

A SOIL COLUMN STUDY OF THE IMPACT OF MUNICIPAL
EFFLUENT IRRIGATION ON TWO MANITOBA SOILS

by

Chittaranjan Ray

A thesis
presented to the University of Manitoba
in partial fulfillment of the
requirements for the degree of
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in
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ABSTRACT

Changes in chemical and some physical properties of the Roblin and the Erickson soils were studied on soil columns in a greenhouse under simulated average year and dry year rainfall and simulated day length period for the growing season in Roblin, Manitoba.

Historical weather data were used to simulate the rainfall in an average year and in a dry year. Theoretical day length hours for the growing period in Roblin were obtained from meteorological tables. Evapotranspiration demand of brome grass in the greenhouse was compared with that expected in field conditions.

The physical changes in the soil columns were measured in terms of bulk density, water stability index of soil aggregates and the amount of root mass. The chemical changes were measured in terms of the major and minor nutrient concentration, pH and salinity in the individual horizons of the soil columns.

The water stability index of the soil aggregates was reduced considerably. Bulk densities of individual horizons did not change significantly. Salinity and pH of the soil horizons increased. Concentration of major nutrients changed in most of the cases. The Sodium Adsorption Ratio (SAR) of the saturation extracts of each soil horizon increased substantially. Trace element concentration did not change substantially. Concentration of boron and manganese was higher in the leachates as compared to that in the effluent.

Average crop yield was of the order of 3.0 tonnes per hectare per cut. A linear relationship was observed between the amount of effluent applied within the evapotranspiration range of the crop and the yield of dry matter. The plant tissues were slightly deficient in nitrogen and phosphorus.

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CONTENTS

ABSTRACT	i
ACKNOWLEDGEMENTSiii

<u>Chapter</u>	<u>page</u>
I. INTRODUCTION	1
II. RELATED RESEARCH	4
Case Studies	4
Suitability of Effluent for Irrigation	7
Land Treatment Processes	12
Selection of Process and Design of System	12
Soil Factors affecting Effluent Irrigation	15
Guidelines for Effluent Irrigation	17
Legal Aspects	17
Regulations in the U. S. A. and Canada	18
Soil Properties Affected by Land Treatment	20
Physical Properties	20
Soil and Groundwater Chemistry and Plant Response	26
III. METHODS AND PROCEDURE	42
Soil Column Model Study	42
Roblin Effluent Irrigation Experimental Site	42
Location	42
General Description	43
Soil Description	44
Planning the Experiment	46
Treatment Selection	46
Handling the Soil	46
Soil Holding Boxes	49
Water and Effluent used for the Experiment	51
Rainwater	51
Effluent	51
Loading of the Boxes	52
Instrumentation and Calibration	53
Mechanical Devices	53
Strain Transducer	53
Recording Devices	55
Experimental Setting in the Greenhouse	55
Initiation of Irrigation	57
Simulation of Climatic Variables	58
Irrigation Study over the Growing Season	60

Analytical Procedures	63
Sampling	63
Soils	63
Plant Tissues	64
Effluent	65
Rainwater	65
Leachates	65
Physical Analysis	66
Soils	66
Root Mass	67
Plant Tissue	68
Chemical Analysis	68
Soils	68
Plant Tissue	68
Effluent, Rainwater and Leachates	69
Statistical Analysis	70
IV. RESULTS AND DISCUSSION	71
Irrigation Water	71
Effluent	71
Rainwater	74
Baseline Analysis of the soil	74
Analysis of the Leachates	77
Irrigation Water and Nutrient Loading	81
Changes in Physical Properties of Soil Columns	88
Bulk Density and Porosity	88
Aggregate Stability	91
Root Mass	93
Changes in Chemical Properties of Soils	95
Major Nutrients	95
Nitrate Nitrogen	95
Available Phosphorus	98
Available Potassium	101
Sulphate Sulphur	104
Exchangeable Cations	107
Soil pH and Salinity	115
Trace Elements	122
Soil Organic Matter, Total Nitrogen and Total Phosphorus	124
Crop Response	125
Yield of Dry Matter	125
Nutrient Uptake	128
Fate of Selected Nutrients	132
V. CONCLUSIONS AND RECOMMENDATIONS	133
Conclusions of the Study	133
Suggestions for Future Work	135
REFERENCES	137

<u>Appendix</u>	<u>page</u>
A. CHARACTERISTICS OF DOMINANT SOILS	147
B. RESULTS OF SOIL ANALYSIS	149
C. RESULTS OF LEACHATE ANALYSIS	155
D. ESTIMATION OF EVAPOTRANSPIRATION FOR ROBLIN AREA	158
E. STATISTICAL ANALYSIS	161
F. RESULTS OF PLANT TISSUE ANALYSIS	165
G. CALIBRATION OF TRANSDUCER	168
H. YIELD OF DRY MATTER	170

LIST OF TABLES

<u>Table</u>	<u>page</u>
2.1 Effluent Irrigation Systems on the Canadian Prairies	9
2.2 Irrigation Water Quality Standards for Manitoba	13
3.5 Expected Rainfall for Periods of Ten Days at Different Levels of Probability	62
4.1.1 Quality of Effluent used for Irrigation	72
4.1.2 Quality of Rainwater used for Rain Simulation	75
4.2 Major Nutrient Content of Individual Horizons of the Roblin and the Erickson Soils Before Effluent Application and the Recommended N-P-K-S Fertilizer Applications	76
4.3.1 Mass of Chemicals Leached out of Roblin Soil	78
4.3.2 Mass of Chemicals Leached out of Erickson Soil	78
4.4.1 Mass of Nutrients Added to the Roblin Soil through Irrigation (Effluent plus Rainwater)	82
4.4.2 Mass of Nutrients Added to the Erickson Soil through Irrigation (Effluent plus Rainwater)	83
4.4.3 Evapotranspiration Study for Roblin Soil Columns	84
4.4.4 Evapotranspiration Study for Erickson Soil Columns	85
4.4.5 Plant Population Study	87
4.5.1.1 Changes in Bulk Density for the Roblin Soil	89
4.5.1.2 Changes in Bulk Density for the Erickson Soil	90
4.5.2.1 Soil Aggregate Stability Index for the Roblin Soil	92
4.5.2.2 Soil Aggregate Stability Index for the Erickson Soil	92
4.5.3 Analysis of Root Mass	94
4.7.1.1 Yield of Dry Matter	127

<u>Table</u>	<u>page</u>
4.7.1.2 Product Moment Correlation Analysis	127
4.7.2.1 Removal of Major Nutrients by the Crop	131
4.7.2.2 Recommended Major Nutrient Application at the End of the Irrigation Season	131
A Characteristics of the Dominant Soils at the Roblin Wastewater Irrigation Project	148
B-1 Results of Soil Analysis for the Roblin Soil at the Conclusion of the Experiment	150
B-2 Results of Soil Analysis for the Erickson Soil at the Conclusion of the Experiment	151
B-3 Detailed Textural Analysis	152
B-4 Gravimetric Moisture Content of the Air-dried Soil . . .	153
B-5 Field-measured Soil Bulk Densities.	153
B-6 Percentage of Particles Greater than 2.0 mm	154
C-1 Quality of Leachates Collected under the Roblin Soil . .	156
C-2 Quality of Leachates Collected under the Erickson Soil. .	157
D Evapotranspiration of Grass in the Roblin Area (Blaney-Criddle Method)	160
E-1 Analysis of Variance for Changes in Bulk Density	162
E-2 Analysis of Variance for Root Mass	163
E-3 Analysis of Variance for Dry Matter	163
E-4 Duncan's Multiple Range Test for Mean Values of the Changes in Bulk Density	164
E-5 Duncan's Multiple Range Test for Mean Values of Root Mass and Dry Matter	164
F-1 Results of Plant Tissue Analysis for the Roblin Soil. . .	166
F-2 Results of Plant Tissue Analysis for the Erickson Soil. .	167
H Yield of Dry Matter for Brome Grass	171

LIST OF FIGURES

<u>Figure</u>		<u>page</u>
2.1	Distribution of municipal effluent irrigation projects on the Canadian Prairies	8
3.3	Soil Series Map (1:6560) SW 1/4 20-25-28W	45
3.4.1	Arrangement of the individual boxes in the greenhouse.	47
3.4.3	Sketch of a plywood box for holding the soil	50
3.4.6.1	Hydraulic jack and platform balance	54
3.4.6.2	Transducer	54
3.4.6.3	Placement of hygrothermograph and maximum-minimum thermometer	56
3.4.7	Arrangement of the soil columns in the greenhouse	56
3.5.1	Theoretical daylight hours for Roblin from May 15 to September 15	59
3.5.2	A sample log-probability plot of the rainfall data for the period between July 29 and August 7 (9th block of simulation) to calculate expected rainfall at 50 percent probability	61
4.4.1	Temperature and humidity conditions in the greenhouse during the experiment	86
4.6.1.1.1	Changes in the NO ₃ -N content of the saturation extracts of the Roblin soil after irrigation with municipal sewage effluent	96
4.6.1.1.2	Changes in the NO ₃ -N content of the saturation extracts of the Erickson soil after irrigation with municipal sewage effluent	97
4.6.1.2.1	Changes in the available P content of the saturation extracts of the Roblin soil after irrigation with municipal sewage effluent	99
4.6.1.2.2	Changes in the available P content of the saturation extracts of the Erickson soil after irrigation with municipal sewage effluent	100
4.6.1.3.1	Changes in the available K content of the saturation extracts of the Roblin soil after irrigation with municipal sewage effluent	102
4.6.1.3.2	Changes in the available K content of the saturation extracts of the Erickson soil after irrigation with municipal sewage effluent	103
4.6.1.4.1	Changes in the SO ₄ -S content of the saturation extracts of the Roblin soil after irrigation with municipal sewage effluent	105

