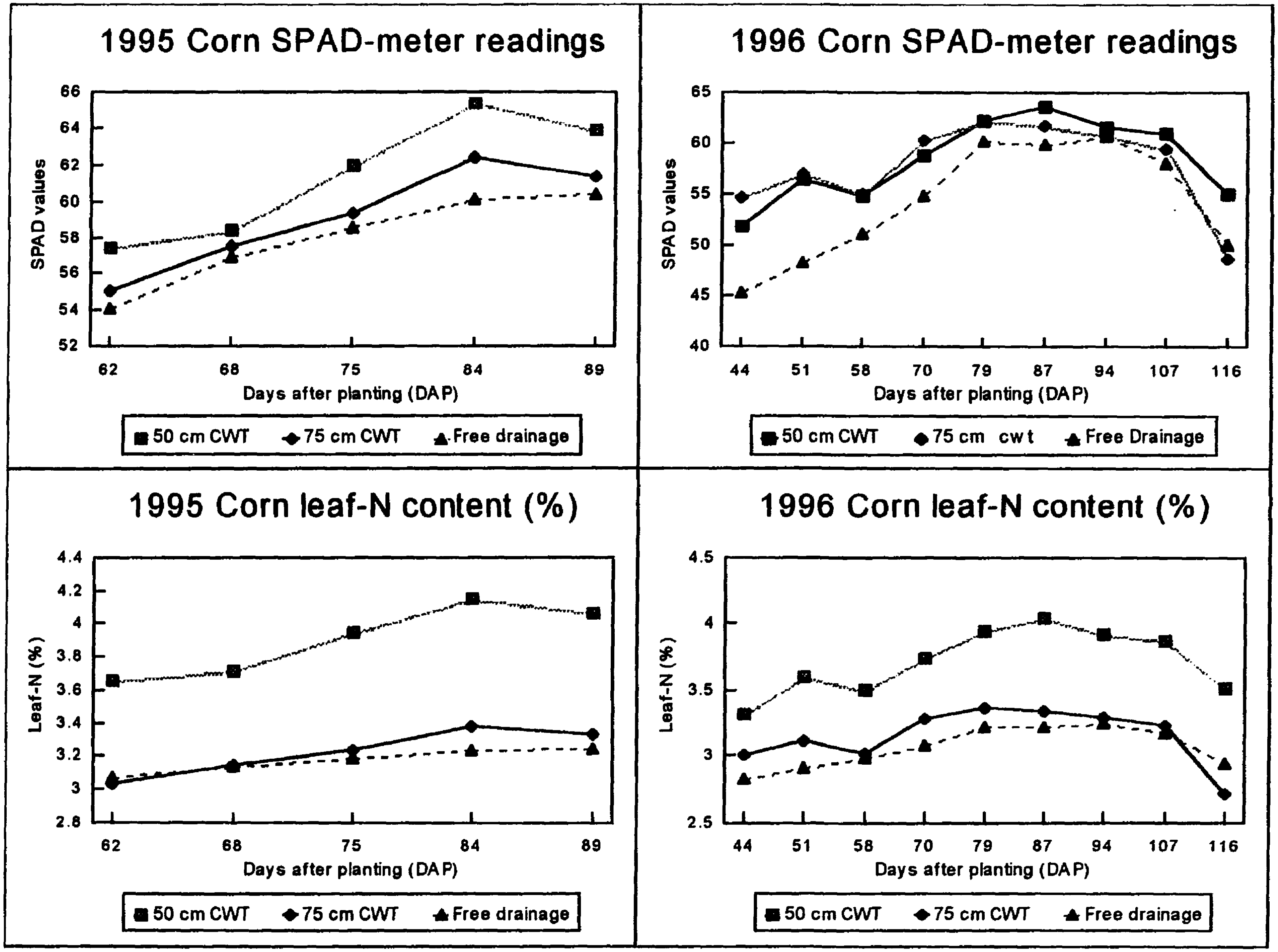


Figure 4.17 1995 and 1996 N-uptake of corn.

When compared with the results from the leaf sample digestions, the SPAD readings showed a positive correlation with leaf-N content. This linear relationship was used to convert SPAD readings to leaf-N levels. Leaf-N contents in all treatments for 1995 and 1996 are shown in Figure 4.17. The downward trends after 84 days after planting (DAP) (August 3, 1995) and 87 DAP (August 22, 1996) were due to N-translocation to the grains and plant senescence. Overall, the leaf-N content of the CWT corn plants were higher than in the FD plants throughout the growing season. The probability levels of the differences among treatments are shown below in Table 4.12.

Table 4.12 Probability levels for corn leaf-N comparisons in 1995 and 1996.

