University of Alberta

# PULP MILL EFFLUENT IRRIGATION FOR FORAGE PRODUCTION

by

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## Dedication

To my one and only,
family and friends
for their undying love,
exceptional encouragement,
persistent patience, and
unlimited understanding.

ABSTRACT

Effluent irrigation can potentially provide an alternative to effluent discharge and employ the soil/plant system in utilizing effluent water and nutrients without degrading soil and water quality. This study was conducted on an Eluviated Dystric Brunisol in northern Alberta for which there is little information on irrigation potential, wastewater use and forage species adaptation. Research objectives were to quantify effects of pulp mill effluent irrigation rates, forages and nitrogen fertilization rates on soil moisture, soil properties and forage properties.

Three forage species were established at a field site near the Alberta-Pacific pulp mill. Treatments did not affect soil physical properties. Irrigation and fertilizer rates influenced soil chemical properties and forage quality and composition. Differences between effluent rates were not determined, but irrigation increased soil moisture under limiting moisture conditions. Reed canary grass was the highest producer, while alfalfa had the best forage quality. Fertilization improved grass biomass and quality under irrigation.

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# 1 AN INTRODUCTION TO BLEACHED KRAFT PULP MILL EFFLUENT IRRIGATION FOR FORAGE PRODUCTION

## 1.1 BACKGROUND

In the early 1980s, the Alberta Government enhanced the forest industry by accepting proposals for pulp mill construction (Lindsay and Smith 1995). Existing pulp mills were upgraded and expanded and new pulp and paper mills were constructed in the province. An agreement between Alberta and federal environment ministers demanded an environmental impact assessment to address public environmental concerns with the development of one pulp mill in particular; the Alberta-Pacific Forest Industries Inc. (Alberta-Pacific) bleached kraft pulp mill (Alberta-Pacific Scientific Review Panel 1990).

Throughout the process, Alberta-Pacific developed new technologies to reduce chlorinated organic compounds in wastewater (or effluent) and minimize the volume discharged into the Athabasca River. Currently the river receives approximately 70,000 $m^3$ (70 million litres) of secondary treated pulp mill effluent daily (Patterson 2003), which must meet Alberta industrial wastewater limits and monitoring requirements (Alberta Environment 1999). Regardless of technology advancements to improve effluent quality, such treated effluents may still retain organic matter, suspended solids, nutrients and toxic elements that when discharged into water bodies can cause oxygen depletion, eutrophication, chemical toxicity and salinity (Cameron et al. 1997). Thus, increasing public concerns about cumulative adverse effects of effluent discharge on water quality and strict government regulations have encouraged the industry to find alternative disposal methods.

## 1.2 AN ALTERNATIVE DISPOSAL METHOD TO EFFLUENT DISCHARGE

Water reclamation and reuse practices have been sought globally to address water shortages, environmental concerns and stricter amendments to existing regulations (Hrudey 1981; Sakadevan et al. 2000). Land treatment systems have been discussed as economical, viable alternatives to effluent discharge systems, reducing effluent discharge volumes and thus protecting watercourses from undesirable environmental effects (Cameron et al. 1997). Since effluents contain essential plant nutrients and large amounts of water, they have the potential to provide quality water for cropland irrigation (Sakadevan et al. 2000). The objective of any land application system is to use biological, chemical and physical properties of the soil/plant system to utilize waste components without potentially contaminating air, soil and water quality (Hawke and Summers 2003). However, land applications of effluent could have adverse effects on the receiving environment depending on the physical, chemical and biological characteristics of the wastewater (Cameron et al. 1997).

According to agricultural water use guidelines, effluent must be comprehensively characterized and monitored regularly because of large variations of quality over time (Alberta Environment 2000). Key biological and chemical parameters include pH, electrical conductivity (EC), sodium adsorption ratio (SAR), macro and micro nutrients and trace elements. Prior to wastewater irrigation, irrigation water quality guidelines must be met; although no guidelines for pulp mill wastewater irrigation exist, current guidelines for municipal wastewater irrigation are utilized (Alberta Environment 2000). If the treated effluent quality standards for wastewater irrigation are met, then irrigation of authorized crops can proceed, provided the land meets irrigable requirements.

The effluent from the Alberta-Pacific pulp mill secondary treatment system has significant calcium (Ca), magnesium (Mg), chloride (Cl), potassium (P), sodium (Na) and sulfate ($SO_4$) concentrations, which are used in the bleached kraft pulping process (Patterson et al. 2002). While these elements are essential nutrients for plant growth, some could potentially degrade soil and water quality under poorly managed irrigation.

### 1.2.1 Potential Problems Created with Pulp Mill Effluent Irrigation

Environmental consequences in the long-term may transpire if wastewaters such as pulp mill effluents are applied to land without proper management and monitoring. Potential problems created with wastewater irrigation are related to its biological and chemical composition (Coppola et al. 2004). Elements common in pulp mill effluents can be associated with increases in soil salinity and soil structure deterioration, toxicities and nutrient imbalances in crops, and soil and water contamination, all of which can be associated with decreased long-term crop productivity (Howe and Wagner 1999). Bond (1998) stated that excessive nutrient leaching, groundwater impacts, and effects of salinity and sodicity on current and future land uses are key limitations to sustainable land application of most effluents.

Since pulp mill effluents contain high Na, sodic conditions may occur, reducing soil aggregate stability, decreasing infiltration rates and increasing surface runoff potential (Cameron et al. 1997). Sodium in irrigation water can replace Ca and Mg ions by mass action, leading to greater clay swelling and dispersion, thereby reducing permeability and aeration, causing waterlogged conditions (Cromer et al. 1984; Bond 1998). The deterioration of soil physical properties, and eventually reduced plant productivity, may increase with increasing soil pH (Bond 1998), as high pH effluents applied beyond liming requirements may decrease organic matter decomposition and nutrient availability (Cameron et al. 1997). If effluent irrigation ceases, changed landuse may lead to structural deterioration (Bond 1998). Effluent irrigation has potential to induce long-term sustainability problems with salinity, also associated with decreased soil permeability (Balks et al. 1998). Most salts in wastewater added during industrial processes are only minimally removed during treatment (Tarchitzky et al. 1999).

High salt concentrations in effluents may create saline soil conditions, which reduce soil osmotic potential and decrease plant available water, thus reducing plant productivity (Cameron et al. 1997). Accumulation of salts and other elements in the soil increase surface runoff potential of these contaminants into nearby water bodies (Bond 1998). Thus, salts accumulating in the soil must be leached out beneath the root zone (Bond 1998; Mohammad and Mazahreh 2003). This may cause waterlogging and/or increase groundwater recharge, accompanied by salts and other elements, causing salinization of well waters or a progressive rise of the water table, which may re-infuse the soil with salts between irrigations (Bond 1998; Hillel 1998). Depending on the effluent source, other contaminants including nutrients, heavy metals and toxic organic chemicals may accumulate in the soil or be leached to groundwater (Bond 1998).

The fate of inorganic and organic compounds is controlled by volatilization, degradation, sorption, leaching and bioaccumulation, which are affected by properties of the compound itself, wastewater and receiving soil, as well as environmental conditions at the time (Cameron et al. 1997). There may be an excessive loss of nutrients or other effluent constituents into surface and ground waters induced by large increases in water and nutrient/organic carbon from effluent irrigation (Speir 2002).

Effluents contain a finite ratio of nutrients that may not satisfy all crop requirements; therefore additional nutrients may be needed (Tillman and Surapaneni 2002). Secondary treated pulp mill effluents often contain much less N than required by plants, thus requiring costly fertilization. In coarse textured soils, such as required for irrigation, the mineralization of soil organic matter in response to irrigation, may release nitrate into the soil solution (Bond 1998). Any excess nitrates may leach beyond the root zone, potentially contaminating ground waters. If effluents are applied to meet minimum plant requirements, some nutrients may be added in excess.

Continuous applications of wastewater may lead to soil accumulations of plant nutrients and heavy metals beyond crop removal causing nutrient imbalances in the soil (Mohammad and Mazahreh 2003). If accumulations occur from effluent irrigation, plant uptake may potentially increase concentrations beyond plant requirements, creating problems, such as nutrient toxicities, thereby reducing plant growth (Cameron et al. 1997; Howe and Wagner 1999). Nutrient imbalances in plants may have adverse effects on grazing animals, resulting in nutrient related animal metabolic disorders such as grass tetany and milk fever (Cameron et al. 1997). Speir (2002) suggests gradual changes like leaching of nutrients, in addition to reduced hydraulic conductivity, structural integrity and plant productivity may occur and could give rise to a new soil with altered capacity for sustainable effluent irrigation.

### 1.2.2 Potential Benefits of Pulp Mill Effluent Irrigation

Wastewater use for irrigation usually offers environmental and socio-economic benefits, mainly due to reduction in effluent disposal in receiving water bodies (Coppola et al. 2004). This alternative disposal method avoids eutrophication, biological and chemical toxicities and salinization of waterways, thereby protecting water quality (Cameron et al. 1997). High quality waters can be preserved for potable uses, while lower quality water such as effluents or wastewaters can be used for irrigation, particularly when the demand for water is great (Mohammad and Mazahreh 2003).

A key component to wastewater irrigation is plant use of effluent components and protection of soil quality (Cameron et al. 1997). Selection of suitable species with potential to maximize water and nutrient use will minimize adverse environmental effects from wastewater irrigation (Edraki et al. 2004). Perennial plants, such as forages, are candidates because of their potential for high biomass yield, use of the entire growing season, and tolerance to frequent harvests, thus maintaining active, season-long nutrient uptake (Bole and Bell 1978; Macoon et al. 2002). Their extensive deep root systems act as natural soil stabilizers and biofilters, optimizing nutrient and water uptake, and reducing nutrient and salt accumulations in the root zone. Forages like reed canary grass have been used as catch crops for nutrients in land treatment of wastewaters (Geber 2002). Dewatering characteristics of alfalfa and other perennial grasses have successfully controlled soil salinization, enabling long-term sustainability of crop production systems (Entz et al. 2002). These species, which may be marketed locally as livestock feed or exported for special uses, can be another step in removing undesirable elements in effluents beyond industrial treatment processes, thereby protecting soil quality.

If wastewater irrigation is properly managed and monitored, soil quality can be enhanced through additions of plant nutrients and soil organic matter (Mohammad and Mazahreh 2003). Pulp and paper mill sludge applications have improved soil quality by increasing soil organic matter, water holding capacity, cation exchange capacity and soil pH (Cabral et al. 1998; Naidu et al. 2004). Studies using various wastewaters reported effluent applications increased soil carbon (C), microbial biomass and activity, soil enzyme activity, N mineralization, earthworm numbers and infiltration rates (Cameron et al. 1997; Sparling et al. 2001; Speir 2002). Perennial forages with deep root systems can contribute to soil C and N pools, resulting in long-term storage (Entz et al. 2002; Mapfumo et al. 2002). Enhanced perennial forage growth may potentially increase C sequestration and reduce net $CO_2$ emissions from agricultural systems (Mapfumo et al. 2002). Forages can improve soil fertility and physical conditions, reducing soil erosion potential (AAFRD 1981; Entz et al. 2002). The better growing conditions irrigation and wastewater characteristics provide may thus improve poor quality soils.

Effluents contain a significant amount of water and contain key nutrients, that otherwise would be added as fertilizers, to achieve satisfactory forage production (Bond 1998). Marten et al. (1980) claimed municipal wastewater applications increased crude protein levels, thereby improving forage quality. Nutrients such as sulphur (S), Ca and Mg, characteristic of pulp mill effluents, are important secondary nutrient sources for plant production (O'Connor et al. 2005). Effluent irrigation provides an alternative water source during prolonged and intermittent droughts and thus can reduce feed shortages. The forage produced under more favourable growing conditions can be redistributed to nearby regions that experience yield losses due to water deficits (Entz et al. 2002).

Potential forage species suited for effluent irrigation, like alfalfa and timothy, may provide additional income as local cash hay crops or be exported to world markets as they are recognized as palatable and nutritious feedstuffs (AAFRD 2001). Enhanced growth of specific forages provides opportunity for agricultural producers located near pulp mills to diversify their operations. If the forage produced is of low feed quality because of growing conditions or adverse effects due to wastewater irrigation, there is the potential for alternative uses. Recently, researchers have been studying effects of converting fiber components (cellulose and hemicellulose) of forages, particularly reed canary grass, to produce ethanol, otherwise known as biofuel, in place of petroleum fuel (Pahkala and Pihala 2000; Geber 2002). Non-woody plants such as reed canary grass have the capability to diversify pulp mill operations since they are potential fibre sources (Pahkala and Pihala 2000; Finell and Nilsson 2004).

## 1.3 SIGNIFICANCE OF RESEARCH

Over the past few decades, several studies throughout the world have determined beneficial and detrimental environmental effects of wastewater or effluent land applications. Most effluent irrigation studies used municipal sources such as sewage or water treatment plants, while some used other agricultural or industrial sources as mentioned by Hrudey (1981), and most recently by Cameron et al. (1997). Studies to determine effects of wastewater irrigation on biomass and quality of forages used various effluent sources. Agricultural effluents from dairy farms and rendering plants were used to irrigate reed canary grass, alfalfa, rye, bermudagrass, corn, sorghum, peanut and a legume-based pasture (Bole and Gould 1985; Macoon et al. 2002; Bolan et al. 2004). Numerous studies investigating land applications of municipal wastewaters did so using various forage species in different regions. Bole and Bell (1978), Marten et al. (1980), Linden et al. (1981), Campbell et al. (1983), Bole et al. (1981), Mohammad and Ayadi (2004) and Edraki et al. 2004 studied effects of municipal wastewater (usually treated sewage effluent) irrigation on the yield and composition of several forage species including alfalfa, reed canary grass, smooth bromegrass, wildrye, tall wheatgrass, wheat, Rhodes grass, maize and sweet corn.

Of the industrial sources, past crop irrigation studies conducted with pulp mill effluents are few and outdated (Narum and Moeller 1977; Hayman and Smith 1979; Juwarkar and Subrahmanyam 1987). Of these studies, the forages irrigated with pulp or paper mill effluent were alfalfa, barley, kenaf, sesbenia, oat, wheat and corn; as well as several types of grasses. Recent studies investigated effects of pulp and paper mill effluent irrigation on trees rather than forages (Howe and Wagner 1996; Howe and Wagner 1999). The most recent was a greenhouse study by Patterson et al. (2002), studying effects of pulp mill effluent compared to municipal effluent and pulp mill waste activated sludge on the growth and composition of hybrid poplar and reed canary grass.

Research has also been conducted on soil quality to determine effects of effluent irrigation on biological, chemical and physical properties (Hawke and Summers 2003). Some measured biogeochemical processes, while most investigated soil chemical (pH, cation exchange capacity, inorganic and organic nutrient concentrations) and physical properties (particle size distribution, porosity, bulk density and hydraulic conductivity). Few studies monitored readily and total available water (Sparling et al. 2001).

Wastewater irrigation has been suited for several crops under different climatic conditions (Mohammad and Ayadi 2004). Most effluent irrigation research occurred in warmer climates such as New Zealand and southern United States. Few studies have been conducted in cooler regions like Canada, let alone Alberta (Bole and Bell 1978; Bole and Gould 1985; Patterson et al. 2002). The majority of studies investigating impacts of effluents have not included plants representative of northern Canadian climates such as timothy (*Phleum pratense*), which is an integral part of Canada's rural economy. The soils in the Canadian Boreal forest have different properties than soils in warmer regions of the world. Thus effects of effluent irrigation on soil and water quality will likely be different (Hayes et al. 1990).

Research and monitoring programs are necessary to ensure waste application systems are sustainable and do not damage soil quality (Cameron et al. 1997). To develop a successful long-term sustainable effluent irrigation scheme the following is required.

- Provide good waste characterization as unique properties of each wastewater make it difficult to create common management strategies (Halliwell et al. 2001).
- Assess land to determine suitability for effluent irrigation and select the most suitable site by evaluating water and nutrient balances (Bond 1998).
- Quantify soil physical and chemical properties since regional rules restricting effluent application rates to avoid adverse effects don't take into account soil heterogeneity (Hawke and Summers 2003).
- Understand nutrient availability and mobility in effluent irrigated soils to develop guidelines for sustainable wastewater use to manage key nutrients based on specific crop requirements, plant production and quality and water quality (Howe and Wagner 1999; Sakadevan et al. 2000; Mohammad and Mazahreh 2003).
- Monitor long-term crop health, soil and water quality as gradual adverse changes may not be noticed until it is too late to rectify the problem without compromising sustainable land treatment (Speir 2002).
- Provide appropriate guidelines to minimize adverse effects and maximize benefits, optimal wastewater application rates, frequency and timing; as well as carefully monitor land application effects (Cameron et al. 1997).

Thus to determine if pulp mill effluent irrigation is sustainable for forage production in Alberta, a study was conducted to monitor changes in soil quality, soil water dynamics and forage productivity and quality. This study is unique in that it is conducted on soils and under a climate where there is little information about potential of irrigation, use of wastewater effluent and forage species adaptation. The research objectives were to quantify effects of pulp mill effluent irrigation rates, forage treatments and nitrogen fertilization rates on soil moisture regime, soil physical and chemical properties and forage biomass and composition.

### 1.4 References

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# 2 PHYSICAL AND CHEMICAL PROPERTIES OF AN ELUVIATED DYSTRIC BRUNISOLIC SOIL IRRIGATED WITH BLEACHED KRAFT PULP MILL EFFLUENT

## 2.1 INTRODUCTION

Land-based effluent applications provide an alternative to discharging wastes into water bodies by using soil/plant systems to filter highly saline/sodic, nutrient-rich effluents without adversely affecting water, air and soil quality (Bond 1998; Hawke and Summers 2003). Brady and Weil (1996) define soil quality as the capacity of a soil to function within natural or managed ecosystems, to sustain plant and animal productivity, and/or to maintain or enhance water and air quality. To maintain or enhance soil quality and ensure irrigation sustainability, site assessments must be done to determine irrigation suitability, water balance scenarios must be evaluated and plant/animal productivity and health must be monitored (Bond 1998; Sparling et al. 2001). Monitoring soil physical and chemical property changes is equally important because of the potential adverse environmental effects of effluent irrigation (Bond 1998). Thus several effluent irrigation studies have been undertaken to understand the soil parameter changes and to develop safe, successful and sustainable effluent irrigation management schemes (Howe and Wagner 1999).

Sparling et al. (2001) discussed studies showing positive soil changes due to meat works, slaughterhouse, dairy and secondary-treated sewage effluent applications, such as increased microbial biomass and activity, earthworm activity, nitrogen availability and pH of forest soils. Few studies found adverse effects such as decreased permeability, drainage and infiltration, particularly with tertiary-treated sewage effluent. They compared two long-term and short-term dairy factory effluent irrigation schemes and found greater changes with greater loadings. Soils with longer applications had greater microbial biomass, nitrogen transformations and unsaturated hydraulic conductivity.

In a laboratory study, Tarchitzky et al. (1999) applied suspended organic matter in reclaimed sewage effluent (secondary treated activated sludge) to sandy soil from the coastal plain region of Israel. Soil hydraulic conductivity decreased from clay dispersion and plugging or size reduction of soil pores. Halliwell et al. (2001) reviewed effects of wastewater sodium (Na) on hydraulic conductivity and infiltration rates and concluded adverse effects of sodicity may be evident in some cases, but effects are mostly not developed or visible until effluent irrigation stops and land use changes. Thus under field conditions, it would be harder to predict soil reactions to effluent irrigation.

Balks et al. (1998) conducted a field study in New South Wales, Australia tree plantations and found increased Na from sewage effluent irrigation increased soil dispersion but not saturated hydraulic conductivity. They concluded increased sodicity would not affect continued land-based effluent application, unless land use changes with disturbance such as cultivation occurred. Sakadevan et al. (2000) conducted a field study in Sydney, Australia on a well drained, sandy soil pasture receiving alternate and continuous recycled water (secondary treated sewage effluent). They concluded N and P in recycled water could be used efficiently to increase production and greater nitrate leaching may occur with continuous application rather than intermittent with fresh water. Mohammad and Mazahreh (2003) near Ramtha, Jordan, studied field vetch and corn irrigated with secondary treated municipal wastewater. Wastewater significantly impacted soil chemistry and fertility. They concluded continuous applications may result in nutrient and heavy metal accumulations but properly managed irrigation and long-term monitoring can enhance soil fertility and productivity and sustain long-term irrigation.

Hawke and Summers (2003) thought rules to mitigate soil quality effects failed to take soil heterogeneity into account. They identified changes in silt loam under long-term pasture receiving farm dairy effluent irrigation. Despite the soil's low nutrient retention because of low clay and organic matter, small, significant increases in plant available nutrients occurred in the upper 10 cm. They concluded annual loading calculations are problematic because of effluent composition and irrigation spatial variability. Howe and Wagner (1999) conducted a nutrient accumulation study in Arizona on a fine, mesic Ustollic Haplargid soil irrigated with untreated effluent from a kraft pulping process for 15 years. Wastewater application effects on soil chemistry to 2.5 m were evident 15 years after treatment. Effluent irrigated soil had significantly higher N, P, Na, magnesium (Mg), electrical conductivity (EC) and pH; Na and pH decreased with depth.

Patterson et al. (2002) at Edmonton, Alberta studied effects of municipal effluent, pulp mill waste activated sludge and pulp mill secondary treated effluent on soil chemical and nutrient properties in the greenhouse. All macro nutrients and Na, chloride (Cl), manganese (Mn), boron (B) and zinc (Zn) were elevated in effluent treated soils. N and P were higher in the municipal effluent treatment; Na and sulphate ($SO_4$) were higher in pulp mill effluent treatments. They concluded salt loadings should be used to establish application rates for pulp mill effluents; nutrient loadings should be used for municipal effluents; and a site's leaching potential is required to maintain plant productivity and site sustainability.

In 1974, the Shasta pulp and paper mill in California flood irrigated wheat and oats fields with secondary treated effluent (Narum and Moeller 1977). After 13 months, soils showed slight deficiencies in calcium (Ca) and Mg from Na displacement from the effluent. This would be corrected by adding gypsum or dolomitic limestone. Hansen et al. (1980) conducted a paper mill secondary effluent flood irrigation study in Michigan with *Populus* and *Salix*. The receiving soil, predominantly sand, showed significant increases in Na, Cl and total Kjeldahl nitrogen (TKN), non-significant increases in pH, P, Ca, Mg and organic carbon (C) at the surface and no change in soil K or $SO_4$ despite concentrations in the effluent. They concluded that even with low concentrations of some nutrients in the effluent, large applications would provide suitable soil fertility levels, but pose potential groundwater contamination via salt leaching. Juwarker and Subrahnamyan (1987) investigated irrigation potential of pulp mill anaerobically treated wastewater diluted with river water on a loamy sand soil in India. Undiluted wastewater increased soil pH, organic matter, EC and exchangeable Na percentage (ESP). High ESP did not deleteriously affect infiltration rate because of the coarse soil. Since irrigation may cause sodicity problems, especially in heavy textured soils, they suggested diluting wastewater.

After a literature review discussing soil biochemical properties as early warning indicators of adverse effects of effluent irrigation on treatment sustainability and/or soil health, Speir (2002) concluded that in long-term, successful effluent irrigation schemes, soil biochemical properties reflect soil health, but these improvements occur slowly and require long-term monitoring. He stated adverse effects due to effluent irrigation are difficult to recognize and interpret because of methodological limitations and lack of understanding parameters that should be measured and their relevance to soil processes.

Most effluent irrigation studies have occurred in semi-arid or arid regions where recycled waters are used to meet increasing demands for water and/or to protect or enhance water quality. Few studies occur in the cooler and more humid Boreal Forest of Canada. Many studies used untreated or primary-treated effluents from municipal or domestic sources such as sewage treatment facilities. Others used agricultural and industrial wastewaters from dairy operations, meat processing facilities, piggeries, poultry farms and feedlots (Halliwell et al. 2001). These effluents vary in composition and from pulp mill effluents in general. Very few current effluent irrigation studies used secondary treated or final pulp mill effluents which have lower N and P than pulp mill effluents from the past because of new technologies. Industries have improved effluent quality and consistency of quality over time. Despite their efforts, composition variation still occurs and there is a need to understand and monitor long-term potential adverse and beneficial effects of pulp mill effluents on soil chemical and physical properties.

## 2.2 Research Objectives

The research objectives were to determine the effects of pulp mill effluent irrigation rates, N fertilization rates and forage treatments on soil physical and chemical properties. Specific objectives were to determine if soil physical properties, such as bulk density and penetration resistance, and soil chemical properties, including select total available macro and micro nutrients, pH, EC, soluble salts, sodium adsorption ratio (SAR), TKN and total C differed among irrigation, forage and fertilizer treatments.

## 2.3 Materials and Methods

### 2.3.1 Study Site

The study site is located in the Mid Boreal Mixedwood Ecoregion, approximately 200 km northwest of Edmonton, Alberta (Strong and Leggat 1992) and approximately 2 km south of the Alberta-Pacific Forest Industries Inc. bleached kraft pulp mill. The study area is 72 m x 43 m or 0.31 ha in size and is relatively uniform with 2 to 3% slopes, declining to the west or northwest. Specifically, the high effluent rate treatment and adjacent non-irrigated replicate was located upslope from the low effluent rate treatment and its adjacent non-irrigated replicate.

Soils are medium to coarse textured Luvisols and Eluviated Dystric Brunisols which are relatively low in pH, low in salt and well to rapidly draining (Proudfoot 2000). In low lying areas, gleying is evident with subsoil mottling indicative of imperfect drainage. Groundwater in monitoring wells in the northern and southern parts of the site was found between 216 and 278 cm (Proudfoot 2000). The site has been classified with good irrigation capability by sprinkler methods only.

Historical climate data from Canadian Climate Normals 1971 to 2000 (Environment Canada 2002) obtained from the Athabasca weather station about 72 km away, show average daily temperatures for the growing season (May to September) range from 10.6 °C in May, to a high of 16.2 °C in July, to a low of 9.8 °C in September. The Athabasca region averages 504 mm of precipitation annually, with 70% occurring during the growing season. The average number of growing degree days (degree days for a given day represent the number of Celsius degrees that the mean temperature is above 5 °C) from May to September is 1270 with the most (346) occurring in July.

Prior to this study, the field was summerfallowed for three years and before seedbed preparation in August 2002, glyphosate was applied for weed control. A fertilizer blend of 9-38-15 was broadcast at 323 kg $ha^{-1}$, supplying 30 kg $ha^{-1}$ of N, 123 kg $ha^{-1}$ of $P_2O_5$ and 50 kg $ha^{-1}$ of $K_2O$ to help with seed establishment.

### 2.3.2 Meteorological Measurements

A Campbell Scientific UT10 meteorological station was installed at the site in June 2002 to record daily minimum and maximum air temperatures and relative humidity (HMP45C gauge), saturated and non-saturated vapour pressures, net radiation (Kipp and Zonen net radiometer) and total precipitation (TE525 tipping bucket). To compare average precipitation and temperature trends at the study site to long-term normals, 2003 and 2004 climate data and 1971 to 2000 long-term normals were obtained from Environment Canada's climate database for the Athabasca weather station.

### 2.3.3 Experimental Design

A split-strip plot design was used to study irrigation, forage and fertilizer treatment effects (Figure 2.1). There were 36 (3 x 3 x 4) treatment combinations replicated twice for a total of 72 experimental units or plots (each 2 m x 8 m).

Irrigation treatments were nested within replicates and consisted of non-irrigated (NI-1x and NI-2x), low effluent rate (Eff-1x) and high effluent rate (Eff-2x) treatments. The irrigation system was installed in 2003 consisting of a solid set sprinkler system with 5 cm diameter laterals and 12 m spacings between sprinklers along each lateral, covering approximately a 10 m radius. Irrigation timing was determined from on-site soil moisture measurements and weather, with no irrigation occurring under windy or rainy conditions. During irrigation events, catch cans were placed strategically among the plots to evaluate irrigation variability.

Within each replicate, forage treatments were randomly seeded in rows or horizontal strips. The forage species were selected for their winter hardiness, successful establishment and tolerance to wet soil conditions. Alfalfa (*Medicago sativa* L. var. Algonquin), timothy (*Phleum pratense* L. var. Climax) and reed canary grass (*Phalaris arundinacea* L. var. Vantage) were seeded in early August 2002 at rates of 11, 11, and 10 kg/ha, respectively. For detailed forage species descriptions refer to the Appendix.

Fertilizer treatments, 0, 100, 200 and 400 kg N $ha^{-1}$ $yr^{-1}$ of ammonium nitrate (34-0-0-0), were randomly applied to the forage species in vertical strips (Figure 2.1). The fertilizer treatments were split into two applications and hand broadcast in spring and immediately after the first clipping. In 2003 the plots received applications of 0, 50, 100 and 200 kg N $ha^{-1}$ $yr^{-1}$ on June 4 and July 31. An error occurred during the July 31 application with all plots in the non-irrigated replicate adjacent the high effluent rate (NI-2x) receiving incorrect rates. Instead of 100 N receiving 50 kg N $ha^{-1}$ $yr^{-1}$, it got 100 kg N $ha^{-1}$ $yr^{-1}$; 200 N received 50 kg N $ha^{-1}$ $yr^{-1}$ instead of 100 kg N $ha^{-1}$ $yr^{-1}$; no fertilizer plots received 200 kg N $ha^{-1}$ $yr^{-1}$; 400 N received no fertilizer. The fertilizer application error was corrected in 2004 with 0, 50, 100 and 200 kg N $ha^{-1}$ $yr^{-1}$ applied to the original fertilizer treatments on June 2 and July 14. On June 2, an error occurred in Replicate 4 of the low effluent rate treatment with 0 N plots receiving 50 kg N $ha^{-1}$ $yr^{-1}$; 100 N received no fertilizer. This error was corrected during the July 14 fertilization. For total application rates applied per treatment by year, please refer to Table 2.1.

### 2.3.4 Effluent Characterization

The wastewater was a secondary treated effluent from a bleached kraft pulp mill. Laboratory analyses to characterize effluent salinity, nutrients (analyzed monthly) and trace elements (analyzed quarterly) provide the following medians. Monthly analyses (2002 to present) indicated a sodium adsorption ratio (SAR) of 10.7 and an adjusted SAR of 12.9, while daily analyses indicated electrical conductivity (EC) and pH were 2 dS $m^{-1}$ and 7.8, respectively. According to Alberta irrigation water quality standards, this effluent has pH values comparable to most natural surface waters and is considered fit for irrigation (Alberta Environment 2000). The same standards described the effluent as having hazardous SARs (>9) and possibly safe ECs (1.0 to 2.5 dS $m^{-1}$), making it available for restrictive irrigation purposes, and requiring a leaching fraction.

Ca (110 mg $L^{-1}$) and Mg (14 mg $L^{-1}$) occur in the effluent, but it is not a good source of N (0.10 mg $NO_3$-N $L^{-1}$ and 1.63 mg total Kjeldahl nitrogen (TKN) $L^{-1}$), P (0.67 mg dissolved P $L^{-1}$ and 1.03 mg total P $L^{-1}$) or potassium (K) (31 mg $L^{-1}$) as concentrations are low relative to plant requirements. Total organic carbon was 39.0 mg $L^{-1}$; no water use guidelines for irrigation purposes were found. Sulphate ($SO_4$) (532.5 mg $L^{-1}$), Na (312.5 mg $L^{-1}$) and chloride (Cl) (132.5 mg $L^{-1}$) occur in high concentrations and are of particular concern when considering effluent irrigation effects on plants and soil. All other micronutrients and trace metals were not detected or below 1 mg $L^{-1}$. Of those detected effluent contained aluminium (Al), iron (Fe) and manganese (Mn) at 0.40, 0.21 and 0.10 mg $L^{-1}$, respectively.

### 2.3.5 Soil Measurements and Sampling

Baseline soil samples prior to treatment application were collected in June 2002 with a hydraulic corer to 60 cm in 20 cm increments from all four corners of the site. In May 2003, surface bulk density was measured at random locations on the site at 0 to 10 and 10 to 20 cm depth intervals with a Uhland core sampler to obtain cores 9.5 cm in height and 7.5 cm in diameter (volume 419.70 $cm^3$) (Uhland 1949). Samples were weighed, oven dried at 95 °C for at least 72 hours and weighed to determine bulk density. In October 2003, bulk density with depth was determined with a Campbell Pacific Nuclear 501 depth moisture/density gauge using 16 second counts. Measurements were taken at 10 cm depth intervals in aluminium access tubes installed to a depth of 2 m in the middle of the alfalfa 0 and 400 N treatments. Tubes were placed in these treatments to capture soil moisture changes in extreme fertilizer rates with a high water using, deeply rooted species; measurement depths with tube length below ground and presence of water. Bulk densities with depth were determined by difference between wet bulk densities (from manufacturer's calibration equation) and volumetric moisture content (from locally derived calibration equation).

Ground surface penetration resistance was measured in October 2003 with a hand pushed, large cone penetrometer (21 mm diameter; 3.464 $cm^2$) in all treatments. Five random sample readings were recorded within each plot.

In late May 2004, soil samples were collected from non-irrigated treatments to determine effects of the July 2003 fertilizer misapplication on NI-2x or Replicate 1. Samples for chemical analyses were collected in early October 2004. For both sampling times, two subsamples were randomly taken at the west and east ends of each plot with a Dutch hand auger at two 20 cm depth intervals (0 to 20 and 20 to 40 cm). A composite sample of the subsamples was sent to EnviroTest Labs in Edmonton for analyses.

### 2.3.6 Laboratory Analyses

Samples from May were analyzed to determine available ammonium ($NH_4$-N), extracted with 2.0 M KCl, and available nitrate ($NO_3$-N), extracted with 0.001M $CaCl_2$. Soil fertility was assessed analyzing available nitrate ($NO_3$-N) and available sulphate ($SO_4$-S), extracted with 0.001M $CaCl_2$ (Maynard and Kalra 1993; Combs et al. 1998), available phosphate ($PO_4$-P) and available K, extracted with modified Kelowna extract (0.25N HOAc, 0.0115N $NH_4F$ and 0.025N $NH_4OAc$ at pH 4) (Qian et al. 1994). B was determined by hot water extraction (Keren 1996) and available micronutrients Fe, copper (Cu), Mn and Zn were extracted with 0.005m DTPA (Liang and Karamanos 1993).

Soil salinity was assessed by analyzing Cl, K, $SO_4$, Na, Ca and Mg in a saturated paste extract and calculating SAR (Janzen 1993). Soil pH and EC were determined in saturated paste (Hendershot et al. 1993; Janzen 1993). Total C was determined by combustion and thermal conductivity detection and inorganic C by acid digestion and $CO_2$ capture (Nelson and Sommers 1996). Total organic C was the difference between total and inorganic C. Total Kjeldahl N (TKN) was determined by digestion in $H_2SO_4$, with $K_2SO_4$ and $CuSO_4 \cdot 5H_2O$ as catalysts (McGill and Figueiredo 1993).

### 2.3.7 Statistical Analyses

Analyses of Variance were conducted using the SAS Proc Mixed procedure (Littel et al. 1996) based on a split-strip plot design (Figure 2.1) (Milliken and Johnson 1992). Replicates nested within irrigation treatments was considered random, while all other effects were fixed (Appendix). When the F-test indicated significant main and interaction effects ($P < 0.05$), least square means (LSMeans) were used to determine significant differences between treatment means via Tukey-Kramer (Littel et al. 1996).

Of the soil physical parameters, only average penetration resistance was analysed since measurements were taken from all treatment combinations with 10 sample locations each; whereas average bulk densities consisted of two measurements from alfalfa plots only. All chemical parameters were analysed by irrigation treatments with 24 sample locations each, by forage species with 24 and by fertilizer rates with 18.

## 2.4 RESULTS AND DISCUSSION

### 2.4.1 Meteorological Trends

Annual precipitation at Athabasca was 2.4% below and 13.5% above the long-term normal (LTN) in 2003 and 2004, respectively (Table 2.2). The corresponding growing season precipitation was 7.1% below and 10.8% above LTN, respectively. On-site annual total precipitation was 28.4% and 8.3% less, and growing season precipitation was 35.5% less and 2.9% more than at Athabasca for 2003 and 2004, respectively. On-site precipitation in 2003 was notably low in May and July to September and notably high in June. In 2004 precipitation was notably high in May and July to September and notably low in June. The total number of rainy days on-site during the growing season was 82 in 2004 and 41 in 2003.

The 2003 and 2004 growing seasons at Athabasca had 213 and 101 degree days fewer than the LTN, respectively (Table 2.3). On-site growing season data indicated 231 more and 109 fewer degree days than at Athabasca in 2003 and 2004, respectively. On-site, the 2003 growing season had 228 degree days more than 2004. Both data sets indicated July had the highest number of growing degree days.

Average daily temperatures for the growing seasons were similar between locations, while Athabasca annual temperatures were similar to LTN (Table 2.3). May and September 2004 had lower average temperatures than the same months in 2003 and the LTN, while June and July for both years had similar average temperatures on-site and at Athabasca. The greatest difference in average daily temperatures between years occurred in August when 2003 averages were 2 to 3 °C higher than 2004. August and September 2004 were notably wetter and cooler than in 2003.

In summary, 2003 was a drier year on-site with more growing degree days than 2004, which received almost twice the precipitation over the growing season. Thus the weather conditions may have influenced soil properties as total soil water and soil moisture content increased and decreased with precipitation events.

### 2.4.2 Effluent Irrigation Depths and Variability

In late summer 2003, low effluent rate treatments received an average of 30 mm of effluent, while high rate treatments received 60 mm, via two irrigation events on August 20 and September 5. Irrigation did not occur prior to August due to different maturation and harvest timing of the forages. In 2004, low and high rate treatments received 75 and 150 mm, respectively, over three irrigation events on June 24, June 26 and July 28. No further irrigation events occurred in 2004 due to wet soil moisture conditions from many precipitation events.

During irrigation events, measured depths of applied effluent indicated that not all plots received the same amount of effluent in a given irrigation event (data not shown). Plots on the outer edge of the treatment blocks received less than 50% of the amount received along the sprinkler laterals (Figure 2.1). Replicate blocks south of the laterals received slightly more effluent than blocks on the north side. Possible reasons for this include sprinkler rotation setup and wind direction at the time of irrigation.

### 2.4.3 Soil Physical Properties

Average soil texture was sandy loam for most depth intervals (Table 2.4). Cores from all corners of the site had similar texture with an increase in sand and a decrease in silt with depth. Interestingly, soil adjacent the high effluent rate treatment had the lowest silt and clay content beyond 40 cm resulting in loamy sand and sandy textures. Near surface bulk densities (0 to 20 cm) surrounding the study site in spring 2003 ranged from 1.33 to 1.70 and averaged 1.46 Mg $m^{-3}$ (Table 2.5). The 0 to 10 cm depth averaged 1.41 Mg $m^{-3}$; the 10 to 20 cm depth averaged 1.50 Mg $m^{-3}$. Fall 2003 bulk densities did not differ greatly among treatments from a plant perspective and averaged between 1.43 and 1.64 Mg $m^{-3}$ (Table 2.6). Since the soil had moderately high sand content and a sandy loam texture, high bulk densities were expected. Hillel (1998) suggested sandy soils have a bulk density as high as 1.6 Mg $m^{-3}$. There were no significant differences in penetration resistance (PR) among irrigation, forage or fertilizer treatments (Table 2.7). All treatments had values < 2 MPa, the threshold beyond which root growth is considered limited for most plant species (Mapfumo et al. 1999). Thus plant or root growth was not likely inhibited in any treatment. Although no statistical differences were found among irrigation treatments ($P = 0.1309$), the high effluent rate had the lowest PR, averaging 0.67 compared to 0.97 and 1.03 MPa for the low effluent rate and non-irrigated treatments, respectively. At the time the non-irrigated treatment had the lowest soil moisture and the low effluent rate had the highest (see Chapter 3).

The lower soil moisture in the non-irrigated treatment may explain the higher PR as a decrease in soil moisture increases penetration resistance (Perumpral 1987; Bengough and Mullins 1990; Bennie 1991). The low effluent rate treatment had higher soil moisture than the non-irrigated and high effluent rate treatments, but had similar PR to the non-irrigated treatment. The low effluent treatment had higher PR than the high rate likely due to slightly higher clay content (Table 2.4).

### 2.4.4 Available Nutrients

Available nutrients followed no consistent pattern in response to irrigation, forage and fertilizer treatments (Table 2.8). With increasing irrigation rates at 0 to 20 cm depths, available P and S increased and N, K, Mn, Fe and Cu decreased; at 20 to 40 cm, P and S increased and N, K and Cu decreased. With increased fertilizer rate application, N and Mn increased and K and S decreased at 0 to 20 cm; at 20 to 40 cm, N increased and P and Fe decreased.

For N at 0 to 20 cm, the irrigation by forage by fertilizer interaction was significant (P=0.0189) (Figure 2.2) with most treatments at 400 N having higher $NO_3$-N than the other treatments because of increasing ammonium nitrate added. The non-irrigated timothy treatment at 400 N had unexplained, very low concentrations. The non-irrigated alfalfa treatment at 400 N had significantly higher $NO_3$-N than all but one of the 0, 100 and 200 N treatments. Few differences occurred among species at 400 N, except the aforementioned non-irrigated timothy and both effluent irrigated reed canary grass treatments, which had significantly lower $NO_3$-N than the non-irrigated alfalfa treatment. For 20 to 40 cm, the forage by fertilizer interaction was significant (P = 0.0101) with timothy having significantly higher concentrations at 400 N than other fertilizer rates and other species (Figure 2.2). Slight increases in $NO_3$-N from the first to the second depth interval occurred at the highest fertilizer rate in most effluent treatments indicating potential leaching. Prior to seeding, concentrations were higher near the surface and baseline soils (data not shown) had optimal $NO_3$-N levels according to recommended soil test levels (Keyes et al. 2002) (Table 2.9). After two growing seasons, most treatments had deficient (<20 ppm) soil $NO_3$-N, except a few 400 N treatments which were marginal to optimal and low effluent rate timothy at 400 N which had nearly excess $NO_3$-N (>60 ppm).

For $PO_4$-P no significant main effects or interactions occurred for either depth interval. However the high effluent rate, particularly for 0 to 20 cm, had noticeably higher $PO_4$-P than the low effluent rate or non-irrigated treatments (P = 0.2431). Baseline soils were optimal for crop growth at 0 to 20 cm (data not shown). At the end of the study, $PO_4$-P was deficient in non-irrigated and low effluent treatments, but marginal in the high effluent.

No significant differences in available K occurred among irrigation or forage treatments (Table 2.8). Since the effluent had a long-term K average of 32.3 mg $L^{-1}$, available K should have been greater in effluent treatments; this was not the case probably due to luxury consumption by irrigated plants. Significant differences occurred among fertilizer rates at 0 to 20 cm (P = 0.0365), in which 0 N had higher K than 400 N likely due to enhanced plant uptake or competitive exclusion from the ammonium ($NH_4$) in the fertilizer; this also occurred at 20 to 40 cm (P = 0.2242). Baseline soils had marginal K for good growth, while by fall 2004 K was deficient.

At 0 to 20 cm, the main effect for forage species was significant with alfalfa soils having higher $SO_4$-S than timothy (P = 0.0365) (Table 2.8). The non-irrigated, unfertilized alfalfa treatment at this depth had unusually high unexplained $SO_4$-S compared to the other treatments. The effluent treatments had higher $SO_4$-S than the non-irrigated treatment for either depth interval ($P_{0\text{-}20\ cm}$ = 0.1826 and $P_{20\text{-}40\ cm}$ = 0.1204) with an increase with depth in irrigated treatments indicative of potential leaching. At 20 to 40 cm, the irrigation by forage by fertilizer interaction was significant (P = 0.0465). $SO_4$-S prior to the study was optimal for plant growth. After the study, $SO_4$ at 0 to 40 cm was marginal in the non-irrigated treatment, but excessive in low and high effluent treatments. Higher concentrations were attributed to $SO_4$ from the effluent.