<u>Figure</u>	<u>page</u>
4.6.1.4.2	Changes in the SO ₄ -S content of the saturation extracts of the Erickson soil after irrigation with municipal sewage effluent 106
4.6.2.1	Changes in the exchangeable Na content of the saturation extracts of the Roblin soil after irrigation with municipal sewage effluent. 108
4.6.2.2	Changes in the exchangeable Na content of the saturation extracts of the Erickson soil after irrigation with municipal sewage effluent 109
4.6.2.3	Changes in the exchangeable Mg content of the saturation extracts of the Roblin soil after irrigation with municipal sewage effluent 111
4.6.2.4	Changes in the exchangeable Mg content of the saturation extracts of the Erickson soil after irrigation with municipal sewage effluent 112
4.6.2.5	Changes in the exchangeable Ca content of the saturation extracts of the Roblin soil after irrigation with municipal sewage effluent 113
4.6.2.6	Changes in the exchangeable Ca content of the saturation extracts of the Erickson soil after irrigation with municipal sewage effluent 114
4.6.2.7	Changes in the Sodium Adsorption Ratio (SAR) of the saturation extracts of the Roblin soil after irrigation with municipal sewage effluent 116
4.6.2.8	Changes in the Sodium Adsorption Ratio (SAR) of the saturation extracts of the Erickson soil after irrigation with municipal sewage effluent 117
4.6.3.1	Changes in the pH of the saturation extracts of the Roblin soil after irrigation with municipal sewage effluent 118
4.6.3.2	Changes in the pH of the saturation extracts of the Erickson Soil after irrigation with municipal sewage effluent 119
4.6.3.3	Changes in the salinity (electrical conductivity) of the saturation extracts of the Roblin soil after irrigation with municipal sewage effluent. . . 120
4.6.3.4	Changes in the salinity (electrical conductivity) of the saturation extracts of the Erickson soil after irrigation with municipal sewage effluent. . . 121

Chapter I

INTRODUCTION

The practice of irrigating using municipal sewage effluent is becoming more and more popular due to the success in both crop production and wastewater disposal. The increasing public awareness and participation in clean environment protection has been the key force behind new attitudes to land treatment systems.

Land application of lagoon-treated wastewater has been considered as a tertiary treatment process in terms of the removal of pollutants from the wastewater by the soil matrix before reaching the groundwater body. The present approach to land disposal is more scientific in comparison to the old "out of sight out of mind" approach. Land application of wastewater whether for disposal per se, or for crop irrigation, has been proven to be most convenient and economical in small communities.

There are, however, some problems connected with effluent irrigation on the Canadian prairies. The wide variation in seasonal rainfall from year to year results in variable irrigation and effluent application requirements. Many farmers on the prairies still follow the practice of summer fallowing. Farmers participating in a wastewater irrigation project are bound by certain conditions, such as pumping out a certain minimum volume of effluent from the lagoon every summer. Under such circumstances, the farmers may have to apply some effluent on the fallow land.

The purpose of this study was to determine the changes in the chemical and some physical properties of two Manitoba soils with and without crop cover, after one season of irrigation using municipal effluent. This study was done using soil columns of the Roblin and the Erickson soils which are the characteristic soils of the Roblin area. Individual horizons of both the soils up to a depth of 1.0 m were taken from the field and were rebuilt in pre-fabricated plywood boxes according to the field bulk densities. To this end soil columns of the two soils were exposed in a greenhouse to rainfall regimes likely to occur in a dry and in an average year respectively, with supplemental effluent irrigation.

The two rainfall regimes for simulation purposes were determined using historic weather data for the Roblin area and probabilistic methods. The combination of cropped (brome grass) and fallow land, and dry and average year regimes, resulted in four different treatments as follows:

- A - fallow, average-year rainfall
- B - fallow, dry-year rainfall
- C - grassed, dry-year rainfall
- D - grassed, average-year rainfall

The above letter designations have been used in the thesis for the various treatments. Each treatment was replicated five times and, therefore, there was a total of twenty soil columns of each Roblin and Erickson soils respectively, for an overall total of forty soil columns.

effluent, municipal wastewater, wastewater, effluent, and sewage water are used interchangeably in this report accordingly. Similarly, the terms land treatment, land disposal, land application, and wastewater renovation are considered as equivalents.

Chapter II

RELATED RESEARCH

2.1 CASE STUDIES

Land application of sewage water was practiced by the ancient Romans and Greeks. However, the earliest well documented sewage farm was established in Edinburgh, Scotland in 1650 (U. S. Environmental Protection Agency (EPA), 1978). In the same publication a clear description of the development of sewage effluent irrigation projects in the United Kingdom and the United States, since 1840, can be found. Further, according to Tietjen (1975)

Braunsweig was one of the German towns which followed the examples in England where in about 1843, at Edinburgh, Ashburton, or Devon, the first sewage fields were established for the two fold purpose of keeping the rivers clean and manuring the soil.

Thomas (1973) says

Land disposal of collected urban water dates back at least four centuries, and some of the systems presently in use began operation before the turn of the 20th century. Historically, the purpose of land treatment approaches has emphasized wastewater disposal, whereas the current trend is away from the concept of disposal and toward the concept of treatment and/ or reuse. We are in the midst of an evolution from an 'out of sight out of mind' land disposal approach to a scientifically oriented treatment and/ or reuse system.

Egeland (1973) discussed the success of land disposal of wastewater against various constraints. According to him

In the short span of four years, the practice of land disposal has been raised from near extinction to a position of national eminence. Fortunately, the wastewater technology professionals continue to meet the crisis of the day and

proceed methodically toward the goal of selective separation and useful recycling of wastewater resources. Demeaned by the Senate committee, discredited by the army, maligned by the youthful consumer advocates, ridiculed in the popular journals and hampered by a lack of adequate research funds, these professionals are nevertheless hammering out a standard pollution profile and seem to be on the verge of dramatic breakthroughs in their quest for methods of treatment that will be ecologically beneficial and economically profitable, and which will place minimum demands on the nation's natural and energy resources.

Today, there are more than 3000 land application systems in the U. S. A. and some have been effective for more than half a century. These systems use various types of wastewater such as domestic, food processing, animal, petroleum and other different origins. Loehr et al. (1979a) have described 14 existing land application projects in Australia, the United Kingdom and the United States.

McKim (1979) reported on the world wide developments of land treatment systems. According to him, in Poland, sewage represents over 50 percent of all the surface water flow during dry years. Therefore, application of sewage to grassland and fodder and root crops is necessary not only because of its fertilizer value but because it is the only water available for irrigation. He also describes the development of sewage farming in Iran, Chile, Soviet Union, and India in the form of range irrigation, forage and crop irrigation and aquaculture.

Feinmesser and Wikinski (1979) reported that in Israel, a total of 4409 ha was under effluent irrigation in 1978 out of which about 73 percent was used for growing field crops. As reported by Lau (1979), effluent can be applied as supplemental water for furrow irrigation of sugarcane in Hawaii without detriment to groundwater quality and sugar yield. Further, for the irrigation of bermudagrass on golf courses,

effluent irrigation is a feasible means of water conservation and wastewater disposal.

A significantly large number of projects in the U. S. A. are operating successfully. The Bakersfield project in California handles 50 ML day^{-1} (13 million U. S. gal per day) of wastewater and irrigates 560 ha (1400 ac) of cropland (Uiga, 1978). Surface irrigation method is used to apply the wastewater to corn, cotton, alfalfa, and barley. Referring to the Lubbock project of Texas (Gray, 1977), a participating farmer says that presently 2000 ha (5000 ac) of diverse crops is under effluent irrigation. Other well known projects such as Muskegon county in Michigan and University Park in Pennsylvania, are also working successfully.

Canadian experiences with land application of wastewater has been very limited. Oldham (1979) says

Climatic conditions, although they do not preclude such land application, cause the acceptability of the method to be severely reduced when compared with many areas of the USA. Severe winter conditions in Central and Eastern Canada impose very basic restrictions on the length of the irrigation season, while the amount of precipitation on the West Coast imposes limitations on the amount of liquid that can be applied per unit land area.