	50 cm CWT vs. 75 cm CWT	75 cm CWT vs. FD	50 cm CWT vs. FD
1995	0.00017**	0.24465^{ns}	0.00004**
1996	0.00004**	0.16799^{ns}	2.8×10^{-6}**

*****significant at the 0.05 probability level, and ^{ns} is not significant.***

There were no significant differences in corn leaf-N between the 75 cm CWT and Fd in both years. However, 50 cm CWT vs. 75 cm CWT and 50 cm CWT vs. FD showed very significant differences for both years. It can be concluded that the higher water tables increased corn N-uptake.

4.6.2 Soybean N-uptake

The SPAD-meter was unable to detect any significant differences in leaf-chlorophyll levels among the different water table treatments for both years. The chlorophyll levels for soybean in 1995 and 1996 are plotted in Figure 4.19. The statistical differences among treatments are shown in Table 4.13.

Table 4.13 Probability levels for soybean SPAD value comparisons in 1995 and 1996.

	50 cm CWT vs. 75 cm CWT	75 cm CWT vs. FD	50 cm CWT vs. FD
1995	0.46364^{ns}	0.16798^{ns}	0.19534^{ns}
1996	0.44414^{ns}	0.44184^{ns}	0.49673^{ns}

^{ns} *means the comparison is not significant at the 95% confidence level.*

When the SPAD-meter readings were converted to leaf-N, however, significant differences were observed. Soybean leaf-N contents for all treatments in 1995 and 1996 are shown in Figure 4.19. The probability levels for the differences in soybean leaf-N levels among the treatments are shown in Table 4.14.

Table 4.14 Probability levels for soybean leaf-N comparisons in 1995 and 1996.

	50 cm CWT vs. 75 cm CWT	75 cm CWT vs. FD	50 cm CWT vs. FD
1995	0.06610*	0.00017**	3.3×10^{-7} **
1996	0.27504^{ns}	0.01149*	1.0×10^{-8}**

**significant at the $0.05 \le P \le 0.10$ level,* ***significant at the 0.05 probability level, and* ^{ns} *is not significant.*

Overall, although the differences in chlorophyll levels among the treatments were statistically inconclusive, the leaf-N contents of the CWT plants were statistically significantly higher than in the FD plants for both years. Therefore, it appears that the higher water tables increased plant N-uptake.

4.7 Corn harvest parameters

4.7.1 Yield

Overall, the best harvest results were found on the CWT plots. The harvest results (mean per treatment) and the treatment comparisons are shown in Table 4.15. The highest corn yields were found in the CWT plots for both years. In 1995, the yield differences between the 50 and 75 cm CWT plots, and between the 75 cm CWT and FD plots were not significant. However, the difference between the 50 cm CWT and FD plots was significant ($P=0.03768$). Therefore, the 50 cm CWT treatment plots yielded 13.8% (+1.72 t/ha) more corn than the FD plots.

In 1996, there were no significant differences among all the treatments at the 0.05 probability level. However, the difference in yield between 75 cm CWT (highest yielding plots) and FD (lowest yielding plots) was nearly significant since $P=0.05215$ ($0.05 \leq P \leq 0.10$). Regardless, the highest yields were again found in the CWT plots. Compared to FD, the 50 and 75 cm CWT plots gave 6.6% (+0.45 t/ha) and 6.9% (+0.47) higher yields, respectively. Because of the weather, 1996 did not show as dramatic an increase in yield with WTM as in 1995 (Figure 4.18). The wet summer of 1996 probably reduced the beneficial effects of subirrigation since all the plots received adequate rainfall to meet crop needs. The late planting date and lower CHU in 1996 also reduced yields as compared to 1995.

4.7.2 Grain size

The 100-kernel weights were taken to see if WTM had an effect on grain size. Assuming that all grains had uniform density, a higher 100-kernel weight means bigger grains.

In 1995, the 50 and 75 cm CWT plots produced the largest grain sizes (Table 4.15).

In 1995, the 50 and 75 cm CWT plots produced the largest grain sizes (Table 4.15). Compared to FD, 50 and 75 cm CWT produced grains that were larger by 14.0% and 3.1%, respectively. Although the size difference between 75 cm CWT and FD was not significant, the differences between 50 and 75 cm CWT plots, and between 50 cm CWT and FD were signigicant and highly significant, respectively.

In 1996, the CWT plots again produced the largest grains (Table 4.15). Grain size was significantly different between 75 cm CWT and FD, marginally significant between 50 and 75 cm CWT and nonsignificant between 50 cm CWT and FD. The 50 and 75 cm CWT plots produced kernels which were 4.1% and 10.1% larger, respectively, as compared to FD. Again, due to a wet year, grain sizes in 1996 were smaller than in 1995. The increases in grain size were proportional to the increases in total grain yield for both years.