No significant micronutrient differences occurred among main effects or interactions for Fe and Zn for both depths and Mn and B for 20 to 40 cm (Table 2.8). The irrigation by forage by fertilizer interaction was significant (P = 0.0070) for Mn at 0 to 20 cm. Mn was generally higher at 400 N than the other fertilizer treatments. The high effluent rate had lower Cu (P = 0.0262), Fe (P = 0.2564) and B (P = 0.0916) than the other irrigation treatments (Table 2.8). B and Zn at 20 to 40 cm had similar results ($P_B$ = 0.0755, $P_{Zn}$ = 0.1111). At 20 to 40 cm, the irrigation by fertilizer interaction was significant (P = 0.0070) for Cu. Long-term effluent analyses indicated no Cu, Zn or B thus increases would not be expected. At 0 to 20 cm, alfalfa had significantly lower soil B than other species because it has a higher requirement than grasses. According to critical soil test levels (McKenzie 1992) baseline soils had deficient to marginal Cu and B, while Fe, Mn and Zn were more than sufficient. After the study, Fe, Mn and Zn were still adequate. Interestingly, Cu increased in non-irrigated and low effluent rate treatments to sufficient levels, while the high effluent rate soil was still deficient. Soil B remained in between deficient (mostly in the high effluent rate treatment) and marginal.

### 2.4.5 Salinity

Salinity was assessed through several parameters and very few statistically significant differences were found for irrigation, forage and fertilizer main effects at either the 0 to 20 or the 20 to 40 cm depth increments (Table 2.10 and Figure 2.3). Soil pH and EC were similar with treatment and depth, averaging 6.0 and 0.7 dS $m^{-1}$, respectively. Although not significant ($P_{0\text{-}20cm}$ = 0.0809 and $P_{20\text{-}40cm}$ = 0.1039), SAR was lowest in the non-irrigated treatment and highest in the high effluent rate treatment, at both depth increments (Figure 2.4), obviously linked to high Na concentrations. Baseline (Table 2.11) and recent soil analyses were similar in the non-irrigated treatment; but the irrigated treatments had higher values. According to land capability classification schemes for agriculture in Alberta, an SAR of < 4 is ideal for crop growth (Alberta Soils Advisory Committee (Pettapiece 1987). All treatments generally met this criterion; however, higher SARs between 4 and 8 sometimes occurred in individual samples closer to the sprinklers in the high effluent rate treatment.

Na concentrations at 0 to 20 cm were significantly higher with the high effluent rate than the non-irrigated treatment (P = 0.0485) (Figure 2.3). The same trend occurred at 20 to 40 cm, but was not statistically significant (P = 0.1092). Na in the non-irrigated treatment was similar to baseline soils (Table 2.11); whereas in irrigated treatments it was above original concentrations. The irrigation by forage by fertilizer interaction was significant for Ca at both depths ($P_{0\text{-}20\ cm}$ = 0.0005 and $P_{20\text{-}40\ cm}$ = 0.0150). Compared to baseline soils, Ca was lower after two growing seasons. The three way interaction for Mg was significant for 0 to 20 cm (P = 0.0425) with no apparent trends. For 20 to 40 cm, the 400 N fertilizer treatment was significantly higher than 100 N (Table 2.10). Mg was slightly lower than baseline at 0 to 20 cm and higher at 20 to 40 cm.

The irrigation by forage by fertilizer interaction for K was significant (P = <0.0001) for 0 to 20 cm. At 20 to 40 cm, the forage by fertilizer interaction was significant (P = 0.0239). K was slightly lower than baseline soils for 0 to 20 cm.

Irrigated treatments consistently had higher $SO_4$ than non-irrigated treatments ($P_{0\text{-}20\ cm}$ = 0.1398 and $P_{20\text{-}40\ cm}$ = 0.0904) (Table 2.10). At 0 to 20 cm, the forage by fertilizer interaction was significant (P = 0.0305). At 20 to 40 cm, the irrigation by forage by fertilizer interaction was significant (P = 0.0065). Most treatments had $SO_4$ well above baseline soils, with the exception of a few non-irrigated treatments, in particular timothy.

Cl was greater in the high effluent rate than the low rate, followed by the non-irrigation treatment (P = 0.2133) (Figure 2.3). The irrigation by forage by fertilizer interaction was significant for 0 to 20 cm (P = 0.0032). For 20 to 40 cm, the forage main effect was significant with alfalfa having significantly higher Cl than both grasses (P = 0.0069) (Table 2.10). Recent analyses from the irrigated treatments, especially at the high rate, generally had higher Cl than baseline soils.

Soil pH in effluent treatments was slightly higher than the non-irrigated treatment ($P_{0\text{-}20\ cm}$ = 0.3229 and $P_{20\text{-}40\ cm}$ = 0.2227) (Table 2.10). The fertilizer main effect was significant at 0 to 20 cm with pH at 400 N significantly lower than the other treatments (P = 0.0009). At 20 to 40 cm, the irrigation by forage by fertilizer interaction was significant (P = 0.0163). Within the non-irrigated treatment, pHs at 400 N were lower than the other fertilizer treatments. These values at 400 N are not ideal for alfalfa according to Pettapiece (1987) who stated a soil pH of 5.5 would negatively affect alfalfa as 6.5 to 7.5 was ideal for crop growth. Original soil pHs were below this range and were similar to the non-irrigated treatment.

EC at 0 to 20 cm in non-irrigated soils was slightly lower than in effluent treatments; the highest effluent rate had the highest EC. The irrigation by forage by fertilizer interaction was significant for EC for both depths ($P_{0\text{-}20\ cm}$ = 0.0176 and $P_{20\text{-}40\ cm}$ = 0.0.0439) (Figure 2.5). At 0 to 20 cm alfalfa at 0 N had significantly higher EC than most treatments, with the exception of a few treatments at high fertilizer rates. Only the low effluent rate reed canary grass and timothy treatments at 400 N were significantly lower than the other 400 N treatments. At 20 to 40 cm only timothy at 400 N in the non-irrigated and low effluent rate treatments had significantly higher EC than the non-irrigated timothy treatment at 0 and 100 N. EC was slightly higher in the high effluent treatment than other irrigation treatments (Table 2.10). With the exception of four non-irrigated treatments, ECs were similar to baseline soils (Table 2.11). According to Pettapiece (1987), the ideal EC for crop growth is 2 to 4 dS $m^{-1}$.

Generally soluble salts, Na, $SO_4$ and Cl, at 0 to 20 cm increased with an increase in effluent rate, while Ca decreased. No apparent trends among irrigation treatments occurred for Mg and K; K overall had the lowest concentrations compared to the other soluble salts. The alfalfa treatment had noticeably higher K and Cl than grass soils. Timothy and reed canary grass soils had increasing Ca with increasing fertilizer rates.

### 2.4.6 Soil Carbon and Nitrogen

No statistically significant differences in Kjeldahl N or C occurred for 0 to 20 cm (Table 2.12). The low effluent rate treatment generally had highest total ($P = 0.3163$), inorganic ($P = 0.2410$) and organic ($P = 0.3551$) C and TKN ($P = 0.1993$). The irrigation by forage by fertilizer interaction was significant for 20 to 40 cm in all aforementioned parameters except inorganic C which was very low. Reed canary grass at 400 N in the non-irrigated treatment had significantly higher TKN than most non-irrigated and all high effluent rate treatments. Soil organic matter was above 2% in non-irrigated and high effluent treatments and above 3% in the low effluent treatment. Thus soil quality was not poor according to Pettapiece (1987) who stated soil OM below 2% is poor.

### 2.4.7 General Discussion

Changes in soil physical properties, specifically soil texture, bulk density and penetration resistance, due to irrigation, forage or fertilizer treatments were not apparent during this two year study. However, it seemed that soil moisture and texture may have had more influence on slight differences in penetration resistance among treatment blocks. Some researchers stated adverse effects of sodicity on soil physical properties are mostly not developed or visible until irrigation stops and land use changes (Balks et al. 1998; Halliwell et al. 2001). Since either scenario had not occurred during the study, no definitive conclusions can be made about the effects of effluent irrigation rates on soil physical properties. Due to increased soil moisture, the low effluent rate had the highest organic matter and grasses had more organic matter than alfalfa likely due their extensive sod-forming root systems.

As expected, soil available $NO_3$-N, $PO_4$-P, K and analyzed micro nutrients did not increase, but $SO_4$-S did with increasing effluent rates since the effluent consisted of significant $SO_4$-S concentrations relative to other nutrients. This was contrary to studies using agricultural, municipal or untreated pulp mill effluents that contained significant concentrations of N and P (Sakadevan et al. 2000; Hawke and Summers 2003; Mohammad and Mazarhreh 2003); thus the need for N fertilization in this study. Although not significant, soil in alfalfa had higher $NO_3$-N and lower B levels than grasses likely due to rooting characteristics and nutrient requirements. Increasing N fertilizer rates increased soil $NO_3$-N and decreased K, indicating more residual $NO_3$-N and plant uptake of K occurred in the 400 N treatments.

Soil pH decreased with increasing fertilizer rates as high rates of ammonium fertilizers can acidify soil and reduce plant Mg uptake (Havlin et al. 1999), as indicated by the increase in Mg at 20 to 40 cm. EC, SAR, Na, $SO_4$ and Cl increased with increasing effluent irrigation rates, as secondary treated pulp mill effluents contain significant salt concentrations. A greenhouse study conducted with secondary treated pulp mill effluent also found increased soil Na, $SO_4$, and Cl (Patterson et al. 2002). Unlike this study, they found increased Ca and Mg; whereas Ca and Mg slightly decreased from the low to high effluent rate. The addition of $SO_4$ and Cl may have increased desorption and leaching of Mg in this coarse-textured soil (Havlin et al. 1999). Narum and Moeller (1977) also found decreased Ca and Mg due to Na displacement. Among forage species, alfalfa soils had the highest Ca, $SO_4$ and Cl due to high concentrations in the unfertilized non-irrigated plot, likely due to inherent soil nutrient variability.

Perhaps the lack of statistical significance in certain nutrients among treatments was due to irrigation non-uniformity or inherent soil variability since unexplained high concentrations occurred in some unfertilized alfalfa and grass treatments in the high effluent rate.

## 2.5 CONCLUSIONS

Irrigation rates, forage treatments and nitrogen fertilization rates did not affect soil physical parameters and soil C and N. Generally, forage species did not have any pronounced effects on soil physical and chemical properties beyond their nutrient requirements. However, irrigation and fertilizer treatments affected soil chemical properties as available nutrients, cations and anions increased in relation to constituents present in the effluent. Fertilizer effects were evident with decreased soil pH and K, as soil $NO_3$-N increased with increasing fertilizer rates.

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**Table 2.1 Fertilizer application rate totals (kg N ha$^{-1}$ yr$^{-1}$) for replicates 1 and 4**

| Replicate | Treatment | June 2003 | July 2003 | 2003 Total | June 2004 | July 2004 | 2004 Total |
|---|---|---|---|---|---|---|---|
| 1 | 0 | 0 | 200 | 200 | 0 | 0 | 0 |
| | 100 | 50 | 100 | 150 | 50 | 50 | 100 |
| | 200 | 100 | 50 | 150 | 100 | 100 | 200 |
| | 400 | 200 | 0 | 200 | 200 | 200 | 400 |
| 4 | 0 | 0 | 0 | 0 | 50 | 0 | 50 |
| | 100 | 50 | 50 | 100 | 0 | 50 | 50 |
| | 200 | 100 | 100 | 200 | 100 | 100 | 200 |
| | 400 | 200 | 200 | 400 | 200 | 200 | 400 |

**Table 2.2 Average total precipitation for 2003 and 2004, including long-term normals for Athabasca**

| Month | Total Precipitation (mm) | | | | |
|---|---|---|---|---|---|
| | On-site | | Athabasca* | | |
| | 2003 | 2004 | 2003 | 2004 | LTN |
| **January** | 24.6 | 26.4 | 45.7 | 43.0 | 24.9 |
| **February** | 22.9 | 19.1 | 19.0 | 7.0 | 18.6 |
| **March** | 29.5 | 24.6 | 26.2 | 17.0 | 17.7 |
| **April** | 9.9 | 16.0 | 23.4 | 32.0 | 25.5 |
| **May** | 11.4 | 103.6 | 45.7 | 69.7 | 47.3 |
| **June** | 109.0 | 29.2 | 149.3 | 11.7 | 91.7 |
| **July** | 42.3 | 116.1 | 78.1 | 165.9 | 104.5 |
| **August** | 36.6 | 76.5 | 35.8 | 60.9 | 62.3 |
| **September** | 9.4 | 71.9 | 14.8 | 78.0 | 42.8 |
| **October** | 27.7 | 18.0 | 18.9 | 34.5 | 21.4 |
| **November** | 21.3 | 5.1 | 20.5 | 14.5 | 21.1 |
| **December** | 7.4 | 17.3 | 14.0 | 37.0 | 25.5 |
| **Growing Season** | 208.7 | 397.3 | 323.7 | 386.2 | 348.6 |
| **Annual Total** | 352.0 | 523.7 | 491.4 | 571.2 | 503.3 |

* Data from weather station located near Athabasca
LTN = Long-term Canadian climate normals 1971-2000
Growing Season = May to October

**Table 2.3 Average growing degree days and air temperature for 2003 and 2004, including long-term normals for Athabasca**

| Month | Growing Degree Days (above 5 °C) | | | | | Average Air Temperature (°C) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | On-site | | Athabasca* | | | On-site | | Athabasca | | |
| | 2003 | 2004 | 2003 | 2004 | LTN | 2003 | 2004 | 2003 | 2004 | LTN |
| January | 0.9 | 0.0 | 0.0 | 0.0 | 0.3 | -14.3 | -18.2 | -13.6 | -17.2 | -14.9 |
| February | 0.0 | 0.0 | 0.0 | 0.0 | 0.6 | -12.3 | -9.4 | -10.8 | -8.5 | -10.7 |
| March | 0.0 | 0.9 | 0.0 | 2.0 | 1.3 | -9.9 | -4.0 | -9.1 | -2.4 | -4.4 |
| April | 42.0 | 26.4 | 49.8 | 32.9 | 47.6 | 3.5 | 4.2 | 3.7 | 4.4 | 4.2 |
| May | 156.7 | 94.7 | 164.0 | 110.1 | 177.8 | 9.5 | 7.2 | 9.3 | 7.5 | 10.6 |
| June | 251.3 | 241.2 | 132.0^ | 273.2 | 278.3 | 13.7 | 14.0 | 14.8 | 14.1 | 14.2 |
| July | 373.5 | 366.4 | 380.5 | 389.6 | 346.1 | 17.3 | 17.1 | 17.3 | 17.6 | 16.2 |
| August | 349.4 | 250.1 | 351.0 | 291.4 | 314.6 | 16.4 | 13.5 | 16.3 | 14.4 | 15.2 |
| September | 157.1 | 108.0 | 162.0 | 105.4 | 153.6 | 9.7 | 7.8 | 10.2 | 8.3 | 9.8 |
| October | 77.6 | 43.4 | 79.0 | 32.5 | 47.9 | 5.0 | 1.2 | 5.6 | 1.3 | 4.1 |
| November | 0.0 | 1.1 | 0.0 | 1.0 | 1.5 | -9.5 | -1.9 | -8.5 | -1.3 | -6.2 |
| December | 0.0 | 0.0 | 0.0 | 0.5 | 0.3 | -12.0 | -11.7 | -11.2 | -11.2 | -12.9 |
| Growing Season | 1288.0 | 1060.4 | 1057.5 | 1169.7 | 1270.4 | 13.3 | 11.9 | 13.6 | 12.4 | 13.2 |
| Annual Total | 1408.5 | 1132.1 | 1186.3 | 1238.6 | 1369.9 | 1.43 | 1.65 | 2.00 | 2.25 | 2.10 |

Growing degree days represent number of Celsius degrees that mean temperature > 5 °C
* Data from weather station located near Athabasca
LTN = Long-term Canadian climate normals 1971-2000
^ Daily average temperatures incomplete from June 4 to 17, 2003

**Table 2.4 Baseline soil particle size analyses and textures**

| Treatment | Depth (cm) | Clay (%) | Sand (%) | Silt (%) | Texture |
|---|---|---|---|---|---|
| **Eff-2x** | 0-20 | 10 | 54 | 36 | SL |
| | 20-40 | 6 | 72 | 22 | SL |
| | 40-60 | 4 | 86 | 10 | LS |
| | 60-80 | 4 | 91 | 5 | S |
| | 80-100 | 4 | 89 | 7 | S |
| **NI-2x** | 0-20 | 8 | 58 | 34 | SL |
| | 20-40 | 12 | 65 | 23 | SL |
| | 40-60 | 10 | 73 | 17 | SL |
| | 60-80 | 6 | 79 | 15 | LS |
| | 80-100 | 11 | 71 | 18 | SL |
| **Eff-1x** | 0-20 | 14 | 53 | 33 | L/SL |
| | 20-40 | 16 | 59 | 25 | SL |
| | 40-60 | 7 | 78 | 15 | LS |
| | 60-80 | 8 | 77 | 15 | SL/LS |
| | 80-100 | 18 | 65 | 17 | SL |
| **NI-1x** | 0-20 | 11 | 55 | 34 | SL |
| | 20-40 | 15 | 57 | 28 | SL |
| | 40-60 | 17 | 48 | 35 | L |
| | 60-80 | 11 | 63 | 26 | SL |
| | 80-100 | 12 | 71 | 17 | SL |
| **Average** | 0-20 | 11 | 55 | 34 | SL |
| | 20-40 | 12 | 63 | 25 | SL |
| | 40-60 | 10 | 71 | 19 | SL |
| | 60-80 | 7 | 78 | 15 | LS |
| | 80-100 | 11 | 74 | 15 | SL |

L = loam
SL = sandy loam
LS = loamy sand
S = sand

**Table 2.5 Bulk density as measured by Uhland core (May 2003)**

| Depth Interval | Sample No. | Bulk Density ($Mg\ m^{-3}$) | Vol. Moisture (%) |
|---|---|---|---|
| 0-10 cm | 1 | 1.53 | 20.5 |
| | 2 | 1.47 | 19.7 |
| | 3 | 1.44 | 16.1 |
| | 4 | 1.33 | 14.5 |
| | 5 | 1.39 | 15.0 |
| | 6 | 1.51 | 17.5 |
| | 7 | 1.44 | 30.7 |
| | 8 | 1.46 | 30.6 |
| | 9 | 1.36 | 21.4 |
| | 10 | 1.36 | 21.0 |
| | 11 | 1.33 | 14.6 |
| | 12 | 1.36 | 14.8 |
| 10-20 cm | 1 | 0.83 * | 10.6 * |
| | 2 | 1.36 | 15.4 |
| | 3 | 1.54 | 16.8 |
| | 4 | 1.53 | 14.0 |
| | 5 | 1.52 | 20.0 |
| | 6 | 1.70 | 20.2 |
| | 7 | 1.39 | 31.5 |
| | 8 | 1.50 | 32.6 |
| | 9 | 1.45 | 33.3 |
| | 10 | 1.38 | 32.7 |
| | 11 | 1.48 | 30.5 |
| | 12 | 1.60 | 19.2 |
| | 13 | 1.41 | 24.2 |
| | 14 | 1.46 | 24.8 |
| | 15 | 1.61 | 10.1 |
| | 16 | 1.62 | 9.7 |
| Average | 0-10 cm | 1.41 (0.02)^ | 19.7 (1.66) |
| | 10-20 cm | 1.50 (0.03) | 22.3 (2.15) |
| | Overall | 1.46 (0.02) | 21.0 (1.88) |

* Unusually low values not included in average
^ Mean (standard error)

**Table 2.6 Average bulk density with depth by irrigation treatments (Fall 2003)**

| Depth (cm) | NI | Eff-1x | Eff-2x | Mean | Standard Error |
|---|---|---|---|---|---|
| **15** | 1.57 | 1.39 | 1.53 | 1.50 | 0.03 |
| **25** | 1.63 | 1.55 | 1.51 | 1.56 | 0.03 |
| **35** | 1.62 | 1.62 | 1.64 | 1.63 | 0.02 |
| **45** | 1.63 | 1.57 | 1.65 | 1.62 | 0.03 |
| **55** | 1.62 | 1.61 | 1.69 | 1.64 | 0.03 |
| **65** | 1.61 | 1.59 | 1.60 | 1.60 | 0.03 |
| **75** | 1.56 | 1.59 | 1.50 | 1.55 | 0.02 |
| **85** | 1.54 | 1.55 | 1.55 | 1.54 | 0.04 |
| **95** | 1.58 | 1.54 | 1.59 | 1.57 | 0.03 |
| **105** | 1.51 | 1.51 | 1.55 | 1.52 | 0.03 |
| **115** | 1.54 | 1.51 | 1.56 | 1.54 | 0.02 |
| **125** | 1.45 | 1.57 | 1.55 | 1.52 | 0.03 |
| **135** | 1.52 | 1.45 | 1.47 | 1.49 | 0.03 |
| **145** | 1.56 | 1.31 | 1.50 | 1.49 | 0.06 |
| **155** | 1.64 | 1.35 | 1.58 | 1.54 | 0.08 |
| **165** | 1.56 | 1.60 | 1.53 | 1.55 | 0.02 |
| **175** | 1.49 | n/a | 1.38 | 1.43 | 0.06 |

n/a = not available due to presence of water at depth
NI = non-irrigated
Eff-1x = low irrigation rate
Eff-2x = high irrigation rate

**Table 2.7 Average penetration resistance measurements (Fall 2003)**

| Forage Species | Fertlizer Treatment | Irrigation Treatment NI | Eff-1x | Eff-2x |
|---|---|---|---|---|
| **ALF** | **0** | 1.18 (0.13)^ | 0.90 (0.13) | 0.57 (0.13) |
| | **100** | 1.06 (0.13) | 1.02 (0.13) | 0.52 (0.13) |
| | **200** | 0.92 (0.13) | 0.93 (0.13) | 0.56 (0.13) |
| | **400** | 1.17 (0.13) | 0.96 (0.13) | 0.61 (0.13) |
| **RCG** | **0** | 1.09 (0.13) | 1.05 (0.13) | 0.75 (0.13) |
| | **100** | 1.02 (0.13) | 1.04 (0.13) | 0.86 (0.13) |
| | **200** | 0.89 (0.13) | 0.95 (0.13) | 0.63 (0.13) |
| | **400** | 1.12 (0.13) | 1.00 (0.13) | 0.74 (0.13) |
| **TIM** | **0** | 1.09 (0.13) | 0.88 (0.13) | 0.73 (0.13) |
| | **100** | 0.81 (0.13) | 1.01 (0.13) | 0.75 (0.13) |
| | **200** | 0.92 (0.13) | 0.95 (0.13) | 0.60 (0.13) |
| | **400** | 1.11 (0.13) | 0.92 (0.13) | 0.78 (0.13) |
| **Ave** | | 1.03 (0.09) | 0.97 (0.09) | 0.67 (0.09) |

^LSMean (standard error)
NI = non-irrigated; Eff-1x = low irrigation rate; Eff-2x = high irrigation rate
RCG = reed canary grass; TIM = timothy; ALF = alfalfa
0 = no fertilizer; 100 = 100 kg N $ha^{-1}$ $yr^{-1}$; 200 = 200 kg N $ha^{-1}$ $yr^{-1}$; 400 = 400 kg N $ha^{-1}$ $yr^{-1}$
There were no significant treatment differences

Table 2.8 Soil available nutrients (Fall 2004)

| Depth (cm) | Trt | $NO_3$-N | $PO_4$-P | K | $SO_4$-S | Mn | Fe | Cu | Zn | B |
|---|---|---|---|---|---|---|---|---|---|---|
| | | ug cc$^{-1}$ | | | | | | | | |
| 0-20 | NI | 12.3 (2.4)^ | 12 (6.8) | 63 (8.4) | 10.2 (2.5) | 10.7 (1.3) | 270 (34) | 0.75 (0.05)$^{a}$ | 1.43 (0.27) | 0.58 (0.06) |
| | Eff-1x | 9.3 (1.7) | 10 (4.8) | 50 (5.9) | 16.8 (1.8) | 7.9 (0.9) | 177 (24) | 0.77 (0.04)$^{a}$ | 1.88 (0.19) | 0.73 (0.04) |
| | Eff-2x | 8.4 (1.7) | 26 (4.8) | 52 (5.9) | 19.3 (1.8) | 8.8 (0.9) | 183 (24) | 0.33 (0.04)$^{b}$ | 1.43 (0.19) | 0.47 (0.04) |
| | RCG | 7.3 (1.7) | 17 (5.6) | 56 (4.6) | 14.4 (1.5)$^{ab}$ | 8.0 (0.9) | 186 (27) | 0.61 (0.04) | 1.37 (0.22) | 0.63 (0.03)$^{ab}$ |
| | TIM | 8.8 (1.7) | 19 (5.6) | 51 (4.6) | 12.8 (1.5)$^{b}$ | 8.6 (0.9) | 237 (27) | 0.62 (0.04) | 1.73 (0.22) | 0.63 (0.03)$^{a}$ |
| | ALF | 14.0 (1.7) | 13 (5.6) | 59 (4.6) | 19.0 (1.5)$^{a}$ | 10.7 (0.9) | 208 (27) | 0.62 (0.04) | 1.64 (0.22) | 0.52 (0.03)$^{b}$ |
| | 0 | 3.3 (2.3) | 18 (3.3) | 68 (5.0)$^{a}$ | 18.0 (2.3) | 7.9 (1.0) | 200 (18) | 0.59 (0.03) | 1.56 (0.15) | 0.55 (0.03) |
| | 100 | 4.9 (2.3) | 16 (3.3) | 53 (5.0)$^{ab}$ | 13.6 (2.3) | 7.0 (1.0) | 209 (18) | 0.64 (0.03) | 1.54 (0.15) | 0.59 (0.03) |
| | 200 | 6.6 (2.3) | 16 (3.3) | 51 (5.0)$^{ab}$ | 14.3 (2.3) | 7.1 (1.0) | 197 (18) | 0.60 (0.03) | 1.56 (0.15) | 0.59 (0.03) |
| | 400 | 25.2 (2.3) | 15 (3.3) | 49 (5.0)$^{b}$ | 15.7 (2.3) | 14.3 (1.0) | 235 (18) | 0.63 (0.03) | 1.66 (0.15) | 0.63 (0.03) |
| 20-40 | NI | 19.4 (3.3) | 9 (3.2) | 71 (11) | 10.3 (4.4) | 4.9 (0.7) | 226 (26) | 1.04 (0.10) | 0.67 (0.10) | 0.38 (0.03) |
| | Eff-1x | 13.6 (3.3) | 9 (3.2) | 54 (11) | 26.4 (4.4) | 2.9 (0.7) | 128 (26) | 1.00 (0.10) | 1.04 (0.10) | 0.49 (0.03) |
| | Eff-2x | 7.6 (4.7) | 15 (4.5) | 55 (15) | 39.1 (6.2) | 4.7 (1.0) | 181 (37) | 0.41 (0.14) | 0.51 (0.13) | 0.28 (0.04) |
| | RCG | 9.5 (3.2) | 10 (3.6) | 67 (8.5) | 24.3 (4.3) | 4.0 (0.8) | 171 (30) | 0.94 (0.08) | 0.78 (0.10) | 0.39 (0.03) |
| | TIM | 20.0 (3.2) | 12 (3.6) | 58 (8.5) | 28.5 (4.3) | 3.5 (0.8) | 197 (30) | 0.76 (0.08) | 0.68 (0.10) | 0.39 (0.03) |
| | ALF | 11.2 (3.2) | 11 (3.6) | 55 (8.5) | 22.9 (4.3) | 5.0 (0.8) | 167 (30) | 0.74 (0.08) | 0.76 (0.10) | 0.37 (0.03) |
| | 0 | 2.2 (4.0) | 12 (2.3) | 63 (7.6) | 23.8 (4.8) | 4.3 (0.5) | 182 (20) | 0.73 (0.07) | 0.78 (0.13) | 0.37 (0.03) |
| | 100 | 2.3 (4.0) | 12 (2.3) | 64 (7.6) | 23.4 (4.8) | 4.8 (0.5) | 195 (20) | 0.95 (0.07) | 0.78 (0.13) | 0.39 (0.03) |
| | 200 | 5.1 (4.0) | 10 (2.3) | 60 (7.6) | 32.3 (4.8) | 3.6 (0.5) | 164 (20) | 0.83 (0.07) | 0.77 (0.13) | 0.38 (0.03) |
| | 400 | 44.7 (4.0) | 10 (2.3) | 53 (7.6) | 21.4 (4.8) | 4.0 (0.5) | 173 (20) | 0.74 (0.07) | 0.63 (0.13) | 0.39 (0.03) |

^LSMean (standard error)
NI = non-irrigated; Eff-1x = low irrigation rate; Eff-2x = high irrigation rate
RCG = reed canary grass; TIM = timothy; ALF = alfalfa
0 = no fertilizer; 100 = 100 kg N ha$^{-1}$ yr$^{-1}$; 200 = 200 kg N ha$^{-1}$ yr$^{-1}$; 400 = 400 kg N ha$^{-1}$ yr$^{-1}$
Same letters within treatments are not significantly different ($p < 0.05$); no letters indicate non-significance

Table 2.9 Critical soil nutrient levels (ppm or kg ha$^{-1}$)

| Parameter | Deficient | | Marginal | | Optimal | | Excess | |
|---|---|---|---|---|---|---|---|---|
| | ppm | kg ha$^{-1}$ | ppm | kg ha$^{-1}$ | ppm | kg ha$^{-1}$ | ppm | kg ha$^{-1}$ |
| $NO_3$-N | <20 | <90 | 20-40 | 90-179 | 40-60 | 179-269 | >60 | >269 |
| $PO_4$-P | <15 | <34 | 15-25 | 34-56 | 25-60 | 56-134 | >60 | >134 |
| K | <100 | <224 | 100-200 | 224-448 | 200-500 | 448-1120 | >500 | >1120 |
| $SO_4$-S | <2 | <9 | 2-10 | 9-45 | 10-20 | 45-90 | >20 | >90 |

Based on Keyes et al. 2002

**Table 2.10 Soil salinity parameters (Fall 2004)**

| Depth (cm) | Trt | pH | EC dS m$^{-1}$ | SAR | Na | Ca | Mg | K | $SO_4$ | Cl |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | mg L$^{-1}$ | | | | | |
| 0-20 | NI | 5.7 (0.3)^ | 0.56 (0.07) | 0.33 (0.5) | 12 (13)[b] | 82 (9.8) | 15 (2.8) | 3.29 (0.34) | 49 (20) | 21 (8.4) |
| | Eff-1x | 6.3 (0.2) | 0.60 (0.05) | 1.63 (0.4) | 55 (8.9)[ab] | 62 (6.9) | 17 (2.0) | 1.33 (0.24) | 107 (14) | 29 (6.0) |
| | Eff-2x | 6.2 (0.2) | 0.70 (0.05) | 3.80 (0.4) | 107 (8.9)[a] | 50 (6.9) | 11 (2.0) | 2.33 (0.24) | 150 (14) | 50 (6.0) |
| | RCG | 6.1 (0.2) | 0.59 (0.05) | 1.93 (0.3) | 62 (7.5) | 59 (6.2) | 14 (1.8) | 2.00 (0.24) | 96 (13) | 34 (5.1) |
| | TIM | 6.1 (0.2) | 0.60 (0.05) | 1.85 (0.3) | 52 (7.5) | 63 (6.2) | 13 (1.8) | 1.67 (0.24) | 85 (13) | 24 (5.1) |
| | ALF | 6.1 (0.2) | 0.68 (0.05) | 1.98 (0.3) | 60 (7.5) | 72 (6.2) | 15 (1.8) | 3.29 (0.24) | 124 (13) | 43 (5.1) |
| | 0 | 6.2 (0.2)[a] | 0.58 (0.07) | 2.08 (0.5) | 62 (12) | 60 (9.2) | 15 (18.3) | 3.44 (0.32) | 114 (18) | 43 (7.3) |
| | 100 | 6.2 (0.2)[a] | 0.46 (0.07) | 1.75 (0.5) | 49 (12) | 48 (9.2) | 11 (18.3) | 1.44 (0.32) | 91 (18) | 31 (7.3) |
| | 200 | 6.2 (0.2)[a] | 0.53 (0.07) | 2.16 (0.5) | 61 (12) | 49 (9.2) | 12 (18.3) | 1.50 (0.32) | 98 (18) | 34 (7.3) |
| | 400 | 5.7 (0.2)[b] | 0.92 (0.07) | 1.69 (0.5) | 60 (12) | 102 (9.2) | 18 (18.3) | 2.89 (0.32) | 104 (18) | 26 (7.3) |
| 20-40 | NI | 5.6 (0.3) | 0.74 (0.11) | 0.30 (0.3) | 11 (14) | 105 (16) | 23 (5.3) | 2.88 (0.70) | 51 (37) | 16 (3.4)[b] |
| | Eff-1x | 6.6 (0.3) | 0.76 (0.11) | 0.47 (0.3) | 20 (14) | 97 (16) | 32 (5.3) | 1.33 (0.70) | 190 (37) | 23 (3.4)[b] |
| | Eff-2x | 5.9 (0.4) | 0.92 (0.16) | 2.24 (0.5) | 89 (19) | 99 (23) | 21 (7.5) | 3.88 (0.98) | 332 (52) | 35 (4.8)[a] |
| | RCG | 6.1 (0.2) | 0.64 (0.11) | 0.97 (0.3) | 39 (10) | 75 (16) | 22 (5.3) | 2.04 (0.52) | 179 (32) | 23 (3.1) |
| | TIM | 6.0 (0.2) | 1.07 (0.11) | 1.03 (0.3) | 45 (10) | 142 (16) | 32 (5.3) | 2.58 (0.52) | 220 (32) | 17 (3.1) |
| | ALF | 6.0 (0.2) | 0.70 (0.11) | 1.00 (0.3) | 37 (10) | 84 (16) | 21 (5.3) | 3.46 (0.52) | 173 (32) | 34 (3.1) |
| | 0 | 6.1 (0.2) | 0.57 (0.12) | 1.08 (0.4) | 36 (18) | 64 (18) | 19 (5.9)[ab] | 2.50 (0.56) | 174 (44) | 35 (4.5) |
| | 100 | 6.1 (0.2) | 0.50 (0.12) | 0.79 (0.4) | 28 (18) | 62 (18) | 17 (5.9)[b] | 1.94 (0.56) | 181 (44) | 20 (4.5) |
| | 200 | 6.0 (0.2) | 0.81 (0.12) | 1.08 (0.4) | 48 (18) | 107 (18) | 23 (5.9)[ab] | 2.78 (0.56) | 263 (44) | 23 (4.5) |
| | 400 | 5.9 (0.2) | 1.34 (0.12) | 1.05 (0.4) | 48 (18) | 170 (18) | 41 (5.9)[a] | 3.56 (0.56) | 147 (44) | 20 (4.5) |

^ LSMean (standard error)
NI = non-irrigated; Eff-1x = low irrigation rate; Eff-2x = high irrigation rate
RCG = reed canary grass; TIM = timothy; ALF = alfalfa
0 = no fertilizer; 100 = 100 kg N ha$^{-1}$ yr$^{-1}$; 200 = 200 kg N ha$^{-1}$ yr$^{-1}$; 400 = 400 kg N ha$^{-1}$ yr$^{-1}$
Same letters within treatments are not significantly different ($p < 0.05$); no letters indicate non-significance

**Table 2.11 Baseline soil salinity analyses**

| Depth (cm) | Treatment* | pH | EC dS m$^{-1}$ | SAR | Na | Ca | Mg | K | $SO_4$ | Cl |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | mg L$^{-1}$ | | | | | |
| 0-20 | NI-1x | 5.2 | 1.35 | 0.4 | 22 | 202 | 33 | 6.4 | 37 | 17 |
| | NI-2x | 5.4 | 0.62 | 0.3 | 13 | 92 | 9 | 7 | 38 | 5 |
| | Eff-1x | 7.1 | 0.8 | 0.3 | 16 | 115 | 28 | 1.2 | 89 | 13 |
| | Eff-2x | 5.0 | 1.27 | 0.3 | 16 | 201 | 22 | 6.7 | 28 | 14 |
| | Ave | 5.7 | 1.01 | 0.33 | 17 | 152 | 23 | 5.3 | 48 | 12 |
| 20-40 | NI-1x | 5.0 | 0.82 | 0.5 | 20 | 99 | 26 | 1.1 | 23 | 26 |
| | NI-2x | 4.9 | 0.51 | 0.3 | 12 | 66 | 10 | 4.1 | 18 | 5 |
| | Eff-1x | 7.1 | 0.4 | 0.4 | 12 | 47 | 0.4 | 1 | 54 | 7 |
| | Eff-2x | 4.7 | 0.8 | 0.3 | 13 | 111 | 18 | 3.5 | 13 | 18 |
| | Ave | 5.4 | 0.63 | 0.38 | 14 | 81 | 14 | 2.4 | 27 | 14 |

*Soil cores taken adjacent to treatment

**Table 2.12 Soil carbon and nitrogen (Fall 2004)**

| Depth (cm) | Trt | Inorg C | Tot Org C | Tot C | TKN |
|---|---|---|---|---|---|
| | | ---------------------------% | ----------------------------- | | |
| 0-20 | NI | 0.03 (0.007)^ | 1.51 (0.23) | 1.53 (0.22) | 0.12 (0.016) |
| | Eff-1x | 0.05 (0.005) | 1.83 (0.16) | 1.88 (0.15) | 0.16 (0.012) |
| | Eff-2x | 0.03 (0.005) | 1.45 (0.16) | 1.49 (0.15) | 0.11 (0.012) |
| | RCG | 0.03 (0.005) | 1.64 (0.19) | 1.67 (0.18) | 0.13 (0.013) |
| | TIM | 0.04 (0.005) | 1.64 (0.19) | 1.68 (0.18) | 0.14 (0.013) |
| | ALF | 0.04 (0.005) | 1.51 (0.19) | 1.54 (0.18) | 0.12 (0.013) |
| | 0 | 0.03 (0.006) | 1.54 (0.12) | 1.58 (0.11) | 0.13 (0.008) |
| | 100 | 0.04 (0.006) | 1.56 (0.12) | 1.60 (0.11) | 0.13 (0.008) |
| | 200 | 0.04 (0.006) | 1.59 (0.12) | 1.61 (0.11) | 0.13 (0.008) |
| | 400 | 0.03 (0.006) | 1.57 (0.12) | 1.59 (0.11) | 0.13 (0.008) |
| 20-40 | NI | 0.03 (0.005) | 0.73 (0.09) | 0.74 (0.09) | 0.06 (0.007) |
| | Eff-1x | 0.05 (0.005) | 0.84 (0.09) | 0.90 (0.09) | 0.09 (0.007) |
| | Eff-2x | 0.03 (0.007) | 0.49 (0.13) | 0.50 (0.13) | 0.04 (0.010) |
| | RCG | 0.04 (0.006) | 0.68 (0.10) | 0.73 (0.10) | 0.07 (0.005) |
| | TIM | 0.03 (0.006) | 0.77 (0.10) | 0.80 (0.10) | 0.06 (0.005) |
| | ALF | 0.03 (0.006) | 0.60 (0.10) | 0.62 (0.10) | 0.06 (0.005) |
| | 0 | 0.04 (0.007) | 0.60 (0.09) | 0.62 (0.09) | 0.06 (0.006) |
| | 100 | 0.03 (0.007) | 0.64 (0.09) | 0.68 (0.09) | 0.07 (0.006) |
| | 200 | 0.04 (0.007) | 0.62 (0.09) | 0.66 (0.09) | 0.07 (0.006) |
| | 400 | 0.03 (0.007) | 0.60 (0.09) | 0.61 (0.09) | 0.07 (0.006) |

^LSMean (standard error)
NI = non-irrigated; Eff-1x = low irrigation rate; Eff-2x = high irrigation rate
RCG = reed canary grass; TIM = timothy; ALF = alfalfa
0 = no fertilizer; 100 = 100 kg N $ha^{-1}$ $yr^{-1}$; 200 = 200 kg N $ha^{-1}$ $yr^{-1}$; 400 = 400 kg N $ha^{-1}$ $yr^{-1}$
There were no significant treatment differences

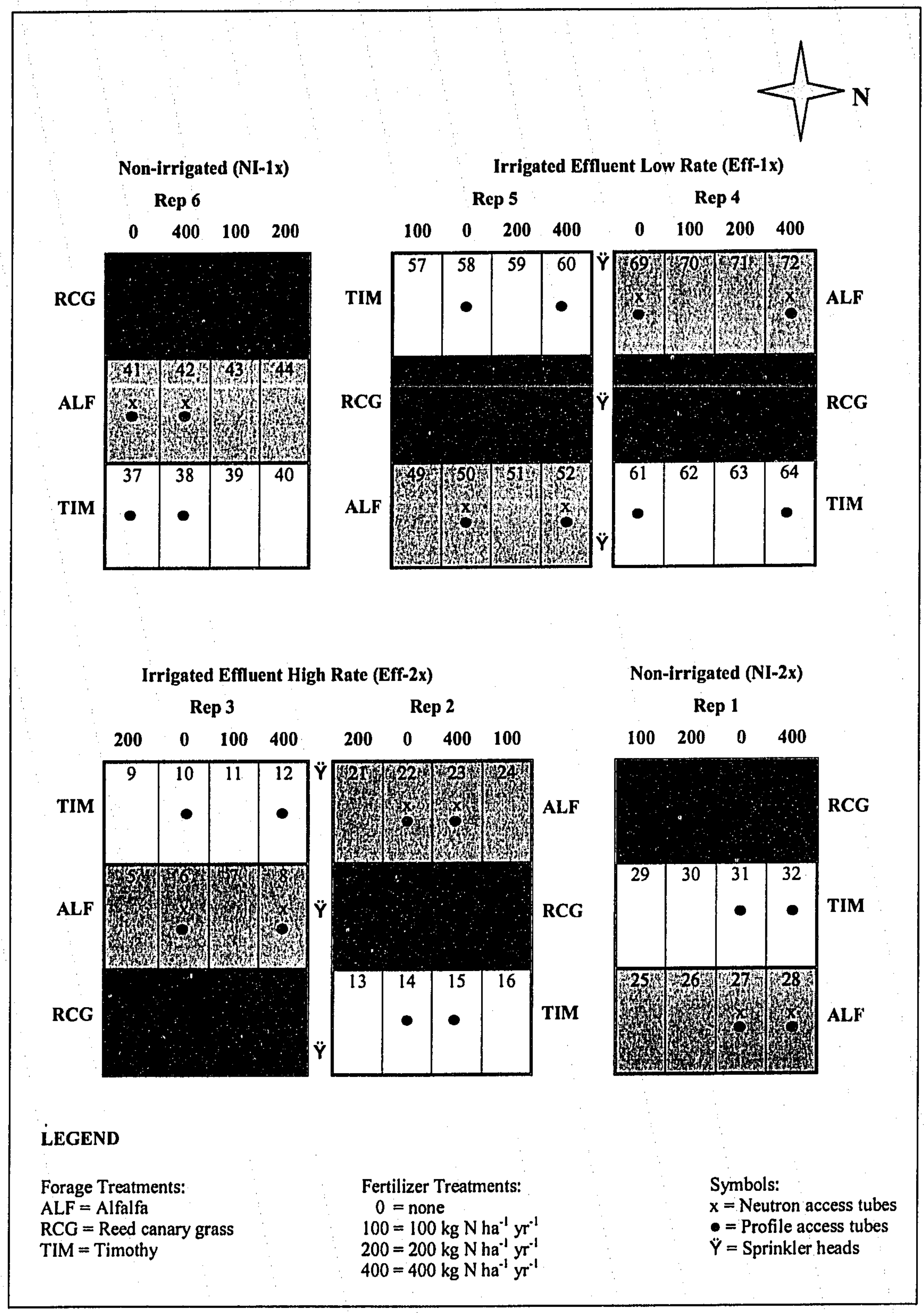


**Figure 2.1 Study site plot plan indicating irrigation, forage and fertilizer treatments, and profile and neutron probe access tubes within numbered plots**