According to him, there are three wastewater irrigation projects in British Columbia which use wastewater from food processing. In Ontario, the wastewater is mostly of industrial origin and a major portion of this wastewater comes from the food processing industry. Horgan (1980) describes the design and the installation of the Landsdowne project in Ontario and says that the success of this particular project will encourage other municipalities to install new and even larger systems.

In Western Canada, the practice of municipal effluent irrigation is hardly 20 years old. Fig. 2.1 shows the distribution of licensed effluent irrigation projects on the prairies. The irrigation potential, ownership, and the year of development for the individual projects are shown in Table 2.1. All these projects except for Medicine Hat use sprinkler irrigation. The Medicine Hat project uses the border dike method. The Roblin project uses a combination of sprinkler and gated pipe irrigation.

2.2 SUITABILITY OF EFFLUENT FOR IRRIGATION

Municipal wastewater has the characteristics of both irrigation water and fertilizer. A high liquid content of 99.9 percent shows its comparability to irrigation water from natural sources. However, its chemical characteristics determine its potential for irrigation. Bouwer and Chaney (1974) reported that effluents in general are considered as cheap source of irrigation water without taking into account their high nutrient content and in particular their high nitrogen content.

The concentration of soluble salts is an important factor in land treatment of wastewater and the electrical conductivity (EC) is an accurate measure of the soluble salt concentration in wastewater. According to Stewart and Meek (1977), about 700 ppm of NaCl in wastewater can result in 1 mS cm^{-1} of EC. The Ca content in wastewater alters this value to some extent.

Another important parameter in estimating salt effects of wastewater on soils is the Sodium Adsorption Ratio (SAR) as it considers the presence of other exchangeable cations such as Ca and Mg. Alberta

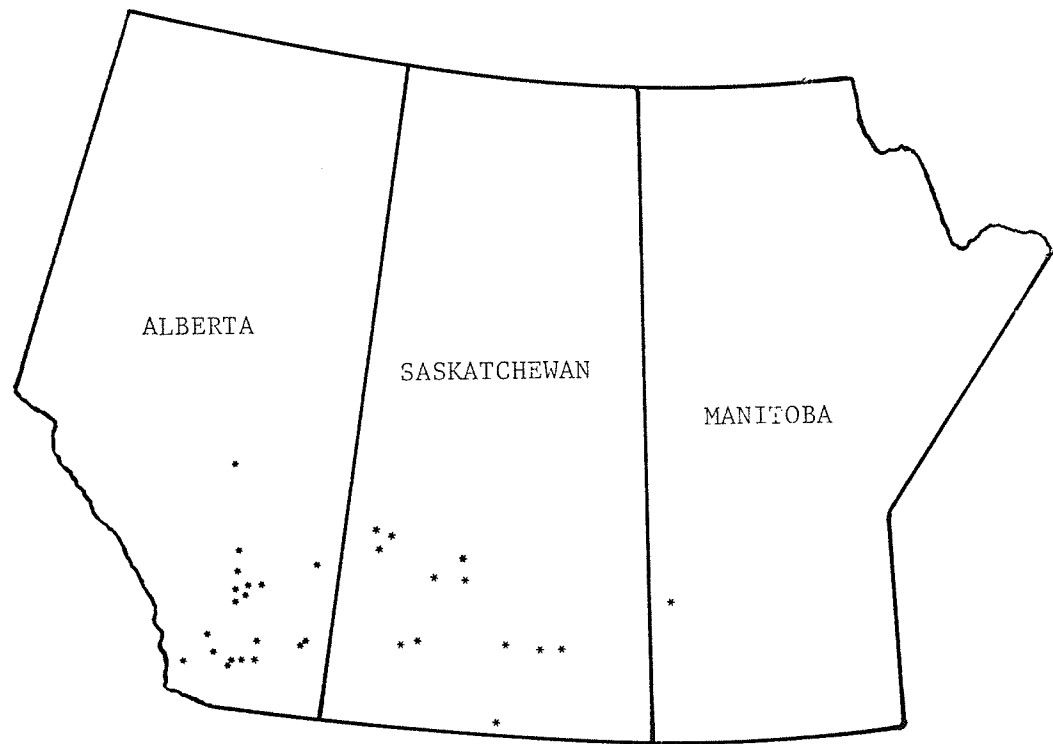


Fig. 2.1 Distribution of municipal effluent irrigation projects on the Canadian Prairies.

Table 2.1 Effluent Irrigation Systems on the Canadian Prairies

Province and System	Irrigable Area (ha)	Ownership	Developed (year)
ALBERTA			
Bowden	2	town	1979
Calgary	75	city	1975
Clareshom	60	private	1976
Coaldale	50	private	1976
Cowley	7	private	1976
Crossfield	20	private	1978
Edmonton Subdivision	40	private	1975
Esso Service Station	2	private	1974
Granum	14	private	1970
Lethbridge Air Port	10	Government	1978
Medicine Hat	90	private	1965
Okatoks	50	private	1976
Oyen	20	private	1977
Rockyford	10	private	1979
Springbank Air Port	10	Government	1978
Strathmore	64	private	1979
Taber	155	town	1970
(INDUSTRIAL)			
Medicine Hat Fertilizer	60	private	1977
Vauxhall Food Processing	100	private	1970
Carseland Ammonia Plant	270	private	1975
Lakeside Meat Packers	130	private	1975
Lethbridge Rendering	20	private	1975
SASKATCHEWAN			
Balgonie	53	private	1976
Biggar	91	private	1982
Coronach	82	private	1981
Davidson	21	private	1974
Etonia	43	private	1974
Gull Lake	22	private	1976
Maidstone	48	private	1974
Marshall	21	town	1982
Moose Jaw	1485	city	1982
Neilburg	25	private	1972
Swift Current	759	private	1979
Wolesley	77	private	1976
MANITOBA			
Roblin	64	private	1982

Environment (1977) in its guidelines for municipal wastewater irrigation, suggest that effluent with a SAR higher than eight is considered unsatisfactory and wastewater with an EC of 2.5 mS cm^{-1} or greater should also be considered unsuitable unless the soil to which it is applied is very well drained. Small wastewater irrigation projects with effluent which has a high SAR and low EC can possibly be made suitable by modifying the water quality by adding gypsum. However, in South Africa (Hayman, 1977) it was observed that FeSO_4 worked better than gypsum in terms of crop yield when added to effluent with high sodium content. The U. S. Environmental Protection Agency standards for a 20-year application period as reported by Reynolds et al. (1979) suggest a SAR value less than four to be suitable for crop irrigation. According to the same source, the permissible ranges for some other constituents and characteristics are as follows:

pH : 4.5 to 9.0

Total dissolved solids : 500 mg L^{-1} to 1000 mg L^{-1}

Electrical conductivity : 0.75 mS cm^{-1} to 1.50 mS cm^{-1}

Chlorides : 5 meq L^{-1} to 40 meq L^{-1}

A number of other sources {Jame and Nicholaichuk (1979), Ayers and Westcot (1976), and Shainberg and Oster(1978)} discuss the salinity problems. In general, the authors have suggested the inclusion of a leaching fraction in irrigation water in order to flush the salts out of the root zone. However, authors like Hook and Kardos (1978) have shown that excess leaching of wastewater adds more pollutants to groundwater and the loss of nutrients becomes excessive.

It was found that to maintain a steady-state salt profile the concept of leaching fraction is very important. Bernstein and Francois (1973) showed that a steady-state profile could be reached very slowly especially when the leaching fraction is low. Using saline effluent ($EC = 2.0 \text{ mS cm}^{-1}$) with a leaching fraction of 0.062, about 20 irrigations were required (total water application of 3250 mm) to achieve a steady-state condition. According to the same authors, a steady-state profile cannot be achieved with zero leaching fraction and salts will continue to accumulate imposing severe limitations to plant growth till they finally precipitate. The authors have pointed out that when a crop is irrigated with effluent with applications using a small leaching fraction, steady-state salinity profile tends to develop and the salinity gradually increases from the surface to the bottom of the root zone. The level of salinity at the surface is controlled by the salinity of irrigation water and the level at the bottom of the root zone is primarily determined by the leaching fraction. As the crop uptake of moisture is mainly from the upper layers of the soil where the salt concentration is the lowest, a lower leaching fraction can be used without fear of significant reduction in crop yield.

Ayers and Westcot (1976) in their previously referenced publication gave clear guidelines for the quality of water suitable for irrigation. The effluent used for crop irrigation should satisfy the same criteria.

Gilley (1976) stated that municipal wastes contain significant amount of major plant nutrients. However, some wastes, because of unfavourable physical characteristics or toxic chemicals, are not suitable for irrigation. Even desirable chemicals (plant nutrients) can become

undesirable if added in excessive amounts. Proper management practices are highly essential even if the effluent is highly suitable for crop irrigation and more so if it is least suitable.

The Clean Environment Commission of Manitoba (1979) has specified the required quality of irrigation water (Table 2.2) and any effluent used for irrigation should meet the stipulations of the guidelines.

2.3 LAND TREATMENT PROCESSES

2.3.1 Selection of Process and Design of System

The two principal criteria in the selection of the type of land treatment system and in its design are the potential to minimize environmental pollution and the maintenance requirement of the system under the given conditions.