4.7.3 Harvest Index

Harvest index (HI) is the ratio of above-ground plant biomass to total grain produced by the plant. It indicates how the plant allocates its resources (i.e. more leaf and stem production vs. grain production). The CWT plants had higher HI compared to FD which indicated that the CWT plants produced more biomass than FD plants for both years (Table 4.15). All the differences in HI comparisons between treatments were not significant in both years. However, it might be speculated that since the 50 cm CWT vs. FD comparison in 1995 was nearly significant, this could perhaps be an additional factor affecting the significant increased yield in 1995 from the 50 cm CWT plot. The fact that the 50 cm CWT plants produced more biomass could indicate that more biomass would have provided more N to be used for grain production and this could explain the bigger grains and yield increases.

From the SPAD-readings and corn harvest parameters, it can be concluded that WTM can enhance corn performance. Higher water and N availability are the two most likely benefits of WTM to which the improved corn performance can be attributed. In the literature, SPAD values have been positively correlated with yield increases (Dwyer et al., 1994). Other researchers have also found similar increases in corn yields as a result of WTM practices (Kalita and Kanwar, 1993; Kaluli and Madramootoo, 1995).

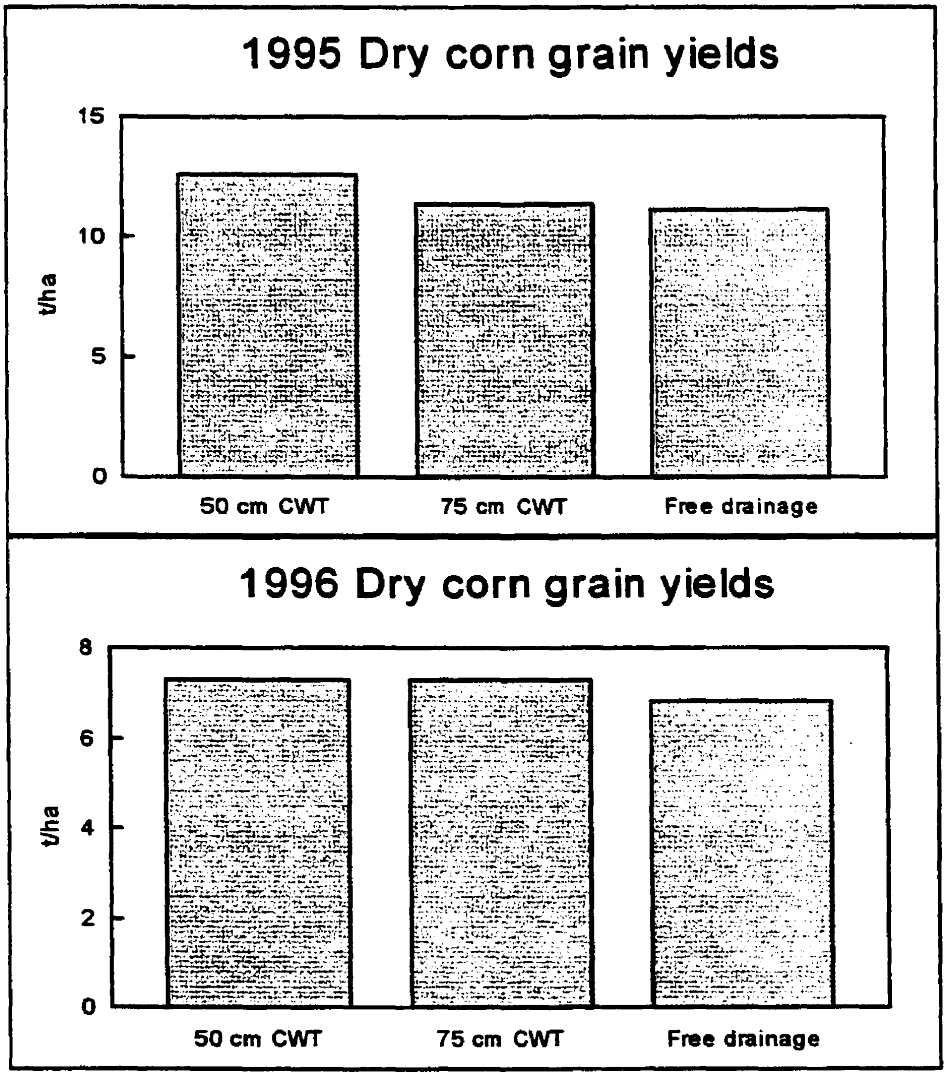


Figure 4.18 Corn harvest yields for 1995 and 1996.

Table 4.15 1995 and 1996 Results of corn harvest parameters and associated t-test probabilities.