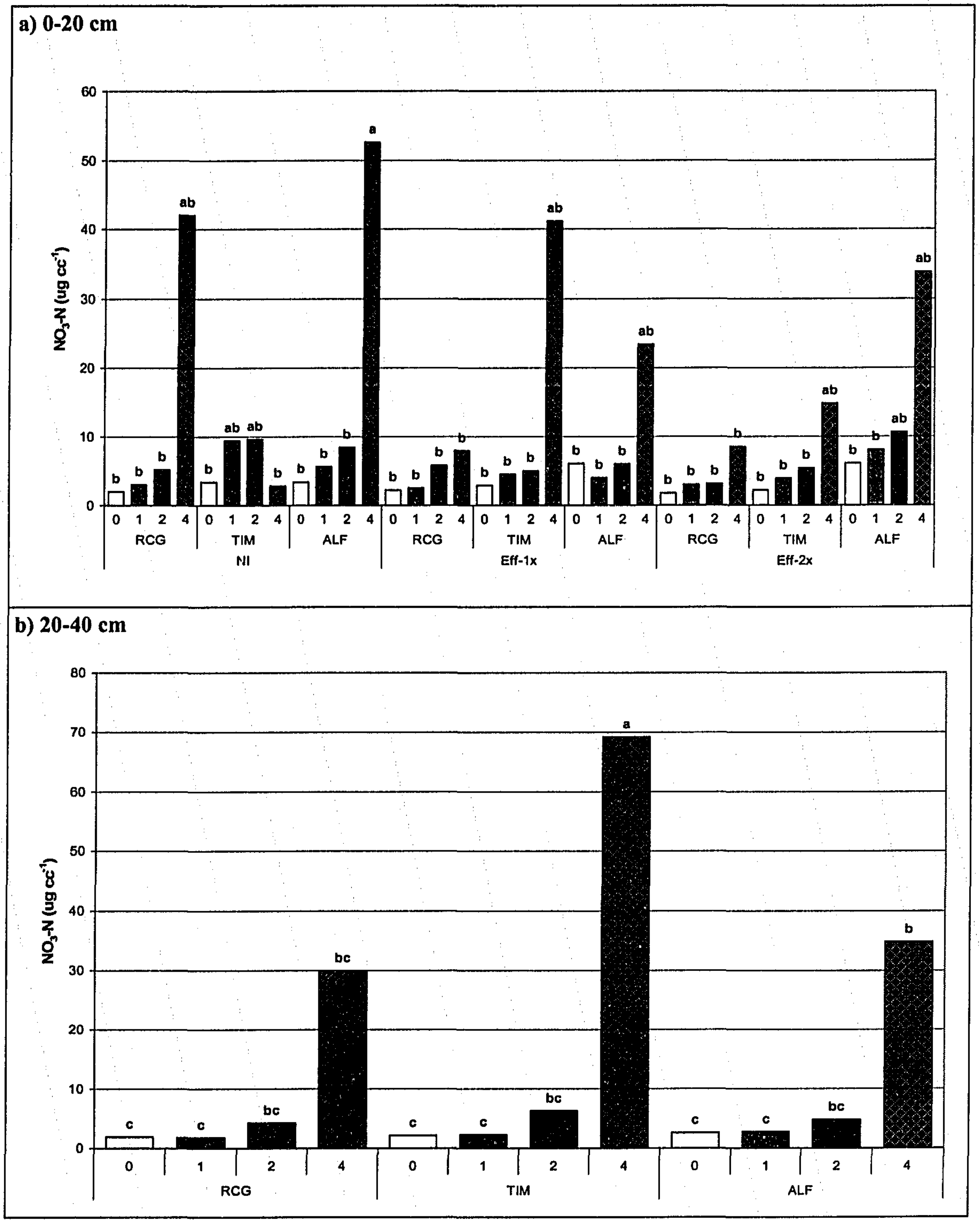


**Figure 2.2 Average soil $NO_3$-N concentrations for the 0-20 and 20-40 cm depth intervals**
0 = no fertilizer; 1 = 100 kg N $ha^{-1}$ $yr^{-1}$; 2 = 200 kg N $ha^{-1}$ $yr^{-1}$; 4 = 400 kg N $ha^{-1}$ $yr^{-1}$
RCG = reed canary grass; TIM = timothy; ALF = alfalfa
NI = non-irrigated; Eff-1x = low effluent irrigation rate; Eff-2x = high effluent irrigation rate
Same letters are not significantly different ($p < 0.05$)

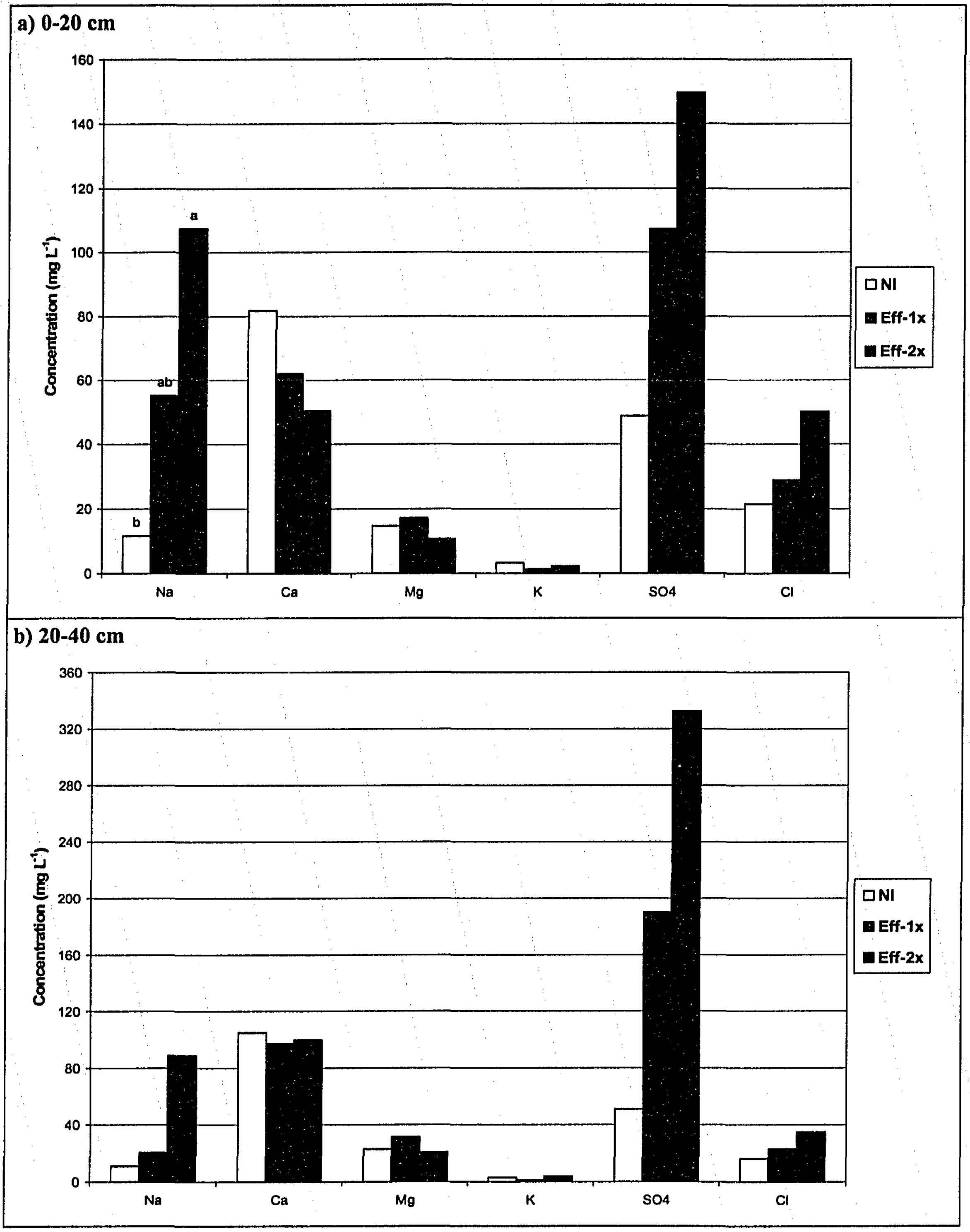


**Figure 2.3 Soil cation and anion concentrations for 0-20 and 20-40 cm depth intervals**
Same letters within treatments are not significantly different ($p < 0.05$); no letters indicate non-significance

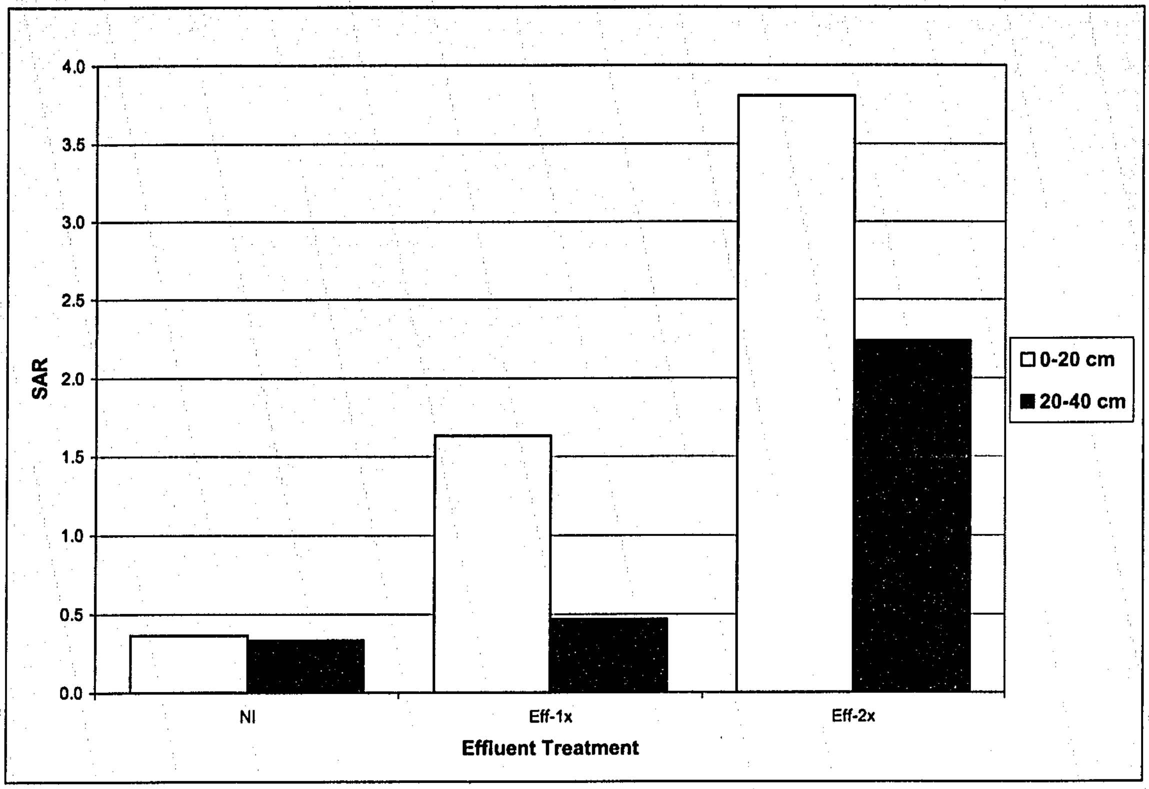


**Figure 2.4 Soil SAR values for the 0-20 and 20-40 cm depth intervals**
NI = non-irrigated; Eff-1x = low effluent irrigation rate; Eff-2x = high effluent irrigation rate
There were no significant treatment differences

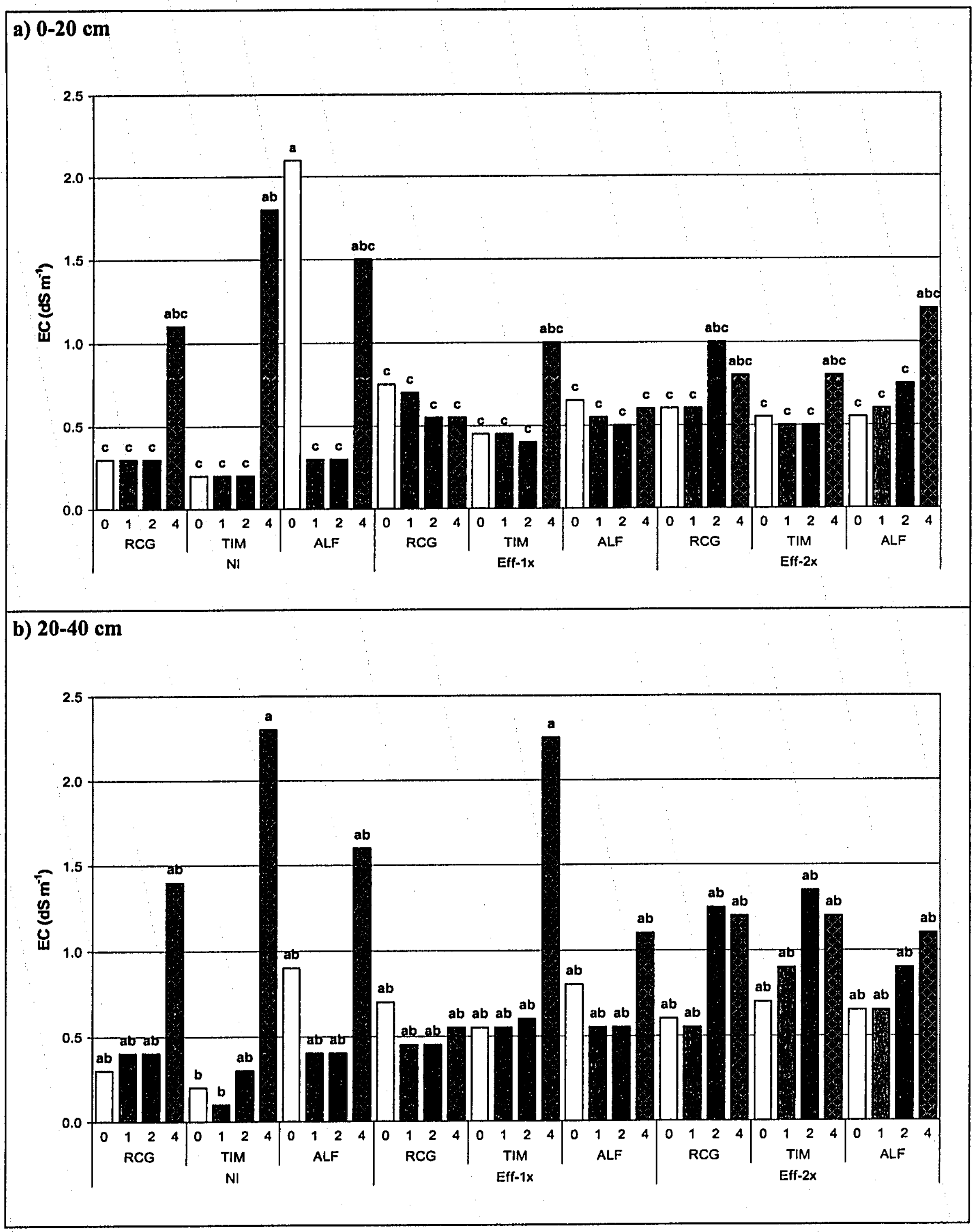


**Figure 2.5 Soil EC levels for the 0-20 and 20-40 cm depth intervals**
0 = no fertilizer; 1 = 100 kg N $ha^{-1}$ $yr^{-1}$; 2 = 200 kg N $ha^{-1}$ $yr^{-1}$; 4 = 400 kg N $ha^{-1}$ $yr^{-1}$
RCG = reed canary grass; TIM = timothy; ALF = alfalfa
NI = non-irrigated; Eff-1x = low irrigation rate; Eff-2x = high irrigation rate
Same letters are not significantly different ($p < 0.05$)

# 3 SOIL MOISTURE REGIMES OF AN ELUVIATED DYSTRIC BRUNISOL IRRIGATED WITH PULP MILL EFFLUENT

## 3.1 INTRODUCTION

Plant productivity depends on soil water availability and storage, which are affected by evaporation, transpiration, infiltration, soil water retention and internal drainage (Singh et al. 1998). If water is supplied in sufficient quantity and frequency to minimize moisture stress during the growing season, forage yields can be optimized (Hillel 1998). The goal of any irrigation scheme is to maintain a favourable soil water regime for optimal production (Singh et al. 1998). Land based effluent applications such as wastewater effluent irrigation can provide this water resource for forages, especially in areas with seasonal water deficits (Tillman and Surapaneni 2002).

Water becomes unavailable for plant productivity via surface runoff or deep drainage, but is retained through infiltration (Holechek et al. 1998). The amount and rate of water uptake depends on several factors including plant properties (growth stage and root development) and soil water retention and transmission properties (wetness, hydraulic conductivity, diffusivity, matric suction and salinity) (Hillel 1998; Singh et al. 1998). Meteorological conditions such as radiation, air temperature, relative humidity and wind speed, affect plant transpiration and soil water extraction rates (Hillel 1998) as well as soil water availability through hydrological processes (Singh et al. 1998). Seasonal distribution patterns, total quantity and intensity of growing season precipitation influence the degree to which soil-plant processes occur (Holechek et al. 1998), and often control maximum effluent irrigation applied without overloading soil hydrological capacity or reducing the effluent filtering process (Mahmood et al. 2003).

Land management practices, such as fertilization and harvesting, affect the soil water regime through effects on hydrologic processes (Twerdoff et al. 1999; Burk et al. 2000). For instance, mowing and haying reduce plant biomass thus decreasing evapotranspiration and water demand (Burk et al. 2000). However, reduced vegetative cover also increases bare ground and evaporation, reducing surface soil water; after harvest, increased plant growth increases evapotranspiration, increasing water demand.

Debaeke and Aboudrare (2004) reviewed several management practices to reduce water loss and increase water use efficiency in water limited environments. Nitrogen fertilization influenced soil water use in irrigated soils (Havlin et al. 1999). Fertilization improves water use efficiency and drought tolerance by enhancing root development, thereby increasing soil volume for water extraction (Havlin et al. 1999), and/or increasing the amount of water extracted from specific soil layers (Debaeke and Aboudrare 2004).

Eradki et al. (2004) studied nitrogen fertilization effects on the water balance of swamp mahogany and Rhodes grass plantations irrigated with treated sewage effluent. Recharge and discharge trends were similar among treatments, but nitrogen fertilizer treatments showed depth differences in water extraction. Wight and Black (1978) stated grassland productivity and water use efficiency can be greatly enhanced by fertilization and previous research has shown that nitrogen fertilization increases root growth and soil water extraction. On a mixed upland range fertilized vegetation extracted more soil water than non-fertilized, increasing over winter soil water recharge efficiency and providing a large storage reservoir when precipitation was adequate to recharge the soil profile.

Plant and soil characteristics, as well as land management practices, influence the amount, timing and/or frequency of irrigation. Thus applying optimum quantities of effluent via proper irrigation scheduling is important (Mahmood et al. 2003). Tillman and Surapaneni (2002) stated historical hydraulic properties determined wastewater application quantities and rates, and when wastewater disappeared and no surface runoff into waterways occurred, the disposal system was considered a success. They cautioned that amounts of wastewater applied in these systems were in excess of requirements for optimum productive use of irrigation water. By maintaining a sustainable hydraulic loading rate and by selecting plant species with high nutrient and water requirements, nutrient and water losses can be minimized (Eradki et al. 2004).

Legumes with long taproots, like alfalfa, withdraw water from deep in the soil profile, well below wilting point (-1.5 MPa) and the rooting zone of annual species (Jefferson and Cutforth 1997; Volenec and Nelson 2003). Jefferson and Cutforth (1997) found the largest alfalfa root mass in the upper 30 cm of soil, and soil water below 1.2 to 1.5 m was available to alfalfa, but unavailable to shallow rooted perennial grasses.

Where excess moisture creates an unfavourable environment for many forages, sod-forming reed canary grass can tolerate long-term waterlogged conditions (Volenec and Nelson 2003). Its persistence on poorly drained soils is superior; under moisture deficits, it is equal or superior to other cool season grasses because of its extensive root system (AAFRD 1981). When irrigated with municipal and industrial effluents, this grass has superior capacity to utilize nutrients and water (Linden et al. 1981; Patterson et al. 2002). Timothy has a medium to high water requirement and is somewhat tolerant of spring flooding, but not drought (AAFRD 2001). Therefore, irrigating timothy can greatly enhance productivity in dry climates or during drought periods (AAFRD 2001).

In the last decade, researchers have agreed that appropriate monitoring and evaluation of soil water is necessary to manage and operate land treatment systems or sustainable effluent irrigation schemes (Bond 1998). Maintaining soil moisture in the root zone at high levels and soil moisture suction at low levels will increase crop yields. However, the manager must take precautions to avoid excessive wetting, nutrient leaching and percolation, which might cause the groundwater table to rise and create salinization problems, possibly hindering future land use for crop production (Hillel 1998). Management must avoid such adverse effects by attempting to predict precipitation events and monitoring soil moisture content (Mahmood et al. 2003).

Soil water dynamics involve complex interactions among land management practices, cropping systems, soil properties and meteorological conditions (Twerdoff et al. 1999). Crop growth is dependent on antecedent soil water and efficiency of soil water storage in the profile (Twerdoff et al. 1999). Therefore management practices must ensure adequate soil water for plant growth, while minimizing adverse environmental effects to maintain a sustainable effluent irrigation scheme. The simplest method to monitor the adequacy of plant available soil water is to measure soil water content.

Most irrigation studies reviewed were conducted in arid and semi-arid regions and focussed on effects effluent irrigation had on soil physical properties such as hydraulic conductivity, infiltration and deep drainage rather than volumetric soil water content. For managers to operate sustainable and successful effluent irrigation schemes, they need simple methods to monitor soil water dynamics so they can make environmentally safe, short-term management decisions. To our knowledge, few wastewater irrigation studies have investigated the effects of pulp mill effluent irrigation on the soil water regime.

## 3.2 RESEARCH OBJECTIVES

The research objectives were to quantify effects of pulp mill effluent irrigation rates, forage treatments and nitrogen fertilization rates on the soil moisture regime; namely, total soil water, soil water with depth and soil water with time.

## 3.3 MATERIALS AND METHODS

### 3.3.1 Study Site

The study site is located in the Mid Boreal Mixedwood Ecoregion, approximately 200 km northwest of Edmonton, Alberta (Strong and Leggat 1992) and approximately 2 km south of the Alberta-Pacific Forest Industries Inc. bleached kraft pulp mill. The study area is 72 m x 43 m or 0.31 ha in size and is relatively uniform with 2 to 3% slopes, declining to the west or northwest. Specifically, the high effluent rate treatment and adjacent non-irrigated replicate was located upslope from the low effluent rate treatment and its adjacent non-irrigated replicate.

Soils are medium to coarse textured Luvisols and Eluviated Dystric Brunisols which are relatively low in pH, low in salt and well to rapidly draining (Proudfoot 2000). In low lying areas, gleying is evident with subsoil mottling indicative of imperfect drainage. Groundwater in monitoring wells in the northern and southern parts of the site was found between 216 and 278 cm (Proudfoot 2000). The site has been classified with good irrigation capability by sprinkler methods only.

Historical climate data from Canadian Climate Normals 1971 to 2000 (Environment Canada 2002) obtained from the Athabasca weather station about 72 km away, show average daily temperatures for the growing season (May to September) range from 10.6 °C in May, to a high of 16.2 °C in July, to a low of 9.8 °C in September. The Athabasca region averages 504 mm of precipitation annually, with 70% occurring during the growing season. The average number of growing degree days (degree days for a given day represent the number of Celsius degrees that the mean temperature is above 5 °C) from May to September is 1270 with the most (346) occurring in July.

Prior to this study, the field was summerfallowed for three years and before seedbed preparation in August 2002, glyphosate was applied for weed control. A fertilizer blend of 9-38-15 was broadcast at 323 kg $ha^{-1}$, supplying 30 kg $ha^{-1}$ of N, 123 kg $ha^{-1}$ of $P_2O_5$ and 50 kg $ha^{-1}$ of $K_2O$ to help with seed establishment.

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### 3.3.2 Meteorological Measurements

A Campbell Scientific UT10 meteorological station was installed at the site in June 2002 to record daily minimum and maximum air temperatures and relative humidity (HMP45C gauge), saturated and non-saturated vapour pressures, net radiation (Kipp and Zonen net radiometer) and total precipitation (TE525 tipping bucket). To compare average precipitation and temperature trends at the study site to long-term normals, 2003 and 2004 climate data and 1971 to 2000 long-term normals were obtained from Environment Canada's climate database for the Athabasca weather station.

### 3.3.3 Experimental Design

A split-strip plot design was used to study irrigation, forage and fertilizer treatment effects (Figure 3.1). There were 36 (3 x 3 x 4) treatment combinations replicated twice for a total of 72 experimental units or plots (each 2 m x 8 m).

Irrigation treatments were nested within replicates and consisted of non-irrigated (NI-1x and NI-2x), low effluent rate (Eff-1x) and high effluent rate (Eff-2x) treatments. The irrigation system was installed in 2003 consisting of a solid set sprinkler system with 5 cm diameter laterals and 12 m spacings between sprinklers along each lateral, covering approximately a 10 m radius. Irrigation timing was determined from on-site soil moisture measurements and weather, with no irrigation occurring under windy or rainy conditions.

During irrigation events, catch cans were placed strategically among the plots to evaluate irrigation variability.

Within each replicate, forage treatments were randomly seeded in rows or horizontal strips. The forage species were selected for their winter hardiness, successful establishment and tolerance to wet soil conditions. Alfalfa (*Medicago sativa* L. var. Algonquin), timothy (*Phleum pratense* L. var. Climax) and reed canary grass (*Phalaris arundinacea* L. var. Vantage) were seeded in early August 2002 at rates of 11, 11, and 10 kg/ha, respectively. For detailed forage species descriptions refer to the Appendix.

Fertilizer treatments, 0, 100, 200 and 400 kg N $ha^{-1}$ $yr^{-1}$ of ammonium nitrate (34-0-0-0), were randomly applied to the forage species in vertical strips (Figure 3.1). The fertilizer treatments were split into two applications and hand broadcast in spring and immediately after the first clipping. In 2003 the plots received applications of 0, 50, 100 and 200 kg N $ha^{-1}$ $yr^{-1}$ on June 4 and July 31. An error occurred during the July 31 application with all plots in the non-irrigated replicate adjacent the high effluent rate (NI-2x) receiving incorrect rates. Instead of 100 N receiving 50 kg N $ha^{-1}$ $yr^{-1}$, it got 100 kg N $ha^{-1}$ $yr^{-1}$; 200 N received 50 kg N $ha^{-1}$ $yr^{-1}$ instead of 100 kg N $ha^{-1}$ $yr^{-1}$; no fertilizer plots received 200 kg N $ha^{-1}$ $yr^{-1}$; 400 N received no fertilizer. The fertilizer application error was corrected in 2004 with 0, 50, 100 and 200 kg N $ha^{-1}$ $yr^{-1}$ applied to the original fertilizer treatments on June 2 and July 14. On June 2, an error occurred in Replicate 4 of the low effluent rate treatment with 0 N plots receiving 50 kg N $ha^{-1}$ $yr^{-1}$; 100 N received no fertilizer. This error was corrected during the July 14 fertilization. For total application rates applied per treatment by year, please refer to Table 3.1.

### 3.3.4 Effluent Characterization

The wastewater was a secondary treated effluent from a bleached kraft pulp mill. Laboratory analyses to characterize effluent salinity, nutrients (analyzed monthly) and trace elements (analyzed quarterly) provide the following medians. Monthly analyses (2002 to present) indicated a sodium adsorption ratio (SAR) of 10.7 and an adjusted SAR of 12.9, while daily analyses indicated electrical conductivity (EC) and pH were 2 dS $m^{-1}$ and 7.8, respectively. According to Alberta irrigation water quality standards, this effluent has pH values comparable to most natural surface waters and is considered fit for irrigation (Alberta Environment 2000). The same standards described the effluent as having hazardous SARs (>9) and possibly safe ECs (1.0 to 2.5 dS $m^{-1}$), making it available for restrictive irrigation purposes, and requiring a leaching fraction.

Ca (110 mg $L^{-1}$) and Mg (14 mg $L^{-1}$) occur in the effluent, but it is not a good source of N (0.10 mg $NO_3$-N $L^{-1}$ and 1.63 mg total Kjeldahl nitrogen (TKN) $L^{-1}$), P (0.67 mg dissolved P $L^{-1}$ and 1.03 mg total P $L^{-1}$) or potassium (K) (31 mg $L^{-1}$) as concentrations are low relative to plant requirements. Total organic carbon was 39.0 mg $L^{-1}$; no water use guidelines for irrigation purposes were found. Sulphate ($SO_4$) (532.5 mg $L^{-1}$), Na (312.5 mg $L^{-1}$) and chloride (Cl) (132.5 mg $L^{-1}$) occur in high concentrations and are of particular concern when considering effluent irrigation effects on plants and soil. All other micronutrients and trace metals were not detected or below 1 mg $L^{-1}$. Of those detected effluent contained aluminium (Al), iron (Fe) and manganese (Mn) at 0.40, 0.21 and 0.10 mg $L^{-1}$, respectively.

### 3.3.5 *Soil Moisture Instrumentation and Measurements*

Volumetric soil moisture was monitored throughout the 2003 and 2004 growing seasons via two methods. In early June 2003, 2 m aluminum access tubes were installed in the middle of the 0 and 400 N alfalfa plots to facilitate soil moisture readings with a Campbell Pacific Nuclear Model 503DR Hydroprobe (Gardner and Kirkham 1952). These treatments represented extreme fertilizer rates with high water using, deep rooted species. Readings were taken every two weeks in 10 cm depth intervals, starting at 15 cm below ground surface to the bottom of the tube. In 2003 readings began June 5 and ended October 7; in 2004 readings began May 12 and ended October 7. Water was present in several access tubes and depths to water were monitored consistently. In 2003 tubes located in the west plots had water at different depths; in 2004 all tubes had water at some point in the season. Where water was present, tubes were bailed and then measurements taken to 20 cm above the tube end or as deep as the rising water level.

For increased accuracy of near surface soil water, weekly readings were taken with a Delta T profile probe (type PR1) and a moisture meter (type HH2). Fifty cm long, closed-bottom fibreglass tubes were installed in the same fertilizer treatments as the aluminium access tubes, but in all three forages. June 2003 data consisted of only one replicate since half the access tubes were not installed until early July. In alfalfa plots, tubes were placed approximately 1 m east of the aluminum tubes. Readings began at 7.5 cm and continued at 10 cm intervals to 37.5 cm. 2003 readings started and ended at approximately the same dates as neutron probe readings; 2004 readings began on the same date, but ended one week later. Over the study and particularly in 2004, water was present in the bottom of one or two tubes within each irrigation treatment block, preventing readings at 27.5 and 37.5 cm. During readings condensation within the tubes was evident, and upon tube removal the silicon sealing at the bottom was found defective allowing soil water to enter the tube. In the spring some caps preventing water from entering the tubes came off, most likely due to air pressure changes within the tubes.

Instruments were calibrated to local field conditions to determine equations for volumetric moisture content. Volumetric moisture content was converted to cumulative total soil water (TSW) to 40 cm (TSW40) for the profile probe and 40 cm (TSW40), 80 cm (TSW80), 120 cm (TSW120) and 80 to 120 cm (TSW80-120) for the neutron probe.

To evaluate volumetric moisture with depth under extreme conditions, representative dates were selected. October 7, 2003 was selected as a dry day, and September 21, 2004 as the wet day. Total soil water was presented over time with previously determined wilting point (WP) and field capacity (FC) for the study site to indicate the range of available soil moisture.

### 3.3.6 Statistical Analyses

Data were not subjected to Analyses of Variance for total soil water or volumetric moisture over time or with depth for either profile or neutron probe data. Total soil water and volumetric moisture were discussed to characterize the site by irrigation and fertilizer treatments for neutron probe data since tubes were placed in alfalfa treatments only. Profile probe data were presented to include forage treatment comparisons since tubes were placed in all forage treatments.

Means and standard errors of means were determined for the neutron probe total soil water data, using four sample locations in each irrigated block (Eff-1x and Eff-2x) and 2 in each non-irrigated block for treatments since large variations in soil moisture occurred between the two non-irrigated replicates. Means and standard errors of means were also calculated for the two extreme fertilizer treatments with 6 sample locations each. Calculations were also made for profile probe data using 12 sample locations for each species.

Higher inherent soil moisture on the west side of the site, where the low effluent rate treatment (Eff-1x) and the adjacent non-irrigated replicate (NI-1x) were located, would not have reflected true differences among irrigation treatments compared to the east side where the high rate treatment (Eff-2x) was located. Thus, comparisons between Eff-1x and Eff-2x were deemed tenuous, but comparisons were made between an irrigation treatment and its adjacent non-irrigated replicate (NI-1x with Eff-1x and NI-2x with Eff-2x).

## 3.4 Results And Discussion

### 3.4.1 Meteorological Trends

Annual precipitation at Athabasca was 2.4% below and 13.5% above the long-term normal (LTN) in 2003 and 2004, respectively (Table 3.2). The corresponding growing season precipitation was 7.1% below and 10.8% above LTN, respectively. On-site annual total precipitation was 28.4% and 8.3% less, and growing season precipitation was 35.5% less and 2.9% more than at Athabasca for 2003 and 2004, respectively. On-site precipitation in 2003 was notably low in May and July to September and notably high in June. In 2004 precipitation was notably high in May and July to September and notably low in June. The total number of rainy days on-site during the growing season was 82 in 2004 and 41 in 2003.

The 2003 and 2004 growing seasons at Athabasca had 213 and 101 degree days fewer than the LTN, respectively (Table 3.3). On-site growing season data indicated 231 more and 109 fewer degree days than at Athabasca in 2003 and 2004, respectively. On-site, the 2003 growing season had 228 degree days more than 2004. Both data sets indicated July had the highest number of growing degree days.

Average daily temperatures for the growing seasons were similar between locations, while Athabasca annual temperatures were similar to LTN (Table 3.3). May and September 2004 had lower average temperatures than the same months in 2003 and the LTN, while June and July for both years had similar average temperatures on-site and at Athabasca. The greatest difference in average daily temperatures between years occurred in August when 2003 averages were 2 to 3 °C higher than 2004. August and September 2004 were notably wetter and cooler than in 2003.

In summary, 2003 was a drier year on-site with more growing degree days than 2004, which received almost twice the precipitation over the growing season. Thus the weather conditions may have influenced soil properties as total soil water and soil moisture content increased and decreased with precipitation events.

### 3.4.2 Effluent Irrigation Depths and Variability

In late summer 2003, low effluent rate treatments received an average of 30 mm of effluent, while high rate treatments received 60 mm, via two irrigation events on August 20 and September 5. Irrigation did not occur prior to August due to different maturation and harvest timing of the forages. In 2004, low and high rate treatments received 75 and 150 mm, respectively, over three irrigation events on June 24, June 26 and July 28. No further irrigation events occurred in 2004 due to wet soil moisture conditions from many precipitation events.

During irrigation events, measured depths of applied effluent indicated that not all plots received the same amount of effluent in a given irrigation event (data not shown). Plots on the outer edge of the treatment blocks received less than 50% of the amount received along the sprinkler laterals (Figure 3.1). Replicate blocks south of the laterals received slightly more effluent than blocks on the north side. Possible reasons for this include sprinkler rotation setup and wind direction at the time of irrigation.

### 3.4.3 Soil Moisture Access Tube Depths to Water

Water was found in the open ended access tubes in low rate effluent treatment blocks and adjacent non-irrigated (NI-1x) replicates in both years; whereas noticeable water was found in tubes in high rate treatment blocks and adjacent non-irrigated replicates (NI-2x) only in 2004 (Figure 3.2). In 2003, depths to water were greater than 125 cm, but in 2004 depths were less than 125 cm from late July until the end of the study; hence likely having a significant influence on soil moisture over that period. Over 2003, depths to water gradually increased for all treatment blocks, while in 2004 depths to water decreased, especially following precipitation events. Similar trends occurred between the effluent irrigated treatments over time, but tubes in the low rate treatment along with its non-irrigated replicate had the shallowest depths to water. Tubes in each non-irrigated replicate had similar depths to water as their adjacent irrigated treatment.

### 3.4.4 Neutron Probe

#### 3.4.4.1 Total Soil Water

Non-irrigated treatments in both years had lower total soil water to 40 cm (TSW40) than their respective irrigated treatments throughout the study (Table 3.3). For visual trends in TSW40 in relation to precipitation amounts and irrigation timing, refer to Figure 6.1 in Appendix. When precipitation was low and the first irrigation event occurred in mid August 2003, the difference between the high rate and its respective non-irrigated treatment increased, while the difference between the low rate and its non-irrigated treatment decreased. After all irrigation events occurred, non-irrigated values decreased to 50 and 85 mm lower than low and high irrigation rates, respectively.

In 2004, the first irrigation event in late June also increased the difference between the low and high rates and their non-irrigated treatments. The low rate had 39 mm more TSW40 than NI-1x before irrigation and 66 mm after irrigation; the high rate had 18 mm more than NI-2x prior to irrigation and 67 mm more thereafter (Table 3.3). Non-irrigated trends were similar to irrigated treatments over time, except after June irrigation when NI-1x had 65 mm lower soil water than the low rate and NI-2x had 67 mm lower than the high rate. After July irrigation, high effluent rate values increased while other treatments showed little change.

For non-irrigated replicates, total soil water trends were similar with time, with differences between them from 8 to 21 mm in 2003 and 2 to 30 mm in 2004 and greatest differences occurring in August of both years. NI-1x (adjacent the low rate treatment) had higher TSW40 than NI-2x (adjacent the high rate treatment) through most of the study except in July 2003. Similarly, the low rate mostly had higher values than the high rate.

TSW40 generally decreased over time in 2003 and increased in 2004 (Table 3.3). In the first year, NI-1x and NI-2x TSW40 was below wilting point 50 and 60% of the time, respectively, when little precipitation occurred (mid July onwards). In 2004, they were above wilting point 100 and 91% of the time, being near it only once (June 28) due to the large amount of precipitation (Table 3.1). Low and high effluent rate TSW40 remained above wilting point throughout both years. However, in late July 2003, prior to irrigation, TSW40 for the high rate was near wilting point. Low effluent rate values in 2003 were below field capacity 70% of the time (after late July) again when precipitation was low, but throughout 2004 remained near or above field capacity. High effluent rate soil water remained below field capacity throughout 2003, but in 2004, remained below until late July when irrigation occurred, after which it was near field capacity.

In 2003, effluent irrigation increased the difference in TSW40 between irrigated and non-irrigated treatments (Table 3.3). Although there was more precipitation in 2004, soil water differences between non-irrigated and irrigated treatments were still evident after irrigation events in late June and late July. At the end of 2004 measurements, there was less difference in TSW40 between irrigated and non-irrigated treatments, while differences in soil water increased between the two effluent rate treatments compared to immediately after irrigation.

Trends in TSW80 were similar to TSW40 for both growing seasons with the low effluent rate treatment being highest and irrigated treatments having higher total soil water than their respective non-irrigated treatments throughout the study (Table 3.4). However, differences in TSW80 between irrigated treatments decreased after irrigation in 2003 only. Where differences between the low rate and NI-1x TSW40 values at the end of the season were more evident, TSW80 values between the two became closer; whereas the high rate still had higher TSW80 than NI-2x. After irrigation, differences in TSW80 again were greater between irrigated versus non-irrigated treatments, being most evident between the high effluent rate and NI-2x.

High rate TSW80 generally remained below field capacity, except in September and October 2004 when values were near field capacity (Table 3.4). Low rate values were above field capacity 20% (early June and July) and 73% (after June) of the time in 2003 and 2004, respectively. Most irrigation treatments were generally above wilting point, except NI-2x, which was below wilting point 70% and 18% of the time in 2003 (from late August onwards) and 2004, respectively. TSW80 for NI-1x remained near or above wilting point the latter part of 2003, but surpassed field capacity the latter part of 2004.

Irrigated treatments had higher TSW120 than non-irrigated treatments, particularly the high effluent rate after irrigation in 2003 and the first event in 2004 (Table 3.5). Similar trends between irrigated and adjacent non-irrigated treatments occurred again, except in the latter part of 2003 and late June 2004 after irrigation. Greater differences in TSW120 were evident between NI-1x and NI-2x and their associated low and high rate treatments compared to TSW80.

For TSW120, NI-2x was the only treatment near or below wilting point, particularly in 2003; while NI-1x and low and high rate treatments were always above wilting point (Table 3.5). Most treatments remained below field capacity, except NI-1x and the low rate. In 2004, NI-1x and low rate values were near, and even surpassed field capacity about mid July. The low rate had TSW120 values above field capacity 20% (early June and July) and 82% (after June) of the time in 2003 and 2004, respectively.

Unlike TSW40, TSW80 and most TSW120 values, average TSW80-120 values for NI-1x were similar to those of the low rate, while NI-2x was similar to the high rate throughout the study (Table 3.6). Differences between the two irrigation rates were most noticeable as TSW80-120 was as much as 77 and 55 mm higher for the low rate than the high rate in 2003 and 2004, respectively.

TSW40, TSW80, TSW120 and TSW80-120 magnitudes and trends were similar for the two extreme fertilizer treatments in both years (Tables 3.3 to 3.6). For instance, only a difference of 3.8% (relative) in total soil water occurred between 80 and 120 cm.

### 3.4.4.2 Volumetric Moisture Content with Depth

The low rate had highest volumetric soil moisture throughout the soil profile for both representative dry and wet days (Figure 3.3). Both NI-1x and NI-2x had lower moisture near the surface than their respective effluent rate treatments with smaller differences occurring on the wet day.

For the dry day, NI-1x had slightly higher soil moisture than the low rate beyond 55 cm. The high rate had higher moisture than NI-2x to a depth of 75 cm, after which they were similar. Beyond 125 cm, NI-2x had higher soil moisture than the high rate. The non-irrigated treatments had especially low moistures (less than 10%, absolute) at depths shallower than 40 cm for NI-1x and 80 cm for NI-2x on the dry day.

For the wet day, NI-2x had lowest soil moisture to 80 cm, beyond that values were similar to the high rate. Above 40 cm, NI-1x had slightly lower moisture than the low rate. Again, the low rate treatment had the highest soil moisture to 35 cm, after which values were similar to NI-1x.

All treatments gained soil moisture at most depths between dry and wet days, especially near the surface (Figure 3.3). The NI-2x and high effluent rate treatments gained water at all depths, whereas other treatments gained little beyond 120 to 140 cm.

#### 3.4.4.3 Volumetric Moisture Content with Time

Volumetric moisture content at depths of 35 and 65 cm generally decreased over time in 2003 (Figure 3.4) and increased in 2004 (Figure 3.5). At 35 cm, the NI-2x treatment had the lowest moisture for both years and was substantially lower than the high effluent rate treatment most of the time, unlike NI-1x, which was only slightly lower than the low rate. All treatments had moisture contents below field capacity in 2003, while NI-1x and NI-2x had values below wilting point after August. In 2004, most treatments were above wilting point, except NI-2x which was near wilting point most of the time, except in the latter part of the season when all other treatments were near or above field capacity.

For depths of 65, 95 and 125 cm for both years, trends were consistent, as the low rate and NI-1x were similar; the high rate and NI-2x also had similar values. Non-irrigated replicate moisture contents mimicked their adjacent irrigated treatment most of the time, except at 65 cm when NI-2x had lower moisture than the high effluent rate in the latter part of 2003 and 2004. Volumetric moisture generally increased with depth, while the two effluent rate treatments became more similar. In 2004, all treatments had more similar values at 125 cm.

Moisture contents at 65 cm for the high rate and NI-2x treatments were near wilting point most of 2003 and 2004, except when NI-2x values decreased after August 2003 and high rate values increased in September 2004. Values at 65 cm for the low rate and NI-1x were near field capacity at the start of the 2003 season, declining thereafter; while 2004 values were near or above field capacity at all times. At 95 cm, high rate and NI-2x values for both years were between field capacity and wilting point most times, with moisture contents near field capacity at the end of the 2004 season . The low rate and NI-1x had moisture contents near or above field capacity throughout 2003 and 2004. Values for field capacities and wilting points beyond 100 cm were not available.