Bouwer and Chaney (1974) say that the choice of system is mainly controlled by the soil, hydrogeological conditions and by the availability of land. The U. S. Environmental Protection Agency (EPA), (1977) classifies the land treatment systems into three major groups. They are

1. Slow-rate or crop irrigation
2. Rapid infiltration
3. Overland flow

In a slow-rate system, vegetation is the critical component in managing the load of water and nutrients. This is the most common land treatment practice. Rapid infiltration is an approach by which a significantly large portion of wastewater applied to land infiltrates the soil surface, percolates through the pores of the soil and recharges

Table 2.2 Irrigation Water Quality Standards for Manitoba¹

Items	Units	Maximum Limits
Electrical Conductivity	mS cm ⁻¹	up to 1.0 - safe 1.0 to 2.0 - possibly safe more than 2.0 - hazardous
Filtrable Residue	mg L ⁻¹	up to 700 - safe 700 to 1400 - possibly safe more than 1400 - hazardous
pH	units	5.0 to 9.0
As	mg L ⁻¹	0.1
B	mg L ⁻¹	0.3
Cd	mg L ⁻¹	0.01
Cu	mg L ⁻¹	0.2
Pb	mg L ⁻¹	5.0
Ni	mg L ⁻¹	0.2
Zn	mg L ⁻¹	2.0
Cr	mg L ⁻¹	0.05
Ca	mg L ⁻¹	*
Mg	mg L ⁻¹	*
Mn	mg L ⁻¹	0.2
Fe	mg L ⁻¹	5.0
Na	mg L ⁻¹	*
F	mg L ⁻¹	1.0
NO ₃ -NO ₂ -N	mg L ⁻¹	30.0
Cl	mg L ⁻¹	350
SO ₄ -S	mg L ⁻¹	400
Co	mg L ⁻¹	0.05
Sodium Adsorption Ratio (SAR)	-	up to 4 - safe 4 to 8 - possibly safe more than 8 - hazardous

NOTE: 0.043 Na

$$* \text{ SAR} = \frac{\text{Na}}{(0.025 \text{ Ca} + 0.04 \text{ Mg})^{0.5}}$$

¹ Reproduced from 'Report on Proposal Concerning Surface Water Quality Objectives and Stream Classification for the Province of Manitoba', by the Clean Environment Commission, Revised Edition, May 1979.

the groundwater. In this case, evapotranspiration is a negligible portion of the effluent loading rate. Overland flow is the process by which the wastewater is renovated by physical, chemical and biological means when the wastewater is allowed to flow in a thin sheet down a relatively impermeable soil. This is a relatively new approach. The objectives of this process are wastewater treatment and, to a minor extent, crop production. This method can also be used for the production of forage grasses and the maintenance of open spaces and green belts. Kemp et al. (1979) compared the slow-rate system and the overland flow system. Both systems have their own advantages and limitations.

Schrauben (1981) reported the presently followed irrigation methods in the rural communities of Michigan. They are:

1. Border irrigation
2. Sprinkler irrigation
 - a) Solid set
 - b) Side roll
 - c) Center pivot
3. Gated pipe overland flow irrigation
4. Drip irrigation (orchard, forest etc.)

Sheaffer (1978) describes the six basic components of the land treatment system employed to manage and to use the wastewater. They are:

1. Transportation of wastewater to the application site.
2. Pre-treatment facility to avoid the spreading of raw sewage on land. The levels of Biochemical Oxygen Demand (BOD), suspended

solids, and the coliform bacteria should not exceed the EPA specifications.

3. Storage for non-use periods.
4. Irrigation site where crops can be grown.
5. "Living filter" which includes crops and soils and where herbage remove the nutrients.
6. Subsurface drainage system, which can be either natural (an area of groundwater recharge) or installed drain tiles.

2.3.2 Soil Factors affecting Effluent Irrigation

Soil works as a treatment medium in the land treatment system. In such a system, the wastewater is not "disposed of", but rather the nutrients from wastewater are retained in the soil, removed by plants or passed through the soil to groundwater. The potential for prolonged irrigation of soil by sewage effluent depends upon soil properties such as texture, structure, infiltration capacity, available water holding capacity (AWC), permeability and cation exchange capacity (CEC) (Loehr et al. 1979b). In addition to the above-mentioned soil properties, Sheaffer (1978) considers a few more properties such as total organic nitrogen, total organic carbon, exchangeable Ca, Mg, Na, and K, total soluble salts, and bulk density. Biological, chemical and physical mechanisms work to renovate wastewater after its application to soil.

Soil texture describes the size distribution of mineral particles and soil structure describes the organization of individual particles. These variables can be linked to the conduction of water in the soil.

Infiltration rate depends upon soil permeability, moisture content and topography. The available water holding capacity refers to the micropore water which plant roots can extract from the soil. Thus essentially, it is the water storage capacity of the soil. A high available water holding capacity increases the residence time of wastewater in the soil, thus promoting renovation of wastes (Loehr et al., 1979b).

The cation exchange capacity is a rough index of the ion interchange between charged particles of the nutrients in wastewater and the clay and colloidal fraction of the soil. The cation exchange capacity of the soil varies greatly depending upon the amount and type of clay present and the amount of organic matter (Brady, 1974). A high soil CEC indicates a higher potential for wastewater renovation.

Soil pH exceeding 8 indicates the impact of Na in water. In heavy metal removal, a moderately high pH is considered to be an essential and desirable factor (Sheaffer, 1978).

Phosphate is another concern in soil from a pollution point of view. It is held by Ca at pH above 6 and by Fe and Al at pH below 6. The content of CaCO_3 in soil is very important in wastewater renovation as it is a buffer against heavy metals and phosphate. Still, according to Sheaffer, one percent of CaCO_3 in soil would certainly hold 6500 ppm of Zn or 1900 ppm of P in separate instances.

Organic carbon in soils is responsible for increasing the CEC of soils. The ratio of total organic nitrogen to total organic carbon in the top 60 cm of soil profile should be of the order of 10:1 to 12:1. Any reduction in this ratio causes greater likelihood of liberating ammonia.

Exchangeable cations, total soluble salts, and chlorides are also of interest to the irrigator. From the irrigation point of view, it is important in estimating the impact of a known concentration of Na in wastewater.

Taylor (1981) modified the EPA considerations slightly and specified the ranges of soil characteristics and soil properties for land treatment process. According to him, soil depth, slope and permeability evaluated together allow preliminary assesment of the suitability of a soil for land treatment. For slow-rate irrigation, he specified the ranges of soil depth to be at least 60 cm (24 in), the slope between 0 percent and 20 percent and soil permeability between 5 mm hr⁻¹ to 300 mm hr⁻¹ (0.2 in hr⁻¹ to 6.0 in hr⁻¹).

Schneider and Erickson (1972) gave different soil ratings in terms of their capabilities to handle wastewater. They have also indicated that phosphorus adsorption capacity is one of the important soil properties to be considered in land treatment systems.

2.4 GUIDELINES FOR EFFLUENT IRRIGATION

2.4.1 Legal Aspects

The Federal Law PL 92-500 of the U. S. A. emphasizes that preference should be given to waste management alternatives which are cost effective and with long range capacity for the reuse and recycling of wastes. Land application of wastes meets these recommendations more than any other treatment alternative (Loehr et al., 1979c). According to the same source, the the U. S. A. National Environmental Policy Act (NEPA) of 1969 requires an environmental impact statement to be filed

for any project that uses federal funds. The U. S. A. Safe Drinking Water Act (SDWA) sets standards for groundwater quality that the land application systems would have to meet, if they discharge to groundwater used for drinking water supplies. Thus it appears that land application is both encouraged and restricted by laws in the U. S. A.

Thomas (1981) reported that as of July, 1974, it became mandatory in the U. S. A. to consider the land treatment of wastewater as a treatment alternative. The Clean Water Act of 1977 (CWA) provides monetary incentives of up to 85 percent for the design and implementation of such projects. The Best Practicable Waste Treatment Technology (BPWTT) criteria published by EPA in October, 1975 gave strong emphasis to the protection of groundwater as a result of land treatment of wastewater.

2.4.2 Regulations in the U. S. A. and Canada

The State guidelines pertaining to the land application of wastewater in the U. S. A. include the following criteria (Loehr et al., 1979c).

1. Loading rate
2. Application system
3. Buffer zone
4. Monitoring
5. Cover crop
6. Storage
7. Public access
8. Effluent quality

Most of the States in the U. S. A. have set guidelines instead of setting regulations by law. According to the climatic zones, the individual states have been grouped into different regions. In each region, one of the participating States has been chosen as a representative example, with the most comprehensive guidelines. In the northern region, Minnesota is the representative State.