1995	Corn harvest results			Student's *t*-test probability levels (P)		
	50 cm CWT	75 cm CWT	Free drainage	50 vs. 75	75 vs. FD	50 vs. FD
Yield (t/ha)	12.61	11.39	11.08	0.15729^{ns}	0.33342^{ns}	0.03768**
100-kernel wt.(g)	29.82	26.97	26.15	0.00724**	0.22003^{ns}	0.00014**
Harvest Index	1.82	1.80	1.71	0.80406^{ns}	0.12091^{ns}	0.08897*
1996	50 cm CWT	75 cm CWT	Free drainage	50 vs. 75	75 vs. FD	50 vs FD
Yield (t/ha)	7.29	7.31	6.84	0.47967^{ns}	0.05215*	0.12845^{ns}
100-kernel wt.(g)	25.73	27.22	24.72	0.09716*	0.00517**	0.12453^{ns}
Harvest Index	1.79	1.79	1.78	0.92903^{ns}	0.93158^{ns}	0.84715^{ns}

Table 4.16 1995 and 1996 Results of soybean harvest parameters and associated t-test probabilities.

1995	Soybean harvest results			Student's *t*-test probability levels (P)		
	50 cm CWT	75 cm CWT	Free drainage	50 vs. 75	75 vs. FD	50 vs. FD
Yield (t/ha)	3.44	3.58	3.17	0.26599^{ns}	0.01869**	0.07079*
100-seed wt.(g)	19.02	19.49	18.04	0.36773^{ns}	0.15114^{ns}	0.22203^{ns}
# of pods/plant	23.89	26.30	24.84	0.19392^{ns}	0.52333^{ns}	0.68994^{ns}
1996	50 cm CWT	75 cm CWT	Free drainage	50 vs. 75	75 vs. FD	50 vs. FD
Yield (t/ha)	3.24	3.12	2.36	0.29789^{ns}	0.00115**	0.00043**
100-seed wt.(g)	20.72	21.48	19.77	0.09569*	0.00135**	0.04319**
# of pods/plant	18.46	25.46	13.94	0.10556^{ns}	0.00065**	0.00531**

* *means the comparison is significant at the 90% confidence level, ** is significant at the 95% level, while* ns *is non-significant.*

4.8 Soybean harvest parameters

4.8.1 Yield

The highest grain yields were found in the CWT plots for both years. The harvest results and the treatment comparisons are shown in Table 4.16. In 1995, although the grain yields in the CWT treatments were not significantly different, the comparison in yields between 75 cm CWT vs. FD and 50 cm CWT vs. FD were significantly different at the 95% and 90% confidence levels, respectively. The 50 cm CWT and 75 cm CWT plots had 8.5% (+0.27 t/ha) and 12.9% (+0.41 t/ha) higher yields than FD, respectively (Figure 4.20).

In 1996, the yields in both CWT's were not significantly different. However, the yields in both the 75 cm CWT vs. FD and 50 cm CWT vs. FD comparisons were significantly higher than FD at the 95% confidence level. Compared to FD, the 50 cm CWT and 75 cm CWT plots gave 37.3% (+0.88 t/ha) and 32.2% (+0.76 t/ha) higher yields, respectively. The yield increases in 1996 were higher than those of 1995 in spite of the wet year. The beneficial effect of subirrigation in June and August probably boosted the yields in 1996 (Figure 4.19).

4.8.2 Seed size

The 100-seed weights were taken to see if WTM had an effect on grain size. Assuming that all grains had uniform mass and density, a higher 100-seed weight means bigger grains. In 1995, the 50 cm CWT and 75 cm CWT plots produced the largest grain sizes (Table 4.16). Compared to FD, the 50 cm CWT and 75 cm CWT produced grains that were larger by 5.4% and 8.0%, respectively. These differences were not significant, however.

In 1996, the CWT plots again produced the largest grains (Table 4.16). Grain size differences were significant for all comparisons. The 50 cm CWT and 75 cm CWT plots produced soybean seeds that were 4.8% and 8.6% larger than FD seeds, respectively.

4.8.3 Number of pods per plant

In 1995 the plants which produced the most pods per plant were found in the 75 cm CWT plots, followed by those in the FD and 50 cm CWT plots (Table 4.16). However, the differences in the number of pods per plant were not significant. In 1996, both CWT plots produced the most pods per plant. Although the difference in number of pods among the CWT plots was not significant, both CWTs produced significantly more pods per plant than FD at the 95% confidence level. The 50 cm CWT and 75 cm CWT treatment plots produced 32% and 82% more pods per plant, respectively, than FD in 1996. Combined, the CWT plots produced 57% more pods per plant than FD, which was reflected in the 35% increase in 1996 grain yields.