### 3.4.5 Profile Probe

#### 3.4.5.1 Total Soil Water

Average TSW40 for each forage species decreased in 2003, then slightly increased in 2004 (Table 3.7). All species had similar increases and decreases in average TSW40 over time. Reed canary grass generally had slightly higher TSW40 than the other forage species; timothy had the lowest throughout the study, although treatment differences were small. Differences in TSW40 between reed canary grass and alfalfa were less than 9 mm in 2003 and 11 mm in 2004, while differences between reed canary grass and timothy were less than 18 mm in 2003 and 12 mm in 2004. The greatest difference among forage species occurred early in 2003 when reed canary grass and alfalfa had similar, but higher TSW40 than timothy.

Within non-irrigated treatments, reed canary grass had the highest total soil water followed by alfalfa and timothy (data not shown). Interestingly within NI-1x, differences in total soil water among species were smaller than differences within NI-2x. Irrigated treatments had different rankings and magnitudes in TSW40 among species. In the low effluent rate treatment, all forage species had similar results. Conversely, alfalfa had clearly the highest TSW40 in the high effluent rate treatment, followed by reed canary grass then timothy. Differences among forage species in the high rate treatment were greater than any other irrigation treatment. These trends were consistent throughout both years with smaller differences occurring in the wetter year (2004).

### 3.4.5.2 Volumetric Moisture Content with Depth

Among forage treatments, less than 5% (absolute) differences in moisture with depth occurred, particularly when soil moisture was high (Figure 3.6). Moisture content remained similar or increased with depth for all forage species on the wet day, but on the dry day decreased below 27.5 cm, especially for reed canary grass. This species was the most dynamic water user with different trends with depth within irrigation treatments.

Reed canary grass in NI-1x, had the lowest near surface soil moisture and highest moisture mid profile for both days; alfalfa was similar to timothy with depth (Figure 3.6). Similar near surface trends were evident in low effluent rate treatments as timothy was highest, followed by alfalfa then reed canary grass for both moisture conditions. Below 17.5 cm in the low rate treatment, reed canary grass had the highest and alfalfa the lowest moisture for the dry day. For the wet day, timothy had the highest moisture throughout the profile, while alfalfa and reed canary grass were similar. Within NI-2x, all species had similar moisture near the surface; while at the bottom of the profile, reed canary grass had higher percentages than timothy and alfalfa. Alfalfa in the high rate treatment consistently had highest moisture throughout the profile, while reed canary grass and timothy had the lowest near the surface and at the bottom of the profile, respectively.

### 3.4.5.3 Volumetric Moisture Content with Time

Forages had similar volumetric moisture with time during both growing seasons, especially at 37.5 cm. However, at 7.5 cm, timothy had noticeably lower volumetric moisture than reed canary grass and alfalfa, which were similar (data not shown).

Within irrigation treatments, average moisture at 7.5 cm among forage species was similar. Within the high effluent rate treatment timothy had 4 to 11% (absolute) lower volumetric moisture than alfalfa and reed canary grass at times during the study. At 37.5 cm, similar moisture occurred among species in the non-irrigated replicate adjacent the low effluent rate treatment block. Within the other non-irrigated replicate, reed canary grass had 10 to 15% (absolute) higher moisture than the other species, which were similar. Smaller differences among forage species occurred in irrigated treatments. Alfalfa had the highest moisture in the high rate treatment, while timothy had the highest moisture in the low rate treatment for both years.

### 3.4.6 General Discussion

Prior to irrigation events in both years, soil moisture was highest in the low effluent rate treatment, followed by the high rate, the non-irrigated replicate adjacent the low rate and the non-irrigated replicate adjacent the high rate. The study site slopes downwards from the southeast corner (where high rate treatment blocks were located) to the northwest corner (where low effluent rate treatment blocks were located). Since there was less distance to water in the soil moisture access tubes in the low effluent rate treatment throughout the study, the water table was likely consistently higher in the low effluent rate treatment and its associated non-irrigated replicate than in other treatment blocks. Therefore, soil moisture could have been naturally higher in the low effluent rate treatment than in the high rate treatment. This could have influenced plant water demands and responses to irrigation events, and made it difficult to assess the influence of irrigation rate on soil moisture regime. Hence, no definitive conclusions can be drawn regarding irrigation rate treatment effects on the soil moisture regime.

Total soil water and volumetric moisture content increases occurred only in the high effluent rate treatment post-irrigation for both years, while the low effluent rate maintained soil moisture longer than the high rate. This was more evident in total soil water from 0 to 80 cm as few changes occurred over time from 80 to 120 cm. This was also evident with volumetric moisture content with depth for dry and wet days. Lack of response to effluent applications of the low effluent rate in 2003 may have been due to late timing and low number of irrigation events in this drier year, and thus low amounts of effluent applied. Shallow groundwater also helped forage stands establish better thus increasing water demand on the west side of the site, compared to the east side where the high rate treatment had poor forage establishment due to low soil moisture. In 2004, soil moisture in the low effluent rate treatment was near or above field capacity at 40 cm later in the season and beyond 40 cm during the entire study, thus there was little variation in moisture content, but a constant increase with continuous rain events over the season.

Singh et al. (1998) found that with above normal precipitation, irrigation treatments were similar, but below normal averages, advantages of treatments become evident. They concluded irrigation treatments may not have affected soil water content as expected because of favourable inherent soil characteristics such as high organic matter content and good aggregation. Similarly in this study, if the soil had low moisture contents at all times prior to irrigation treatments, then treatment effects may have been more evident. For instance, when moisture conditions were poor in the latter part of the 2003 growing season, the high rate treatment clearly had higher total soil water and volumetric moisture than the adjacent non-irrigated replicate after irrigation events.

The constant increase in soil moisture in 2004 was evident with non-irrigated treatment replicates. However, in the latter part of 2003, when irrigated treatments remained above wilting point, non-irrigated treatment replicates were below wilting point, illustrating that irrigation was needed to maintain plant available water, as evident with low and high rate irrigation treatments. In 2004, irrigated treatments maintained pre-irrigation soil moisture after the first irrigation, while soil moisture contents of non-irrigated treatment replicates decreased to wilting point. This also indicated irrigation successfully maintained plant available water at this time. This was not as evident after the second irrigation event because of the amount of rain received prior to irrigation.

Considering forage species within irrigation treatments, only non-irrigated treatment blocks had higher soil moisture in reed canary grass than other forages for both years. Interestingly, both non-irrigated treatment blocks had reed canary grass down slope from the other species, which may have decreased the depth to water from ground surface. Alfalfa, with one replicate located down slope from the other species, had the shallowest depth to water and highest total soil water with the high effluent rate.

Differences among forage species in total soil water to 40 cm were smaller in the low effluent rate treatment and its adjacent non-irrigated replicate than the high rate treatment and its non-irrigated replicate. The uniformity among forage species in total soil water within the low effluent rate could be because the land was sloped less than in the high rate treatment, thus decreasing depth to water. Due to differences in forage treatment location on the slope, it was difficult to discern which forage species was the higher water user. However, timothy, with its short fibrous roots, seemed to use the most water within 40 cm of the surface in the high effluent rate treatment compared to other deeper rooted species known to be higher water users. Reed canary grass was the most dynamic water user within most irrigation treatments. Since the profile probe only measured to 40 cm depths in each forage treatment, one cannot compare forage species and their soil water regimes beyond 40 cm. However, Hillel (1998) stated that non-uniformity of water uptake from different soil depths have been due to different root development. If root density is high (in soil surface layer) then water depletion is high, but if root density is low (as in lower layers) then water depletion is low.

The soil moisture regime could have been influenced by forage harvest, as increases in soil moisture occurred in each irrigation treatment after harvests. This was particularly true immediately after the first harvest in 2004 when both non-irrigated replicates had a sharp increase in soil moisture. Mowing and haying reduces plant biomass and thus reduces evapotranspiration, decreasing the demand for water (Burk et al. 2000). However, plant growth after harvest increases evapotranspiration, thereby increasing the demand for water as seen with slight decreases a few days after harvest (Burk et al. 2000), especially when moisture was limiting in 2003.

No differences existed in soil moisture regimes between 0 N and 400 N fertilizer treatments. This was unexpected as N promotes vegetative growth and thus increases photosynthetic activity and evapotranspiration, depleting soil moisture reserves (Havlin et al. 1999). The lack of response could be due to random placement of fertilizer strips and their relative adjacent locations to the sprinklers. Irrigation efficiency patterns as detected by the catch cans indicated amounts of effluent applied were greater near the sprinkler laterals than the outer edge of treatment blocks. Therefore if in one replicate, 0 N was placed further from the sprinklers than 400 N (as in Eff-2x in Figure 3.1), then 0 N would receive less effluent and vice versa, thus dampening fertilizer effects on soil water differences. Conversely, the fertilizer application error that occurred in NI-2x in late July 2003 did not seem to affect soil water differences between fertilizer treatments as trends prior to and after the error were similar.

Improved growth and more plant canopy cover from additional fertilizer would likely reduce surface evaporation, thus conserving near-surface soil moisture. Fertilizer would improve plant and root growth, increasing water demand and decreasing available water deeper in the profile around the root zone. Eradki et al. (2004) found that in low N treatments, as surface soil went through recharge and discharge cycles, layers below 40 cm had high water with little response to irrigation or rainfall; in high N treatments, water extraction occurred from most soil layers. They also discussed that fertilization decreases crop water requirements, increases early plant canopy growth, providing more residues, thus reducing soil evaporation and decreasing water losses.

## 3.5 CONCLUSIONS

The effects of irrigation rates, forage treatments and nitrogen fertilization rates on the soil water regime at the study site were difficult to quantify, for several reasons, and hence the specific hypotheses could not be definitively assessed. Shallow water levels where the low effluent rate treatment and its non-irrigated replicate were located and the large amount of precipitation received in 2004 caused the low irrigation rate to have higher soil water than the high rate, an unexpected result. However, irrigation at the high rate increased soil moisture under low soil moisture conditions in the latter part of 2003, compared to its adjacent non-irrigated replicate.

Only small differences between the two extreme fertilizer treatments were evident, but that may have been due to treatment location relative to the sprinkler laterals and to irrigation non-uniformity. Only small differences in soil moisture, most evident in the wet year, occurred among forage treatments. However, reed canary grass was the most dynamic water user with depth.

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**Table 3.1 Fertilizer application rate totals (kg N $ha^{-1}$ $yr^{-1}$) for replicates 1 and 4**

| Replicate | Treatment | June 2003 | July 2003 | 2003 Total | June 2004 | July 2004 | 2004 Total |
|---|---|---|---|---|---|---|---|
| 1 | 0 | 0 | 200 | 200 | 0 | 0 | 0 |
| | 100 | 50 | 100 | 150 | 50 | 50 | 100 |
| | 200 | 100 | 50 | 150 | 100 | 100 | 200 |
| | 400 | 200 | 0 | 200 | 200 | 200 | 400 |
| 4 | 0 | 0 | 0 | 0 | 50 | 0 | 50 |
| | 100 | 50 | 50 | 100 | 0 | 50 | 50 |
| | 200 | 100 | 100 | 200 | 100 | 100 | 200 |
| | 400 | 200 | 200 | 400 | 200 | 200 | 400 |

**Table 3.2 Average total precipitation for 2003 and 2004, including long-term normals for Athabasca**

| Month | Total Precipitation (mm) | | | | |
|---|---|---|---|---|---|
| | On-site | | Athabasca* | | |
| | 2003 | 2004 | 2003 | 2004 | LTN |
| January | 24.6 | 26.4 | 45.7 | 43.0 | 24.9 |
| February | 22.9 | 19.1 | 19.0 | 7.0 | 18.6 |
| March | 29.5 | 24.6 | 26.2 | 17.0 | 17.7 |
| April | 9.9 | 16.0 | 23.4 | 32.0 | 25.5 |
| May | 11.4 | 103.6 | 45.7 | 69.7 | 47.3 |
| June | 109.0 | 29.2 | 149.3 | 11.7 | 91.7 |
| July | 42.3 | 116.1 | 78.1 | 165.9 | 104.5 |
| August | 36.6 | 76.5 | 35.8 | 60.9 | 62.3 |
| September | 9.4 | 71.9 | 14.8 | 78.0 | 42.8 |
| October | 27.7 | 18.0 | 18.9 | 34.5 | 21.4 |
| November | 21.3 | 5.1 | 20.5 | 14.5 | 21.1 |
| December | 7.4 | 17.3 | 14.0 | 37.0 | 25.5 |
| Growing Season | 208.7 | 397.3 | 323.7 | 386.2 | 348.6 |
| Annual Total | 352.0 | 523.7 | 491.4 | 571.2 | 503.3 |

* Data from weather station located near Athabasca
LTN = Long-term Canadian climate normals 1971-2000
Growing Season = May to October

**Table 3.3 Average growing degree days and air temperature for 2003 and 2004, including long-term normals for Athabasca**

| Month | Growing Degree Days (above 5 °C) | | | | | Average Air Temperature (°C) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | On-site | | Athabasca* | | | On-site | | Athabasca | | |
| | 2003 | 2004 | 2003 | 2004 | LTN | 2003 | 2004 | 2003 | 2004 | LTN |
| **January** | 0.9 | 0.0 | 0.0 | 0.0 | 0.3 | -14.3 | -18.2 | -13.6 | -17.2 | -14.9 |
| **February** | 0.0 | 0.0 | 0.0 | 0.0 | 0.6 | -12.3 | -9.4 | -10.8 | -8.5 | -10.7 |
| **March** | 0.0 | 0.9 | 0.0 | 2.0 | 1.3 | -9.9 | -4.0 | -9.1 | -2.4 | -4.4 |
| **April** | 42.0 | 26.4 | 49.8 | 32.9 | 47.6 | 3.5 | 4.2 | 3.7 | 4.4 | 4.2 |
| **May** | 156.7 | 94.7 | 164.0 | 110.1 | 177.8 | 9.5 | 7.2 | 9.3 | 7.5 | 10.6 |
| **June** | 251.3 | 241.2 | 132.0^ | 273.2 | 278.3 | 13.7 | 14.0 | 14.8 | 14.1 | 14.2 |
| **July** | 373.5 | 366.4 | 380.5 | 389.6 | 346.1 | 17.3 | 17.1 | 17.3 | 17.6 | 16.2 |
| **August** | 349.4 | 250.1 | 351.0 | 291.4 | 314.6 | 16.4 | 13.5 | 16.3 | 14.4 | 15.2 |
| **September** | 157.1 | 108.0 | 162.0 | 105.4 | 153.6 | 9.7 | 7.8 | 10.2 | 8.3 | 9.8 |
| **October** | 77.6 | 43.4 | 79.0 | 32.5 | 47.9 | 5.0 | 1.2 | 5.6 | 1.3 | 4.1 |
| **November** | 0.0 | 1.1 | 0.0 | 1.0 | 1.5 | -9.5 | -1.9 | -8.5 | -1.3 | -6.2 |
| **December** | 0.0 | 0.0 | 0.0 | 0.5 | 0.3 | -12.0 | -11.7 | -11.2 | -11.2 | -12.9 |
| **Growing Season** | 1288.0 | 1060.4 | 1057.5 | 1169.7 | 1270.4 | 13.3 | 11.9 | 13.6 | 12.4 | 13.2 |
| **Annual Total** | 1408.5 | 1132.1 | 1186.3 | 1238.6 | 1369.9 | 1.43 | 1.65 | 2.00 | 2.25 | 2.10 |

Growing degree days represent number of Celsius degrees that mean temperature > 5 °C
* Data from weather station located near Athabasca
LTN = Long-term Canadian climate normals 1971-2000
^ Daily average temperatures incomplete from June 4 to 17, 2003

Table 3.4 Neutron probe total soil water (mm) to 40 cm (TSW40) for 2003 and 2004

| Date | Ppt* (mm) | Irrigation | | | | Fertilizer | |
|---|---|---|---|---|---|---|---|
| | | NI-1x | Eff-1x | NI-2x | Eff-2x | 0 N | 400 N |
| **2003** | | | | | | | |
| **June 5** | n/a | 90.0 (1.7)^ | 125.0 (1.0) | 72.4 (2.6) | 103.8 (4.1) | 102.9 (8.4) | 103.8 (8.7) |
| **June 19** | 0.3 | 60.0 (0.9) | 102.0 (3.6) | 42.3 (4.0) | 67.4 (6.3) | 74.9 (10.1) | 72.2 (10.5) |
| **July 3** | 102.8 | 73.5 (1.1) | 128.2 (0.7) | 83.6 (6.6) | 100.1 (2.9) | 102.4 (9.3) | 102.2 (9.5) |
| **July 16** | 13.7 | 51.1 (1.9) | 115.2 (3.4) | 59.3 (9.5) | 76.4 (3.9) | 85.2 (11.5) | 79.3 (11.4) |
| **July 31** | 20.6 | 32.9 (3.6) | 82.1 (13.1) | 15.5 (8.1) | 39.3 (3.0) | 52.4 (13.5) | 44.7 (11.9) |
| **August 13** | 28.2 | 45.1 (3.3) | 104.4 (2.1) | 27.9 (13.7) | 45.9 (4.9) | 62.1 (13.7) | 62.4 (14.4) |
| **August 28** | 7.4 | 22.8 (0.0) | 74.6 (11.1) | 2.1 (2.1) | 63.9 (13.9) | 44.7 (13.2) | 55.9 (15.8) |
| **September 10** | 2.8 | 16.2 (2.3) | 67.6 (9.4) | 0.0 (0.0) | 85.5 (15.4) | 51.7 (15.4) | 55.8 (18.4) |
| **September 23** | 7.6 | 18.8 (0.3) | 65.4 (9.6) | 0.0 (0.0) | 72.3 (13.0) | 45.7 (13.2) | 52.4 (16.0) |
| **October 7** | 0.0 | 18.7 (1.7) | 57.4 (8.9) | 0.0 (0.0) | 53.8 (11.6) | 35.9 (9.8) | 44.5 (13.6) |
| **2004** | | | | | | | |
| **May 12** | n/a | 75.8 (0.8) | 114.3 (2.6) | 73.5 (1.6) | 95.4 (4.5) | 93.4 (8.1) | 96.1 (7.0) |
| **May 26** | 21.1 | 66.1 (3.8) | 111.7 (2.5) | 57.7 (0.6) | 86.7 (7.2) | 86.3 (10.2) | 87.2 (9.4) |
| **June 9** | 75.7 | 76.0 (1.7) | 114.7 (2.6) | 73.4 (0.2) | 90.7 (4.2) | 92.5 (7.8) | 94.2 (7.5) |
| **June 28** | 23.9 | 45.3 (4.9) | 110.9 (4.8) | 20.9 (2.3) | 88.0 (5.4) | 78.0 (14.9) | 76.6 (15.7) |
| **July 13** | 65.0 | 94.8 (0.9) | 130.1 (4.2) | 74.6 (2.5) | 105.2 (4.2) | 107.2 (9.2) | 106.1 (9.0) |
| **July 29** | 50.5 | 92.1 (2.6) | 133.6 (4.2) | 83.2 (5.1) | 126.9 (4.3) | 117.0 (8.9) | 115.1 (10.2) |
| **August 10** | 37.1 | 95.1 (1.6) | 133.5 (2.3) | 85.4 (6.6) | 113.9 (3.8) | 113.0 (7.8) | 112.1 (8.9) |
| **August 24** | 15.0 | 79.1 (4.6) | 127.7 (2.9) | 49.5 (10.2) | 97.5 (7.8) | 94.7 (12.1) | 98.3 (13.6) |
| **September 7** | 51.3 | 107.2 (0.1) | 147.3 (1.5) | 93.5 (8.1) | 125.3 (2.3) | 125.2 (8.1) | 123.4 (9.7) |
| **September 21** | 45.5 | 128.6 (2.1) | 157.8 (0.8) | 108.7 (2.2) | 129.3 (2.0) | 134.8 (7.8) | 135.7 (8.0) |
| **October 7** | 0.0 | 112.6 (3.9) | 139.4 (3.7) | 88.5 (2.5) | 111.6 (4.9) | 115.7 (8.5) | 118.6 (8.3) |

Ppt = Precipitation since previous date
^ Mean (standard error)
Field capacity = 112 mm; wilting point = 38 mm
NI-1x = non-irrigated replicate adjacent to the low rate (Eff-1x)
NI-2x = non-irrigated replicate adjacent to the high rate (Eff-2x)
Irrigation: August 20 and September 5, 2003; June 24 and 26 and July 28, 2004
Harvest: mid to late July and mid to late September 2003; late June to early July and late August to mid September 2004

**Table 3.5 Neutron probe total soil water (mm) to 80 cm (TSW80) for 2003 and 2004**

| Date | Ppt* (mm) | Irrigation | | | | Fertilizer | |
|---|---|---|---|---|---|---|---|
| | | NI-1x | Eff-1x | NI-2x | Eff-2x | 0 N | 400 N |
| **2003** | | | | | | | |
| **June 5** | n/a | 205.6 (6.9)^ | 234.4 (2.3) | 108.4 (4.5) | 152.2 (8.5) | 178.0 (21.0) | 184.4 (21.7) |
| **June 19** | 0.3 | 167.6 (5.8) | 198.6 (2.7) | 76.2 (3.5) | 119.1 (10.5) | 145.3 (20.2) | 147.8 (21.6) |
| **July 3** | 102.8 | 183.0 (7.5) | 245.1 (4.6) | 127.1 (3.9) | 159.3 (5.0) | 184.5 (19.2) | 188.5 (21.1) |
| **July 16** | 13.7 | 159.1 (1.3) | 220.8 (4.5) | 100.7 (5.5) | 132.6 (7.9) | 162.5 (19.9) | 159.7 (21.6) |
| **July 31** | 20.6 | 140.1 (6.9) | 178.5 (12.2) | 51.8 (2.4) | 90.1 (6.9) | 121.9 (21.7) | 121.1 (22.9) |
| **August 13** | 28.2 | 159.0 (10.5) | 203.8 (3.6) | 61.6 (10.9) | 91.2 (7.7) | 131.3 (23.7) | 138.9 (27.6) |
| **August 28** | 7.4 | 121.3 (0.4) | 163.7 (10.1) | 20.0 (2.2) | 108.0 (15.0) | 105.4 (22.1) | 122.8 (23.2) |
| **September 10** | 2.8 | 100.4 (0.6) | 148.6 (9.7) | 6.8 (1.6) | 136.4 (28.7) | 101.8 (20.5) | 123.9 (30.0) |
| **September 23** | 7.6 | 105.6 (2.5) | 144.3 (9.3) | 4.3 (1.8) | 116.2 (22.3) | 93.9 (20.1) | 116.4 (26.0) |
| **October 7** | 0.0 | 107.7 (2.9) | 134.4 (9.3) | 5.0 (3.8) | 91.9 (19.2) | 82.1 (18.7) | 106.3 (23.1) |
| **2004** | | | | | | | |
| **May 12** | n/a | 193.7 (4.7) | 220.6 (6.3) | 124.3 (11.2) | 151.4 (14.2) | 166.9 (20.3) | 187.1 (14.0) |
| **May 26** | 21.1 | 168.8 (0.3) | 207.6 (6.8) | 103.7 (8.0) | 141.5 (17.4) | 151.1 (20.1) | 172.5 (16.1) |
| **June 9** | 75.7 | 199.9 (0.4) | 233.5 (6.9) | 131.5 (8.9) | 165.1 (13.0) | 182.2 (19.7) | 194.0 (16.1) |
| **June 28** | 23.9 | 162.0 (3.6) | 219.9 (10.2) | 63.6 (4.1) | 146.7 (11.4) | 156.4 (25.8) | 163.2 (23.4) |
| **July 13** | 65.0 | 216.0 (4.1) | 247.2 (11.7) | 107.6 (1.4) | 154.8 (10.6) | 184.1 (24.8) | 191.8 (24.1) |
| **July 29** | 50.5 | 219.9 (0.1) | 265.1 (8.6) | 126.6 (3.5) | 194.8 (18.2) | 209.4 (24.4) | 212.7 (21.7) |
| **August 10** | 37.1 | 224.1 (1.1) | 269.7 (4.0) | 124.7 (8.9) | 183.8 (19.2) | 207.7 (25.6) | 210.9 (23.9) |
| **August 24** | 15.0 | 203.4 (6.6) | 252.1 (6.8) | 78.9 (11.0) | 155.6 (18.5) | 177.7 (28.6) | 188.3 (28.7) |
| **September 7** | 51.3 | 246.7 (2.1) | 296.0 (4.5) | 128.1 (8.6) | 207.4 (19.9) | 229.6 (28.8) | 230.9 (26.4) |
| **September 21** | 45.5 | 280.2 (5.1) | 308.7 (3.9) | 171.8 (1.9) | 231.0 (18.4) | 252.1 (25.1) | 258.4 (21.8) |
| **October 7** | 0.0 | 259.8 (6.7) | 280.4 (5.2) | 151.6 (1.2) | 208.2 (18.6) | 227.4 (23.4) | 235.5 (21.7) |

Ppt = Precipitation since previous date
^ Mean (standard error)
Field capacity = 233 mm; wilting point = 82 mm
NI-1x = non-irrigated replicate adjacent to the low rate (Eff-1x)
NI-2x = non-irrigated replicate adjacent to the high rate (Eff-2x)
Irrigation: August 20 and September 5, 2003; June 24 and 26 and July 28, 2004
Harvest: mid to late July and mid to late September 2003; late June to early July and late August to mid September 2004

**Table 3.6 Neutron probe total soil water (mm) to 120 cm (TSW120) for 2003 and 2004**

| Date | Ppt* (mm) | Irrigation NI-1x | Eff-1x | NI-2x | Eff-2x | Fertilizer 0 N | 400 N |
|---|---|---|---|---|---|---|---|
| **2003** | | | | | | | |
| **June 5** | n/a | 145.5 (8.3) | 144.2 (2.0) | 79.8 (2.5) | 88.5 (8.4) | 111.6 (13.9) | 118.7 (13.8) |
| **June 19** | 0.3 | 138.7 (12.9) | 135.0 (3.1) | 70.9 (7.2) | 78.5 (8.1) | 99.6 (14.1) | 112.6 (13.6) |
| **July 3** | 102.8 | 141.1 (12.5) | 146.7 (3.6) | 69.2 (0.5) | 69.2 (9.0) | 103.7 (17.4) | 110.4 (17.7) |
| **July 16** | 13.7 | 142.1 (13.9) | 143.0 (3.6) | 72.6 (0.0) | 73.4 (6.1) | 104.0 (15.4) | 111.9 (16.6) |
| **July 31** | 20.6 | 143.6 (11.9) | 140.3 (3.1) | 82.0 (0.3) | 86.4 (5.2) | 112.9 (10.3) | 113.4 (15.5) |
| **August 13** | 28.2 | 148.4 (8.9) | 144.8 (3.1) | 86.0 (2.5) | 88.9 (7.8) | 112.4 (13.6) | 121.6 (13.4) |
| **August 28** | 7.4 | 140.0 (16.0) | 133.1 (4.5) | 77.1 (3.1) | 70.5 (8.5) | 99.1 (14.8) | 109.0 (14.9) |
| **September 10** | 2.8 | 137.4 (14.8) | 128.7 (4.5) | 74.7 (1.6) | 82.7 (9.0) | 98.6 (12.4) | 113.0 (12.4) |
| **September 23** | 7.6 | 140.8 (15.0) | 128.2 (4.3) | 68.2 (5.6) | 82.5 (7.9) | 97.8 (13.2) | 112.3 (13.0) |
| **October 7** | 0.0 | 141.9 (12.9) | 129.7 (4.3) | 75.8 (4.8) | 83.6 (8.8) | 100.2 (12.8) | 114.6 (12.4) |
| **2004** | | | | | | | |
| **May 12** | n/a | 335.4 (16.8) | 358.6 (7.2) | 225.9 (22.6) | 238.1 (22.0) | 275.4 (32.4) | 309.5 (22.3) |
| **May 26** | 21.1 | 304.9 (14.5) | 339.1 (11.3) | 188.6 (15.4) | 218.5 (21.3) | 250.9 (31.8) | 285.4 (25.4) |
| **June 9** | 75.7 | 344.1 (8.1) | 379.8 (8.3) | 248.7 (14.6) | 266.4 (22.8) | 303.1 (30.0) | 325.5 (23.0) |
| **June 28** | 23.9 | 308.3 (6.8) | 365.9 (12.7) | 170.2 (15.4) | 244.1 (21.7) | 272.4 (37.2) | 293.8 (29.2) |
| **July 13** | 65.0 | 365.8 (14.5) | 398.1 (14.7) | 218.0 (5.8) | 252.6 (22.6) | 304.1 (38.1) | 324.3 (32.4) |
| **July 29** | 50.5 | 376.1 (6.1) | 426.2 (8.5) | 249.3 (4.0) | 305.8 (29.0) | 342.8 (36.8) | 353.7 (27.6) |
| **August 10** | 37.1 | 377.1 (7.7) | 430.1 (4.6) | 239.5 (5.6) | 293.8 (30.5) | 339.5 (39.1) | 348.6 (31.2) |
| **August 24** | 15.0 | 354.9 (14.7) | 405.6 (7.4) | 190.3 (6.7) | 263.4 (30.0) | 302.9 (40.8) | 324.8 (35.8) |
| **September 7** | 51.3 | 403.8 (9.1) | 458.9 (8.5) | 241.0 (2.1) | 319.8 (34.2) | 362.2 (43.8) | 371.9 (33.9) |
| **September 21** | 45.5 | 444.2 (5.9) | 472.6 (8.2) | 298.7 (2.3 ) | 361.6 (29.9) | 396.7 (36.7) | 407.0 (27.3) |
| **October 7** | 0.0 | 418.1 (10.8) | 440.9 (4.7) | 281.6 (2.9) | 338.8 (28.3) | 370.8 (32.7) | 382.2 (26.7) |

Ppt = Precipitation since previous date
^ Mean (standard error)
Field capacity = 367 mm; wilting point = 132 mm
NI-1x = non-irrigated replicate adjacent to the low rate (Eff-1x)
NI-2x = non-irrigated replicate adjacent to the high rate (Eff-2x)
Irrigation: August 20 and September 5, 2003; June 24 and 26 and July 28, 2004
Harvest: mid to late July and mid to late September 2003; late June to early July and late August to mid September 2004

Table 3.7 Neutron probe total soil water (mm) 80 to 120 cm (TSW80-120) for 2003 and 2004

| Date | Ppt* (mm) | Irrigation NI-1x | Irrigation Eff-1x | Irrigation NI-2x | Irrigation Eff-2x | Fertilizer 0 N | Fertilizer 400 N |
|---|---|---|---|---|---|---|---|
| **2003** | | | | | | | |
| **June 5** | n/a | 351.1 (15.2)^ | 378.6 (4.1) | 188.1 (7.0) | 240.7 (16.1) | 289.5 (34.3) | 303.1 (35.0) |
| **June 19** | 0.3 | 306.3 (18.7) | 333.6 (4.8) | 147.1 (10.8) | 197.7 (15.0) | 244.9 (33.9) | 260.5 (34.1) |
| **July 3** | 102.8 | 324.2 (20.0) | 391.7 (8.0) | 196.3 (3.3) | 228.6 (12.7) | 288.2 (35.3) | 298.8 (37.4) |
| **July 16** | 13.7 | 301.3 (15.1) | 363.9 (7.7) | 173.2 (5.5) | 206.0 (10.2) | 266.5 (34.3) | 271.6 (36.3) |
| **July 31** | 20.6 | 283.7 (18.8) | 318.8 (13.5) | 133.7 (2.7) | 176.5 (8.9) | 234.8 (31.5) | 234.6 (37.0) |
| **August 13** | 28.2 | 307.4 (19.5) | 348.6 (6.2) | 147.6 (8.4) | 180.1 (13.8) | 243.7 (36.6) | 260.5 (40.3) |
| **August 28** | 7.4 | 261.3 (16.3) | 296.8 (11.3) | 97.1 (8.4) | 178.5 (20.3) | 204.5 (35.2) | 231.8 (32.5) |
| **September 10** | 2.8 | 237.8 (14.2) | 277.3 (12.8) | 81.5 (0.0) | 219.0 (33.1) | 200.4 (28.7) | 236.9 (36.0) |
| **September 23** | 7.6 | 246.4 (17.5) | 272.4 (11.6) | 72.5 (7.4) | 198.7 (27.3) | 191.8 (30.9) | 228.7 (34.2) |
| **October 7** | 0.0 | 249.7 (15.8) | 264.0 (12.3) | 80.8 (8.7) | 175.5 (24.7) | 182.3 (29.8) | 220.9 (32.0) |
| **2004** | | | | | | | |
| **May 12** | n/a | 141.6 (12.2) | 138.0 (1.2) | 101.7 (11.4) | 86.7 (8.7) | 108.5 (12.6) | 122.4 (10.4) |
| **May 26** | 21.1 | 136.1 (14.2) | 131.5 (4.6) | 84.9 (7.4) | 77.1 (4.5) | 99.8 (12.2) | 112.9 (12.5) |
| **June 9** | 75.7 | 144.2 (8.5) | 146.2 (1.5) | 117.1 (5.7) | 101.3 (9.9) | 120.9 (11.3) | 131.2 (8.4) |
| **June 28** | 23.9 | 146.4 (10.3) | 146.0 (2.5) | 106.6 (11.2) | 97.3 (10.3) | 116.0 (13.1) | 130.6 (9.0) |
| **July 13** | 65.0 | 149.8 (10.3) | 150.9 (3.2) | 110.5 (7.1) | 97.8 (12.1) | 120.0 (14.3) | 132.6 (9.7) |
| **July 29** | 50.5 | 156.2 (5.9) | 161.2 (2.9) | 122.7 (7.4) | 111.0 (11.0) | 133.4 (13.8) | 141.0 (8.3) |
| **August 10** | 37.1 | 153.0 (6.6) | 160.4 (4.5) | 114.8 (3.3) | 110.0 (11.5) | 131.8 (14.4) | 137.7 (8.6) |
| **August 24** | 15.0 | 151.5 (8.1) | 153.5 (0.8) | 111.3 (4.3) | 107.8 (11.7) | 125.3 (12.9) | 136.5 (8.6) |
| **September 7** | 51.3 | 157.0 (7.0) | 162.9 (4.7) | 112.9 (6.5) | 112.4 (14.5) | 132.5 (15.7) | 141.0 (8.9) |
| **September 21** | 45.5 | 164.0 (0.7) | 163.9 (4.5) | 126.8 (4.3) | 130.6 (11.7) | 144.7 (12.1) | 148.6 (6.0) |
| **October 7** | 0.0 | 158.3 (4.1) | 160.5 (4.0) | 130.0 (1.7) | 130.6 (10.0) | 143.4 (10.2) | 146.7 (5.5) |

Ppt = Precipitation since previous date
^ Mean (standard error)
Field capacity = 134 mm; wilting point = 50 mm
NI-1x = non-irrigated replicate adjacent to the low rate (Eff-1x)
NI-2x = non-irrigated replicate adjacent to the high rate (Eff-2x)
Irrigation: August 20 and September 5, 2003; June 24 and 26 and July 28, 2004
Harvest: mid to late July and mid to late September 2003; late June to early July and late August to mid September 20

**Table 3.8 Profile probe total soil water (mm) to 40 cm (TSW40) by forage treatment for 2003 and 2004**

| Date | Ppt* (mm) | Forage Treatment RCG | ALF | TIM |
|---|---|---|---|---|
| **2003** | | | | |
| **June 5** | n/a | 101.7 (3.4)^ | 99.2 (6.2) | 84.3 (9.0) |
| **June 12** | 0.3 | 98.9 (3.6) | 97.7 (6.3) | 81.9 (9.4) |
| **June 19** | 0.0 | 94.6 (4.2) | 92.5 (7.0) | 76.2 (9.4) |
| **June 26** | 78.3 | 105.9 (4.2) | 105.6 (5.2) | 93.4 (7.3) |
| **July 3** | 24.5 | 103.1 (3.6) | 99.3 (3.6) | 93.3 (6.2) |
| **July 18** | 15.7 | 99.7 (3.3) | 95.7 (3.6) | 88.2 (6.4) |
| **July 24** | 14.7 | 98.5 (3.5) | 93.7 (3.9) | 86.1 (6.7) |
| **July 31** | 3.8 | 96.6 (3.8) | 90.1 (4.2) | 80.9 (6.8) |
| **August 7** | 8.4 | 100.5 (3.5) | 92.9 (4.1) | 90.3 (6.7) |
| **August 13** | 19.8 | 97.0 (3.6) | 89.3 (4.2) | 88.0 (6.9) |
| **August 20** | 0.0 | 95.0 (4.0) | 85.9 (4.8) | 86.7 (6.2) |
| **August 27** | 1.3 | 92.1 (3.7) | 83.7 (5.1) | 84.5 (6.1) |
| **September 10** | 8.9 | 93.4 (3.5) | 85.5 (5.6) | 83.6 (5.6) |
| **September 20** | 5.6 | 87.7 (3.5) | 82.3 (5.3) | 79.9 (5.4) |
| **September 24** | 2.0 | 87.4 (3.4) | 80.5 (5.2) | 78.1 (5.4) |
| **October 1** | 0.0 | 84.0 (3.4) | 78.3 (4.9) | 75.6 (5.3) |
| **October 7** | 0.0 | 82.9 (3.5) | 78.9 (4.6) | 74.9 (5.3) |
| **2004** | | | | |
| **May 12** | n/a | 100.3 (2.9) | 97.6 (2.9) | 95.9 (4.6) |
| **May 19** | 16.3 | 102.7 (2.8) | 99.0 (3.0) | 96.2 (4.6) |
| **May 26** | 4.8 | 100.1 (2.9) | 96.1 (3.2) | 93.5 (4.9) |
| **June 26** | 71.1 | 110.2 (2.5) | 107.6 (2.4) | 104.6 (3.9) |
| **June 9** | 146.1 | 103.4 (2.9) | 100.3 (2.8) | 96.5 (4.9) |
| **June 16** | 11.9 | 105.4 (3.5) | 101.3 (2.9) | 97.8 (5.4) |
| **June 21** | 11.9 | 100.6 (3.3) | 97.0 (3.1) | 92.5 (5.7) |
| **June 28** | 0.0 | 97.3 (3.0) | 93.3 (4.4) | 89.0 (6.1) |
| **July 5** | 0.0 | 95.0 (3.5) | 84.6 (4.4) | 82.9 (6.2) |
| **July 13** | 65.0 | 109.6 (2.7) | 104.6 (3.8) | 101.8 (5.0) |
| **July 23** | 40.4 | 109.8 (2.5) | 108.2 (2.8) | 103.9 (4.0) |
| **July 29** | 10.2 | 109.2 (2.3) | 109.1 (3.5) | 104.7 (4.3) |
| **August 5** | 5.6 | 105.3 (2.9) | 102.1 (3.7) | 100.1 (5.1) |
| **August 10** | 31.5 | 109.7 (2.7) | 106.1 (3.1) | 102.9 (4.4) |
| **August 17** | 0.0 | 104.3 (3.3) | 99.3 (4.0) | 96.1 (5.7) |
| **August 24** | 15.0 | 102.9 (3.3) | 100.0 (4.3) | 96.2 (6.0) |
| **September 7** | 51.3 | 113.2 (2.9) | 111.2 (3.1) | 106.3 (4.5) |
| **September 14** | 11.9 | 112.9 (2.8) | 110.6 (2.7) | 105.9 (4.5) |
| **September 21** | 33.5 | 115.0 (2.8) | 112.8 (2.4) | 108.8 (4.4) |
| **September 30** | 0.0 | 111.3 (2.9) | 109.0 (2.6) | 104.3 (4.6) |
| **October 7** | 0.0 | 111.6 (3.3) | 107.2 (2.6) | 103.2 (4.9) |
| **October 14** | 5.8 | 111.4 (2.8) | 109.3 (2.2) | 104.0 (4.8) |

Ppt = Precipitation since previous date
^ Mean (standard error)
Field capacity = 112 mm; wilting point = 38 mm
RCG = reed canary grass; ALF = alfalfa; TIM = timothy
Irrigation: August 20 and September 5, 2003; June 24 and 26 and July 28, 2004
Harvest: mid to late July and mid to late September 2003; late June to early July and late August to mid September 2004

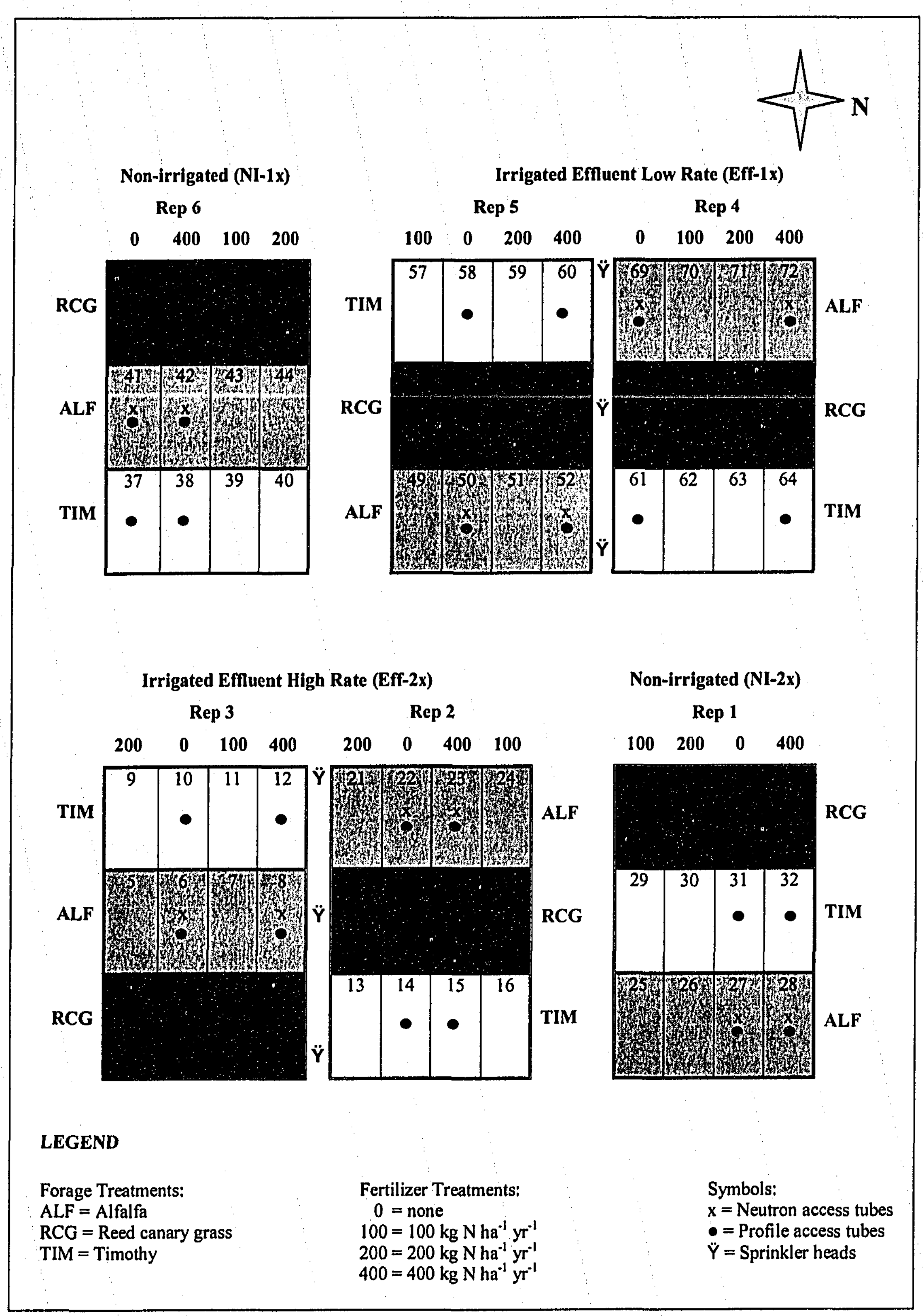


**Figure 3.1 Study site plot plan indicating irrigation, forage and fertilizer treatments, and profile and neutron probe access tubes within numbered plots**