The California guidelines (Ling, 1978) appear to be quite thorough in describing the State regulations, spray irrigation of crops, surface irrigation of crops, landscape irrigation, impoundments, and protection of workers. The Pennsylvania guidelines (Loehr et al., 1979c) consider the soil as a treatment alternative, but still require secondary treatment prior to application. A buffer zone of 60 m (200 ft) around the entire spray field is another requirement. According to the same reference, the maximum application rate in Minnesota is limited to 50 mm (2 in) per week subject to a maximum annual application of 1300 mm (52 in) per year. The spray site should be fenced to prevent access to humans and animals. Warning signs should be posted. It is also mentioned that the site may be abandoned if there is a significant change in the effluent quality from sewage lagoons or groundwater quality as a result of effluent spraying.

In Canada, Alberta and Saskatchewan have guidelines for irrigation using sewage effluent. Saskatchewan guidelines (Environment Saskatchewan, 1976) require a certificate of approval from the Saskatchewan Department of Environment to operate a system. The location of the storage site is recommended to be at least 300 m (1000 ft) away from any residences. The irrigation site should be at least

100 m (300 ft) away from habitations or wells. Engineering and technical assistance is provided by the Conservation and Development Branch, Saskatchewan Department of Agriculture and Environment Saskatchewan. For the Federal Government, the Department of Regional and Economic Expansion (DREE) and the Central Mortgage Housing Corporation (CMHC) provide financial support. Similarly, for Alberta, the permit is issued by the Standards and Approvals Division, Alberta Environment (Alberta Environment, 1977). Assistance is provided by the Earth Sciences and Licencing Division of Alberta Environment, CMHC, and the Prairie Farms Rehabilitation Administration (PFRA).

2.5 SOIL PROPERTIES AFFECTED BY LAND TREATMENT

2.5.1 Physical Properties

The most limiting factor in spray irrigation using wastewater is the maintenance of the infiltration and the percolation capacity of the soil. According to Sopper and Richenderfer (1979), the primary factors affecting infiltration and percolation are the soil porosity, moisture content of the soil, the degree of compaction at the soil surface and the type of vegetative cover. Further, they state that there are three major factors that affect the infiltration and the percolation capacities of the soil due to wastewater disposal. The first factor relates to the physical clogging of the pores by suspended solids. The second relates to the formation of surface mats or slimes due to anaerobic conditions resulting from excess hydraulic loading. This has been a common phenomenon in very fine textured soils at high application rates. The third factor involves increased compaction at the surface soil due to the physical impact of irrigation water.

From a 13-year study at University Park, Pennsylvania, they concluded that spray irrigation of effluent resulted in an increase of infiltration capacity in soils under corn and a decrease of infiltration capacity in soils under reed canarygrass. In forest areas, the infiltration capacity was reduced significantly.

The changes in percolation capacities were statistically insignificant for both forest and agricultural soils. The total and the capillary porosities of the soils did not change significantly but there was a decrease in the non-capillary porosity in the top 7.5-cm layer. The effect on bulk density was insignificant, but there was a significant effect on the stability of soil aggregates. Most of the changes in soil properties occurred in the top 10.0-cm to 17.5-cm layers. Finally, it was observed that effluent treatment caused significant reduction in the root mass as compared to the control sites.

It has always been believed that a high sodium content in the effluent has deteriorating effects on the soil physical properties. In the Pennsylvania study, the average Na concentration of the effluent was only 32.6 mg L^{-1} . Sessing (1961) in his study reported that the high sodium effluent broke down the structure of a silt loam soil particularly between the 15-cm and 105-cm (6-in and 42-in) depths making it gelatinous and waterlogged. On drying, the non-aggregated mass was quite hard. A general increase in the bulk density and the water holding capacity of the soil was observed except in a muck soil, where no significant increase in bulk density was observed. The average Na concentration of the effluent was 34.87 meq L^{-1} (812 mg L^{-1}) which was about 25 times more than the effluent at University Park, Pennsylvania.

Further, it was reported that there was a decrease in non-capillary porosity with a concurrent increase in capillary porosity. The reason was attributed to soil deflocculation caused by the application of NaCl in wastewater. He also reported that the capillary conductivity of effluent irrigated muck soil was found to approach zero at low tension much faster than in the water irrigated muck soils. In such a case, the plant may suffer from drought even though the soil moisture could be at a very high level because at or near zero conductivity all the moisture adjacent to the roots gets used up quickly due to xylem suction and unless the plant roots grow continually to new moisture zones the plants suffer from drought.

Although it has always been assumed that the organic matter in the sewage effluent is the prime factor in the mechanical blocking of the pores and in reducing both infiltration and percolation capacities, Steel and Berg (1954) have inferred that the solubility of Fe and Mn was responsible for the formation of a clay "hard pan" in an effluent-irrigated fine-textured soil. This "hard pan" restricts the rate of water passage through the soil.

Rice (1978) has related the pore clogging to three different factors, namely chemical, biological and physical. Chemical clogging is caused by chemical interaction between dissolved salts in the effluent and the soil. He concludes that this process seldom occurs unless the effluent is excessively rich in Na. The biological clogging can be attributed to the bacterial growth in the pore neck or bacterial byproducts. This condition usually occurs in the surface soil in anaerobic conditions but can occur at any depth.

Lance and Whisler (1972) reported that the loss of infiltration was a result of the gas production (perhaps from denitrifiers) during denitrification when the soil column was intermittently flooded with secondary sewage effluent. De Vries (1972) in an intermittent soil filtration study with high rate application showed that at low temperatures (1 to 7 degree Celsius) surface pores were clogged and the existence of surface deposits of sludge was remarkable. At ordinary room temperature, no clogging problem was observed although biological growth was indicated by a very dark, brownish-gray colour in the top 20 cm of soil.

Rice (1978) also believed that the physical clogging of the pores is due to the presence of the suspended solids in wastewater. When the particles are little smaller than the pore diameter at the soil surface, they enter the soil matrix along with the effluent and lodge in any narrower portion in the flow path. The hydraulic properties of the clogged layer can be best expressed in terms of its hydraulic resistance or impedance to the effluent. The hydraulic resistance is defined as the ratio of the thickness of the blocking layer and its hydraulic conductivity. Impedance is the ratio of the head loss through the layer and the infiltration rate. He also suggested that the concentration of suspended solids should be kept below 10 mg L^{-1} . This can be achieved by sedimentation. The clogged layer can restore its infiltration capacity by drying.

Daniel and Bouma (1974) investigated the clogging of a slowly permeable silt loam soil as a function of effluent quality in Wisconsin. Total residue appeared to be the main factor in soil clogging. They

suggested that the success of effluent disposal on a slowly permeable soil can be achieved when low infiltration rate is maintained at or very near saturation.

Day et al. (1972) in their study in Arizona reported a decrease in infiltration rate in the Ap horizon of a soil under effluent irrigation as compared to normal irrigation with well water and fertilizer. They related the loss of infiltration rate to the loss of the surface soil structure as a function of high Na concentration in the effluent. They also noticed difficulties in terms of water intake in irrigating a previously effluent-irrigated soil. In the same study, in the Ap horizons, the bulk density of the effluent-irrigated soil was lower than a fertilized and well-water-irrigated soil. The modulus of rupture for the effluent-irrigated soil was higher than for the other soil. Modulus of rupture is the force required to disrupt the soil after it has become wet and then it is dried. The authors concluded that the cost of ploughing the land irrigated with effluent would be considerably higher.

Khalel et al. (1981) compiled results from 12 different literary sources including 21 soils with eight different types of crop under seven different types of organic waste applications. They evaluated the resulting changes in bulk density, field capacity, wilting point, and saturated hydraulic conductivity. A linear regression analysis of observed increase in soil organic carbon as a result of waste application on the percent reduction in bulk density indicated a highly significant correlation ($r^2 = 0.69$). The result of the exponential multiple regression analysis of percent sand and increase in organic carbon, on the percent increase in water holding capacity, indicated

that approximately 80 percent of the observed variations in percent increase in water holding capacity, at both field capacity and wilting point, could be attributed to variations in soil texture and to the increase in organic carbon content of the soil. Due to insufficient data on hydraulic conductivity as well as infiltration, the authors could not make any quantitative conclusions.

Kladivko and Nelson (1979) found an increase in organic carbon content of the soil resulting from waste application. They also observed increased soil aggregation, decrease in bulk density, larger pore space, and an increase in water holding capacity. According to Wischmeir and Mannering (1969) organic matter content and soil aggregation are inversely proportional to runoff volume and sediment losses. McAuliffe et al. (1979) studied the effects of dairy factory waste water on soil properties. The treated soil had a significantly lower bulk density (0.75 g cm^{-3}) against the control soil (0.95 g cm^{-3}) in the top 10-cm layer. The authors concluded that the decrease in bulk density was due to an increase in soil organic carbon and microbial activity. They contradicted the report of others presenting an increase of bulk density due to compaction caused by greater soil wetness during the experiment. Further, they suggested that a sufficient gap between two floodings with effluent could help revive the lost infiltration and saturated hydraulic conductivity values.

2.5.2 Soil and Groundwater Chemistry and Plant Response

Chemical changes in soils resulting from effluent application are associated with effluent characteristics, soil properties and the ability of the crop to remove the nutrients and the metals applied in the effluent. The soil and the crop under effluent irrigation have been considered as "living filter" from the beginning.