Therefore, from the SPAD-readings and soybean harvest parameters, it can be concluded that WTM enhanced soybean performance. The increased yields were evident in the size of the grains and number of pods per plant, which resulted in increased yield per hectare. The higher water and N availability provided by WTM are the two most likely benefits of WTM to which the improved soybean performance can be attributed. In the literature, similar yield increases were found with soybeans under WTM (Madramootoo and Papodoupoulos, 1991; Evans et al., 1991; Cooper et al., 1992; Madramootoo et al., 1995a).

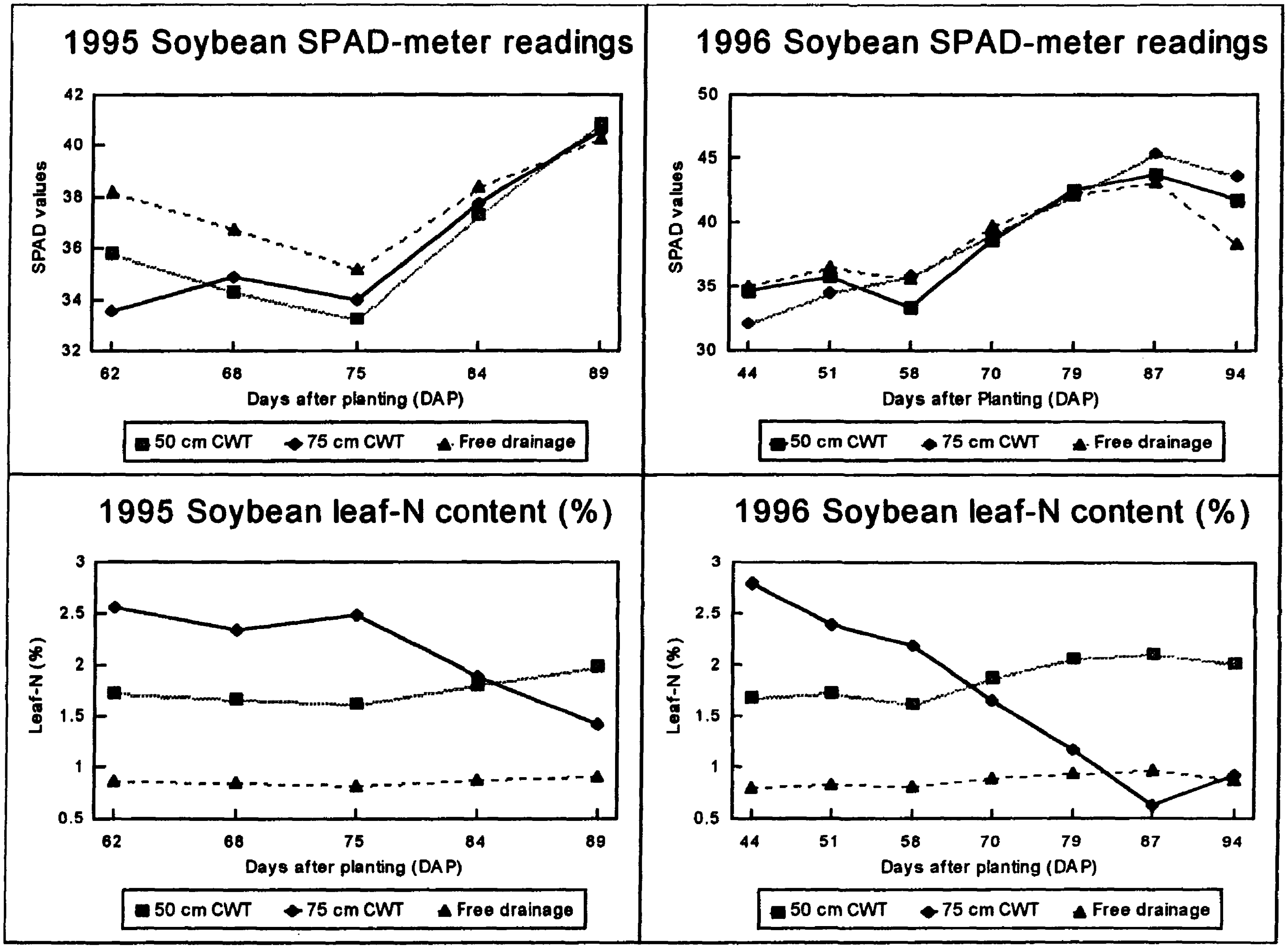


Figure 4.19 1995 and 1996 N-uptake of soybean.