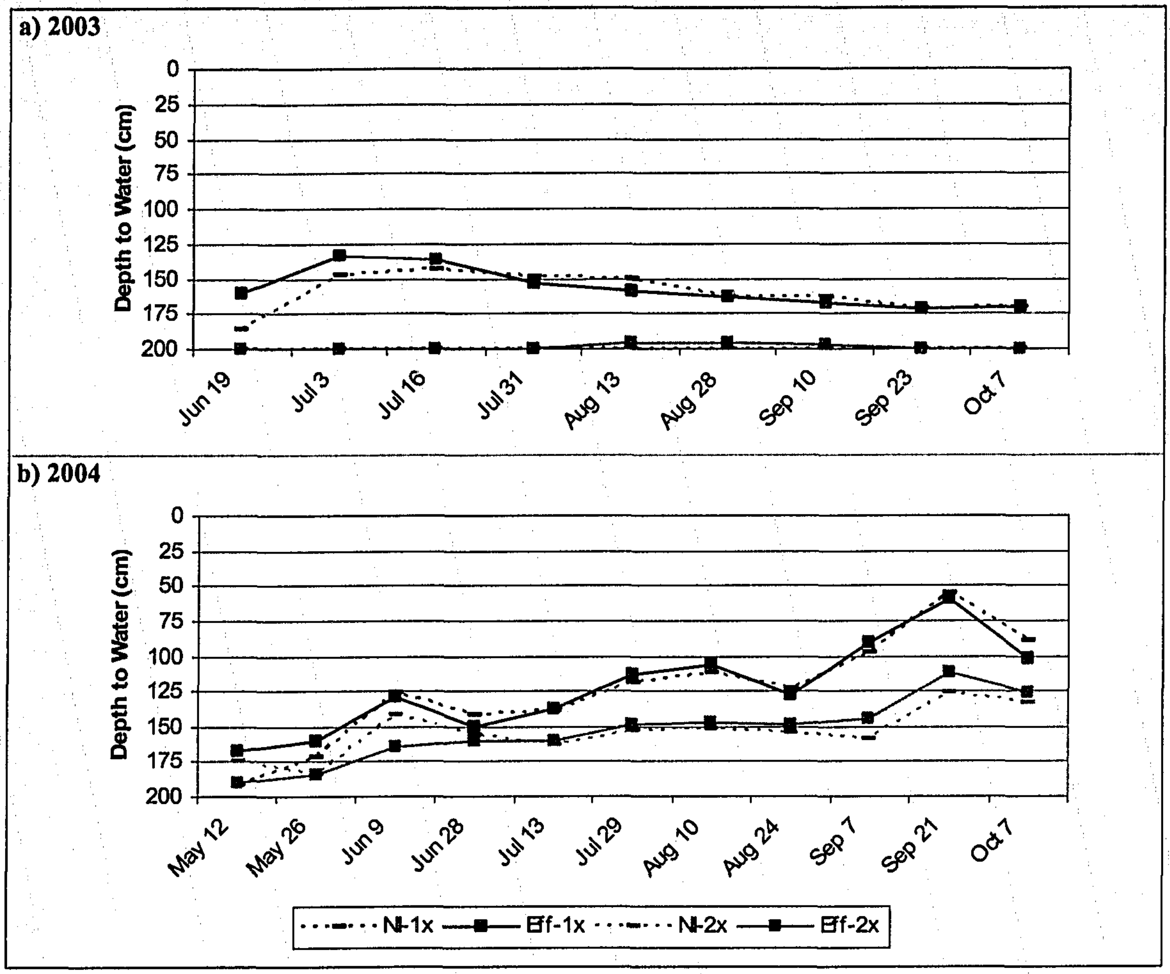


**Figure 3.2 Average depths to water in aluminum access tubes from ground surface for NI-1x, Eff-1x, NI-2x and Eff-2x for 2003 and 2004**

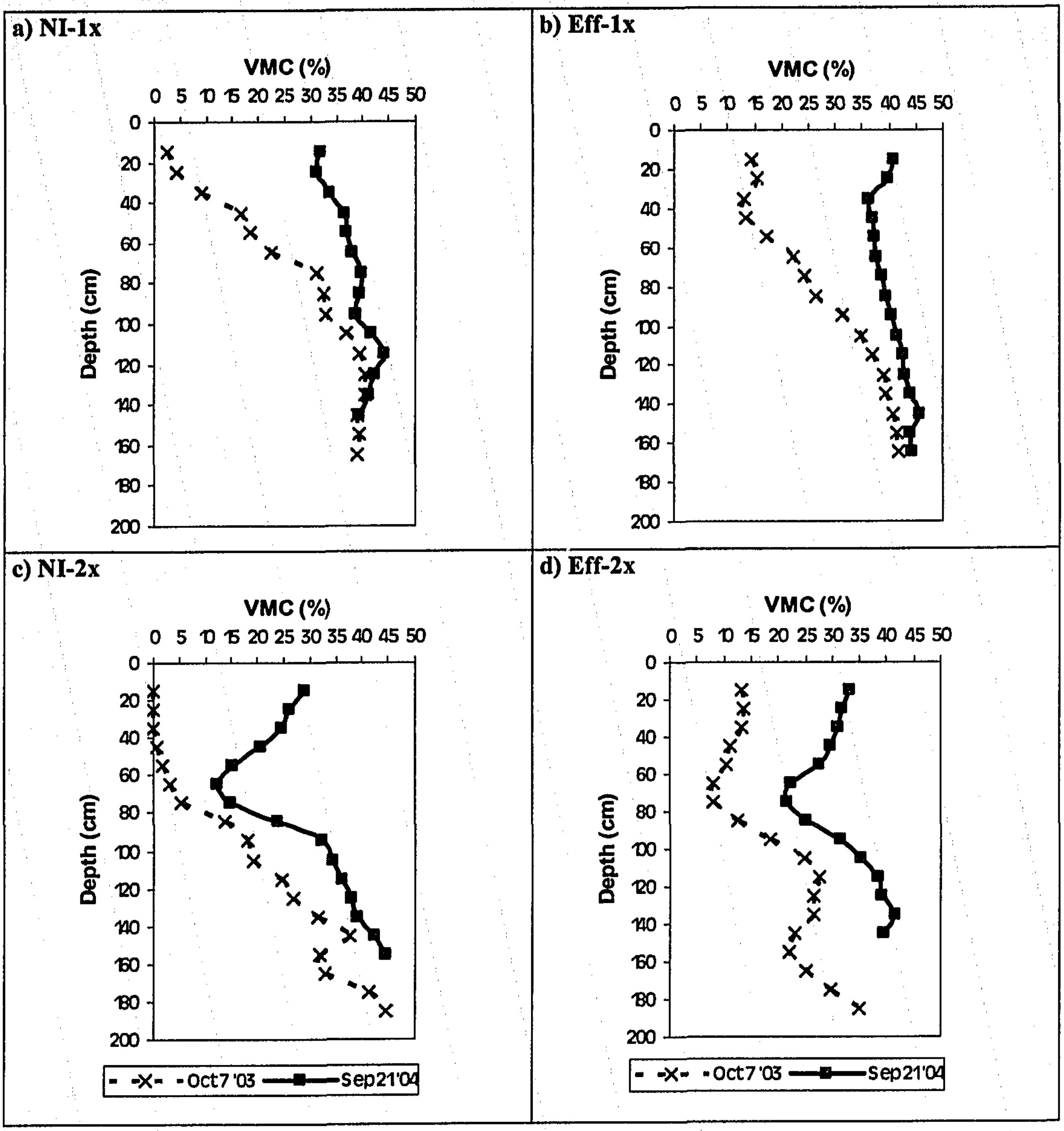


**Figure 3.3 Volumetric moisture content with depth (neutron probe) by dry (October 7, 2003) and wet (September 21, 2004) days for irrigation treatments with adjacent non-irrigated replicates**

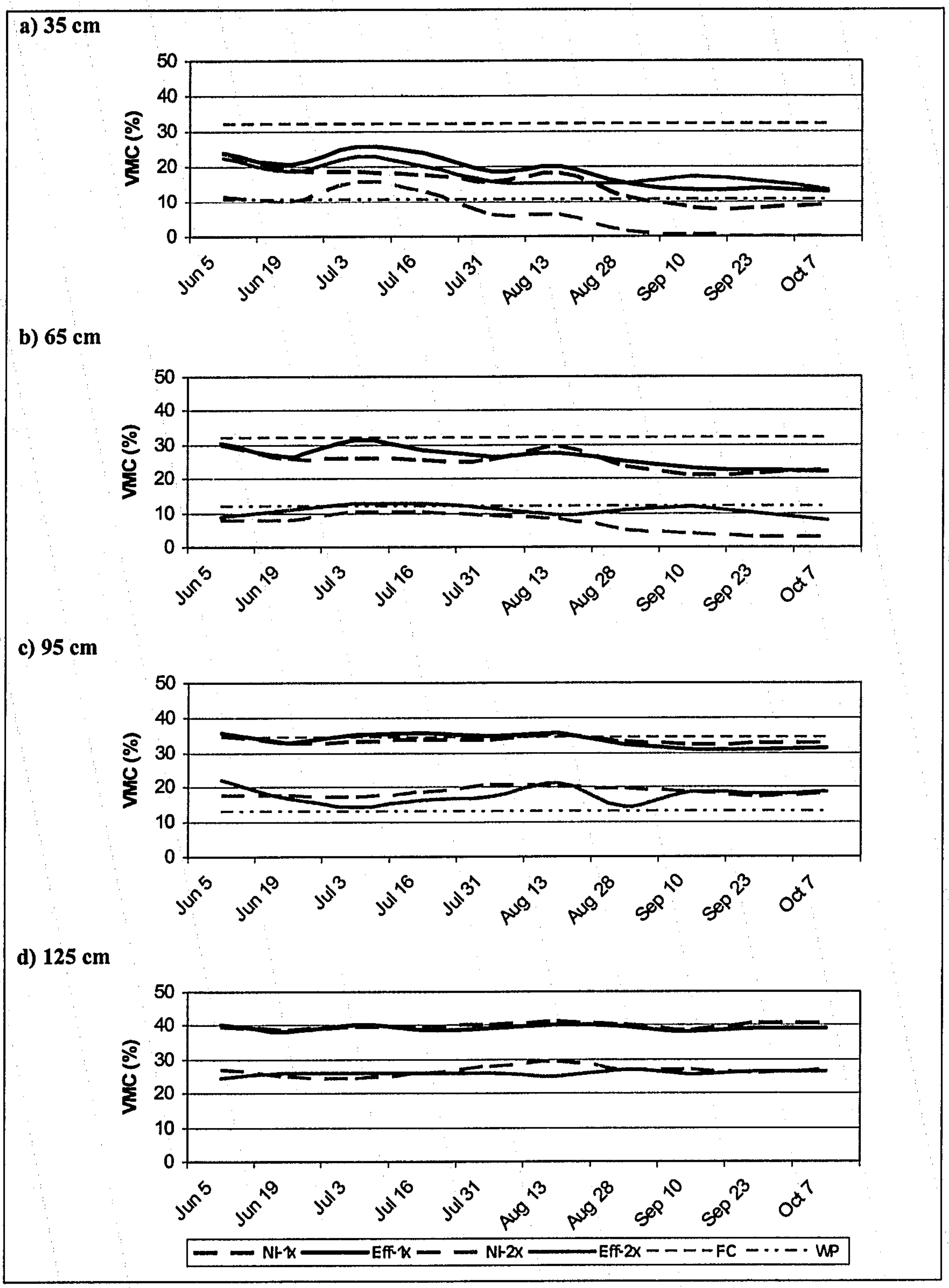


Figure 3.4 Volumetric moisture content (neutron probe) at 35, 65, 95 and 125 cm by irrigation treatments for 2003; field capacities for 20-40, 60-80 and 80-100 are 31.7, 32.0 and 34.0% and wilting points are 10.6, 11.9 and 12.8%, respectively; field capacities not available beyond 100 cm

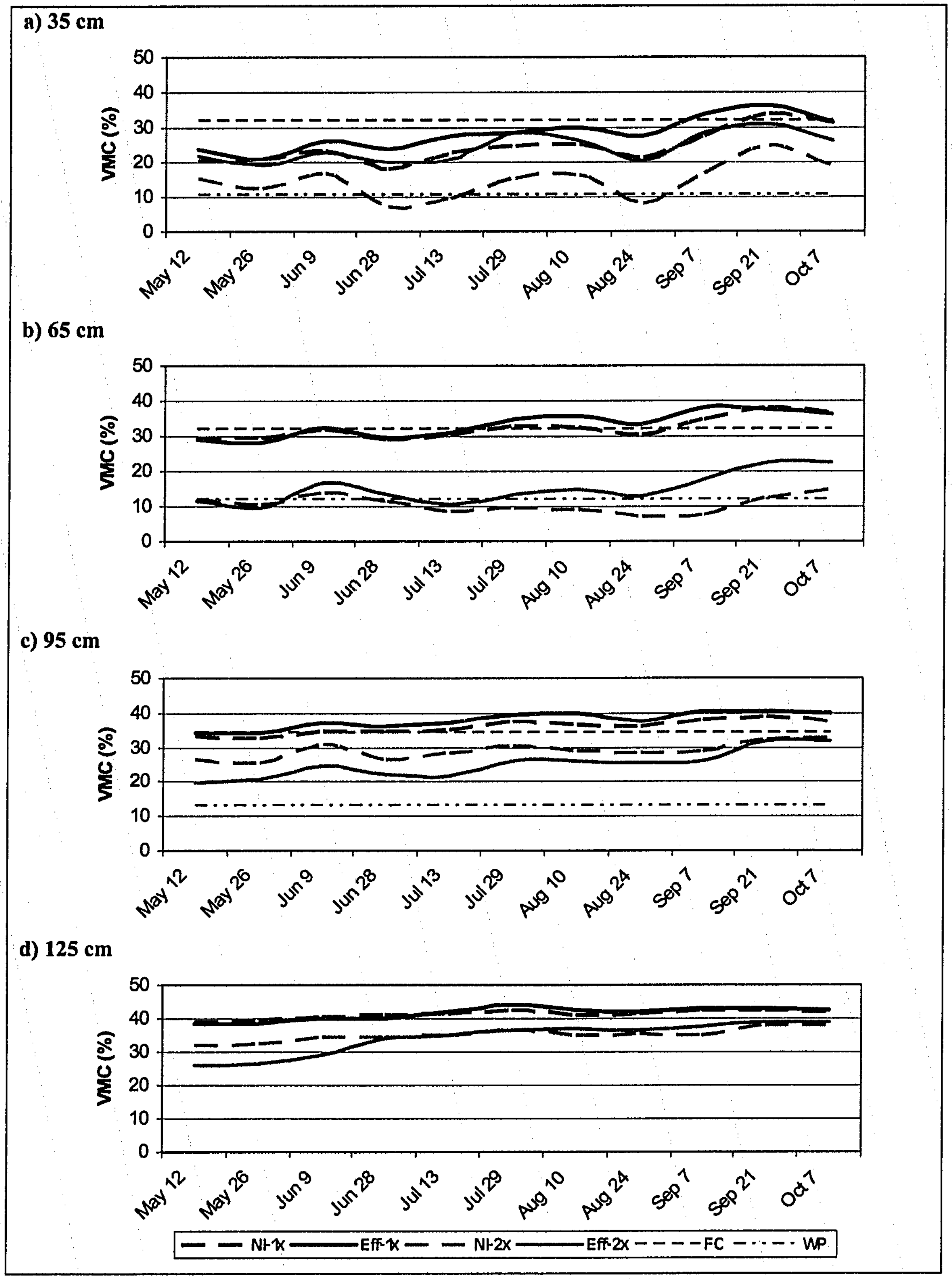


**Figure 3.5 Volumetric moisture content (neutron probe) at 35, 65, 95 and 125 cm by irrigation treatments for 2004; field capacities for 20-40, 60-80 and 80-100 are 31.7, 32.0 and 34.0% and wilting points are 10.6, 11.9 and 12.8%, respectively; field capacities not available beyond 100 cm**

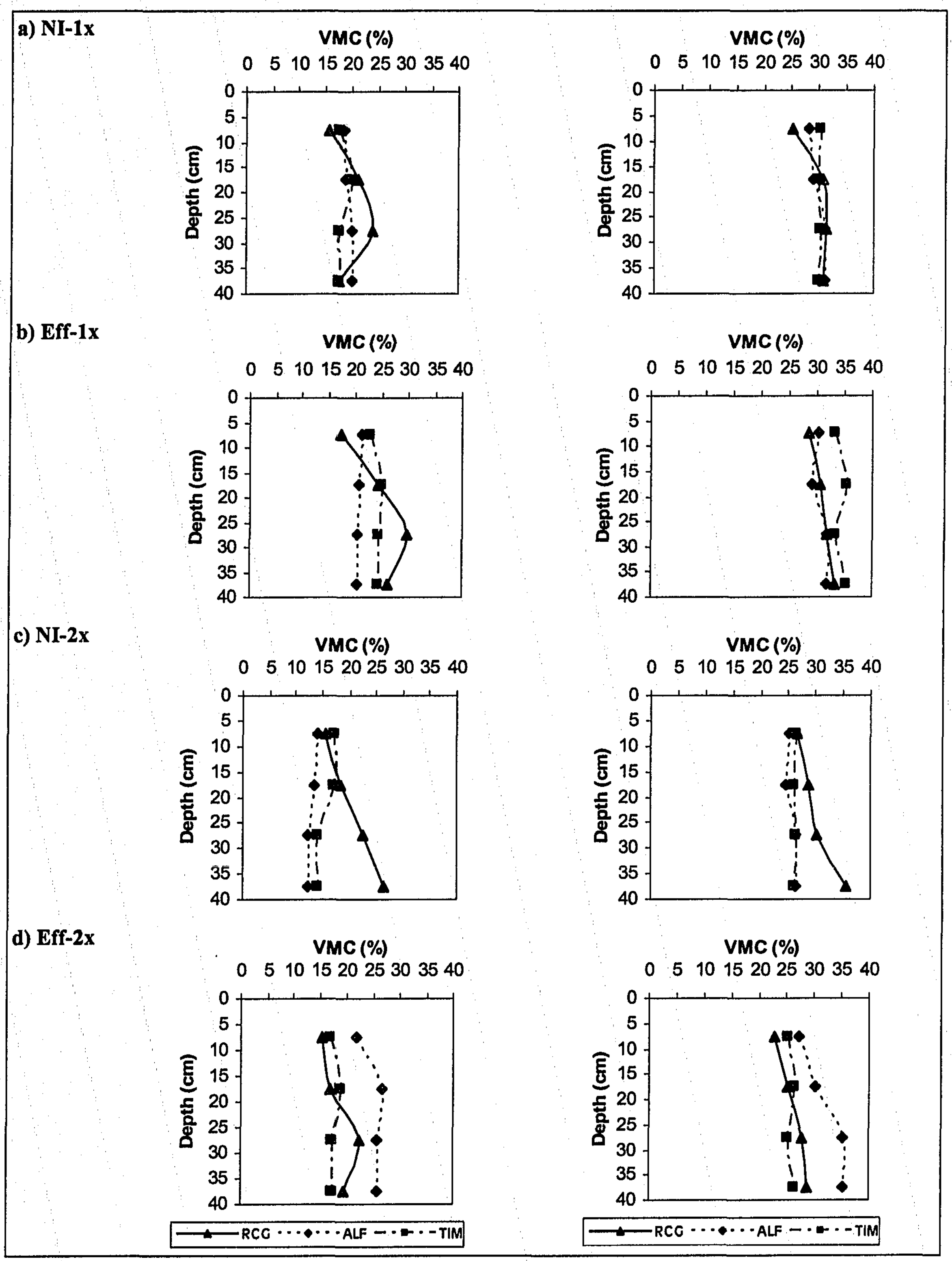


**Figure 3.6 Volumetric moisture content with depth (profile probe) by forage species within irrigation treatments for relative dry (October 7, 2003) (left) and wet (September 21, 2004) (right) days with adjacent non-irrigated replicates**

# 4 BIOMASS PRODUCTION AND QUALITY OF THREE FORAGE SPECIES IRRIGATED WITH BLEACHED KRAFT PULP MILL EFFLUENT

## 4.1 INTRODUCTION

Increasing regulatory pressure and environmental awareness to maintain and enhance water quality have created requirements and guidelines to deal with increasing volumes of wastewater from municipal, agricultural and industrial sources normally discharged into water bodies (Bole and Bell 1978; Hayman and Smith 1979; Hansen et al. 1980). This has created the need for more ecological disposal methods to prevent pollution or minimize contamination of surface and ground waters. One such alternative is wastewater irrigation, a more ecological and economical approach if properly managed (Howe and Wagner 1999; Mohammad and Ayadi 2004). Hansen et al. (1980) discussed the marginal economy of conventional irrigation and the attractiveness of effluent irrigation with the large number of pulp mill effluents generated. Wastewater land application could potentially maximize plant production, while meeting stringent guidelines for effluent disposal and treating effluent by filtering and removing unwanted elements from wastewater (Bole and Bell 1978).

Wastewaters from urban, agricultural and forestry sectors contain important essential plant nutrients with potential for improving plant health and productivity if used on soils with nutrient deficiencies (Cabral et al. 1998; Howe and Wagner 1999). The need for mineral fertilizers is decreased, while reducing inputs, increasing profits and minimizing environmental problems (Cabral et al. 1998). Nutrient rich wastewaters containing organic matter also make good soil amendments, potentially enhancing soil fertility and productivity and increasing crop yields (Mohammad and Ayadi 2004). In arid, semi-arid or drought sensitive regions, wastewater land application can reduce soil water deficits that limit plant production (Bole and Gould 1985). Researchers have explored wastewater availability and quality to alleviate growing water demands for municipal, industrial and agricultural uses (Hussain and Al-Saati 1999). Cabral et al. (1998) stated that there was a global movement towards developing production systems, in particular agriculture systems that are economically and environmentally sustainable.

Crop and site selection are important to successfully develop a sustainable effluent land treatment system by recycling nutrients and reusing water. Selected crops should be tolerant to wet soil conditions and frequent harvests, and have high biomass potential (Macoon et al. 2002). Deep rhizomatous perennials like forages are best suited since they have prolonged vegetative growth over a long growing season, high seasonal evapotranspiration and soil stabilizing and erosion prevention attributes (Bole and Bell 1978). Frequent harvests maintain active nutrient uptake and reduce leaching potential. In drainage or saline water reuse systems, forage suitability also depends on their salt-tolerance, nutritional quality and management practices affecting salinity in the root zone (Robinson et al. 2004; Grattan et al. 2004b). Salt-tolerant forages may play an important role in maintaining a sustainable effluent irrigated cropping system provided effluent elements do not create salinity-induced nutrient imbalances from competitive nutrient uptake, transport and partitioning within the plant (Grieve et al. 2004).

Alfalfa, reed canary grass and timothy have great potential for effluent irrigation in northern Alberta. Alfalfa is a cool season legume with excellent winter hardiness and a very high yield potential (McGraw and Nelson 2003). It can extract nutrients and water from a large soil volume compared to other shallow rooted legumes (Miller and Nelson 2003). However, alfalfa is intolerant of water logging, low soil fertility (if phosphorous (P), potassium (K), and sometimes boron (B) and sulphur (S) are limiting) and low soil pH (<6.5) (McGraw and Nelson 2003). Reed canary grass is a cool season perennial grass with very good winter hardiness and good regrowth potential. It is adapted to moist soils, but is susceptible to frost damage and can have poor to good forage quality (Balasko and Nelson 2003). Timothy is a cool season perennial with excellent winter hardiness and easy establishment. It is fairly tolerant to wet soils and has very good forage quality, but has less potential regrowth than reed canary grass (Balasko and Nelson 2003). Thus it is necessary to evaluate soil moisture and chemical properties prior to and during irrigation, as well as monitor forage chemical composition to ensure optimum quality.

Improper timing of harvesting and management of effluent irrigation may reduce forage yield and quality. Long-term productivity can be suppressed by providing crops with excess nutrients resulting in undesirable accumulations potentially causing imbalances and toxicities in soil and plants (Howe and Wagner 1999). Saline or sodic wastewaters may negatively affect enzyme activity because of excess sodium (Na), resulting in plant nutritional and hormonal imbalances (Howe and Wagner 1996). Sodicity can reduce crop growth by adversely affecting soil structure which indirectly affects root growth (Robinson et al. 2004). Irrigation with saline wastewaters containing soluble salts can be toxic to plants. Thus, ruminants fed forage crops irrigated with such wastewaters could be affected by plant nutrient and metal accumulations (Mohammad and Ayadi 2004). Excessive nutrient loading can result in poor pasture utilization and animal nutrient-related metabolic disorders (Bolan et al. 2004). Thus, research activities should address forage quality, ruminant nutrition and plant health and productivity (Mohammad and Ayadi 2004).

Early research focused on questions concerning plant and soil productivity. Hayman and Smith (1979) studied effects of conventional pulp mill effluent irrigation on grass and pasture species in a South African field trial. Hansen et al. (1980) irrigated *Populus* and *Salix* species with secondary treated pulp mill effluent in Michigan. In Arizona Howe and Wagner (1996) determined effects of (pH chemically altered) pulp mill effluent irrigation and gypsum treatments on growth and Na accumulations in greenhouse grown cottonwood (*Populus deltoides* var. Fraser). In a literature review Cabral et al. (1998) discussed studies on land applications of combined or secondary pulp mill sludge and effects on crop yields in southern Europe due to inherent fertile and mulching (moisture retaining) characteristics of the sludge. Species examined included bluegrass, oats, wheat, maize, lupins, lettuce, ornamental shrubs, red pine and hybrid cottonwood. Very few pulp mill effluent irrigation or sludge application studies investigated forage species and quality via plant nutrient dynamics.

Howe and Wagner (1999) studied nutrient accumulations by analyzing four-wing saltbush plants *Atriplex canescens*, (Pursh) Nutt. around and within a field planted with forages after extended periods (1968-1982) of untreated kraft pulp mill effluent irrigation. A study in Canada by Patterson et al. (2002) determined effects of municipal effluent, pulp mill waste activated sludge and pulp mill secondary treated effluent on greenhouse grown reed canary grass (*Phalaris arundinacea* L. var. Vantage) and hybrid poplar (*Populus deltoides* var. Walker) for plant production and nutrient uptake.

Some studies investigated effects of wastewaters not indicative of the pulp and paper industry. One Lethbridge, Alberta study investigated effects of rendering plant wastewater irrigation with major constituents of nitrogen (N), phosphorus (P) and organic matter on alfalfa and reed canary grass nitrate-nitrogen levels and yields (Bole and Gould 1985). Hussain and Al-Saati (1999) reviewed drainage wastewater irrigation studies with forages such as corn, sorghum and alfalfa grown in pot experiments. One Florida study evaluated crude protein and fibre components under dairy effluent irrigation (Macoon et al. 2002). In New Zealand, Bolan et al. (2004) irrigated perennial rye grass and white clover with dairy farm effluent with and without calcium (Ca) and magnesium (Mg) fertilizers to determine effects on dry matter yield and chemical composition. In the San Joaquin Valley of California, Grattan et al. (2004a) conducted a greenhouse study to determine effects of simulated saline drainage effluent irrigation on forage growth, quality and mineral composition and ruminant nutrition.

Most studies have used municipal and agricultural wastewaters with very different compositions than pulp mill wastewaters, containing more N, P and trace metals. Studies that used residuals from pulp and paper mill industrial processes were untreated or primary pulp mill sludge and effluents rather than secondary treated pulp mill effluents which have different compositions. Wastewaters with similar composition to secondary treated pulp mill effluents were drainage or saline wastewaters. With increasing pressures to improve effluent quality and reduce volumes, technology advancements in the past few decades have changed effluent composition. Thus there is a need to study and monitor effects of renovated wastewaters used for irrigation in crop production systems.

Pulp sludge application investigations have focussed on forest rather than agricultural sites (Cabral et al. 1998). Some studies investigated forage species such as alfalfa and reed canary grass common to western Canada, but they were of different varieties in different regions of the world on different soils. To develop sustainable land treatment systems that can provide profitable and sustainable cropping systems in Canadian climates and soils, pulp mill effluent irrigation studies need to be investigated on forage species commonly grown in local regions. Appropriate forage quality parameters need to be monitored in addition to productivity to avoid problems with plant and ruminant nutrition.

## 4.2 Research Objectives

The research objectives were to determine effects of pulp mill effluent irrigation rates, N fertilization rates and forage treatments on forage productivity and quality. Specific objectives were to determine if forage total dry biomass and quality as measured by fibre, total digestible nutrients, relative feed value, crude protein and selected macro and micro nutrients differed among irrigation, forage and fertilizer treatments.

## 4.3 Materials and Methods

### 4.3.1 Study Site

The study site is located in the Mid Boreal Mixedwood Ecoregion, approximately 200 km northwest of Edmonton, Alberta (Strong and Leggat 1992) and approximately 2 km south of the Alberta-Pacific Forest Industries Inc. bleached kraft pulp mill. The study area is 72 m x 43 m or 0.31 ha in size and is relatively uniform with 2 to 3% slopes, declining to the west or northwest. Specifically, the high effluent rate treatment and adjacent non-irrigated replicate was located upslope from the low effluent rate treatment and its adjacent non-irrigated replicate.

Soils are medium to coarse textured Luvisols and Eluviated Dystric Brunisols which are relatively low in pH, low in salt and well to rapidly draining (Proudfoot 2000). In low lying areas, gleying is evident with subsoil mottling indicative of imperfect drainage. Groundwater in monitoring wells in the northern and southern parts of the site was found between 216 and 278 cm (Proudfoot 2000). The site has been classified with good irrigation capability by sprinkler methods only.

Historical climate data from Canadian Climate Normals 1971 to 2000 (Environment Canada 2002) obtained from the Athabasca weather station about 72 km away, show average daily temperatures for the growing season (May to September) range from 10.6 °C in May, to a high of 16.2 °C in July, to a low of 9.8 °C in September. The Athabasca region averages 504 mm of precipitation annually, with 70% occurring during the growing season. The average number of growing degree days (degree days for a given day represent the number of Celsius degrees that the mean temperature is above 5 °C) from May to September is 1270 with the most (346) occurring in July.

Prior to this study, the field was summerfallowed for three years and before seedbed preparation in August 2002, glyphosate was applied for weed control. A fertilizer blend of 9-38-15 was broadcast at 323 kg $ha^{-1}$, supplying 30 kg $ha^{-1}$ of N, 123 kg $ha^{-1}$ of $P_2O_5$ and 50 kg $ha^{-1}$ of $K_2O$ to help with seed establishment.

### 4.3.2 Meteorological Measurements

A Campbell Scientific UT10 meteorological station was installed at the site in June 2002 to record daily minimum and maximum air temperatures and relative humidity (HMP45C gauge), saturated and non-saturated vapour pressures, net radiation (Kipp and Zonen net radiometer) and total precipitation (TE525 tipping bucket). To compare average precipitation and temperature trends at the study site to long-term normals, 2003 and 2004 climate data and 1971 to 2000 long-term normals were obtained from Environment Canada's climate database for the Athabasca weather station.

### 4.3.3 Experimental Design

A split-strip plot design was used to study irrigation, forage and fertilizer treatment effects (Figure 4.1). There were 36 (3 x 3 x 4) treatment combinations replicated twice for a total of 72 experimental units or plots (each 2 m x 8 m).

Irrigation treatments were nested within replicates and consisted of non-irrigated (NI-1x and NI-2x), low effluent rate (Eff-1x) and high effluent rate (Eff-2x) treatments. The irrigation system was installed in 2003 consisting of a solid set sprinkler system with 5 cm diameter laterals and 12 m spacings between sprinklers along each lateral, covering approximately a 10 m radius. Irrigation timing was determined from on-site soil moisture measurements and weather, with no irrigation occurring under windy or rainy conditions. During irrigation events, catch cans were placed strategically among the plots to evaluate irrigation variability.

Within each replicate, forage treatments were randomly seeded in rows or horizontal strips. The forage species were selected for their winter hardiness, successful establishment and tolerance to wet soil conditions. Alfalfa (*Medicago sativa* L. var. Algonquin), timothy (*Phleum pratense* L. var. Climax) and reed canary grass (*Phalaris arundinacea* L. var. Vantage) were seeded in early August 2002 at rates of 11, 11, and 10 kg/ha, respectively. For detailed forage species descriptions refer to the Appendix.

Fertilizer treatments, 0, 100, 200 and 400 kg N $ha^{-1}$ $yr^{-1}$ of ammonium nitrate (34-0-0-0), were randomly applied to the forage species in vertical strips (Figure 4.1). The fertilizer treatments were split into two applications and hand broadcast in spring and immediately after the first clipping. In 2003 the plots received applications of 0, 50, 100 and 200 kg N $ha^{-1}$ $yr^{-1}$ on June 4 and July 31. An error occurred during the July 31 application with all plots in the non-irrigated replicate adjacent the high effluent rate (NI-2x) receiving incorrect rates. Instead of 100 N receiving 50 kg N $ha^{-1}$ $yr^{-1}$, it got 100 kg N $ha^{-1}$ $yr^{-1}$; 200 N received 50 kg N $ha^{-1}$ $yr^{-1}$ instead of 100 kg N $ha^{-1}$ $yr^{-1}$; no fertilizer plots received 200 kg N $ha^{-1}$ $yr^{-1}$; 400 N received no fertilizer. The fertilizer application error was corrected in 2004 with 0, 50, 100 and 200 kg N $ha^{-1}$ $yr^{-1}$ applied to the original fertilizer treatments on June 2 and July 14. On June 2, an error occurred in Replicate 4 of the low effluent rate treatment with 0 N plots receiving 50 kg N $ha^{-1}$ $yr^{-1}$; 100 N received no fertilizer. This error was corrected during the July 14 fertilization. For total application rates applied per treatment by year, please refer to Table 4.1.

### 4.3.4 Effluent Characterization

The wastewater was a secondary treated effluent from a bleached kraft pulp mill. Laboratory analyses to characterize effluent salinity, nutrients (analyzed monthly) and trace elements (analyzed quarterly) provide the following medians. Monthly analyses (2002 to present) indicated a sodium adsorption ratio (SAR) of 10.7 and an adjusted SAR of 12.9, while daily analyses indicated electrical conductivity (EC) and pH were 2 dS $m^{-1}$ and 7.8, respectively. According to Alberta irrigation water quality standards, this effluent has pH values comparable to most natural surface waters and is considered fit for irrigation (Alberta Environment 2000). The same standards described the effluent as having hazardous SARs (>9) and possibly safe ECs (1.0 to 2.5 dS $m^{-1}$), making it available for restrictive irrigation purposes, and requiring a leaching fraction.

Ca (110 mg $L^{-1}$) and Mg (14 mg $L^{-1}$) occur in the effluent, but it is not a good source of N (0.10 mg $NO_3$-N $L^{-1}$ and 1.63 mg total Kjeldahl nitrogen (TKN) $L^{-1}$), P (0.67 mg dissolved P $L^{-1}$ and 1.03 mg total P $L^{-1}$) or potassium (K) (31 mg $L^{-1}$) as concentrations are low relative to plant requirements. Total organic carbon was 39.0 mg $L^{-1}$; no water use guidelines for irrigation purposes were found. Sulphate ($SO_4$) (532.5 mg $L^{-1}$), Na (312.5 mg $L^{-1}$) and chloride (Cl) (132.5 mg $L^{-1}$) occur in high concentrations and are of particular concern when considering effluent irrigation effects on plants and soil. All other micronutrients and trace metals were not detected or below 1 mg $L^{-1}$. Of those detected effluent contained aluminium (Al), iron (Fe) and manganese (Mn) at 0.40, 0.21 and 0.10 mg $L^{-1}$, respectively.

### 4.3.5 Forage Measurements and Sampling

Perennial grass development growth stages were assessed approximately every month and prior to harvests (Moore et al. 1991). Alfalfa development was monitored according to morphological stages of individual stems (Kalu and Fick 1983). Weed presence and other factors affecting forage establishment and growth, such as insect damage, were recorded. Forage and weed samples were collected to determine forage dry matter biomass and quality twice during each growing season. Harvesting was conducted at times of optimal forage quality, estimated by forage growth development. After each harvest, remaining plant material was mowed and removed to simulate haying operations. Harvest and removal dates are presented in Table 4.2.

At each harvest, four quadrats (0.25 $m^2$) per plot were placed strategically to avoid areas trampled where soil moisture readings occurred. In each quadrat, plant height averages were measured (data not included) and plant material was hand clipped with grass shears at approximately 8 cm above ground. Forage and weed biomass were separated in the field and weighed. Biomass samples were oven dried at 60 °C for at least 72 hours, after which dry weights were determined. Total biomass cut 1 and cut 2 include forage and weed components and weed biomass includes weed biomass separate from forages. All biomass results are presented on a dry matter basis. The four dried forage samples from each plot were combined and a subsample was collected and sent to EnviroTest Labs in Edmonton for quality analyses for ruminants.

### 4.3.6 Laboratory Analyses

Analyses of fiber constituents included acid detergent fiber (ADF) and neutral detergent fiber (NDF). ADF was determined via official methods for fiber (acid detergent) (Association of Analytical Chemists (AOAC) 1990a); while NDF was analyzed with the neutral detergent fiber-amylase procedure recommended by the National Forage Testing Association (Undersander et al. 1993). Total digestible nutrients (TDN) were calculated as per Undersander et al. (1993) based on energy requirements and feed values of legumes for lactating cows. Relative feed value (RFV) was calculated as per Rohweder et al. (1978) as cited in Collins and Fritz (2003). Crude protein (CP) was calculated once TKN was determined via the copper catalyst Kjeldahl method (AOAC 1995). Nitrate ($NO_3$) and Cl concentrations were determined by ion chromatography (Kalbasi and Tabatabai 1985). Macronutrients including total P, K, sulphur (S), Ca and Mg were determined using official methods for minerals in animal feed (AOAC 1990b). Other micronutrients determined via official methods included total Na, copper (Cu), Fe, Mn and zinc (Zn) (AOAC 1990b).

### 4.3.7 Statistical Analyses

Each forage harvest was analyzed separately because of different growing conditions due to irrigation and precipitation events as well as fertilization errors. To determine if the two non-irrigated and two low effluent rate replicates were different due to fertilization errors, t-tests were conducted on total biomass. The two non-irrigated replicates were significantly different from each other for the second cut of 2003 and both cuts of 2004, while the two low effluent rate replicates were only significantly different for the first cut of 2004. Thus data from the affected replicates from these cuts were removed from the biomass and quality analyses and considered missing values.

Tests of normality were conducted on total biomass only using the Proc Univariate procedure of SAS. The Shapiro-Wilk test statistic was used since the number of samples was small. Normality was not rejected since W was not sufficiently smaller than 1 for the four harvests. Tests of normality were not conducted on forage quality because of small sample numbers.

Analyses of Variance (ANOVA) were conducted using the SAS Proc Mixed procedure (Littel et al. 1996). ANOVA was assumed robust enough to complete the analyses based on a split-strip plot design (Figure 4.1) (Milliken and Johnson 1992). Replicates nested within irrigation effects were considered random, while other effects were fixed (Appendix). When the F-test indicated significant main and interaction effects ($P < 0.05$), least square means (LSMeans) were used to determine significant differences between treatment means via Tukey-Kramer (Littel et al. 1996).

## 4.4 RESULTS AND DISCUSSION

### 4.4.1 Meteorological Trends

Annual precipitation at Athabasca was 2.4% below and 13.5% above the long-term normal (LTN) in 2003 and 2004, respectively (Table 4.3). The corresponding growing season precipitation was 7.1% below and 10.8% above LTN, respectively. On-site annual total precipitation was 28.4% and 8.3% less, and growing season precipitation was 35.5% less and 2.9% more than at Athabasca for 2003 and 2004, respectively. On-site precipitation in 2003 was notably low in May and July to September and notably high in June. In 2004 precipitation was notably high in May and July to September and notably low in June. The total number of rainy days on-site during the growing season was 82 in 2004 and 41 in 2003.

The 2003 and 2004 growing seasons at Athabasca had 213 and 101 degree days fewer than the LTN, respectively (Table 4.4). On-site growing season data indicated 231 more and 109 fewer degree days than at Athabasca in 2003 and 2004, respectively. On-site, the 2003 growing season had 228 degree days more than 2004. Both data sets indicated July had the highest number of growing degree days.

Average daily temperatures for the growing seasons were similar between locations, while Athabasca annual temperatures were similar to LTN (Table 4.4). May and September 2004 had lower average temperatures than the same months in 2003 and the LTN, while June and July for both years had similar average temperatures on-site and at Athabasca. The greatest difference in average daily temperatures between years occurred in August when 2003 averages were 2 to 3 °C higher than 2004. August and September 2004 were notably wetter and cooler than in 2003.

In summary, 2003 was a drier year on-site with more growing degree days than 2004, which received almost twice the precipitation over the growing season. Thus the weather conditions may have influenced soil properties as total soil water and soil moisture content increased and decreased with precipitation events.

### 4.4.2 Effluent Irrigation Depths and Variability

In late summer 2003, low effluent rate treatments received an average of 30 mm of effluent, while high rate treatments received 60 mm, via two irrigation events on August 20 and September 5. Irrigation did not occur prior to August due to different maturation and harvest timing of the forages. In 2004, low and high rate treatments received 75 and 150 mm, respectively, over three irrigation events on June 24, June 26 and July 28. No further irrigation events occurred in 2004 due to wet soil moisture conditions from many precipitation events.

During irrigation events, measured depths of applied effluent indicated that not all plots received the same amount of effluent in a given irrigation event (data not shown). Plots on the outer edge of the treatment blocks received less than 50% of the amount received along the sprinkler laterals (Figure 4.1). Replicate blocks south of the laterals received slightly more effluent than blocks on the north side. Possible reasons for this include sprinkler rotation setup and wind direction at the time of irrigation.

### 4.4.3 Forage Biomass

Total biomass (forage and weeds) was not significantly affected by irrigation treatment except in 2004 cut 1 when it was highest under low effluent rate irrigation (P=0.0395) (Table 4.5). Total biomass was numerically highest under low effluent rate irrigation in all other cuts except the final 2004 cut (P=0.4310) when moisture was not limiting (2003 $P_{cut\ 1} = 0.0512$; $P_{cut\ 2} = 0.0904$). About half of the high effluent rate biomass was weeds in 2003 cut 1 due to poor establishment of alfalfa and reed canary grass (Table 4.6). Weed biomass decreased thereafter likely due to plant removal after sampling and better stand establishment that reduced competition.

Determining irrigation rate effects was difficult because of a field anomaly where the low rate had higher soil moisture (see Chapter 3). The lack of expected differences in biomass between high and low irrigation rates include crop loss due to lodging in grasses fertilized at high rates in both irrigated treatments, specifically for timothy in the low rate. Alfalfa canopy defoliation occurred in the last cut due to delayed harvest because of an unexpected snowfall and/or high soil moisture in the low rate.

Contrary to these findings, Patterson et al. (2002) in a recent greenhouse study found reed canary grass significantly increased biomass with increasing pulp mill effluent rates. In another greenhouse study, Brown and Glenn (1999) found saline irrigation at higher volumes increased water consumption and biomass of *Suaeda esteroa*, a succulent salt marsh shrub. Bolan et al. (2004) found legume-based pasture dry matter increased with increasing dairy farm effluent rates. They could not determine if soil moisture or nutrients from the effluent affected yield because there was no water control treatment. Past yield responses were attributed to nutrients, especially N. In a study with a water control treatment, corn and vetch irrigated with municipal secondary treated wastewater had greater yields than the control and N and P fertilized water treatments (Mohammad and Ayadi 2004). They attributed yield increase to high nutrients in wastewater, which enhanced soil physical properties and soil organic matter for optimal plant growth.

Neither forage species had consistently highest biomass (Table 4.5). In 2003 cut 1, timothy biomass was significantly higher than alfalfa and reed canary grass due to poor establishment and weed biomass of the other species (P=0.0016) (Tables 4.6 and 4.7). Weeds and soil moisture differences made it difficult to determine which irrigation rate would produce higher biomass. Entz et al. (2002) explained forage stand establishment is difficult when soil moisture deficits occur. Some species, such as timothy, establish easier than others, while reed canary grass is difficult because of slow seed germination (Balasko and Nelson 2003). Alfalfa is also difficult to establish because of its small seeds and seedling susceptibility to low soil moisture and weeds (McGraw and Nelson 2003).