Settergen and Tennyson (1979) stated that the capacity of a soil to cleanse wastewater is related to the retention time of irrigation water in the root zone of the soil. Long retention time provides increased opportunity for soil adsorption, chemical reaction, precipitation and, plant uptake.

Anderson et al. (1981a) in a lysimeter study using bermudagrass and ryegrass at the University of Arizona reported that a sand removed on the average 52 percent of the applied N over a 42-week growing period. At the same time, a similar type of soil with 2 percent organic matter removed 64 percent of the applied N. The crop removal of N in both the soils were 19 and 27 percent respectively. An increase in application rate from 72 mm per week to 304 mm per week decreased the removal efficiency of N from 75 percent to 40 percent in sand and from 87 percent to 48 percent in the organic mix in the same growing period of 42 weeks. The crop removal of N increased slightly (not at a significant level) by increasing the application rate from 72 mm to 304 mm per week.

In the same experiment Anderson et al. (1981b) also found that at high application rates the concentration of P in the leachates exceeded that of the effluent. It showed that the absorption power of the soil

for P became saturated. The authors also pointed out that in order to limit the $\text{NO}_3\text{-N}$ concentration in the leachates to 10 mg L^{-1} , the loading rate on land for the summer season should not exceed 127 mm per week. The corresponding winter loading should be limited to 136 mm per week. The safe loading rate on the organic mix should be limited to 187 mm and 219 mm per week respectively. They also showed that at safe loading rates (based upon the above $\text{NO}_3\text{-N}$ study) P concentration in the leachates from sand and organic mix would reach 2.0 mg L^{-1} and 1.8 mg L^{-1} in summer and 4.6 mg L^{-1} and 5.1 mg L^{-1} in winter respectively. The authors recommended the occasional application of soil amendments such as lime, to reduce P concentration in the leachates.

There was almost no removal of boron from wastewater by the soil. The fact was that, being an anion, boron as BO_4 was not retained by soil.

A maximum Na concentration of 115 mg L^{-1} in the wastewater produced leachates having SAR between 3 and 4. The authors concluded that the Na content of the wastewater would be unlikely to alter the physical properties of soil.

Lance (1975) discussed the fate of nitrogen applied to soil in sewage effluent. According to him the three basic conditions for N removal are:

1. $\text{NH}_4\text{-N}$, the most significant component of N in effluent must be oxidised to $\text{NO}_3\text{-N}$ (or nitrification should occur before denitrification).
2. $\text{NO}_3\text{-N}$ should move through a zone where oxygen is absent.

3. Organic carbon must be provided in that zone as an energy source for denitrifying bacteria.

Lance also indicated that some amount of N is incorporated into the bodies of the microbes, some amount is fixed by clay and some amount is adsorbed by organic matter. However, a significant amount of N is retained in the soil cation exchange complexes by the process of adsorption. He suggested that if the concentrations of NH_4 , Ca, and Mg ions of the wastewater and the cation exchange capacity of the soil were known, the maximum amount of $\text{NH}_4\text{-N}$ that can be adsorbed by the soil cation exchange complexes could be calculated.

Lund et al. (1981) attempted to carry out a nitrogen balance study. The effluent contained less than 0.01 mg L^{-1} of $\text{NO}_3\text{-N}$, and about 21.2 mg L^{-1} of $\text{NH}_4\text{-N}$. Attempts were made to measure the loss of NH_3 through volatilization in addition to leaching, denitrification and crop removal. Lance and Bouwer (1977) suggested a combination of slow rate and rapid infiltration systems for operation in summer and winter seasons respectively. Lance (1977a) reported that nitrogen removal through denitrification increased up to 80 percent by reducing the infiltration rate from 350 mm to 150 mm per day. Lance and Gerba (1977) said that denitrification is the only reaction capable of rapidly reducing the nitrogen content of sewage in high rate filtration systems. The key to N removal by denitrification is to maintain a proper C: $\text{NO}_3\text{-N}$ ratio when the sewage moves through a reducing zone. Lance and Whisler (1972) have also reported that short and frequent cycles of flooding the soil columns (2 days flooded and 5 days dry) with secondary sewage effluent caused no net removal of N but transformed almost all the N to $\text{NO}_3\text{-N}$ form.

Lance (1977b) also studied phosphate removal from sewage water by soil columns. He showed that a tremendous quantity of $\text{PO}_4\text{-P}$ could be stored in a calcareous sand. Initially about 90 percent of the $\text{PO}_4\text{-P}$ was removed from an effluent with a P concentration of 12 mg L^{-1} . When the initial adsorption capacity became saturated, 75 to 80 percent of the applied $\text{PO}_4\text{-P}$ was removed by maintaining the application rate below 150 mm per day in a 9-day flooding and 5-day drying cycle. Iskandar and Syres (1980) in a similar study in California showed that considerable amounts of dissolved inorganic phosphate (DIP) were found in soil solutions collected at the depths of 80 cm and 160 cm. From the control site it was determined that the soil had a low ability to retain phosphorus. There was no removal of P through crop harvest as the plants were never removed from the field. High application rate was another factor which limited the interaction time between DIP in wastewater and the soil components capable of sorbing P. For the above reasons the performance of the system was poor.

Kardos and Hook (1976) showed that the maximum amount of P was held in the topsoil and there was hardly three percent of leaching of phosphorus. The ability of the particular soil to hold excess P was probably due to its high sesquioxide content. Sawhney (1977) reported that the amount of P sorbed by fine silt loam and silt loam soils in soil columns before breakthrough occurred, were approximately equal to the sorption capacity determined from isotherms obtained over a significantly long reaction time of 200 hours.

Robbins and Smith (1977) concluded that a satisfactory monthly P application (kg ha^{-1}) for a particular site can be approximated by

multiplying the accumulative depth (mm) of clay-size material in the phosphorus clean-up zone by 0.04. The clay-size materials have a diameter less than 0.002 mm and the usual phosphorus clean-up zone is the top 150-cm soil depth. Gravelly and very sandy zones cannot be expected to perform like this.

Beek et al. (1977a and 1977b) studied phosphorus relations in soils in the Netherlands when raw sewage was being applied over pasture for about 50 years. About 96 percent of the applied P was removed by both adsorption and precipitation reactions. PO_4 -P accumulated mainly in the top 50 cm of the soil profile. Further, the phosphorus fractionation method indicated that roughly 15 percent to 20 percent accumulated in organic form. The major part of the inorganic form was present in combination with Al or Fe. The authors believed that P retention in those soils was governed by reaction with Al. The presence of active Al compounds either present in soil (prior to the initiation of effluent application) or added as a component of sewage water would permit the determination of ultimate storage capacity of the soil for P bonding.

Hill and Sawhney (1981) reported that renovation of wastewater over a long period of time reduced the phosphorus sorption capacity of the soil, while periodic resting regenerated sorption sites and increased the potential for phosphorus sorption. In the same study, most of the P retained by that soil was in the upper 15-cm soil layer.

The following literature also deals with the soil removal of nutrients from wastewater. Bond (1979) reported changes in a duplex soil caused by drip irrigation with saline effluent in a vineyard in Australia. The effluent used had an exchangeable sodium percentage

(ESP) of 12.5. After 8 years of application the ESP of the soil reached 26 near the drippers and 12 at the midpoint between rows. PH raised to 9.2 in the A horizon and 8.6 in the B horizon near the drippers.

McAuliffe et al. (1979) reported that acidic effluent increased the soil pH although the latter had a higher value initially. This could be due to the release of NH_4 and Ca ions during the decomposition of waste milk products contained in the effluent. Total N, C, and P concentrations in the top 10 cm of soil were high in the treated site as compared to the control site. In the top 30 cm of the soil profile the concentration of plant-available phosphates were more than 20 times higher than those observed in the control site.

Stevenson and Wilcock (1979) reported that the average annual removal of P in small lucerne plots reached 99 percent while the removal of N was about 47 percent.

Hill (1972) using synthetic effluent in his experiment reported that all acid soils removed PO_4 , K, Ca, and Mg either by fixation or by cation exchange and reduced their concentrations below those found in groundwater. The alkali soils in the same experiment added unwanted hardness to percolates by flushing available Mg from the weathered calcareous mineral soil. All soils removed very little of the applied NO_3 , Cl, SO_4 , and Na. It was also found that the soils which removed maximum amounts of nutrients had the lowest permeabilities. The author reported that in these soils, with hard-pan and clay layers, percolating water moves laterally over the slowly permeable layer. This system could be considered to be much advantageous, because nutrient-rich percolating water remains within the root zone, where plants can utilize it.