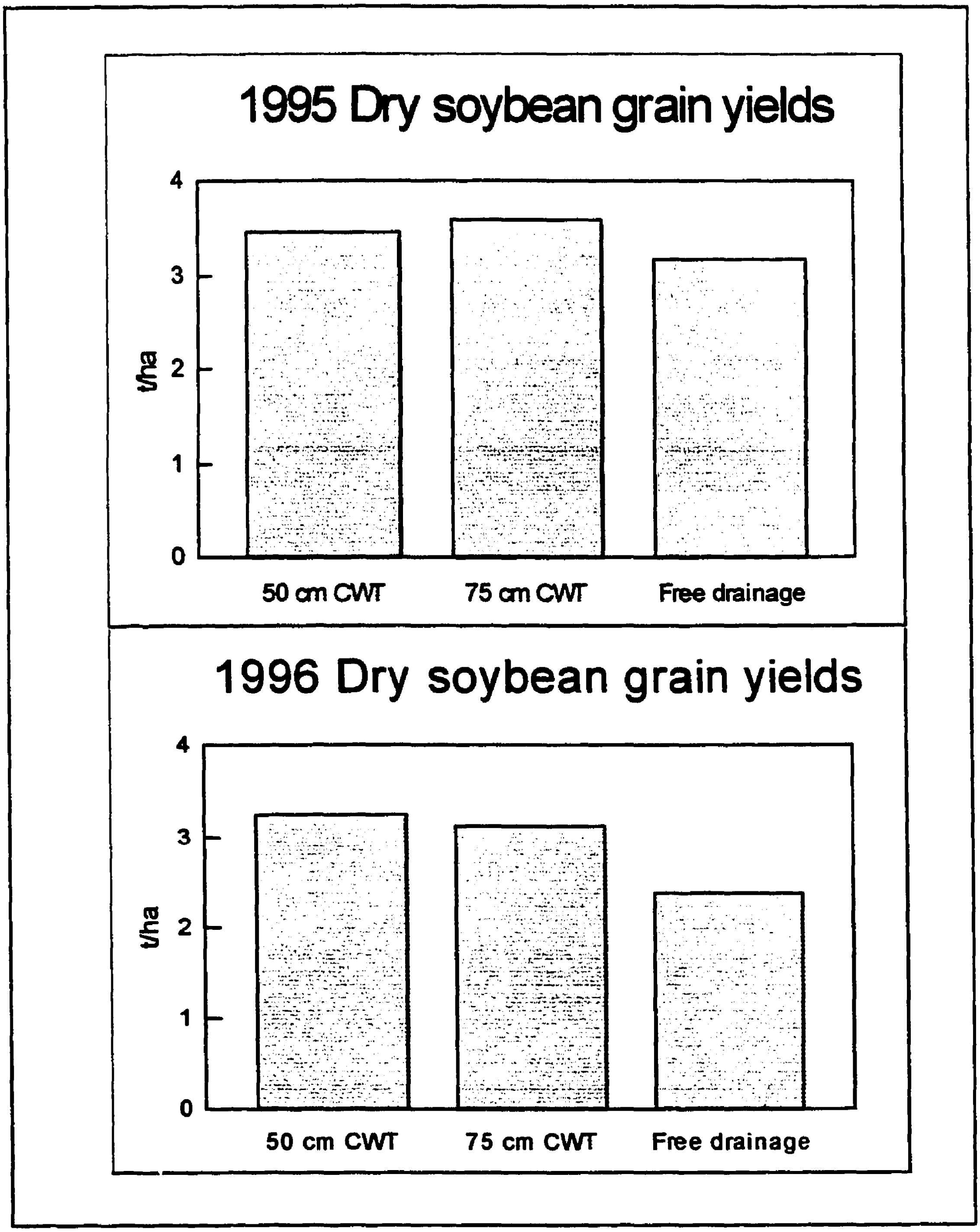


Figure 4.20 Soybean harvest yields for 1995 and 1996.

4.9 Overall results

In 1995, the average water table levels at the 50 cm CWT, 75 cm CWT and FD plots were 91 cm, 103 cm and 130 cm, respectively. In 1996, the average water table levels for the 50 cm CWT, 75 cm CWT and FD plots were 75 cm, 85 cm and 121 cm, respectively. They were significantly different from each other throughout the growing season.

In 1996, overall drainflow and nitrate concentrations were significantly reduced. Nitrate concentrations were reduced by 61% and 52% by the 50cm CWT and 75 cm CWT, respectively, as compared to FD. Thus, the 50cm CWT and 75 cm CWT reduced nitrate loading by 94% and 30%, respectively, as compared to FD. Rainfall distribution affected the amount of nitrate leached in both years. Dramatic improvements in water quality were attributed to both reduced drainage outflow and enhanced denitrification in the CWT plots.