After the first irrigation in late summer 2003, alfalfa and reed canary grass had fewer weeds and significantly higher biomass than timothy (P=0.0132), which had noticeably poor regrowth and grasshopper damage in the non-irrigated treatment (Tables

4.6 and 4.7). Timothy is noted for relatively poor regrowth (Balasko and Nelson 2003). In 2004, no significant differences in total biomass occurred among forages, although reed canary grass produced slightly higher biomass. Over the four cuts, grasses produced higher total biomass than alfalfa.

Fertilizer main effects were not significant during the study with numerical differences more pronounced in 2004 (Table 4.5). The forage by fertilizer interaction was significant in 2004 ($P_{cut\ 1}$ = 0.0.0060; $P_{cut\ 2}$ = 0.0001). Timothy and reed canary grass had significantly higher biomass at 200 and 400 N than 0 N; whereas alfalfa had no differences across fertilizer treatments (Figure 4.2). This was not significant in 2003 when soil moisture was lower. Alfalfa may not require N fertilizer if bacteria are efficiently fixing N, but low pH and other nutrient deficiencies, such as sulphur (S), may reduce bacteria efficiency and thus require N fertilization (Mahli et al. (2002). This would be unlikely under pulp mill effluent irrigation as increases in soil $SO_4$ would occur (see Chapter 2). Researchers reported lower yields, reduced stands and increased weeds when legumes were N fertilized (Cherney et al. 1994). Bolan et al. (2004) explained that lowered legume yields when fertilized occurred because of reduced biological N fixation which depended on application timing, rates and grazing management.

Perennial grasses respond well to N fertilizers depending on N sources, application rates, timing and methods (Mahli et al. 1993). Greatest yield responses were found at the first N increment, after which no significant increases occurred likely due to residual N, evident in this study at higher fertilizer increments (Macoon et al. 2002). Bolan et al. (2004) found pasture dry matter response to fertilizer N increased at low rates and decreased at high rates and was affected by application time, form of N and species.

### 4.4.4 Forage Quality

#### 4.4.4.1 Fibre, Total Digestible Nutrients and Relative Feed Value

Fibre, TDN and RFV were not generally significantly affected by irrigation treatments (Table 4.8). After the first irrigation significant differences occurred in low effluent in 2003 cut 2 with ADF higher (P = 0.0248) and TDN lower (P = 0.0251) than non-irrigated. More soil water in the low rate likely influenced these parameters as plants were more mature (Table 4.7). Low leaf to stem ratios occurred because of high temperature, resulting in higher fibre and reduced quality.

Alfalfa had the highest RFV in both years (Table 4.8). In 2003 both grasses had higher NDF and ADF, but lower TDN and RFV than alfalfa, significant only in cut 1 ($P_{ADF, TDN} = 0.0002$; $P_{NDF, RFV} = <0.0001$). Differences were less pronounced in 2004. Fertilizer treatments had little effect overall. Significant differences occurred in 2003 cut 1 when 0 and 100 N had higher NDF (P = 0.0055) and ADF (P= 0.0057), but lower TDN (P = 0.0057) than 400 N. 400 N had higher RFV than 100 N (P = 0.0089).

In 2004 cuts 1 and 2, the forage by fertilizer interaction was significant for all parameters. When fertilized, timothy had higher NDF and ADF, but lower TDN and RFV, whereas reed canary grass and alfalfa did not respond to fertilizer. Unfertilized timothy was at an earlier developmental stage than both fertilized grasses (Table 4.7). Grass digestibility is most affected by growth development stage with leaf:stem ratios decreasing as grasses develop and stems lignify thereby decreasing digestibility (Balasko and Nelson 2003). Alfalfa did not respond to N fertilizer and other researchers have found alfalfa quality has not been influenced, but high rates of N could lower alfalfa digestibility through increased lignin synthesis (Cherney et al. 1994).

#### 4.4.4.2 Crude Protein and Nitrates

CP and $NO_3$ did not differ significantly among irrigation treatments (Table 4.9). The pulp mill effluent contained little $NO_3$, thus differences were not expected. However, this was difficult to determine because a water control treatment had not been applied. Another saline effluent irrigation study found plant N decreased with increasing rates since plants at lower rates accumulated more tissue N to regulate osmotic potential under highly saline environments (Brown and Glenn 1999).

CP did not differ significantly among forage treatments (Table 4.9). Numerically, alfalfa and reed canary grass had higher CP as they are naturally high in protein (Vetsch et al. 1999; McGraw and Nelson 2003). The irrigation by forage interaction was significant for CP in 2003 ($P_{Cut\,1} = 0.0327$, $P_{Cut\,2} = 0.0436$) and 2004 cut 1 (P = 0.0276). but with no consistent trends. In 2003 cut 1 reed canary grass had lower CP in the low rate than in other irrigation treatments. 2003 cut 2 and 2004 cut 1 reed canary grass had higher CP without irrigation while alfalfa still had higher CP with irrigation (Figure 4.3). In 2003 cut 1 reed canary grass had significantly higher $NO_3$ (P = 0.0129) than alfalfa (Table 4.9). This trend was consistent in subsequent cuts with reed canary grass having higher $NO_3$ than timothy.

Fertilizer main treatment effects were significant in 2003 for CP ($P_{Cut\ 1} = 0.0001$, $P_{Cut\ 2} = 0.0021$) and in 2003 cut 1 for $NO_3$ ($P_{Cut\ 1} < 0.0001$); CP increased with increasing N fertilizer rates (Table 4.9). The irrigation by fertilizer interaction was significant for $NO_3$ in 2003 cut 2 (P = 0.0174) being significantly higher with 400 than 0 and 100 N in irrigated treatments (Figure 4.4). Irrigation likely improved $NO_3$ plant uptake when soil moisture was limiting (Mahli et al. 1993).

In 2004, both cuts had significant forage by fertilizer interactions for CP ($P_{Cut\ 1} = 0.0084$, $P_{Cut\ 2} < 0.0001$) and $NO_3$ ($P_{Cut\ 1} = 0.0279$, $P_{Cut\ 2} < 0.0002$), also significant for $NO_3$ in 2003 cut 2 (P = 0.0484). CP in grasses significantly increased with increasing fertilizer rates, while alfalfa did not (Figure 4.5). $NO_3$ increased in all species with increasing fertilizer rates, but only grasses were significantly higher at 400 than 0, 100 and 200 N (Figure 4.6). Reed canary grass had the highest $NO_3$ at all rates because it can take up N more efficiently than timothy (Barker and Collins 2003).

#### 4.4.4.3 Macro and Micro Nutrients

Irrigation affected availability of some nutrients and met or exceeded plant nutrition requirements (plant nutrition requirements provided in Table 4.10). The high effluent rate had highest P, significantly higher (P = 0.0242) than non-irrigated in 2003 cut 2 when moisture was limiting (Table 4.11). Non-irrigated plant P was borderline deficient (<0.2%) without irrigation. P differed little among forages or fertilizer treatments. In the last cut, reed canary grass had significantly higher P than alfalfa and timothy (P = 0.0170). P significantly differed among fertilizer treatments in 2003 cut 1 (P = 0.0323) and 2004 cut 2 (P = 0.0343) being highest at 400 N and 0 N, respectively. Usually, N fertilizer promotes P uptake by plants as was the case before irrigation began (Havline et al. 1999). Pulp mill effluent contains little P; thus soil physical processes such as sorption-desorption were likely causing higher P under irrigation. Brown and Glenn (1999) found plant P was not significantly different among saline irrigation treatments, but increased slightly with increasing irrigation volume. Increased soil moisture increased P availability and plant uptake in limited moisture conditions (Havlin et al. 1999).

K was highest under high effluent irrigation; both irrigation treatments were significantly higher than non-irrigated in 2004 cut 2 ($P = 0.0321$) (Table 4.11). Mohammad and Ayadi (2004) found K uptake increased in corn when irrigated with municipal wastewater, enhancing crop tolerance to salinity. Bolan et al. (2004) found K increased in a legume based pasture with increasing dairy farm effluent rates. Both studies attributed the increase to excess loading and luxury plant uptake. The irrigation by forage interaction was significant for K in 2003 ($P_{Cut\ 1} = 0.0105$, $P_{Cut\ 2} = 0.0271$) (Forage 4.7). Reed canary grass had highest K in the high rate in cut 1 with no differences occurring among species in other irrigation treatments. In cut 2 both grasses had higher K than alfalfa in both irrigated treatments, but not in non-irrigated. Generally grasses had higher K than alfalfa, particularly in 2004 ($P_{Cut\ 1} = 0.0346$, $P_{Cut\ 2} = 0.0074$) (Table 4.11). Among fertilizer treatments, K was numerically higher at 400 N prior to irrigation, but in 2004 cut 2 ($P = 0.0355$) K decreased with increasing fertilizer rates. High ammonium ($NH_4$) from high N fertilizer rates can restrict K uptake and produce K deficiency symptoms (Havlin et al. 1999). Plants were not deficient in K in this study.

S did not differ significantly for any of the main effects (Table 4.11). Irrigation by forage interactions were significant in cut 2 both years ($P_{03} = 0.0103$, $P_{04} = 0.0130$) with reed canary grass having highest and timothy having lowest S in irrigated versus non-irrigated treatments (Figure 4.8). Prior to irrigation, timothy was slightly S deficient, but not after the first event since pulp mill effluent contains significant S. After the last irrigation, alfalfa and timothy were both deficient (<0.15%) when soil moisture exceeded field capacity (see Chapter 3). The irrigation by fertilizer interaction was significant in 2003 cut 2 ($P = 0.0433$) increasing with increasing fertilizer rates in the high rate, but decreasing in the non-irrigated treatment (Figure 4.9). Increases in $NH_4$ due to fertilization enhance S uptake by plants when moisture conditions are optimal (Havlin et al. 1999). Forage by fertilizer interactions were significant for all other cuts. In 2003 cut 1 grasses increased with increasing fertilizer rates while alfalfa did not because it did not respond to N fertilizer ($P = 0.0472$) (Figure 4.10). In 2004, reed canary grass had significantly higher S when fertilized while other species did not ($P_{Cut\ 1} = 0.0368$, $P_{Cut\ 2} < 0.0001$) (Figure 4.11), likely due to its ability to subsist in wetter conditions.

Significant treatment effects did not generally occur with Ca and Mg (Table 4.12). Alfalfa, naturally high in Ca, had higher Ca than grasses; alfalfa and reed canary grass had higher Mg than timothy. Ca and Mg had significant irrigation by forage interactions after irrigation began. In 2004, alfalfa had significantly higher Ca in non-irrigated than irrigated treatments, while no differences among irrigation treatments occurred for grasses ($P_{cut\ 1} = 0.0175$, $P_{cut\ 2} = 0.0316$) (Figure 4.12). In 2003 cut 2 reed canary grass and alfalfa had higher Mg in non-irrigated and low rate treatments than in the high rate while timothy had no significant differences among irrigation rates ($P = 0.0304$) (Figure 4.13). Ca and Mg likely decreased with increasing effluent rates due to K competition for plant uptake (Bolan et al. 2004). The forage by fertilizer interaction was significant for Ca in 2004 cut 1 ($P = 0.0350$) (Figure 4.14) and for Mg in cut 1 of both years ($P_{03} = 0.0062$, $P_{04} = 0.0268$) (Figure 4.15). The grasses increased in Ca and Mg as fertilizer rates increased, alfalfa showed no response. This was unexpected as high $NH_4$ reduces Ca and Mg uptake, especially in low pH soils (Havlin et al. 1999; Barker and Collins 2003). Three way interactions for Ca in 2003 cut 1 and Mg in 2004 cut 2 were also significant ($P_{Ca} = 0.0238$, $P_{Mg} = 0.0022$).

Prior to irrigation Na did not significantly differ among irrigation treatments (Table 4.13). In 2003 cut 2, both irrigated treatments had significantly higher Na ($P = 0.0393$) than non-irrigated. Consistently alfalfa had higher Na with significant differences in 2003 ($P_{Cut\ 1} = 0.0021$, $P_{Cut\ 2} = 0.0043$) and 2004 cut 2 ($P = 0.0012$). In 2004 cut 1, the irrigation by forage interaction was significant ($P = 0.0127$) (Figure 4.16). Alfalfa had significantly highest Na in the low rate followed by the high rate then non-irrigated, while both grasses had higher Na in the high rate, followed by the low rate. Na significantly differed among forage species with irrigation but not non-irrigated. Na significantly differed among fertilizer treatments with 200 N having the higher value ($P = 0.0157$) in 2004 cut 2 (Table 4.13).

Cl did not differ significantly with irrigation; although concentrations clearly increased with increasing effluent rates (Table 4.13). Reed canary grass had highest Cl, significantly in 2003 cut 1 (P = 0.0005) and 2004 cut 2 (P = 0.0126). In mid study, the forage by fertilizer interaction was significant in 2003 cut 2 (P = 0.0372) and 2004 cut 1 (P = 0.0343) (Figure 4.17). Cl was highest in unfertilized reed canary grass. Reed canary grass significantly decreased in Cl with increasing fertilizer rates, while alfalfa and timothy did not. High $NO_3$ from the fertilizer likely reduced Cl uptake; high $SO_4$ can also reduce plant uptake (Havline et al. 1999)

In 2003 cut 1, reed canary grass had significantly higher Mn (P = 0.0130) than alfalfa and timothy and Mn increased with increasing fertilizer rates (P = 0.0169) (Table 4.14). Mn plant availability increases as soil pH decreases (Barker and Collins 2003). Three way interactions were significant for Mn in 2003 cut 2 (P = 0.0028) and both cuts in 2004 ($P_{Cut\ 1}$ = 0.0323, $P_{Cut\ 2}$ = 0.0186).

In 2003 cut 2 Fe was higher (P = 0.0144) in the high rate and non-irrigated treatments than the low rate (Table 4.14) likely due to soil moisture differences. Fe was highest in alfalfa ($P_{Cut\ 1}$ = 0.0025, $P_{Cut\ 2}$ = 0.0011) in 2003 and highest in reed canary grass in 2004 cut 2 (P = 0.0019). In 2003 cut 1, plants fertilized at 400 N had significantly higher Fe than 0 N (P = 0.0200) likely due to decreased pH as Fe availability increases as soil pH decreases (Barker and Collins 2003). Although not significant, treatments fertilized had higher Fe than unfertilized during other times.

Cu significantly differed among forage treatments only (Table 4.14). Alfalfa had higher Cu ($P_{Cut\ 1}$ = 0.0107, $P_{Cut\ 2}$ = 0.0017) in 2003 and 2004 cut 1 (P = 0.0165), while levels were highest in reed canary grass in 2004 cut 2 ($P_{Cu}$ = 0.0032) when soil moisture increased (see Chapter 3). Cu was generally deficient in all species (<5 ppm).

Zn had significant irrigation by forage interactions in 2003 ($P_{Cut\ 1}$ = 0.0210, $P_{Cut\ 2}$ = 0.0438) (Figure 4.18). Reed canary grass had highest Zn in the high rate and non-irrigated treatments prior to irrigation, while no differences occurred among forages in the low rate. After irrigation began, reed canary grass had highest Zn in both irrigated treatments, likely due to the increase in soil moisture enhancing plant uptake. Zn was significantly higher at 400 N than 0 N in 2003 cut 1 (P = 0.0003), increasing with increasing fertilizer rates (Table 4.14). After irrigation began, the irrigation by fertilizer interaction was significant (P = 0.0117) where Zn increased with increasing fertilizer rates under irrigation (Figure 4.19). The forage by fertilizer interaction was significant in 2003 cut 2 ($P = 0.0148$) and both cuts in 2004 ($P_{Cut\,1} = 0.0179$, $P_{Cut\,2} = 0.0011$) with Zn increasing with fertilizer more in the grasses than alfalfa in 2004 (Figure 4.20). Plant availability of Zn also increases with decreasing soil pH (Barker and Collins 2003).

Generally, plant P, K, S, Na and Cl were higher under irrigation and increased with increasing effluent rate being highest in 2003 cut 2 when biomass was lowest. Increased P can be attributed to water in the effluent while increased S, Na and Cl can be attributed to the effluent. Most micronutrients had no consistent trends among irrigation treatments as the effluent contained very low concentrations. Contrary to this study, Mohammad and Ayadi (2004) found Fe, Mn, Zn and Cu corn uptake increased with municipal wastewater versus potable water, even though wastewater micronutrient concentrations were low.

Reed canary grass likely had higher concentrations of some nutrients because of its requirements or better capability to take up nutrients especially with increased soil moisture. Grasses with shallow, extensive, fibrous roots have more effective surface area for nutrient absorption than legumes with taproots accessing nutrients deeper in the soil (Fageria et al.1997). Thus, immobile nutrients like P concentrated in top layers are taken up easier by grasses than legumes. Grass roots also have lower cation exchange capacities (CEC) and extract monovalent cations (K and Cl) from the soil easier than legumes (Fageria et al. 1997). In drier conditions in 2003, alfalfa had higher concentrations likely due to its ability to uptake nutrients at greater depths.

High rates of fertilizer reduced plant uptake of K and Cl, while enhancing S, Mn and Fe uptake likely due to the decrease in soil pH. High $SO_4$ levels from effluent additions may also have reduced Cl plant uptake.

#### 4.4.4.4 Ruminant Nutrition Requirements

Most treatments met mature beef cow nutrition requirements (55%) (Yurchak and Okine 2004) except alfalfa in the last cut which had TDN < 50%. All treatments in 2003 cut 2 exceeded TDN requirements (> 60%). In 2003, most alfalfa treatments met #1 and #2 hay quality standards (151 < RFV > 103) in the first cut, and prime quality (RFV >

151) in the second cut (Collins and Owens 2003). Most grass treatments were rated #4 (86 < RFV > 75) except in the second cut when they rated #1 (151 < RFV > 125) to #3 (102 < RFV > 87). Thus, according to AAFRD and NRC recommendations, alfalfa had the highest hay quality; in 2003 cut 2 grasses had high quality and in the last cut alfalfa had similar quality to grasses due to plant maturity differences (Table 4.8).

All treatments met minimum CP requirements for a mature beef cow (7%) and at 400 N exceeded or met feeder calf requirements (14%) with values > 24% at times (Yurchak and Okine 2004). Reed canary grass at fertilizer rates < 400 N met calf requirements most of the time, while timothy did not except in 2003 cut 2. Thus, unfertilized and fertilized alfalfa and reed canary grass provided acceptable CP percentages. Low CP in timothy were improved with fertilization and irrigation.

If CP is too high (> 23.75%), $NO_3$ testing is recommended and producers should provide feed with more energy (Cherney et al. 1994). $NO_3$ plant concentrations < 0.5% are safe for livestock (Yaremcio 1991), but most grass treatments and alfalfa in 2004 cut 1 at 400 N had $NO_3$ > 0.5% thus increasing the risk for nitrate poisoning (Vetsch et al. 1999). With irrigation reed canary grass had higher N uptake with 400 N levels > 1.0 %. This could cause nitrate toxicity problems such as calf abortions or cattle death (Yaremcio 1991). If forage is not used for feed and $NO_3$ accumulation is of little concern, reed canary grass can serve as a large sink for N without causing environmental concerns.

Minimum S requirements for growing and finishing cattle (0.15%) were met for most treatments in the first year, except timothy in the first cut (National Research Council (NRC) 1996). This was also true in the next cut. Alfalfa S was slightly below 0.15% in the last cut. Reed canary grass had adequate S and even exceeded the maximum tolerable limit (0.40%) in effluent treatments after irrigation started.

All species met livestock P requirements (0.20%) for most treatments (NRC 1996), except alfalfa and reed canary grass in the non-irrigated treatment in the second cut and alfalfa in the third cut (< 0.17%). Thus, P concentrations slightly improved with irrigation. Alfalfa exceeded Ca requirements for feeder calves (0.7%) and mature beef cows (0.4%) in most cuts except in the last cut when it was near 0.7% (NRC 1996). Grass treatments did not meet calf Ca requirements at any time or beef cow requirements except in 2003 cut 2 with values near 0.4%. With low Ca in most grass treatments, low Ca:P ratios were a potential problem, as 2:1 and 7:1 are considered optimal (Yurchak and Okine 2004). Alfalfa with its high Ca, particularly in the non-irrigated treatment, may have C:P ratios > 7.1.

Minimum plant Mg requirements (0.10%) were met with most unfertilized timothy and alfalfa treatments (NRC 1996). Reed canary grass had Mg > 0.2% and exceeded the maximum tolerable concentration (0.40%) at high fertilizer rates in the low rate and non-irrigated treatments (NRC 1996). All species had K near or > 1.0% and met livestock requirements (0.60%) (NRC 1996). Grasses exceeded optimal concentrations (1.75%) before and after irrigation began (Yurchak and Okine 2004). This potentially can cause grass staggers or tetany with K:Ca+Mg ratios exceeding 2.2 as high K reduces Mg absorption (Grunes 1973; Marx 2002).

Prior to irrigation, almost all treatments did not meet minimum Na requirements (> 0.1%) (Yurchak and Okine 2004). After irrigation, alfalfa and reed canary grass met this requirement in irrigated treatments as Na and Cl increased with irrigation, thus eliminating the need for salt supplements. Although timothy concentrations increased with irrigation, requirements were not met in most cases.

In the first year, Mn requirements were met (20 ppm) by all species (NRC 1996), with close values in low effluent rate alfalfa and timothy. In the second year, most alfalfa treatments did not meet Mn requirements. All treatments did not meet Cu requirements (10 ppm) as most values were < 6 ppm, except alfalfa in 2003 cut 2 with levels between 10 and 19 (NRC 1996). Cu was initially low in all species prior to irrigation and remained below cattle requirements. It was lower in irrigated versus non-irrigated treatments during irrigation, likely due to increased S which can reduce Cu absorption (NRC 1996). Reed canary grass met Fe (50 ppm) requirements most of the time, except in the low rate the first year, ranging between 7 and 45 ppm (NRC 1996). Alfalfa did not meet Fe requirements in the low rate or non-irrigated treatments in the second year, while timothy met requirements only in 2003 cut 2. Generally Fe levels were low and deficient in alfalfa and timothy, but not in reed canary grass providing enough Fe for growth and prevention of anemia (NRC 1996). Timothy and alfalfa had Zn near or slightly below cattle requirements (30 ppm) most of the time, except in the last cut when values were as low as 15 ppm in alfalfa and 21 ppm in timothy. Reed canary grass treatments were near or above Zn requirements.

## 4.5 Conclusions

Whether high irrigation rates affected forage biomass differently than low rates could not be determined because of variable soil moisture which affected forage establishment. However, irrigation produced more biomass when soil moisture was limiting. Reed canary grass once established produced better yields in dry and wet conditions than other species. Fertilizer treatments significantly improved grass productivity when moisture was sufficient.

Most treatments met mature beef cow nutrition requirements. Alfalfa had the best forage hay quality in terms of RFV because of its inherent species characteristics. Effluent irrigation alleviated potential P, K and S plant deficiencies in all species while fertilizer N above 400 kg N $ha^{-1}$ $yr^{-1}$ increased the risk of nitrate poisoning, particularly in reed canary grass. Thus, N application of this magnitude under irrigation is not recommended and may not be economical. Reed canary grass exceeded most animal nutrient requirements under irrigation while timothy was deficient in few micronutrients. Both grasses had low Ca increasing the risk of grass tetany.

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**Table 4.1 Fertilizer application rate totals for replicates 1 and 4**

| Replicate | Treatment | June 2003 | July 2003 | 2003 Total | June 2004 | July 2004 | 2004 Total |
|---|---|---|---|---|---|---|---|
| 1 | 0 | 0 | 200 | 200 | 0 | 0 | 0 |
| | 100 | 50 | 100 | 150 | 50 | 50 | 100 |
| | 200 | 100 | 50 | 150 | 100 | 100 | 200 |
| | 400 | 200 | 0 | 200 | 200 | 200 | 400 |
| 4 | 0 | 0 | 0 | 0 | 50 | 0 | 50 |
| | 100 | 50 | 50 | 100 | 0 | 50 | 50 |
| | 200 | 100 | 100 | 200 | 100 | 100 | 200 |
| | 400 | 200 | 200 | 400 | 200 | 200 | 400 |

**Table 4.2 Forage harvest and excess removal dates for 2003 and 2004 growing seasons**

| Forage Species | Cut 1 | Removal | Cut 2 | Removal |
|---|---|---|---|---|
| **2003** | | | | |
| Timothy | July 10-11 | July 24-25 | September 13 | October 1 |
| Reed Canary Grass | July 17-18 | July 24-25 | September 20 | October 1 |
| Alfalfa | July 23-24 | July 24-25 | September 13 | October 1 |
| **2004** | | | | |
| Timothy | July 5 | July 13 | August 18 | September 21-22 |
| Reed Canary Grass | June 28-29 | June 30 | September 13-14 | September 21-22 |
| Alfalfa | July 6 | July 13 | September 7/13 | September 21-22 |

Alfalfa harvesting on September 7 was interrupted due to early snowfall

**Table 4.3 Average total precipitation for 2003 and 2004, including long-term normals for Athabasca**

| Month | Total Precipitation (mm) On-site 2003 | On-site 2004 | Athabasca* 2003 | Athabasca* 2004 | LTN |
|---|---|---|---|---|---|
| January | 24.6 | 26.4 | 45.7 | 43.0 | 24.9 |
| February | 22.9 | 19.1 | 19.0 | 7.0 | 18.6 |
| March | 29.5 | 24.6 | 26.2 | 17.0 | 17.7 |
| April | 9.9 | 16.0 | 23.4 | 32.0 | 25.5 |
| May | 11.4 | 103.6 | 45.7 | 69.7 | 47.3 |
| June | 109.0 | 29.2 | 149.3 | 11.7 | 91.7 |
| July | 42.3 | 116.1 | 78.1 | 165.9 | 104.5 |
| August | 36.6 | 76.5 | 35.8 | 60.9 | 62.3 |
| September | 9.4 | 71.9 | 14.8 | 78.0 | 42.8 |
| October | 27.7 | 18.0 | 18.9 | 34.5 | 21.4 |
| November | 21.3 | 5.1 | 20.5 | 14.5 | 21.1 |
| December | 7.4 | 17.3 | 14.0 | 37.0 | 25.5 |
| Growing Season | 208.7 | 397.3 | 323.7 | 386.2 | 348.6 |
| Annual Total | 352.0 | 523.7 | 491.4 | 571.2 | 503.3 |

* Data from weather station located near Athabasca
LTN = Long-term Canadian climate normals 1971-2000
Growing Season = May to October

**Table 4.4 Average growing degree days and air temperature for 2003 and 2004, including long-term normals for Athabasca**

| Month | Growing Degree Days (above 5 °C) On-site 2003 | On-site 2004 | Athabasca* 2003 | Athabasca* 2004 | LTN | Average Air Temperature (°C) On-site 2003 | On-site 2004 | Athabasca 2003 | Athabasca 2004 | LTN |
|---|---|---|---|---|---|---|---|---|---|---|
| January | 0.9 | 0.0 | 0.0 | 0.0 | 0.3 | -14.3 | -18.2 | -13.6 | -17.2 | -14.9 |
| February | 0.0 | 0.0 | 0.0 | 0.0 | 0.6 | -12.3 | -9.4 | -10.8 | -8.5 | -10.7 |
| March | 0.0 | 0.9 | 0.0 | 2.0 | 1.3 | -9.9 | -4.0 | -9.1 | -2.4 | -4.4 |
| April | 42.0 | 26.4 | 49.8 | 32.9 | 47.6 | 3.5 | 4.2 | 3.7 | 4.4 | 4.2 |
| May | 156.7 | 94.7 | 164.0 | 110.1 | 177.8 | 9.5 | 7.2 | 9.3 | 7.5 | 10.6 |
| June | 251.3 | 241.2 | 132.0^ | 273.2 | 278.3 | 13.7 | 14.0 | 14.8 | 14.1 | 14.2 |
| July | 373.5 | 366.4 | 380.5 | 389.6 | 346.1 | 17.3 | 17.1 | 17.3 | 17.6 | 16.2 |
| August | 349.4 | 250.1 | 351.0 | 291.4 | 314.6 | 16.4 | 13.5 | 16.3 | 14.4 | 15.2 |
| September | 157.1 | 108.0 | 162.0 | 105.4 | 153.6 | 9.7 | 7.8 | 10.2 | 8.3 | 9.8 |
| October | 77.6 | 43.4 | 79.0 | 32.5 | 47.9 | 5.0 | 1.2 | 5.6 | 1.3 | 4.1 |
| November | 0.0 | 1.1 | 0.0 | 1.0 | 1.5 | -9.5 | -1.9 | -8.5 | -1.3 | -6.2 |
| December | 0.0 | 0.0 | 0.0 | 0.5 | 0.3 | -12.0 | -11.7 | -11.2 | -11.2 | -12.9 |
| Growing Season | 1288.0 | 1060.4 | 1057.5 | 1169.7 | 1270.4 | 13.3 | 11.9 | 13.6 | 12.4 | 13.2 |
| Annual Total | 1408.5 | 1132.1 | 1186.3 | 1238.6 | 1369.9 | 1.43 | 1.65 | 2.00 | 2.25 | 2.10 |

Growing degree days represent number of Celsius degrees that mean temperature > 5 °C
* Data from weather station located near Athabasca
LTN = Long-term Canadian climate normals 1971-2000
^ Daily average temperatures incomplete from June 4 to 17, 2003

**Table 4.5 Average total biomass (Mg ha$^{-1}$) (forage and weeds) for 2003 and 2004**

| Treatment | 2003 | | 2004 | |
|---|---|---|---|---|
| | Cut 1 | Cut 2 | Cut 1 | Cut 2 |
| Eff-2x | 6.17 (0.20)^ | 1.23 (0.28) | 5.41 (0.31)[ab] | 4.05 (0.20) |
| Eff-1x | 7.36 (0.20) | 2.54 (0.28) | 6.46 (0.32)[a] | 4.38 (0.20) |
| NI | 6.79 (0.20) | 0.53 (0.40) | 3.88 (0.44)[b] | 4.59 (0.28) |
| ALF | 5.94 (0.20)[b] | 1.59 (0.21)[a] | 5.30 (0.36) | 4.09 (0.19) |
| RCG | 6.62 (0.20)[b] | 1.74 (0.21)[a] | 4.98 (0.36) | 5.01 (0.19) |
| TIM | 7.76 (0.20)[a] | 0.97 (0.21)[b] | 5.47 (0.35) | 3.92 (0.19) |
| 0 | 6.29 (0.22) | 1.09 (0.30) | 3.15 (0.27) | 2.36 (0.21) |
| 100 | 7.08 (0.22) | 1.39 (0.30) | 5.56 (0.27) | 4.66 (0.21) |
| 200 | 7.06 (0.22) | 1.67 (0.30) | 6.18 (0.25) | 5.19 (0.21) |
| 400 | 6.66 (0.22) | 1.59 (0.30) | 6.11 (0.25) | 5.15 (0.21) |

^LSMean (standard error)
Eff-2x = high irrigation rate; Eff-1x = low irrigation rate; NI = non-irrigated
ALF = alfalfa; RCG = reed canary grass; TIM = timothy
0 = no fertilizer; 100 = 100 kg N ha$^{-1}$ yr$^{-1}$; 200 = 200 kg N ha$^{-1}$ yr$^{-1}$; 400 = 400 kg N ha$^{-1}$ yr$^{-1}$
Same letters within treatments and cut are not significantly different ($p < 0.05$)
No letters indicate non-significance

**Table 4.6 Average weed biomass (Mg ha$^{-1}$) for 2003 and 2004**

| Treatment | 2003 | | 2004 | |
|---|---|---|---|---|
| | Cut 1 | Cut 2 | Cut 1 | Cut 2 |
| Eff-2x | 3.07 (0.22)^ | 0.00 (0.0) | 0.28 (0.09) | 0.06 (0.02) |
| Eff-1x | 1.78 (0.22) | 0.00 (0.0) | 0.18 (0.11) | 0.03 (0.02) |
| NI | 1.99 (0.22) | 0.00 (0.0) | 0.26 (0.12) | 0.04 (0.03) |
| ALF | 3.79 (0.18) | 0.00 (0.0) | 0.63 (0.11)[a] | 0.10 (0.02) |
| RCG | 2.39 (0.18) | 0.00 (0.0) | 0.02 (0.11)[b] | 0.03 (0.02) |
| TIM | 0.67 (0.18) | 0.00 (0.0) | 0.06 (0.11)[b] | 0.00 (0.02) |
| 0 | 2.04 (0.19) | 0.00 (0.0) | 0.10 (0.13) | 0.04 (0.02) |
| 100 | 2.53 (0.19) | 0.00 (0.0) | 0.27 (0.13) | 0.07 (0.02) |
| 200 | 2.49 (0.19) | 0.00 (0.0) | 0.20 (0.12) | 0.02 (0.02) |
| 400 | 2.06 (0.19) | 0.00 (0.0) | 0.40 (0.12) | 0.04 (0.02) |

^LSMean (standard error)
Eff-2x = high irrigation rate; Eff-1x = low irrigation rate; NI = non-irrigated
ALF = alfalfa; RCG = reed canary grass; TIM = timothy
0 = no fertilizer; 100 = 100 kg N ha$^{-1}$ yr$^{-1}$; 200 = 200 kg N ha$^{-1}$ yr$^{-1}$; 400 = 400 kg N ha$^{-1}$ yr$^{-1}$
Same letters within treatments and cut are not significantly different ($p < 0.05$)
No letters indicate non-significance

**Table 4.7 Observed plant development stages for 2003 and 2004**

| Observation Date | Timothy | | Reed Canary Grass | | Alfalfa | |
|---|---|---|---|---|---|---|
| **2003** | | | | | | |
| June 12 | E1 | early elongation | V3-E1 | late vegetative / early elongation | S1 | mid vegetative |
| July 10 | R3 | inflorescence emerged | E3-R0 | late elongation / boot stage | S3-S5 | early to late bud / early flower |
| August 13 | V1-V2 | early to mid vegetative | V1-V3 | early to late vegetative | S1 | mid vegetative |
| September 10 | V2-R3 | mid vegetative / inflorescence emerged | V1-V3 | early to late vegetative | S2-S3 | late vegetative / early bud |
| **2004** | | | | | | |
| June 9 | V4-V5 | late vegetative | V4-E1 | late vegetative / early elongation | S1-S2 | mid to late vegetative |
| June 28 | R2-R3 | inflorescence emerged | E1-R4 | early elongation / anthesis | S2-S3 | late vegetative / early bud |
| July 22 | V0-V2 | early vegetative | V3-E1 | late vegetative / early elongation | S0-S2 | early to late vegetative |
| August 18 | E2-R3 | elongation / inflorescence emerged | E3-R0 | late elongation / inflorescence emergence | S3-S4 | early to late bud |
| September 7 | R2-R3 | inflorescence emerged | E3-R3 | late elongation / inflorescence emerged | S4-S6 | late bud / late flower |

Plant stages were the most common across fertilizer treatments; plots that received no fertilizer were at lower stages of development than indicated

**Table 4.8 Fibre, total digestible nutrients and relative feed value as % dry matter for 2003 and 2004**

| Year | Trt | NDF (%) | | ADF (%) | | TDN (%) | | RFV | |
|---|---|---|---|---|---|---|---|---|---|
| | | Cut 1 | Cut 2 | Cut 1 | Cut 2 | Cut 1 | Cut 2 | Cut 1 | Cut 2 |
| **2003** | | | | | | | | | |
| | **Eff-2x** | 60.8 (0.41)^ | 45.6 (0.62) | 41.4 (0.38) | 27.3 (0.81)$^{ab}$ | 54.4 (0.41) | 69.5 (0.87)$^{ab}$ | 90 (1.34) | 152 (4.70) |
| | **Eff-1x** | 61.4 (0.41) | 49.9 (0.62) | 42.2 (0.38) | 31.2 (0.81)$^{a}$ | 53.5 (0.41) | 65.3 (0.87)$^{b}$ | 88 (1.34) | 129 (4.70) |
| | **NI** | 60.7 (0.41) | 39.7 (0.80) | 41.2 (0.38) | 24.1 (0.98)$^{b}$ | 54.6 (0.41) | 72.9 (1.05)$^{a}$ | 91 (1.34) | 178 (5.92) |
| | **ALF** | 46.6 (0.41)$^{b}$ | 31.2 (0.72)^ | 38.6 (0.38)$^{b}$ | 25.6 (0.72)$^{b}$ | 57.4 (0.41)$^{a}$ | 71.3 (0.77)$^{a}$ | 118 (1.34)$^{a}$ | 211 (4.86) |
| | **RCG** | 67.8 (0.41)$^{a}$ | 52.7 (0.72) | 43.8 (0.38)$^{a}$ | 27.3 (0.72)$^{ab}$ | 51.9 (0.41)$^{b}$ | 69.5 (0.77)$^{ab}$ | 75 (1.34)$^{b}$ | 120 (4.86) |
| | **TIM** | 68.6 (0.41)$^{a}$ | 51.4 (0.62) | 42.5 (0.38)$^{a}$ | 29.6 (0.63)$^{a}$ | 53.3 (0.41)$^{b}$ | 67.0 (0.67)$^{b}$ | 76 (1.34)$^{b}$ | 128 (4.21) |
| | **0** | 61.4 (0.47)$^{a}$ | 45.7 (0.79)^ | 42.0 (0.42)$^{a}$ | 28.5 (1.01) | 53.8 (0.45)$^{b}$ | 68.2 (1.08) | 89 (1.47)$^{ab}$ | 148 (5.94) |
| | **100** | 62.5 (0.47)$^{a}$ | 44.5 (0.79) | 42.9 (0.42)$^{a}$ | 27.0 (1.01) | 52.8 (0.45)$^{b}$ | 69.9 (1.08) | 86 (1.47)$^{b}$ | 156 (5.94) |
| | **200** | 60.7 (0.47)$^{ab}$ | 45.4 (0.79) | 41.5 (0.42)$^{ab}$ | 27.6 (1.01) | 54.3 (0.45)$^{ab}$ | 69.2 (1.08) | 91 (1.47)$^{ab}$ | 151 (5.94) |
| | **400** | 59.2 (0.47)$^{b}$ | 44.7 (0.79) | 40.0 (0.42)$^{b}$ | 27.0 (1.01) | 55.9 (0.45)$^{a}$ | 69.8 (1.08) | 95 (1.47)$^{a}$ | 155 (5.94) |
| **2004** | | | | | | | | | |
| | **Eff-2x** | 62.1 (1.04) | 57.3 (0.63) | 42.8 (0.79) | 39.1 (0.64) | 52.9 (0.84) | 53.9 (0.71) | 85 (2.53) | 86 (1.82) |
| | **Eff-1x** | 62.2 (1.27) | 56.4 (0.63) | 44.0 (0.96) | 38.7 (0.64) | 51.6 (1.02) | 54.3 (0.71) | 83 (3.09) | 87 (1.82) |
| | **NI** | 56.6 (1.48) | 55.9 (0.89) | 38.1 (1.11) | 36.9 (0.90) | 58.0 (1.19) | 56.3 (1.01) | 101 (3.58) | 91 (2.58) |
| | **ALF** | 49.2 (0.86) | 51.8 (0.60) | 43.7 (0.69) | 44.5 (0.56) | 52.0 (0.73) | 47.6 (0.67) | 106 (2.18) | 86 (1.70) |
| | **RCG** | 66.0 (0.86) | 60.9 (0.60) | 40.8 (0.69) | 36.5 (0.56) | 55.1 (0.73) | 56.9 (0.67) | 81 (2.18) | 84 (1.70) |
| | **TIM** | 65.7 (0.86) | 57.0 (0.60) | 40.5 (0.69) | 33.8 (0.56) | 55.4 (0.73) | 60.1 (0.67) | 82 (2.18) | 94 (1.70) |
| | **0** | 57.9 (1.49) | 54.2 (0.56) | 39.3 (1.13) | 35.7 (0.51) | 56.7 (1.21) | 57.7 (0.58) | 96 (3.71) | 96 (1.60) |
| | **100** | 61.4 (1.49) | 57.4 (0.56) | 42.6 (1.13) | 39.0 (0.51) | 53.2 (1.21) | 54.0 (0.58) | 87 (3.71) | 86 (1.60) |
| | **200** | 62.2 (1.33) | 57.1 (0.56) | 43.5 (1.02) | 39.2 (0.51) | 52.2 (1.09) | 53.8 (0.58) | 84 (3.32) | 86 (1.60) |
| | **400** | 59.6 (1.33) | 57.5 (0.56) | 41.3 (1.02) | 39.1 (0.51) | 54.5 (1.09) | 53.8 (0.58) | 91 (3.32) | 85 (1.60) |

^LSMean (standard error)
Eff-2x = high irrigation rate; Eff-1x = low irrigation rate; NI = non-irrigated
ALF = alfalfa; RCG = reed canary grass; TIM = timothy
0 = no fertilizer; 100 = 100 kg N ha$^{-1}$ yr$^{-1}$; 200 = 200 kg N ha$^{-1}$ yr$^{-1}$; 400 = 400 kg N ha$^{-1}$ yr$^{-}$
NDF = neutral detergent fiber; ADF = acid detergent fiber; TDN = total digestible nutrients;
RFV = relative feed value
Same letters within treatments and cut are not significantly different ($p < 0.05$)
No letters indicate non-significance

**Table 4.9 Crude protein and nitrate as % dry matter for 2003 and 2004**

| Year | Trt | Crude Protein (%) | | Nitrate (%) | |
|---|---|---|---|---|---|
| | | Cut 1 | Cut 2 | Cut 1 | Cut 2 |
| 2003 | | | | | |
| | Eff-2x | 15.8 (0.36)^ | 23.9 (0.72) | 0.36 (0.05) | 0.21 (0.03) |
| | Eff-1x | 14.4 (0.36) | 20.6 (0.72) | 0.24 (0.05) | 0.29 (0.03) |
| | NI | 15.3 (0.36) | 22.4 (0.86) | 0.32 (0.05) | 0.09 (0.04) |
| | ALF | 20.4 (0.36) | 24.4 (0.63) | 0.18 (0.05)[b] | 0.15 (0.03) |
| | RCG | 14.8 (0.36) | 23.4 (0.63) | 0.44 (0.05)[a] | 0.29 (0.03) |
| | TIM | 10.3 (0.36) | 19.3 (0.55) | 0.29 (0.05)[ab] | 0.15 (0.02) |
| | 0 | 13.0 (0.41)[c] | 20.0 (0.63)[b] | 0.08 (0.05)[c] | 0.05 (0.03) |
| | 100 | 14.1 (0.41)[bc] | 22.0 (0.63)[ab] | 0.19 (0.05)[bc] | 0.12 (0.03) |
| | 200 | 15.9 (0.41)[ab] | 23.4 (0.63)[a] | 0.36 (0.05)[b] | 0.23 (0.03) |
| | 400 | 17.7 (0.41)[a] | 23.9 (0.63)[a] | 0.60 (0.05)[a] | 0.38 (0.03) |
| 2004 | | | | | |
| | Eff-2x | 14.8 (0.43) | 14.0 (0.32) | 0.39 (0.04) | 0.25 (0.06) |
| | Eff-1x | 15.6 (0.53) | 14.2 (0.32) | 0.36 (0.04) | 0.31 (0.06) |
| | NI | 15.2 (0.61) | 14.4 (0.45) | 0.30 (0.05) | 0.34 (0.08) |
| | ALF | 18.5 (0.40) | 16.3 (0.33) | 0.26 (0.04) | 0.19 (0.05) |
| | RCG | 16.6 (0.40) | 15.8 (0.33) | 0.50 (0.04) | 0.49 (0.05) |
| | TIM | 10.5 (0.40) | 10.4 (0.33) | 0.29 (0.04) | 0.22 (0.05) |
| | 0 | 11.7 (0.64) | 11.6 (0.34) | 0.07 (0.05) | 0.04 (0.07) |
| | 100 | 14.8 (0.64) | 12.5 (0.34) | 0.15 (0.05) | 0.10 (0.07) |
| | 200 | 15.9 (0.58) | 15.3 (0.34) | 0.35 (0.05) | 0.38 (0.07) |
| | 400 | 18.5 (0.58) | 17.3 (0.34) | 0.83 (0.05) | 0.67 (0.07) |