Adriano et al. (1975) reported that there was excessive leaching of $\text{NO}_3\text{-N}$ and $\text{PO}_4\text{-P}$ from a food processing wastewater irrigation site in Michigan. The $\text{PO}_4\text{-P}$ in the leachates clearly violated the Michigan standards for $\text{PO}_4\text{-P}$ (which is 0.05 mg L^{-1}) concentrations entering groundwater. The authors, however, suggested that harvesting the grasses from the field at least three times a year could have removed about 31 percent of the N input and 27 to 80 percent of P input. Iskandar (1978) reported that poor management of the Manteca wastewater irrigation project was the reason for the serious adverse changes of the soil properties. In Chile, Schalscha et al. (1979) reported that after 25 years of raw sewage application to agricultural land, the $\text{NO}_3\text{-N}$ concentration in the unsaturated zone ranged between 20 mg L^{-1} to 35 mg L^{-1} . Even in well waters in that area, the $\text{NO}_3\text{-N}$ concentration was as high as 14 mg L^{-1} .

Smith et al. (1977) reported that the $\text{NO}_3\text{-N}$ in soil water would correlate more closely with the total N in the wastewater than with the $\text{NO}_3\text{-N}$ because most of the organic N eventually becomes $\text{NO}_3\text{-N}$ through microbiological breakdown of the organic matter.

Lo and Clayton (1978) found that the adsorption of $\text{NO}_3\text{-N}$ was strongly dependent upon soil pH and that adsorption could be significant for effluent with pH below 6. From their column tests they found that more than 99 percent of P removal was possible. The accumulation of $\text{PO}_4\text{-P}$ was mainly confined to the top 2.5 cm to 5.0 cm of soil. They also found that the columns removed 80 percent of the applied N in a 12-week test period with an application rate of 50 mm per week. Columns with 100-mm and 200-mm-per-week application rates had N removal ranging from

63 percent to 74 percent. It should be made clear that all these experiments were conducted without using crops. Total N loss in the soil columns amounted to about 65 percent to 80 percent of the N input through wastewater application. The authors believed that a portion of that might be due to denitrification.

Oldham (1974) found difficulty in making a nitrogen balance in the Vernon project of British Columbia because of the uncertainty in predicting the amount of leachates.

Hayman and Smith (1979) studied the effect of saline effluent from a pulp and paper mill in South Africa on soil. The Na content of soil increased with treatment but the Ca increased only in the topsoil (0 to 30 cm) but decreased with depth. No problems were found with infiltration, but the SAR of the leachates increased linearly in the first five years. Hayman (1977) also reported that, due to high Na content, amendments such as CuSO_4 and FeSO_4 were applied. The yields with CuSO_4 , FeSO_4 and with no amendments were 1.5 t ha^{-1} , 1.7 t ha^{-1} and 1.2 t ha^{-1} respectively.

Bole et al. (1981) studied the effects of leaching percentage (LP) on groundwater chemistry along with the resulting changes in the soils under effluent irrigation. The soil under alfalfa had higher levels of salinity as compared to that under fallow and reed canarygrass. Soluble Na content in the soil profile at the 90 cm and 150 cm depths were used to estimate the leaching percentage (LP). Leaching percentage greater than 34 percent in the first two years of the study reduced original soil salinity levels from 3.99 mS cm^{-1} to less than 1.39 mS cm^{-1} . When the irrigation rates were reduced in the last four years, soil salinity

increased up to 2.13 mS cm^{-1} which, nevertheless, was in the safe zone of crop growth. At LP greater than 15 percent the EC and the SAR values of the soils were low, but there was a potential danger of a large net transfer of salts to groundwater because of dissolution of gypsum.

Smith (1976) reported that the soil and plant removed about 90 percent of the applied $\text{NO}_3\text{-N}$ from the wastewater and less than one percent moved to groundwater.

Kneezek et al. (1977) reported that when the applied effluent contains more P than the plant requirements, three possibilities exist. They are, precipitation in the soil, adsorption on the surface of the solid particles and passage through the soil to drainage water. According to them at pH levels of 7.0 or more, P would precipitate as calcium phosphate. In this mechanism phosphorus removal could not be considered to be significant. Adsorption was considered by them as the most important mechanism.

Olsen and Barber (1977) indicated that high rate application of wastes might be considered beneficial from the point of view of availability of nitrogen. Wastewater high in P would cause Zn deficiency in crops due to a P-Zn imbalance. Further, higher loading of K to soils having CEC below $5 \text{ meq } 100\text{g}^{-1}$ would increase available K in relation to Ca and Mg. This would depress the uptake of Ca and Mg, causing crop deficiencies.

Wallingford et al. (1977) found that high rates of application increased the K content of the soil and decreased the Ca content. Tofflemire and Chen (1977) showed that at constant percentage of silt plus clay down the soil profile, the adsorption of P by the soil decreased with depth.

Swift Current Research Station (1981) reported that in general, there were no significant changes in the nutrient status in the top 150 cm of soil in the fields of the farmers operating effluent irrigation systems. Besides the crop removal of nutrients, there was significant leaching. The researchers suggested that it would be more beneficial from the nutrient standpoint to consider frequent and light irrigations. From the salinity study it was found that after three years of wastewater application, the fields exposed to higher leaching percentages (LP) developed a stable salt profile. The EC of the top layers approached that of the wastewater. At low LP (10 to 15 percent) no problem was noticed although the EC values of the lower layers were quite high. On one site, high water table increased the salt content of the top layer.

Linden et al. (1981) concluded that:

Irrigation frequency has little effect on the growth of well adopted species such as reed canarygrass or on the net N removal from municipal wastewater effluent whose primary N-form was NH_4 . For these reasons irrigation scheduling should be based on optimizing pumping and labour conditions.

However, it should be noted that this was the result of a two-year study only.

Leland and Wiggert (1979) had also discussed the possible advantages and disadvantages of winter spraying of effluent in cold regions. NO_3 -N concentration in the groundwater and high P concentration in the surface runoff were the main disadvantages.

Sessing (1961) had also studied the effects of effluent irrigation on the soil chemical properties and plant growth. Higher yields were recorded under effluent irrigation. Phosphorus in the effluent was highly responsible for increased yield in muck soil. Nitrogen leaching

was limited to 6 to 12 percent of the applied amount. Leaching of P and K was insignificant. Concentrations of the cations in the leachates were high. The problem of Na was severe and ESP was 15 percent above the critical standard. He recommended that to make any final conclusion a sufficiently long experimental period should be observed.

Clapp et al. (1977) in a seasonal study in Minnesota in 1975 showed that corn fodder yield was lower under effluent irrigation as compared to the control sites. Nitrogen deficiency in effluent treated blocks, especially early in the season, was one of the principal reasons for lower fodder yield. However, the forage yields for Kentucky blue grass and reed canarygrass were higher under effluent irrigation as compared to the control sites. Further, based upon the concentration of nitrogen in soil water at two different depths, it was found that forage crops removed much more nitrogen than did corn. In a nitrogen balance it was found that most of the N under forage crop was taken up by plants. A small amount was lost to drainage. Changes in the concentration of N in soil water were still negligible. Under corn a smaller portion of N was removed by the crop as compared to the portion lost to drainage. There was significant amount of unaccountable N in the soil-plant-water system.

In a two year test period, Palazzo (1977) found that increasing the effluent application rate from 50 mm to 150 mm per week, forage yield increased from 9.63 t ha^{-1} to 13.68 t ha^{-1} . On an average, the concentration of N, P, and K in the forage tissue also increased with increased application rates. There was reduction in soil pH although effluent pH was higher than the initial pH of the soil. There was 64

percent reduction in the concentration of exchangeable cations after one year of wastewater application. It was further noticed that the rate of decrease in pH was proportional to the increase in the application rate. This lowering of pH was due to the release of hydrogen ions from the wastewater during the transformation of $\text{NH}_4\text{-N}$ to $\text{NH}_3\text{-N}$. There was a significant reduction in exchangeable K alone as compared to other exchangeable cations. The plant removal of K was higher than the application of K through effluent. An increase in the application of wastewater decreased the removal efficiency of N and P by plants. At an application rate of 50 mm per week, the removal of N and P was 97 percent and 35 percent respectively.

Palazzo (1981) also emphasized the importance of the frequency of cutting on the accumulation of dry matter as well as nutrients in orchard grass. Under a typical 75-mm-per-week application rate, the accumulation of dry matter ceased after 31 days of growth in the first cutting. During the second and the third cuttings, the accumulation continued up to 35-40 days of growth. He also compared the uptake of nutrients in relation to dry matter accumulation. The yield of dry matter and the uptake of N, P, and K in the first year were lower than the second year. The average daily accumulation of dry matter in the first cut was highest and in the second and third cut it was 70 percent and 50 percent of the first cut respectively.

Palazzo and Zenkins (1979) reported after a five-year study period that the plant uptake of K in the first four years exceeded the amount applied in irrigation. Potassium uptake increased as the amount of N applied and removed by the forage increased. He suggested that the

total K application should be approximately 90 percent of the amount of N expected to be removed by the crop. The K:N ratio in the effluent was 2.0. He suggested that excess K could cause problems in animal and plant nutrition.