Yields for both corn and soybean were higher with WTM than with FD for both years. In 1995, corn yield was increased by 13.8% and 2.8% by 50 cm CWT and 75 cm CWT, respectively, while soybean yield was increased by 8.5% and 12.9% by 50 cm CWT and 75 cm CWT, respectively. Similarly, corn yields in 1996 were higher in the 50 cm CWT and 75 cm CWT plots than in FD by 6.6% and 6.9%, respectively. 1996 soybean yield was increased by 37.3% in the 50 cm CWT and by 32.2% in the 75 cm CWT. It is believed that yield increases, which were evident in bigger grains and kernels, were most likely due to higher crop water and N-uptake as a result of the higher water tables. Overall, WTM proved to be a highly effective method for minimizing agricultural pollution, and improving crop yield.

5.0 SUMMARY AND CONCLUSION

5.1 Summary

Large areas of drained land in Quebec and Ontario are given to corn monoculture which uses large amounts of inorganic fertilizers. Nitrate leaching conducted through subsurface drains end up deteriorating lakes and rivers. Alternative methods of corn production which do not degrade water resources are needed.

A field study was conducted in Bainsville, Ontario during 1995 and 1996 to evaluate the effects of WTM and corn-soybean strip cropping on water quality and crop yields. There were 15 subsurface lateral drains, 9 of which were monitored for drainflow volumes and NO_3^--N concentrations, while 6 served as buffer drains to separate flows between treatments. There were three laterals per treatment and each drained an area of 1/5 ha. Soil samples were taken for nutrient and moisture level determination. Soil nitrate levels were measured at different depths to examine NO_3^--N movement in the soil profile. Leaf-N levels and grain yields were also measured. Results from the water table treatments of 50 cm CWT and 75 cm CWT were compared with those from conventional FD.

The water table levels were maintained above the drain depth. In 1995, the average water table levels at the 50 cm CWT, 75 cm CWT and FD plots were 91 cm, 103 cm and 130 cm, respectively. In 1996, the average water table levels for the 50 cm CWT, 75 cm CWT and FD plots were 75 cm, 85 cm and 121 cm, respectively. They were significantly different from each other throughout the growing season. As a result, the soil moisture levels in the CWT plots were significantly higher than in FD. Drainflow rates varied, depending on rainfall amounts, while nitrate concentration in drain effluent and total nitrate loadings were reduced. In addition, crop water uptake, N-uptake and crop yields were also increased.

5.2 Conclusions

1. Water table management significantly raised the water table levels, thereby increasing soil moisture levels throughout the growing season. This was achieved despite the difficulties involved in maintaining a constant water table level at the target levels due to highly variable rainfall distribution and high seepage losses.

2. Drainage outflow response to WTM was variable. In general, WTM reduced drain discharge. However, when the water table levels were close to the target levels and large summer storms (>40 mm rain) followed, drain discharge was higher in the CWT plots.

3. Nitrate concentrations in drainage effluent were greatly reduced by WTM. In 1995, nitrate concentrations from the 50 cm CWT and 75 cm CWT effluent were reduced by 84% and 77%, respectively, compared to FD. Likewise, in 1996, nitrate concentrations were reduced in the 50 cm CWT plots' effluent by 61% and in the 75cm CWT plots' effluent by 52%, due to the high water table levels.

4. The water table treatments enhanced denitrification for an adequate period of time to enhance overall denitrification.

5. The amount of nitrate leached was a function of drainflow volume and effluent nitrate concentration, which are dependent on climatic and management practices. Since 1995 was a dry year, WTM had no significant effect on nitrate loadings. In 1996, as

a result of the reductions in both drainflow and nitrate concentrations in drain effluent, WTM greatly reduced nitrate loadings to the surrounding aquatic environment. Nitrate pollution from the 50 cm CWT and 75 cm CWT plots was reduced by 94% and 30%, respectively.

6. The net environmental benefit of WTM with regard to nitrate leaching is due to a combination of decreased drainflow and increased denitrification.

7. Corn N-uptake was significantly increased by WTM as shown by the SPAD-meter results. Crops grown under WTM produced significantly bigger grains for corn and soybean, as well as more pods per plant for soybean. Consequently, corn and soybean yield increases were observed with WTM. In 1995, yield was increased by both CWT treatments by an average of 8.3% for corn and 10.7% for soybean, compared to FD. In 1996, the CWT plots produced 6.7% more corn and 34.7% more soybean, compared to FD.

Results from this study show that WTM is a highly effective method of minimizing nitrate pollution and increasing crop yield. In order to strike a balance between maximum yield and pollution reduction, a water table depth of between 0.5 m and 0.75 m below the surface is recommended for soybean and corn production on fine sandy loam soils in the region. In conclusion, WTM is a profitable practice which minimizes environmental damage.