^LSMean (standard error)
NI = non-irrigated; Eff-1x = low irrigation rate; Eff-2x = high irrigation rate
ALF = alfalfa; RCG = reed canary grass; TIM = timothy
0 = no fertilizer; 100 = 100 kg N $ha^{-1}$ $yr^{-1}$; 200 = 200 kg N $ha^{-1}$ $yr^{-1}$; 400 = 400 kg N $ha^{-1}$ $yr^{-1}$
Same letters within treatments and cut are not significantly different ($p < 0.05$)
No letters indicate non-significance

**Table 4.10 Plant nutrient usual, deficient and toxic concentrations, including minimum plant nutrient concentrations for livestock deficiencies as % dry matter**

| Element | Usual Concentration | Plant Deficiency | Livestock Deficiency[a] | Plant Toxicity |
|---|---|---|---|---|
| **Macronutrient** | | % | | |
| **N** | 1-4 | <1, <2[b] | <1, (<2.5) | n/a |
| **P** | 0.25-0.5 | <0.2 | <0.1 | n/a |
| **K** | 2-4 | <1 | <0.9 | n/a |
| **S** | 0.2-0.3 | <0.15 | <0.2 | n/a |
| **Ca** | 0.5-2.0 | <0.0002 | <0.4, (<0.6) | n/a |
| **Mg** | 0.2-0.8 | <0.05 | <0.1, <0.3 | n/a |
| **Micronutrient** | | ppm | | |
| **Fe** | 50-100 | <35 | <0.1, (<1) | n/a |
| **Mn** | 30-300 | <20 | <15 | >500 |
| **B** | 10-50 | <10 | unknown | >75 |
| **Cu** | 5-15 | <5 | <0.6 | >20 |
| **Zn** | 10-100 | <10 | <4, <6 | >200 |
| **Cl** | 500-10000 | not required | <2000 | >20000 |
| **Na** | 100-200 | not required | <1000, (<2000) | unknown |

Source: Adapted from Barker and Collins 2003
[a] Values in parentheses are for lactating livestock
[b] <1% for grasses, <2% for legumes
n/a = no practical toxic limit; competitive exclusion of other nutrients can occur

**Table 4.11 Phosphorous, potassium and sulphur concentrations as % dry matter for 2003 and 2004**

| Year | Trt | Phosphorous (%) | | Potassium (%) | | Sulphur (%) | |
|---|---|---|---|---|---|---|---|
| | | Cut 1 | Cut 2 | Cut 1 | Cut 2 | Cut 1 | Cut 2 |
| 2003 | | | | | | | |
| | Eff-2x | 0.26 (0.16)^ | 0.32 (0.02)[a] | 2.08 (0.05) | 2.54 (0.11) | 0.20 (0.007) | 0.36 (0.007) |
| | Eff-1x | 0.22 (0.16) | 0.25 (0.02)[ab] | 1.71 (0.05) | 2.02 (0.10) | 0.21 (0.007) | 0.33 (0.007) |
| | NI | 0.21 (0.16) | 0.15 (0.02)[b] | 1.85 (0.05) | 1.42 (0.10) | 0.20 (0.007) | 0.29 (0.009) |
| | ALF | 0.24 (0.14) | 0.22 (0.02) | 1.67 (0.05) | 1.54 (0.08) | 0.22 (0.006) | 0.32 (0.007) |
| | RCG | 0.23 (0.14) | 0.27 (0.02) | 2.03 (0.05) | 2.24 (0.08) | 0.25 (0.006) | 0.39 (0.007) |
| | TIM | 0.22 (0.14) | 0.24 (0.01) | 1.95 (0.05) | 2.21 (0.07) | 0.14 (0.006) | 0.25 (0.006) |
| | 0 | 0.22 (0.01)[b] | 0.24 (0.02) | 1.84 (0.05) | 1.94 (0.13) | 0.18 (0.006) | 0.31 (0.008) |
| | 100 | 0.23 (0.01)[ab] | 0.23 (0.02) | 1.87 (0.05) | 1.96 (0.13) | 0.20 (0.006) | 0.33 (0.008) |
| | 200 | 0.24 (0.01)[ab] | 0.25 (0.02) | 1.87 (0.05) | 2.03 (0.13) | 0.21 (0.006) | 0.34 (0.008) |
| | 400 | 0.25 (0.01)[a] | 0.24 (0.02) | 1.95 (0.05) | 2.06 (0.13) | 0.23 (0.006) | 0.34 (0.008) |
| 2004 | | | | | | | |
| | Eff-2x | 0.24 (0.01) | 0.25 (0.01) | 2.36 (0.11) | 2.04 (0.05)[a] | 0.26 (0.008) | 0.25 (0.009) |
| | Eff-1x | 0.22 (0.02) | 0.23 (0.01) | 1.67 (0.13) | 1.56 (0.05)[a] | 0.25 (0.010) | 0.25 (0.009) |
| | NI | 0.17 (0.02) | 0.21 (0.02) | 1.53 (0.16) | 1.47 (0.07)[b] | 0.18 (0.010) | 0.19 (0.010) |
| | ALF | 0.20 (0.02) | 0.20 (0.01)[b] | 1.63 (0.11)[b] | 1.41 (0.06)[b] | 0.21 (0.009) | 0.15 (0.008) |
| | RCG | 0.24 (0.02) | 0.27 (0.01)[a] | 2.19 (0.11)[a] | 1.80 (0.06)[a] | 0.31 (0.009) | 0.38 (0.008) |
| | TIM | 0.20 (0.02) | 0.22 (0.01)[b] | 1.74 (0.11)[ab] | 1.86 (0.06)[a] | 0.18 (0.009) | 0.15 (0.008) |
| | 0 | 0.21 (0.01) | 0.25 (0.01)[a] | 1.89 (0.14) | 1.82 (0.05)[a] | 0.20 (0.010) | 0.21 (0.008) |
| | 100 | 0.22 (0.01) | 0.23 (0.01)[ab] | 1.91 (0.14) | 1.74 (0.05)[ab] | 0.23 (0.010) | 0.22 (0.008) |
| | 200 | 0.21 (0.01) | 0.22 (0.01)[ab] | 1.78 (0.12) | 1.63 (0.05)[ab] | 0.24 (0.010) | 0.24 (0.008) |
| | 400 | 0.21 (0.01) | 0.21 (0.01)[b] | 1.84 (0.12) | 1.57 (0.05)[b] | 0.26 (0.010) | 0.23 (0.008) |

^LSMean (standard error)
NI = non-irrigated; Eff-1x = low irrigation rate; Eff-2x = high irrigation rate
ALF = alfalfa; RCG = reed canary grass; TIM = timothy
0 = no fertilizer; 100 = 100 kg N $ha^{-1}$ $yr^{-1}$; 200 = 200 kg N $ha^{-1}$ $yr^{-1}$; 400 = 400 kg N $ha^{-1}$ $yr^{-1}$
Same letters within treatments and cut are not significantly different ($p < 0.05$)
No letters indicate non-significance

**Table 4.12 Calcium and magnesium plant concentrations as % dry matter for 2003 and 2004**

| Year | Trt | Calcium (%) | | Magnesium (%) | |
|---|---|---|---|---|---|
| | | Cut 1 | Cut 2 | Cut 1 | Cut 2 |
| 2003 | | | | | |
| | Eff-2x | 0.95 (0.02)^ | 1.13 (0.06) | 0.20 (0.01) | 0.26 (0.01) |
| | Eff-1x | 0.86 (0.02) | 0.99 (0.06) | 0.25 (0.01) | 0.33 (0.01) |
| | NI | 0.88 (0.01) | 1.57 (0.08) | 0.22 (0.01) | 0.41 (0.01) |
| | ALF | 1.89 (0.02) | 2.22 (0.06) | 0.28 (0.01) | 0.36 (0.01) |
| | RCG | 0.45 (0.02) | 0.57 (0.06) | 0.26 (0.01) | 0.37 (0.01) |
| | TIM | 0.35 (0.02) | 0.90 (0.05) | 0.13 (0.01) | 0.27 (0.01) |
| | 0 | 0.89 (0.03) | 1.13 (0.08) | 0.20 (0.01) | 0.31 (0.01) |
| | 100 | 0.86 (0.03) | 1.23 (0.08) | 0.22 (0.01) | 0.34 (0.01) |
| | 200 | 0.91 (0.03) | 1.22 (0.08) | 0.23 (0.01) | 0.34 (0.01) |
| | 400 | 0.93 (0.03) | 1.18 (0.08) | 0.24 (0.01) | 0.34 (0.01) |
| 2004 | | | | | |
| | Eff-2x | 0.70 (0.03) | 0.53 (0.02) | 0.17 (0.01) | 0.18 (0.01) |
| | Eff-1x | 0.75 (0.04) | 0.54 (0.02) | 0.24 (0.01) | 0.24 (0.01) |
| | NI | 0.86 (0.05) | 0.60 (0.02) | 0.22 (0.01) | 0.24 (0.01) |
| | ALF | 1.56 (0.03) | 0.89 (0.02) | 0.22 (0.01) | 0.13 (0.01) |
| | RCG | 0.39 (0.03) | 0.43 (0.02) | 0.28 (0.01) | 0.38 (0.01) |
| | TIM | 0.37 (0.03) | 0.35 (0.02) | 0.13 (0.01) | 0.14 (0.01) |
| | 0 | 0.76 (0.05) | 0.53 (0.02)[ab] | 0.19 (0.01) | 0.18 (0.01) |
| | 100 | 0.77 (0.05) | 0.53 (0.02)[b] | 0.21 (0.01) | 0.20 (0.01) |
| | 200 | 0.73 (0.04) | 0.59 (0.02)[a] | 0.22 (0.01) | 0.25 (0.01) |
| | 400 | 0.82 (0.04) | 0.58 (0.02)[ab] | 0.23 (0.01) | 0.24 (0.01) |

^LSMean (standard error)
NI = non-irrigated; Eff-1x = low irrigation rate; Eff-2x = high irrigation rate
ALF = alfalfa; RCG = reed canary grass; TIM = timothy
0 = no fertilizer; 100 = 100 kg N $ha^{-1}$ $yr^{-1}$; 200 = 200 kg N $ha^{-1}$ $yr^{-1}$; 400 = 400 kg N $ha^{-1}$ $yr^{-1}$
Same letters within treatments and cut are not significantly different ($p < 0.05$)
No letters indicate non-significance

**Table 4.13 Sodium and chloride plant concentrations as % dry matter for 2003 and 2004**

| Year | Trt | Sodium (%) | | Chloride (mg kg$^{-1}$) | |
|---|---|---|---|---|---|
| | | Cut 1 | Cut 2 | Cut 1 | Cut 2 |
| 2003 | | | | | |
| | Eff-2x | 0.035 (0.008)^ | 0.188 (0.019)$^{a}$ | 6349 (406) | 14755 (944) |
| | Eff-1x | 0.056 (0.008) | 0.182 (0.019)$^{a}$ | 6033 (406) | 11173 (944) |
| | NI | 0.032 (0.008) | 0.054 (0.024)$^{b}$ | 6438 (406) | 9632 (1157) |
| | ALF | 0.079 (0.008)$^{a}$ | 0.244 (0.019)$^{a}$ | 5394 (360)$^{b}$ | 7976 (886) |
| | RCG | 0.030 (0.008)$^{b}$ | 0.107 (0.019)$^{b}$ | 8514 (360)$^{a}$ | 16794 (886) |
| | TIM | 0.014 (0.008)$^{b}$ | 0.072 (0.017)$^{b}$ | 4913 (360)$^{b}$ | 10791 (773) |
| | 0 | 0.040 (0.006) | 0.135 (0.017) | 6713 (279) | 12627 (921) |
| | 100 | 0.034 (0.006) | 0.141 (0.017) | 6573 (279) | 12283 (921) |
| | 200 | 0.042 (0.006) | 0.147 (0.017) | 6054 (279) | 11527 (921) |
| | 400 | 0.048 (0.006) | 0.143 (0.017) | 5755 (279) | 10977 (921) |
| 2004 | | | | | |
| | Eff-2x | 0.163 (0.008) | 0.133 (0.009) | 13010 (1170) | 11355 (1484) |
| | Eff-1x | 0.142 (0.010) | 0.131 (0.009) | 10352 (1397) | 9108 (1484) |
| | NI | 0.030 (0.012) | 0.048 (0.013) | 8417 (1654) | 6431 (2099) |
| | ALF | 0.176 (0.008) | 0.173 (0.010)$^{a}$ | 9572 (935) | 6245 (1219)$^{b}$ |
| | RCG | 0.096 (0.008) | 0.109 (0.010)$^{b}$ | 14120 (935) | 12869 (1219)$^{a}$ |
| | TIM | 0.062 (0.008) | 0.031 (0.010)$^{c}$ | 8087 (935) | 7779 (1219)$^{b}$ |
| | 0 | 0.085 (0.012) | 0.081 (0.009)$^{b}$ | 12941 (1564) | 10464 (1262) |
| | 100 | 0.107 (0.012) | 0.089 (0.009)$^{ab}$ | 10545 (1564) | 9497 (1262) |
| | 200 | 0.122 (0.011) | 0.128 (0.009)$^{a}$ | 9599 (1401) | 8469 (1262) |
| | 400 | 0.132 (0.011) | 0.120 (0.009)$^{ab}$ | 9287 (1401) | 7428 (1262) |

^LSMean (standard error)
NI = non-irrigated; Eff-1x = low irrigation rate; Eff-2x = high irrigation rate
ALF = alfalfa; RCG = reed canary grass; TIM = timothy
0 = no fertilizer; 100 = 100 kg N ha$^{-1}$ yr$^{-1}$; 200 = 200 kg N ha$^{-1}$ yr$^{-1}$; 400 = 400 kg N ha$^{-1}$ yr$^{-1}$
Same letters within treatments and cut are not significantly different ($p < 0.05$)
No letters indicate non-significance

**Table 4.14 Micronutrient plant concentrations as % dry matter for 2003 and 2004**

| Year | Trt | Manganese (ppm) | | Iron (ppm) | | Copper (ppm) | | Zinc (ppm) | |
|---|---|---|---|---|---|---|---|---|---|
| | | Cut 1 | Cut 2 | Cut 1 | Cut 2 | Cut 1 | Cut 2 | Cut 1 | Cut 2 |
| 2003 | | | | | | | | | |
| | Eff-2x | 70 (7.4)^ | 115 (9.7) | 47 (5.4) | 103 (5.7)$^{a}$ | 1.2 (0.57) | 6.8 (0.92) | 33 (0.94) | 39 (1.03) |
| | Eff-1x | 40 (7.4) | 49 (9.7) | 33 (5.4) | 63 (5.7)$^{b}$ | 2.8 (0.57) | 9.3 (0.92) | 27 (0.94) | 32 (1.03) |
| | NI | 74 (7.4) | 179 (12.4) | 43 (5.4) | 121 (6.9)$^{a}$ | 2.2 (0.57) | 11.4 (1.16) | 33 (0.94) | 29 (1.23) |
| | ALF | 50 (5.6)$^{b}$ | 61 (10.9) | 57 (4.6)$^{a}$ | 133 (5.2)$^{a}$ | 4.0 (0.56)$^{a}$ | 16.1 (0.95)$^{a}$ | 27 (0.94) | 32 (0.89) |
| | RCG | 77 (5.6)$^{a}$ | 181 (10.9) | 45 (4.6)$^{a}$ | 66 (5.2)$^{b}$ | 0.5 (0.56)$^{b}$ | 5.9 (0.95)$^{b}$ | 37 (0.94) | 37 (0.89) |
| | TIM | 57 (5.6)$^{b}$ | 101 (9.5) | 21 (4.6)$^{b}$ | 87 (4.6)$^{b}$ | 1.6 (0.56)$^{b}$ | 5.7 (0.83)$^{b}$ | 29 (0.94) | 30 (0.79) |
| | 0 | 61 (4.7)$^{ab}$ | 121 (8.1) | 32 (4.0)$^{b}$ | 85 (7.0) | 1.7 (0.40) | 9.3 (0.69) | 27 (0.87)$^{c}$ | 28 (0.94) |
| | 100 | 59 (4.7)$^{b}$ | 101 (8.1) | 40 (4.0)$^{ab}$ | 93 (7.0) | 2.0 (0.40) | 8.8 (0.69) | 30 (0.87)$^{bc}$ | 31 (0.94) |
| | 200 | 57 (4.7)$^{b}$ | 95 (8.1) | 43 (4.0)$^{ab}$ | 103 (7.0) | 2.2 (0.40) | 8.6 (0.69) | 32 (0.87)$^{ab}$ | 36 (0.94) |
| | 400 | 70 (4.7)$^{a}$ | 139 (8.1) | 48 (4.0)$^{a}$ | 100 (7.0) | 2.4 (0.40) | 8.9 (0.69) | 35 (0.87)$^{a}$ | 38 (0.94) |
| 2004 | | | | | | | | | |
| | Eff-2x | 68 (5.4) | 83 (7.4) | 52 (6.7) | 44 (5.1) | 2.8 (1.01) | 3.3 (0.53) | 33 (0.76) | 30 (0.63) |
| | Eff-1x | 33 (6.3) | 40 (7.4) | 33 (7.1) | 31 (5.1) | 4.6 (1.05) | 4.9 (0.53) | 27 (0.93) | 27 (0.63) |
| | NI | 70 (7.6) | 98 (10.5) | 30 (9.4) | 23 (7.2) | 3.8 (1.43) | 3.5 (0.75) | 29 (1.07) | 30 (0.89) |
| | ALF | 27 (4.3) | 23 (8.2) | 33 (7.8) | 14 (5.7)$^{b}$ | 5.3 (0.74)$^{a}$ | 4.5 (0.48)$^{a}$ | 27 (0.90) | 21 (0.72) |
| | RCG | 82 (4.3) | 122 (8.2) | 59 (7.8) | 75 (5.7)$^{a}$ | 2.6 (0.74)$^{b}$ | 6.3 (0.48)$^{a}$ | 34 (0.90) | 39 (0.72) |
| | TIM | 62 (4.3) | 76 (8.2) | 23 (7.8) | 8 (5.7)$^{b}$ | 4.0 (0.74)$^{ab}$ | 1.8 (0.48)$^{b}$ | 27 (0.90) | 27 (0.72) |
| | 0 | 56 (6.9) | 84 (6.5) | 31 (5.7) | 31 (4.5) | 3.6 (0.79) | 3.7 (0.46) | 25 (1.13) | 23 (0.83) |
| | 100 | 50 (6.9) | 56 (6.5) | 38 (5.7) | 29 (4.5) | 4.0 (0.79) | 3.6 (0.46) | 30 (1.13) | 28 (0.83) |
| | 200 | 47 (6.2) | 62 (6.5) | 37 (5.3) | 37 (4.5) | 3.8 (0.76) | 4.2 (0.46) | 30 (1.01) | 31 (0.83) |
| | 400 | 75 (6.2) | 93 (6.5) | 48 (5.3) | 33 (4.5) | 3.4 (0.76) | 4.0 (0.46) | 33 (1.01) | 34 (0.83) |

^LSMean (standard error)
NI = non-irrigated; Eff-1x = low irrigation rate; Eff-2x = high irrigation rate
ALF = alfalfa; RCG = reed canary grass; TIM = timothy
0 = no fertilizer; 100 = 100 kg N $ha^{-1}$ $yr^{-1}$; 200 = 200 kg N $ha^{-1}$ $yr^{-1}$; 400 = 400 kg N $ha^{-1}$ $yr^{-1}$
Same letters within treatments and cut are not significantly different ($p < 0.05$)
No letters indicate non-significance

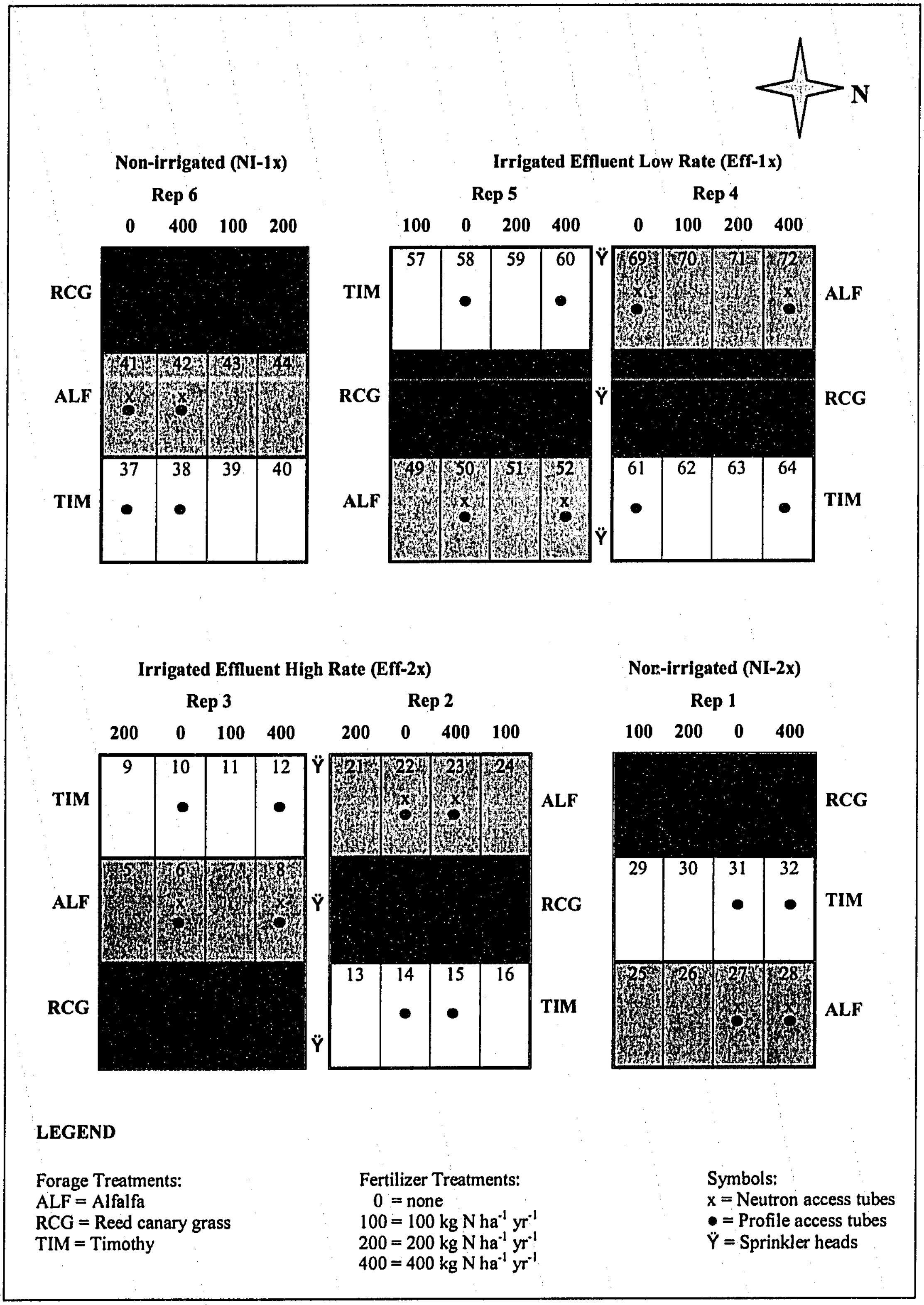


**Figure 4.1 Study site plot plan indicating irrigation, forage and fertilizer treatments, and profile and neutron probe access tubes within numbered plot**

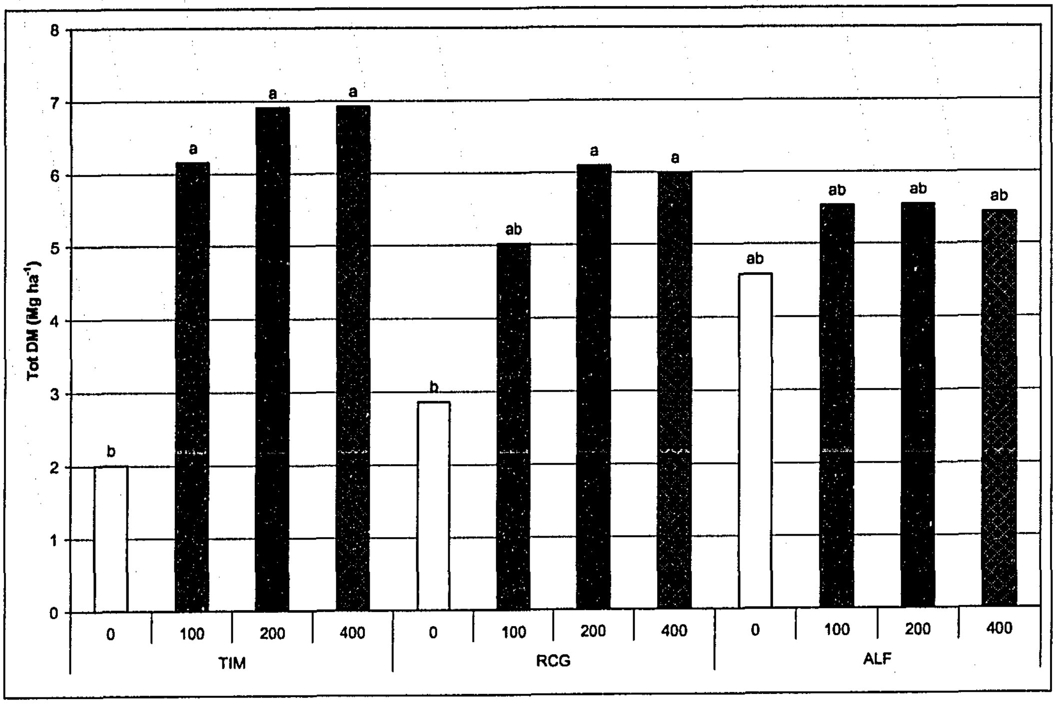


**Figure 4.2 Total biomass for forage by fertilizer interaction (2004 Cut 1)**
Same letters within treatments are not significantly different ($p < 0.05$)

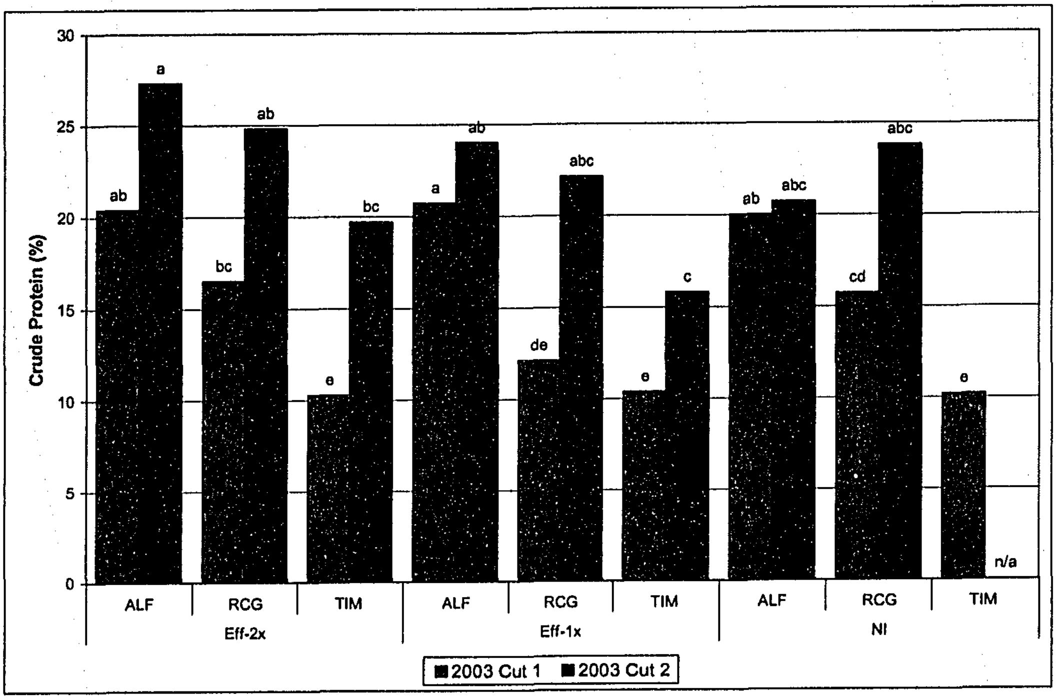


**Figure 4.3 Crude protein for irrigation by forage interaction (2003)**
Same letters within treatments and cut are not significantly different ($p < 0.05$)

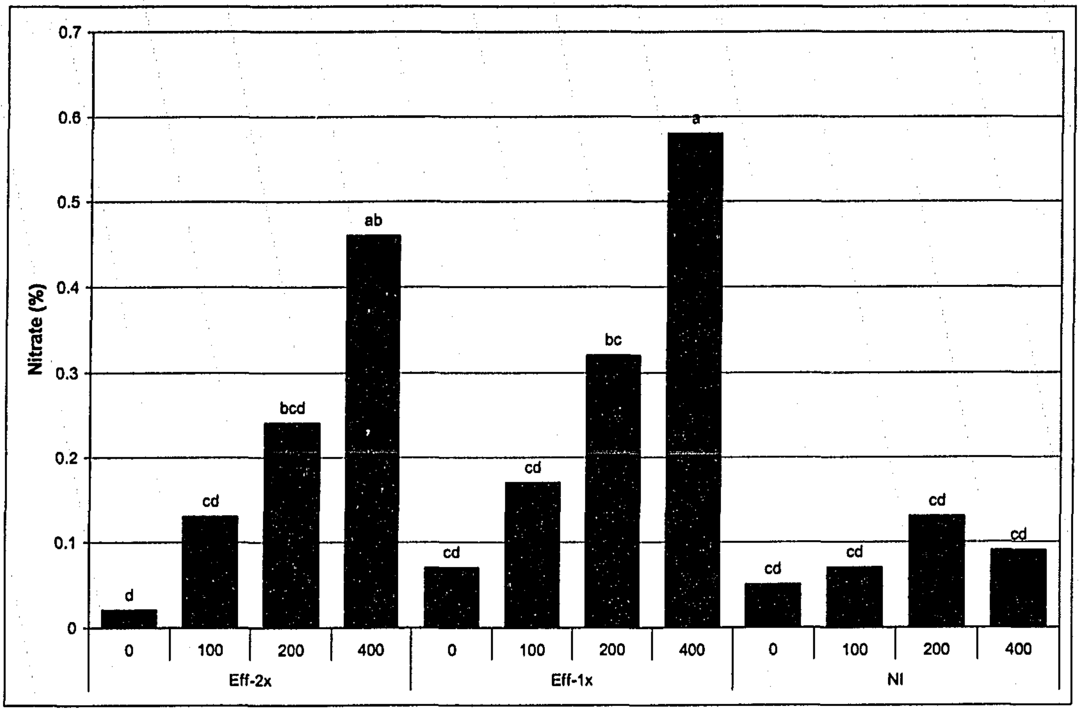


**Figure 4.4 Nitrate plant concentrations for irrigation by fertilizer interaction (2003 cut 2)**
Same letters within treatments are not significantly different ($p < 0.05$)

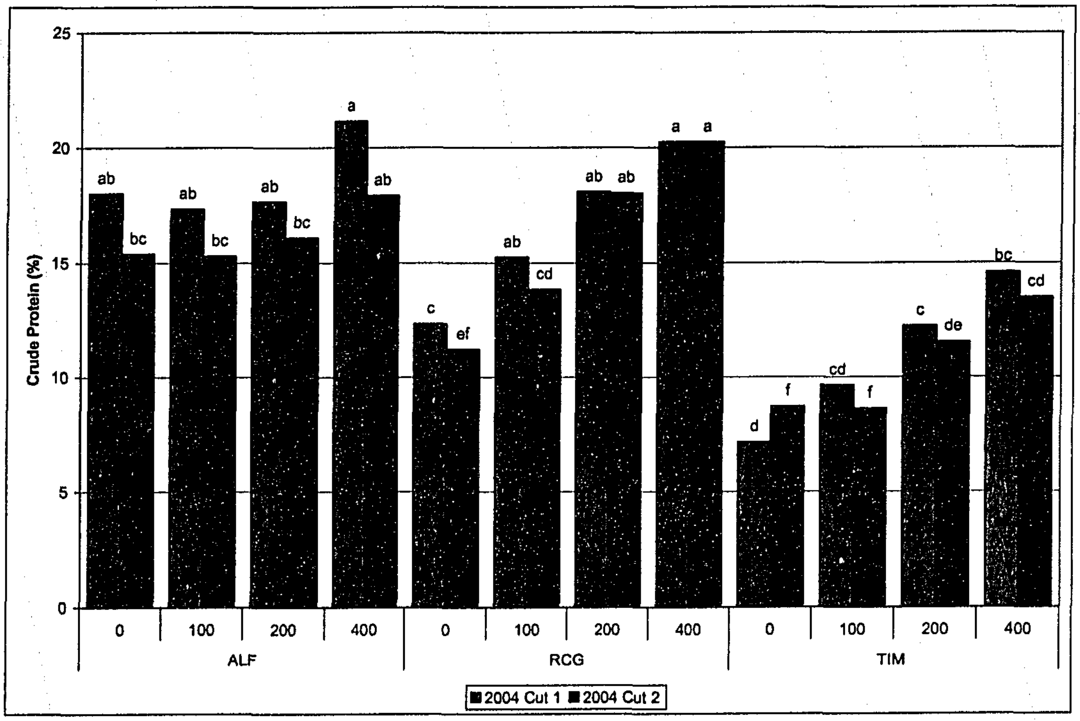


**Figure 4.5 Crude protein content for forage by fertilizer interaction (2004)**
Same letters within treatments and cut are not significantly different ($p < 0.05$)

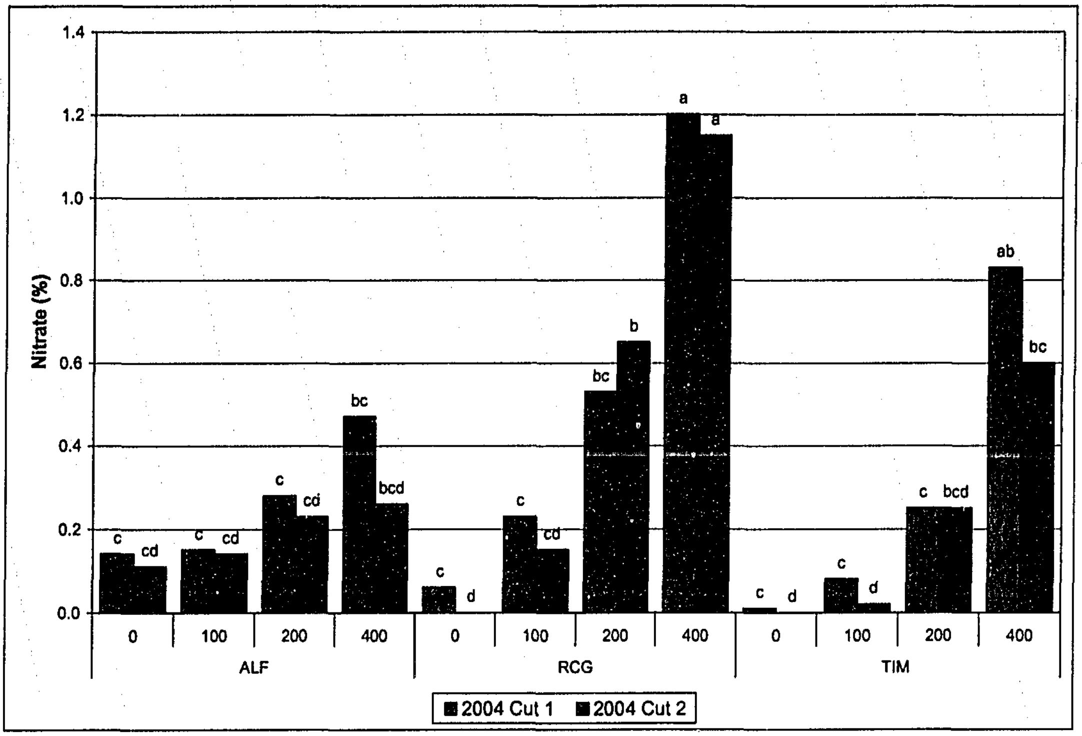


**Figure 4.6 Nitrate concentrations for forage by fertilizer interaction (2004)**
Same letters within treatments and cut are not significantly different ($p < 0.05$)

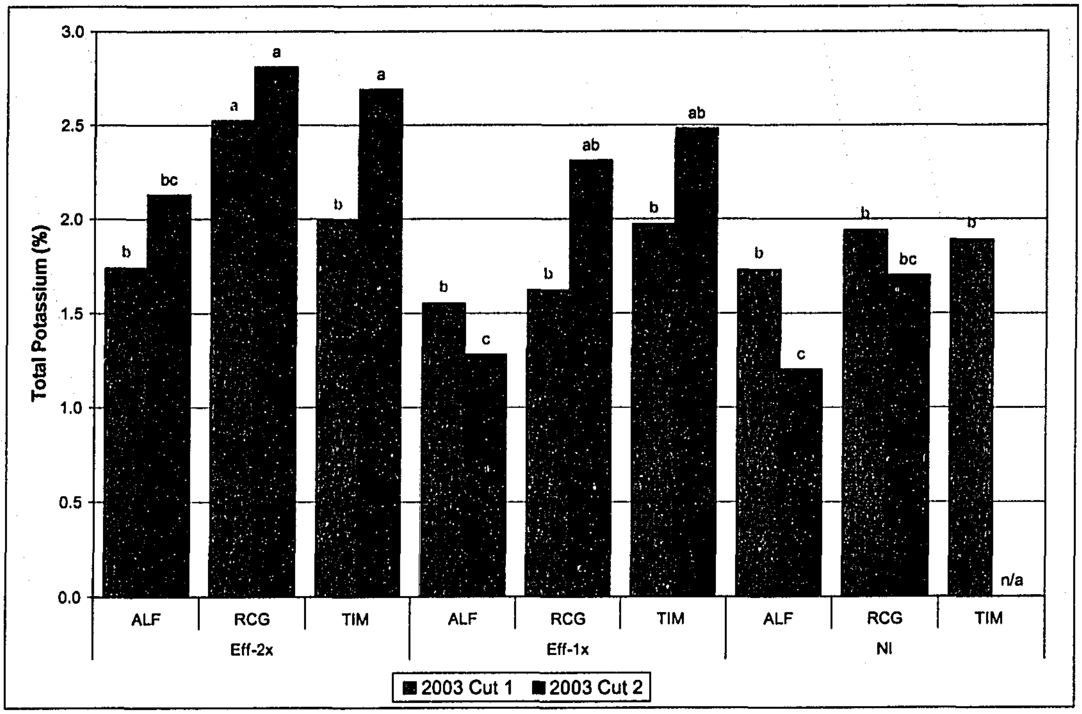


**Figure 4.7 Potassium plant concentrations for irrigation by forage interaction (2003)**
Same letters within treatments and cut are not significantly different ($p < 0.05$)

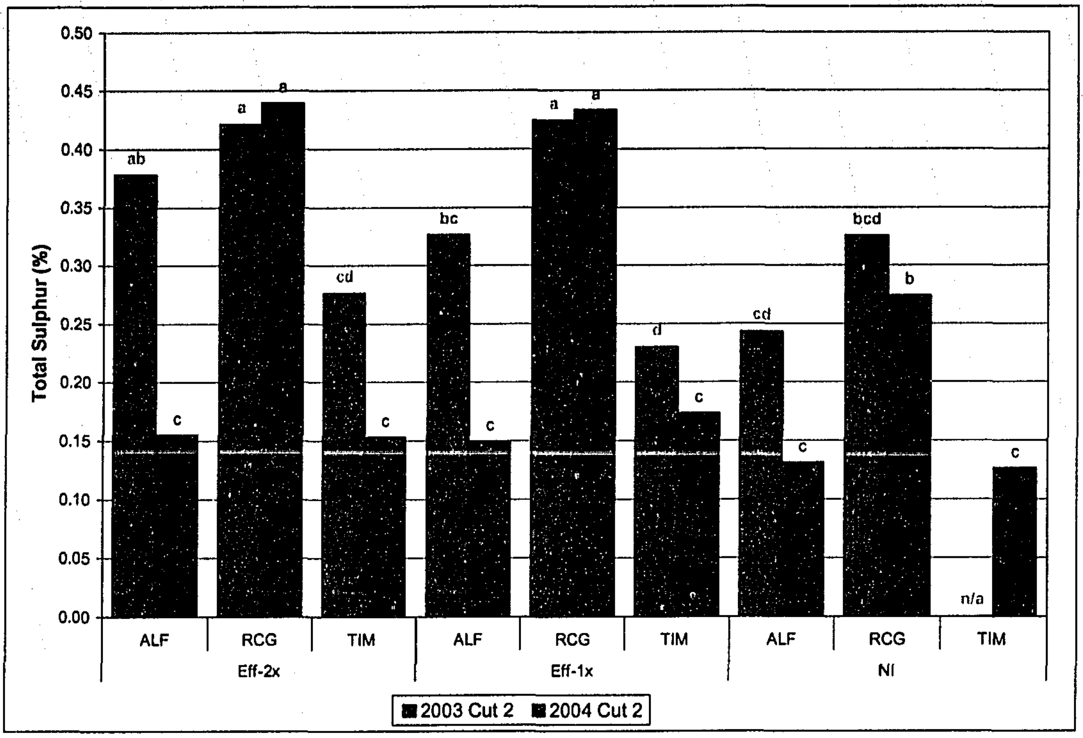


**Figure 4.8 Sulphur plant concentrations for irrigation by forage interaction (cut 2 2003 and 2004)**
Same letters within treatments and year are not significantly different ($p < 0.05$)

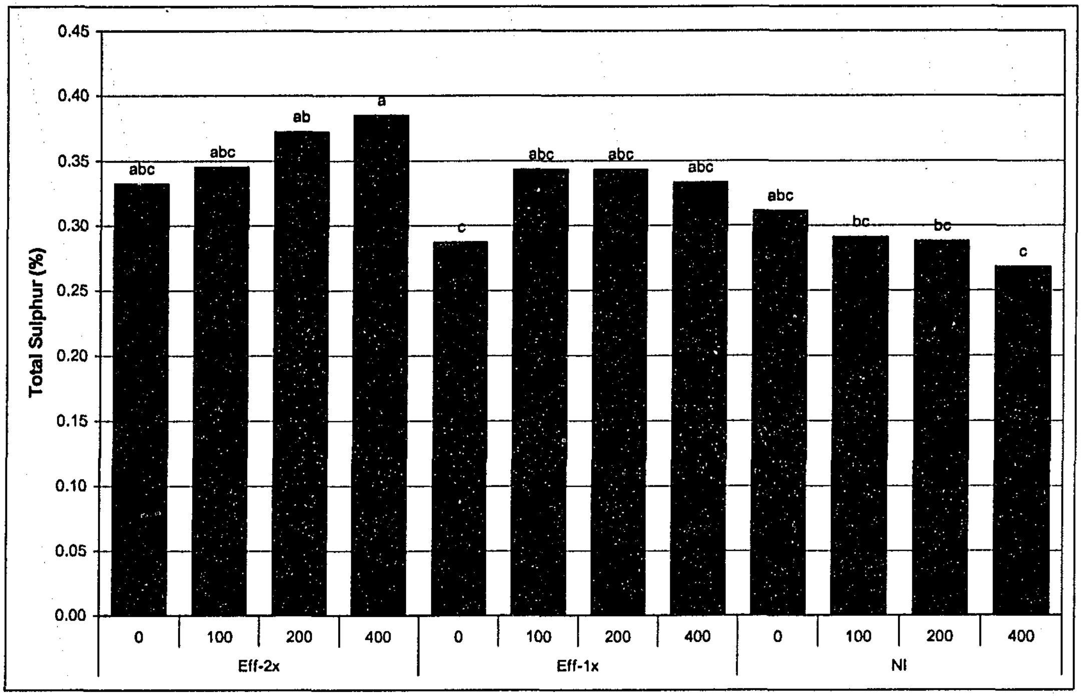


**Figure 4.9 Sulphur plant concentrations for irrigation by fertilizer interaction (2003 cut 2)**
Same letters within treatments are not significantly different ($p < 0.05$)

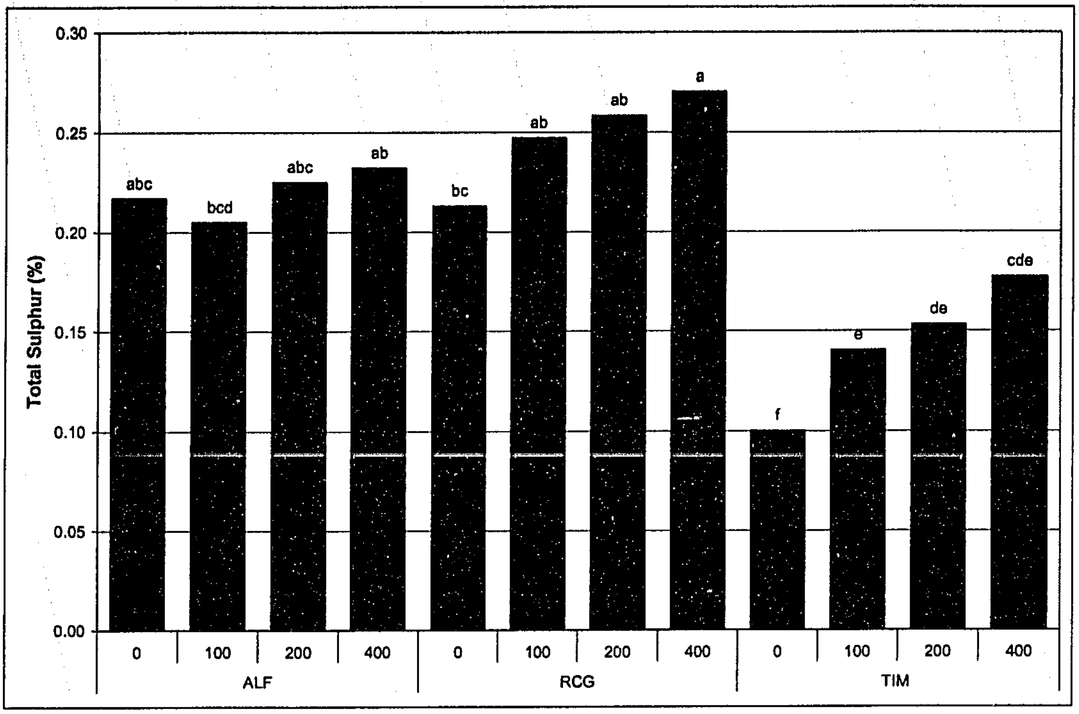


**Figure 4.10 Sulphur plant concentrations for forage by fertilizer interaction (2003 cut 1)**
Same letters within treatments are not significantly different ($p < 0.05$)

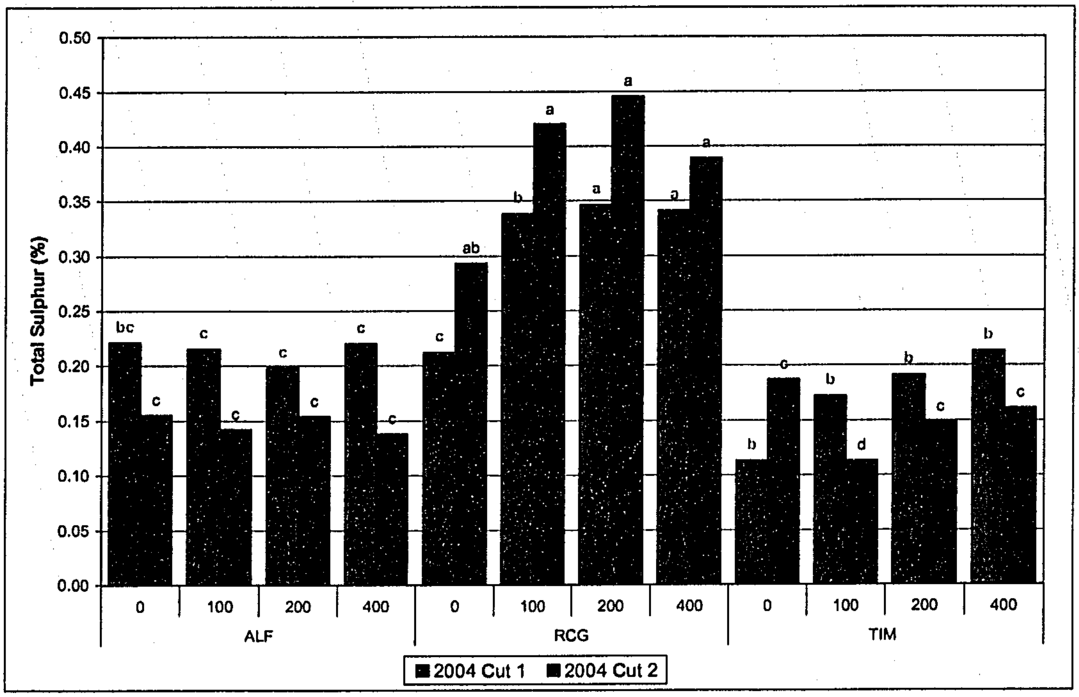


**Figure 4.11 Sulphur plant concentrations for forage by fertilizer interaction (2004)**
Same letters within treatments and cut are not significantly different ($p < 0.05$)

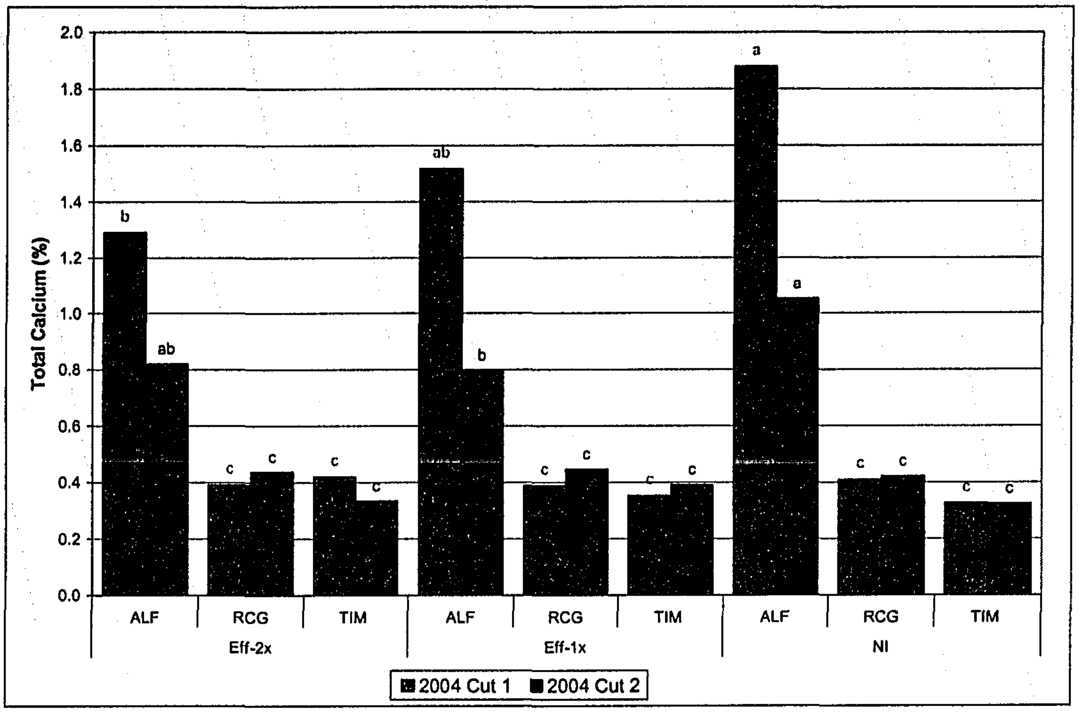


**Figure 4.12 Calcium plant concentrations for irrigation by forage interaction (2004)**
Same letters within treatments and cut are not significantly different ($p < 0.05$)

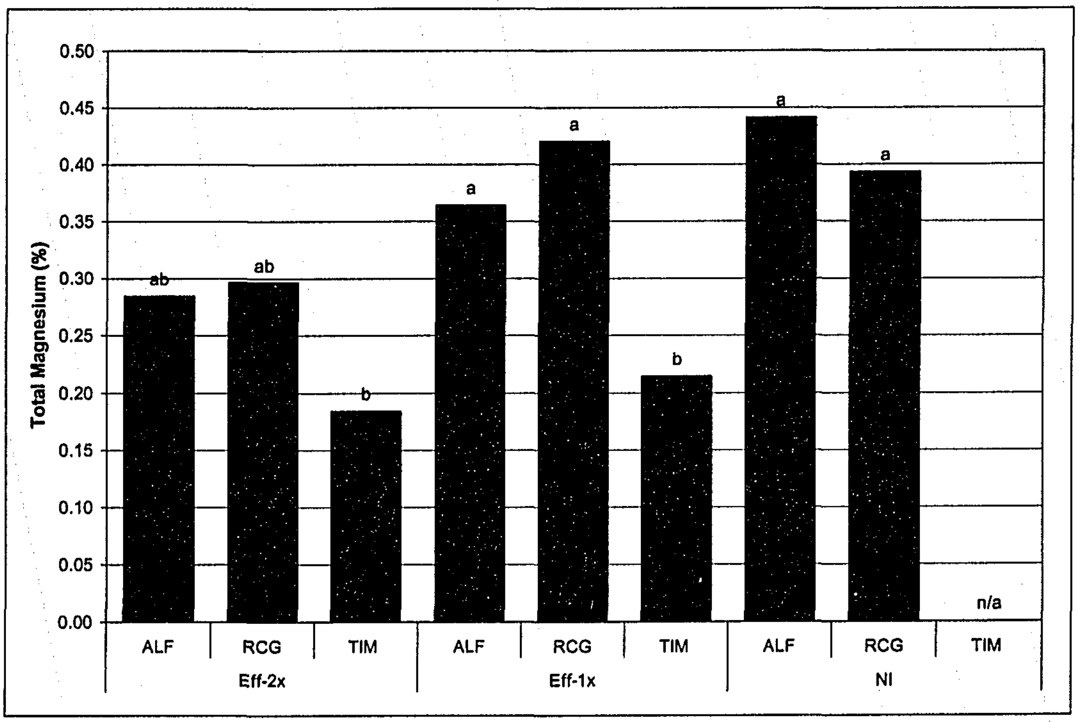


**Figure 4.13 Magnesium concentrations for irrigation by forage interaction (2003 cut 2)**
Same letters within treatments are not significantly different ($p < 0.05$)

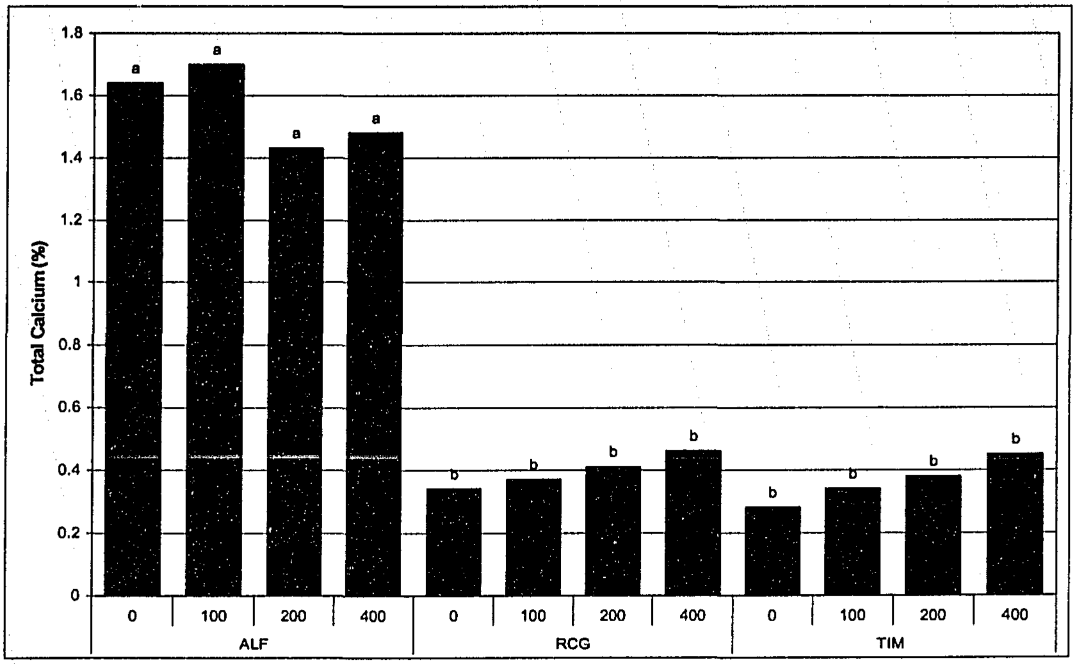


**Figure 4.14 Calcium plant concentrations for forage by fertilizer interaction (2004 cut 1)**
Same letters within treatments are not significantly different ($p < 0.05$)

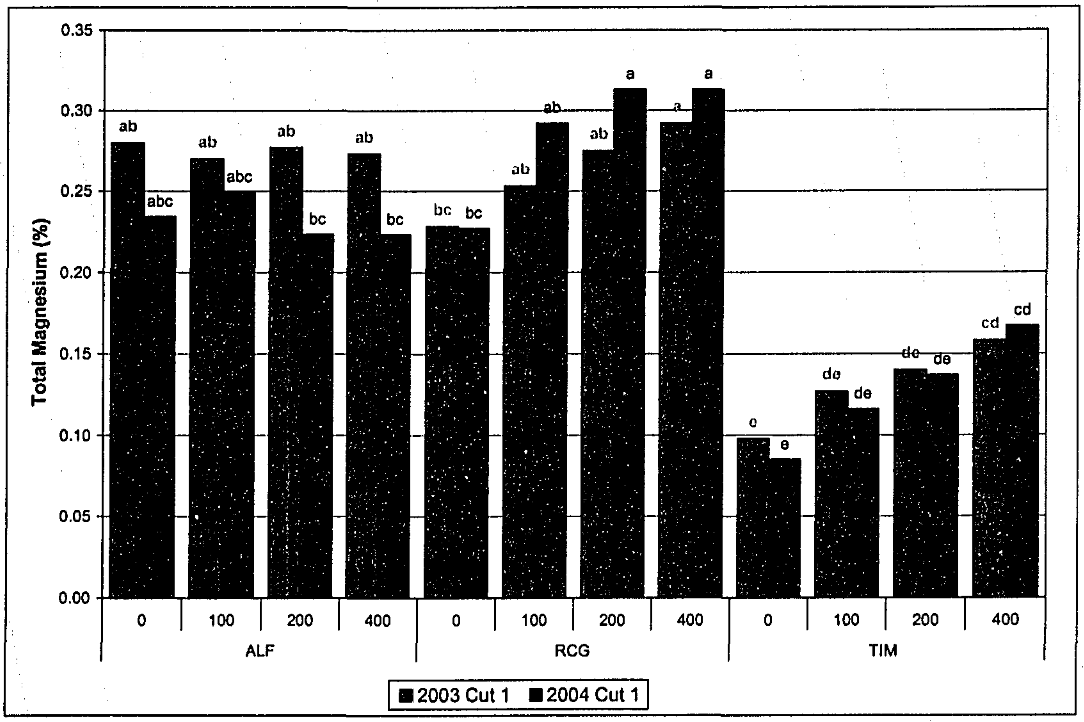


**Figure 4.15 Magnesium plant concentrations for forage by fertilizer interaction (Cut 1)**
Same letters within treatments and year are not significantly different ($p < 0.05$)

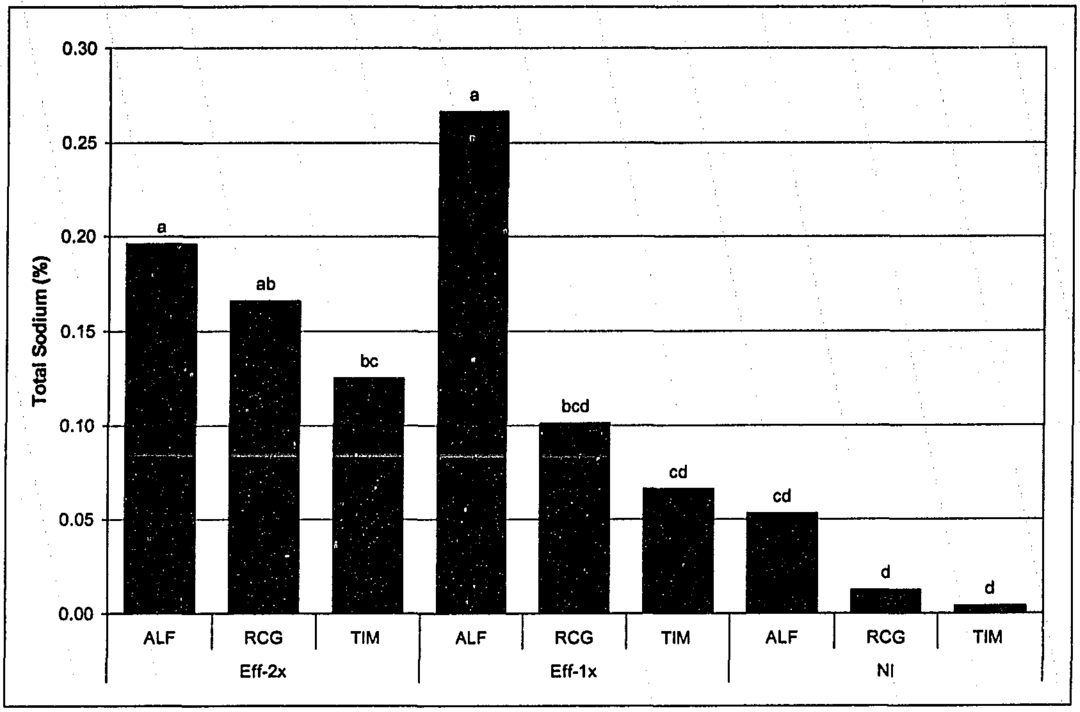


**Figure 4.16 Sodium plant concentrations for irrigation by forage interaction (2004 cut 1)**
Same letters within treatments are not significantly different ($p < 0.05$)

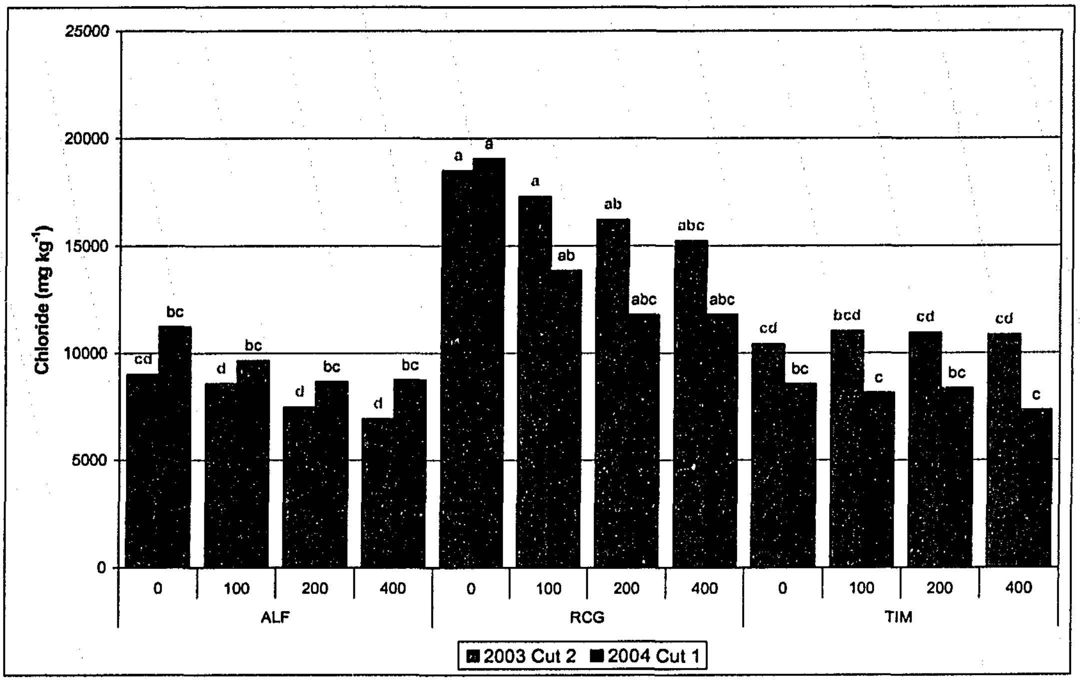


**Figure 4.17 Chloride concentrations for forage by fertilizer interaction (2003 cut 2 and 2004 cut 1)**
Same letters within treatments are not significantly different ($p < 0.05$)

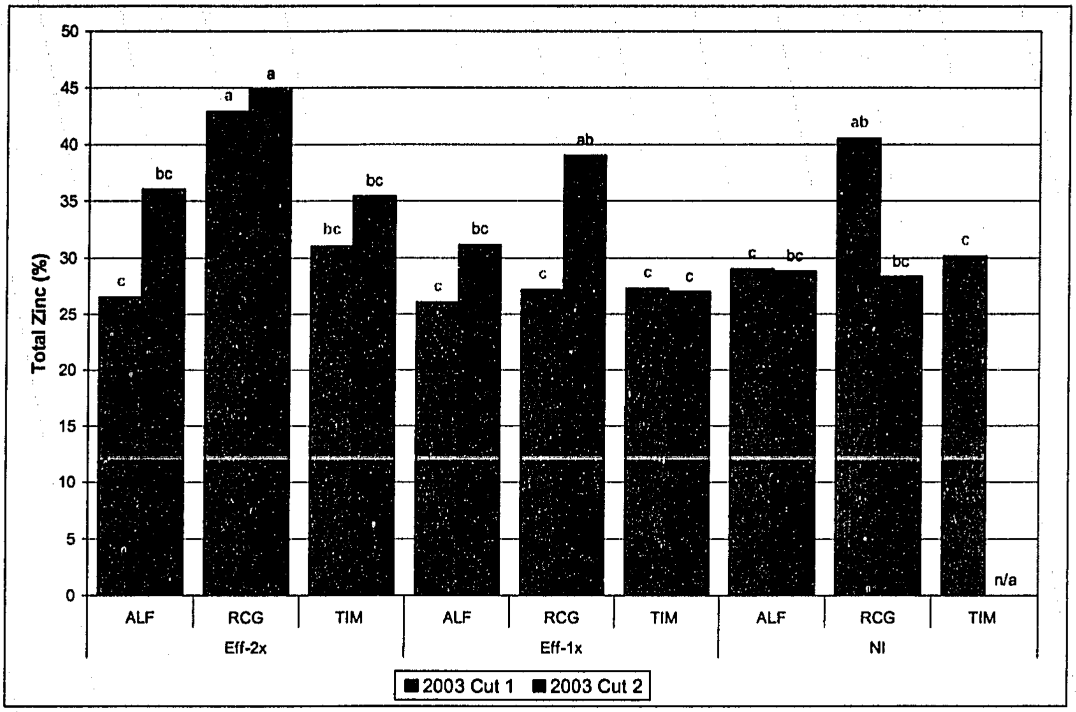


**Figure 4.18 Zinc plant concentrations for irrigation by forage interaction (2003)**
Same letters within treatments and cut are not significantly different ($p < 0.05$)

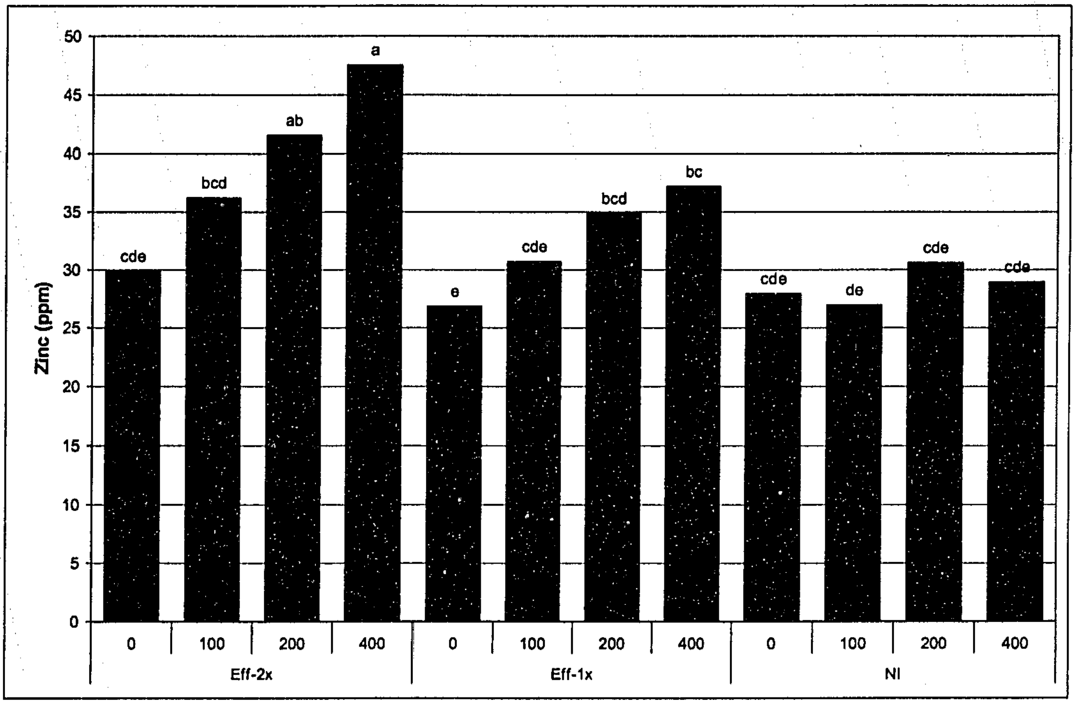


**Figure 4.19 Zinc plant concentrations for irrigation by fertilizer interaction (2003 cut 2)**
Same letters within treatments are not significantly different ($p < 0.05$)

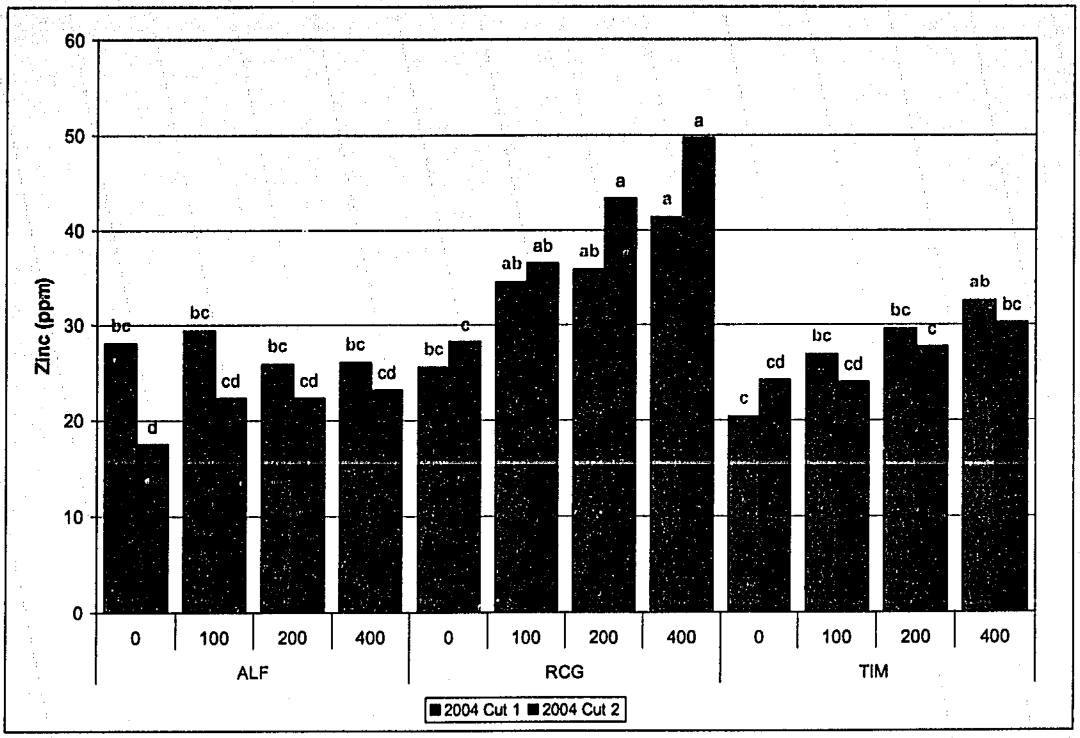


**Figure 4.20 Zinc plant concentrations for forage by fertilizer interaction (2004)**
Same letters within treatments are not significantly different ($p < 0.05$)

# 5 SYNTHESIS

## 5.1 Research Summary

Three forage species tolerant of saline and wet soil conditions, frequent harvests and northern climates were irrigated with pulp mill effluent to determine if sustainable forage production under effluent irrigation could be achieved in northern Alberta. Since pulp mill effluent contains only small concentrations of nitrogen (N), the most limiting plant nutrient, ammonium nitrate fertilizer, was applied at three rates to determine the optimal rate for forage growing conditions. To evaluate whether sustainable effluent irrigation for forage production was possible, pulp mill effluent irrigation, forage species and N fertilizer effects on soil physical and chemical properties, soil moisture regime and forage biomass and quality were evaluated.

Pulp mill effluent irrigation affected soil chemical parameters but did not degrade soil quality. Salts present in pulp mill effluent increased soil concentrations and clearly increased with increasing rates. Irrigated treatments produced higher biomass than non-irrigated when soil moisture was limiting. Differences in relative feed values were determined by plant species rather than irrigation treatments and plant levels of nutrients associated with the effluent increased.

Forage species had no significant effects on soil physical properties or soil moisture regime. However each species because of its growth patterns and requirements affected soil nutrient status and plant uptake differently, resulting in different forage quality. Reed canary grass was the best producer under low and high moisture conditions, while alfalfa had the best forage quality based on hay quality standards.

Fertilizer treatments had no significant effects on soil physical parameters or soil moisture regime, but they affected soil chemical parameters and forage biomass and quality. High fertilizer rates reduced soil pH, thereby affecting nutrient availabilities. Cation competition was induced thereby reducing plant nutrient uptake in grasses, thus grass tetany is a concern. In most cases, fertilizer increased biomass and improved grass crude protein when moisture was sufficient. However, high N application rates increased the risk of nitrate poisoning and thus rates of 400 kg N $ha^{-1}$ $yr^{-1}$ under irrigation are not recommended.

## 5.2 Recommended Future Research

Studies investigating different pulp mill effluent rates and their effects on soil moisture regimes, soil physical and chemical properties, as well as forage biomass and quality, are required to develop guidelines for sustainable effluent irrigation. Based on research, appropriate regulations to minimize adverse effects and maximize benefits, including guidelines for optimal wastewater application rates, frequency and timing must be created and strict monitoring programs of land application effects must be enforced.

These studies must be conducted over longer periods than two years to study the effects of effluent irrigation in northern Alberta. Climate patterns are hard to predict and availability of water does not always match forage seasonal demands; thus when rainfall exceeds evapotranspiration, timing of irrigation events becomes difficult. In this study, high temperatures occurred in the first year and irrigation effects only occurred when soil moisture was limiting. In 2004, effects were not evident when soil moisture was near field capacity due to several rainfall events. Thus investigations need to be conducted over several years to capture effects in different weather conditions. Effluent irrigation may not always be viable for forage production in northern Alberta because of environmental conditions, thus creating the need to find other alternative means to dispose of pulp mill effluent to address environmental concerns of discharging practices. Extensive monitoring programs over the long-term are needed to quantify gradual adverse changes in crop health, soil and water quality before it is too late to rectify the problem without compromising sustainable land treatment (Speir 2002).

Changes in soil physical parameters are not seen in the short-term as they may be evident once irrigation discontinues or changes in land use occur. Potential salinization and sodicity issues could arise with pulp mill effluent irrigation and thus means to alleviate these problems need to be addressed.

Leaching of mobile nutrients like $NO_3$ at high fertilizer rates, and $SO_4$ at high irrigation rates, may occur if soil levels increase beyond plant requirements and there is enough downward water movement from irrigation and/or precipitation. Each forage is adapted to different climate and soil conditions and has different requirements; thus more work needs to be done on how different species in different climates and soils may be used to treat wastewaters and prevent nutrient leaching under effluent irrigation.

Certain key plant nutrients are not found in pulp effluents; thus there is a need to conduct work on fertilizer amendments based on plant requirements for optimal forage production without degrading soil and water quality and creating animal related nutrient disorders. Other nutrients of importance in forage quality not addressed in this study like B, Se and Mo should be addressed.

Irrigation non-uniformity was an issue in this study and is not a new concept. It is very difficult to set up an efficient and economical irrigation field trial with appropriate randomizations and replications to deal with inherent variability. Field site planning and irrigation technologies for irrigation studies need further exploration.

Since a water control treatment was not part of the experimental design, it was difficult to determine if changes in soil chemistry occurred because of effluent composition or nutrient transformation processes induced by increased soil moisture or lack thereof. Thus in addition to having a non-irrigated control a water control should be added to the experimental design.

## 5.3 Pulp Mill Effluent Irrigation for Forage Production In Alberta

The potential for pulp mill effluent irrigation exists in northern Alberta during intermittent and prolonged drought periods. Forage biomass can be significantly increased under effluent irrigation since it is a good source of water and nutrients (S, K, Na and Cl) otherwise needed from potable water sources and expensive fertilizers. However, high yields may come at the expense of forage quality depending on weather conditions, soil moisture regimes, soil nutrient status, etc. Additional fertilizer amendments at extra cost will likely be required to prevent or correct soil and plant nutrient imbalances since pulp mill effluent is not a good source of N. Appropriate guidelines for irrigation rates and timing, as well as extensive long-term monitoring programs for soil, plant and water quality are needed for environmentally sustainable effluent irrigation systems for successful forage production.

# 6 APPENDIX

## 6.1 FORAGE SPECIES DESCRIPTIONS

### 6.1.1 Alfalfa (*Medicago sativa* L.)

Alfalfa is a long-lived perennial adapted to a wide range of well drained soils (Stone and Lawrence 2000). This cool season legume ($C_3$ plant) has excellent winter hardiness and a prominent taproot that grows deep into the soil profile under optimal conditions. Alfalfa can extract nutrients and water from a large soil volume compared to shallow rooted legumes (AAFRD 1981; Miller and Nelson 2003) and thus has a moderate to excellent drought tolerance and responds well to irrigation where moisture is limiting (AAFRD 1981; Stone and Lawrence 2000). Alfalfa is intolerant of flooding, water logging and poor internal drainage, is fairly tolerant of alkalinity and salinity (AAFRD 1981) and very sensitive to soil acidity with an optimal soil pH of 6.5 to 7 (McGraw and Nelson 2003). Alfalfa has poor tolerance to low soil fertility, especially if phosphorous (P), potassium (K), and sometimes boron (B) and sulphur (S), are limiting (McGraw and Nelson 2003). Since alfalfa fixes nitrogen (N), it rarely responds to nitrogen fertilization (McGraw and Nelson 2003). Under good fertilizer management and growing conditions, alfalfa has high biomass production with excellent nutritive quality throughout the growing season (Barnes and Sheaffer 1995). Its upright growth habit and low moisture content make it a desirable, easy to harvest forage (AAFRD 1981). Alfalfa should not be cut twice in the same season without time to store root and crown food reserves (AAFRD 1981). Cutting should be avoided four to six weeks prior to first frost, to ensure quality and regrowth (Stone and Lawrence 2000). The Alberta Forage Manual recommends harvesting legumes from bloom to 10% bloom to obtain maximum yield (AAFRD 1981).

### 6.1.2 Timothy (*Phleum pratense* L.)

Timothy is a cool season perennial bunchgrass well adapted to a wide range of climatic and edaphic conditions, including the cool moist regions of Alberta (AAFRD 1981; McElroy and Kuneluius 1995). This shallow fibrous-rooted grass can live 3 to 5 years, grows best on well-drained moist clay or loam soils and has excellent winter hardiness (AAFRD 2001; Balasko and Nelson 2003). Timothy tolerates somewhat acidic soils with a pH of 5 to 6 and is moderately susceptible to alkalinity and salinity (AAFRD 1981; Fageria et al. 1997). It has a medium to high water requirement needing at least 300 mm of precipitation to produce an average crop. It is somewhat tolerant of spring flooding, but not drought (AAFRD 2001). Irrigation greatly enhances productivity in dry climates or during droughts (AAFRD 2001). Although timothy is tolerant to low fertility, it is very responsive to fertilization, especially N, which increases biomass production and protein content and makes it easy to establish (AAFRD 1981). It has an upright growth habit making it easy to harvest, but has poor regrowth potential, even though it produces a full yield the first year of production (AAFRD 1981; Balasko and Nelson 2003). Timothy is well suited for hay because it cures easily, is free from dust and mold, and if harvested after the critical pre-head period (two weeks before head emergence) and prior to bloom, has good nutritive value (AAFRD 1981; Stone and Lawrence 2000).

### 6.1.3 Reed Canary Grass (*Phalaris arundinacea* L.)

Reed canary grass is a long-lived, sod-forming, cool season perennial well adapted to moist or wet lowlands to dry upland fertile soils (Balasko and Nelson 2003; Sheaffer and Marten 1995). It is better adapted to harsh environmental conditions than most other commonly used perennial grasses, but will suffer from winter injury under sparse snow cover (AAFRD 1981). It has moderate tolerance to saline and acidic conditions requiring a pH of 5 to 6 (Fageria et al. 1997). Its persistence on poorly drained soils is superior, while under moisture deficits, it is equal or superior to other cool season grasses (AAFRD 1981). When irrigated with municipal and industrial effluents, it has superior capacity to utilize nutrients (Linden et al. 1981; Patterson et al. 2002). Establishment can take two full years (AAFRD 1981; Balasko and Nelson 2003). Its tall, coarse leaves prevent lodging which makes this high yielding grass easy to harvest. Its quality is poor to good depending on the cultivar's alkaloid concentrations, even though protein content is comparable to other grasses (AAFRD 1981; Balasko and Nelson 2003). To optimize nutritive quality, reed canary grass should be fertilized, especially with N since yields are so high, and harvested prior to head emergence (AAFRD 1981).

## 6.2 STATISTICAL ANALYSES

**Table 6.1 Analysis of variance for a split-strip plot design**

| Source of Variation | Degrees of Freedom | Mean Square | Observed F-value |
|---|---|---|---|
| Irrigation (I) | m-1 = 3-1 =2 | $MS_I$ | $MS_I$ /($MS_R$) |
| Reps within Irrigation | m(r-1) = 3(2-1) = 3 | $MS_R$ | |
| Forages (A) | a-1 = 3-1 = 2 | $MS_A$ | $MS_A/MS_{EA}$ |
| Forages × Irrigation (AI) | (a-1)(m-1) = 4 | $MS_{AI}$ | $MS_{AI}/MS_{EA}$ |
| Horizontal strip error (EA) | m(r-1)(a-1) = 6 | $MS_{EA}$ | |
| Fertilizer (B) | b-1 = 4-1 = 3 | $MS_B$ | $MS_B/MS_{EB}$ |
| Fertilizer x Irrigation (BI) | (m-1)(b-1) = 6 | $MS_{BI}$ | $MS_{BI}/MS_{EB}$ |
| Vertical strip plot error (EB) | m(r-1)(b-1) = 9 | $MS_{EB}$ | |
| Forages × Fertilizer (AB) | (a-1)(b-1) = 6 | $MS_{AB}$ | $MS_{AB}/MS_E$ |
| Forages × Fertilizer × Irrigation (ABI) | (a-1)(b-1)(m-1) = 12 | $MS_{ABI}$ | $MS_{ABI}/MS_E$ |
| Residual error (E) | m(a-1)(b-1)(r-1) = 18 | $MS_E$ | |
| Total | rabm-1 = 71 | | |

## 6.3 Neutron Probe Total Soil Water to 40 cm

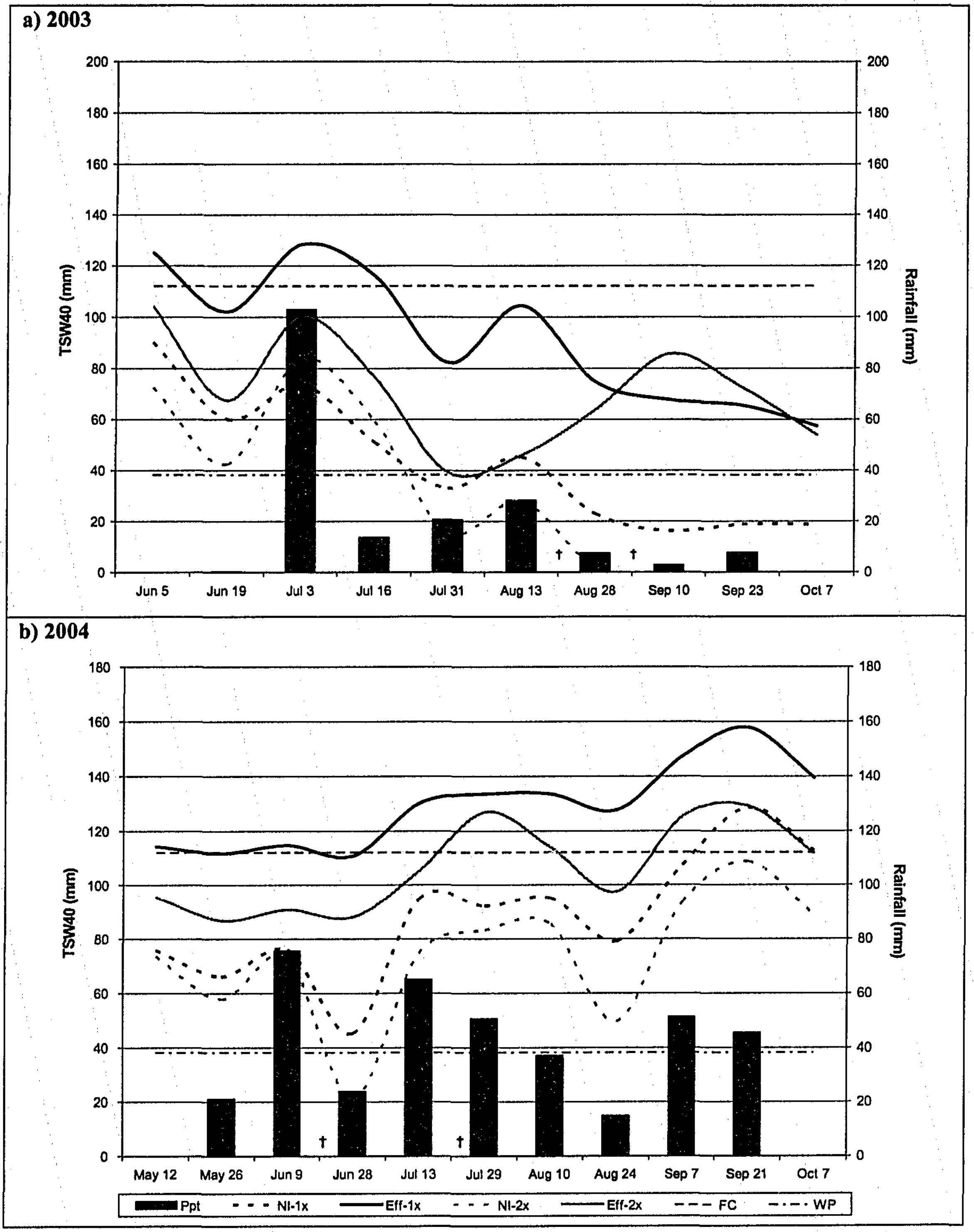


**Figure 6.1 Neutron probe total soil water (mm) to 40 cm (TSW40) for 2003 and 2004 with precipitation amounts (mm) and irrigation events (†).**

## 6.4 References


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