6.0 RECOMMENDATIONS FOR FUTURE RESEARCH

A problem encountered during this study was that WTM increased drainflow after large summer storms. Past experience at this experimental site has shown that although CD reduces drainflow, it does not, by itself, provide a high enough water table for a long enough period to enhance denitrification since seepage and ET losses lower the water table over time. Furthermore, CD may not always provide enough water for crop use, especially if June, July and August are extremely dry. The use of SI, on the other hand, helped to raise the water table thereby enhancing denitrification and crop water uptake. However, since SI partly filled up the soil profile with water, it increased drainflow after heavy summer storms. This tradeoff was unavoidable given the unpredictabe nature of weather. However, this drainflow can be reduced if SI is more tightly controlled. The following recommendations suggest areas for further improvement:

1. Since SI does not need to be constantly on, its scheduling could be based on water requirements (i.e. when soil moisture drops below maximum allowable depletion or even 50% of field capacity), rather than a pre-set water table level. This can perhaps be achieved by coupling tensiometers with an automated SI system.
2. In practice, one water table level of 60 cm might be more beneficial and practical.
3. Investigate the fate of soil nitrate during these drying and wetting cycles and also during the non-growing period.
4. Study the N carryover effects of corn-soybean strip cropping in greater detail.
5. Validate existing computer simulation models with the accumulated field data to predict long-term benefits of WTM.

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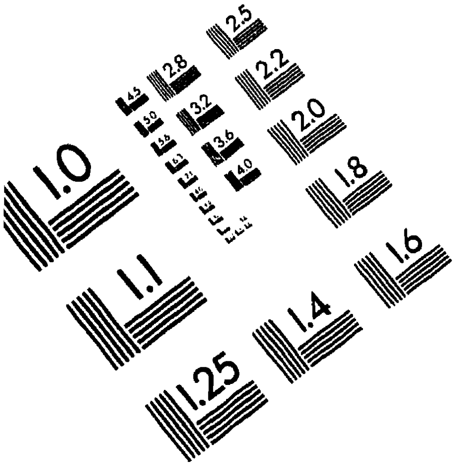

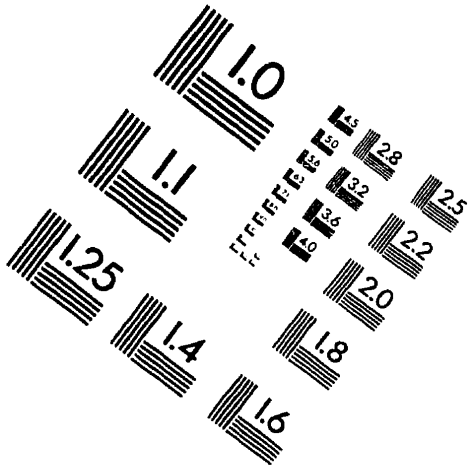

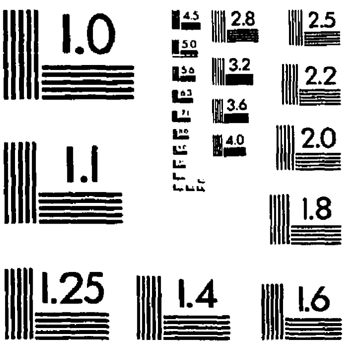

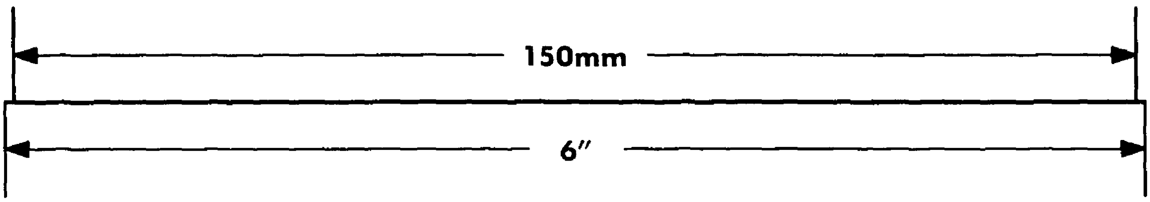

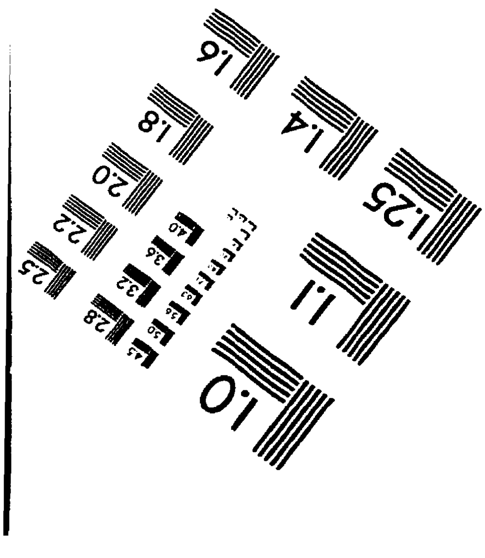

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