Day et al. (1972) gave a comparison between the soil properties after irrigation with wastewater alone and with a mixture of well water and recommended fertilizer. The $\text{NO}_3\text{-N}$ concentration in the Ap horizons of both soils were higher than that of the C horizon. The $\text{NO}_3\text{-N}$ concentration of the Ap horizon of the effluent-irrigated soil was 4.5 times higher than that of soils irrigated with well water and fertilizer. Similar trends were observed for phosphorus. Soluble salt concentration in both Ap and C horizons under effluent irrigation was higher as compared to the respective horizons under well-water irrigation. The accumulation of organic matter was higher in well-water-irrigated soils. However, there was no decrease on crop yield in the effluent irrigated soils as compared to the yield of crops under well water irrigation with fertilizer application.

Day and Kirpatrick (1973), Day and Tucker (1977), and Day et al. (1974, 1975, 1979, 1981, 1982) have also described the crop response to effluent irrigation in Arizona. In these studies, oats, wheat, alfalfa, and cotton were commercially produced. In most of the cases, the crops grown under a mixture of well-water and effluent produced better yields in terms of both quality and quantity as compared to the crops grown under well water irrigation alone.

Hook and Kardos (1977 and 1978) studied the nitrate relationship in the land application systems at University Park, Pennsylvania. In a

hardwood forest site, a 50-mm-per-week application resulted in a nitrate leaching of 83 percent over 6 years. Even at a 25-mm-per-week application the $\text{NO}_3\text{-N}$ in soil water exceeded 10 mg L^{-1} at the 120 cm-depth. In an old field site, the $\text{NO}_3\text{-N}$ concentration in soil water at the 120-cm depth remained within 10 mg L^{-1} and leaching was 30 percent with an application of 50 mm per week. When the application rate increased to 75 mm per week, $\text{NO}_3\text{-N}$ concentration exceeded 10 mg L^{-1} at the same depths. Denitrification was assumed to be the major factor in reducing the $\text{NO}_3\text{-N}$ level in the old field site.

In a hay field with reed canary grass, the concentration of $\text{NO}_3\text{-N}$ at the 120-cm depth with the same application rate was below 10 mg L^{-1} . Over a period of four years, the leaching of $\text{NO}_3\text{-N}$ was 23 percent of the amount added. In the crop field sites under corn, oats, hay, and other grain crops, the crop removal of nitrogen ranged from 40 percent to 100 percent of the applied amount. The $\text{NO}_3\text{-N}$ concentration in soil water at the 120-cm depth was below 10 mg L^{-1} .

Hook and Burton (1979) showed the effect of crop management on $\text{NO}_3\text{-N}$ leaching. They showed that two cuts per year in an old field site controlled $\text{NO}_3\text{-N}$ leaching more effectively than a treatment without harvest. In another site with Kentucky blue grass frequent harvest was not essential for the reduction of $\text{NO}_3\text{-N}$ leaching when the applied effluent had a moderate amount of $\text{NO}_3\text{-N}$. However, the authors suggested that for reliable control of $\text{NO}_3\text{-N}$ leaching removal of nitrogen in biomass is essential. Kardos (1968 and 1977), and Sopper and Kardos (1973) have also described the response of vegetation to effluent irrigation in terms of yield, chemical composition of plant tissues and

other aspects. In their studies, both corn and reed canary grass were effective in removing a higher percentage of N than P. The soil had a strong adsorptive power to fix P in amounts of the order of 23 000 kg ha⁻¹ to a depth of 150 cm as reported in their phosphorus adsorption isotherm study. Thus both the vegetation and the soil were effective in controlling in groundwater pollution and eutrophication of waterbodies.

Burton and Hook (1979) in a mass balance study of the application of wastewater to forest have shown that in a poorly drained soil under heavy application rates, the nitrogen retention was very high. Denitrification under anaerobic conditions was supposed to be the major factor in the reduction of the nitrogen concentration in the soil. The P retention decreased from 95 percent to 66 percent when the rate of application increased from 50 mm to 100 mm per week.

The crop removal of nutrients and the resulting changes in soil were also studied by O'Connor (1979), Feigin et al. (1979 and 1981), Kipnis et al. (1979), McPherson (1977 and 1979), Marten et al. (1980), Karlen et al. (1976), Nichols and Boelter (1982), Sutton et al. (1978), Bole and Bell (1978), Bole and Biederbeck (1979), Barbarick et al. (1982), Bower and Chaney (1974), and Jeffery and Uren (1979). In most of these studies emphasis was given to the rates of nutrient uptake by plants and the resulting changes in soil chemistry in terms of the concentration of major nutrients, salinity, pH, and to some extent heavy metals. Previously referenced Jeffery and Uren (1979) reported that due to a high Cu concentration in the effluent, the concentration of Cu in the tissues of grass reached 26 ppm in four years. They suspected that if the accumulation continued at this rate, the sheep grazing that pasture would suffer from copper toxicity.

Several authors have studied the application of heavy metals to land through effluent and the corresponding plant uptake and accumulation in the soil. Reynolds et al. (1979) indicated that except for Zn, the amounts of metals removed by crops were higher than those applied with effluent. The accumulation of heavy metals during the 20-year study period was within safe limits. Banin et al. (1981) indicated that the maximum accumulation of heavy metals occurred in the top 10-cm to 15-cm zone. Siddle et al. (1976) reported that more than 93 percent of the heavy metals accumulated in the soil and that plant uptake was negligible.

David and Williams (1979) reported that the increase in Zn, Cu, Cd, Cr, Co and Pb concentrations in the surface 2.5-cm soil layer were roughly equivalent to the amount applied in effluent. A small increase in Ni and a slight decrease in Mn were observed. The increase in metal content of the herbage was small in comparison to the substantial input, but when equivalent amounts of metals were added to a control soil in pot culture, they proved toxic to plant growth. The authors concluded that changes in soil properties as a result of waste application, particularly an increase in pH and organic matter content, together with natural fixation reactions have combined to ensure that toxic levels were not reached.

Chapter III

METHODS AND PROCEDURE

3.1 SOIL COLUMN MODEL STUDY

A soil column model study of the Roblin and the Erickson soils under effluent irrigation was carried out before the actual initiation of the field experiment at the Roblin Effluent Irrigation Site. This study was basically aimed at monitoring the changes in some physical and chemical properties of the soils irrigated with effluent of the secondary sewage lagoons of the town of Roblin in dry-year as well as in average-year rainfall conditions with and without crop cover. Such an experiment can not be done in actual field conditions as the simulation of rainfall for an average year or a dry year in an uncontrolled environment is not feasible.

The soil column study modeled the two characteristic soils of the Roblin area. For this reason it is essential to discuss in brief the location, climate, soils and the hydrography of the experimental site.

3.2 ROBLIN EFFLUENT IRRIGATION EXPERIMENTAL SITE

3.2.1 Location

The site of the future effluent irrigation field experiment is located approximately 400 km northwest of Winnipeg, Manitoba. The site is 5.6 km south of the town of Roblin and 0.8 km west of the Manitoba Provincial Highway No. 83. The approximate latitude of the site is

51.14 degrees north. The site is located 0.8 km south and 0.8 km west of the new Roblin sewage lagoon on the southwest quarter of section 20, township 25, range 28 west of the first provincial meridian (SW 1/4 - 20 - 25 - 28 W).

3.2.2 General Description

The mean maximum and minimum temperatures of the growing season (May to September) for the study area are 20.8 and 7.3 degree celsius respectively. The average growing season precipitation is 280 mm.¹ The topography is typical of a hummocky moraine till.² Slopes vary from nearly level in the depressions to gently sloping (0-9 percent). Two significant ridges in the quarter-section are characterised by slopes in the range of 6 to 9 percent. Local relief varies about 3 m to 4 m and maximum relief across the field is 7 m. The hydrography of the site is not well defined. Periodic and seasonal runoff is collected in numerous depressions. The residence time of free water in these depressions is of short duration. Most of the drainage is internal. During the survey, the maximum depth to water table was found to be 11 m.

¹ Shaykewich, C. F. Department of Soil Science, University of Manitoba.-Unpublished report.

² Canada-Manitoba Soil Survey, Soil Investigations for Roblin Waste Water Irrigation Project, September 1980, by R. G. Eilers.

3.3 SOIL DESCRIPTION

A soil survey of the project area was carried out by R. G. Eilers (Department of Soil Science, University of Manitoba) in September, 1980. A second detailed soil survey of the area was completed later but the results are yet to be published. In the first survey, a total of 40 soil inspection sites were described along four north-south traverses (survey intensity level of 1 inspection = 1.6 ha). The soils were mapped at the series level at a scale of 1:6560 (Fig. 3.3). In connection with the soil survey six observation wells were installed to various depths (from 3.7 m to 8.4 m) for ground water studies. The following soil series were identified in the study site.

1. Erickson nearly level (ECK/b)
2. Erickson very gently sloping (ECK/c)
3. Onanole slightly eroded, gently sloping (OOL/ld)
4. Petlura nearly level (PTU/b)
5. Roblin (RBN)

The dominating texture, drainage and classification of each series are explained in Fig. 3.3. The Erickson and the Roblin series combined occupy more than 60 percent of the total area. Both soils belong to the same singular class 'Orthic Dark Gray Chernozem'. A detailed description of the two soils is in Table A of Appendix A.

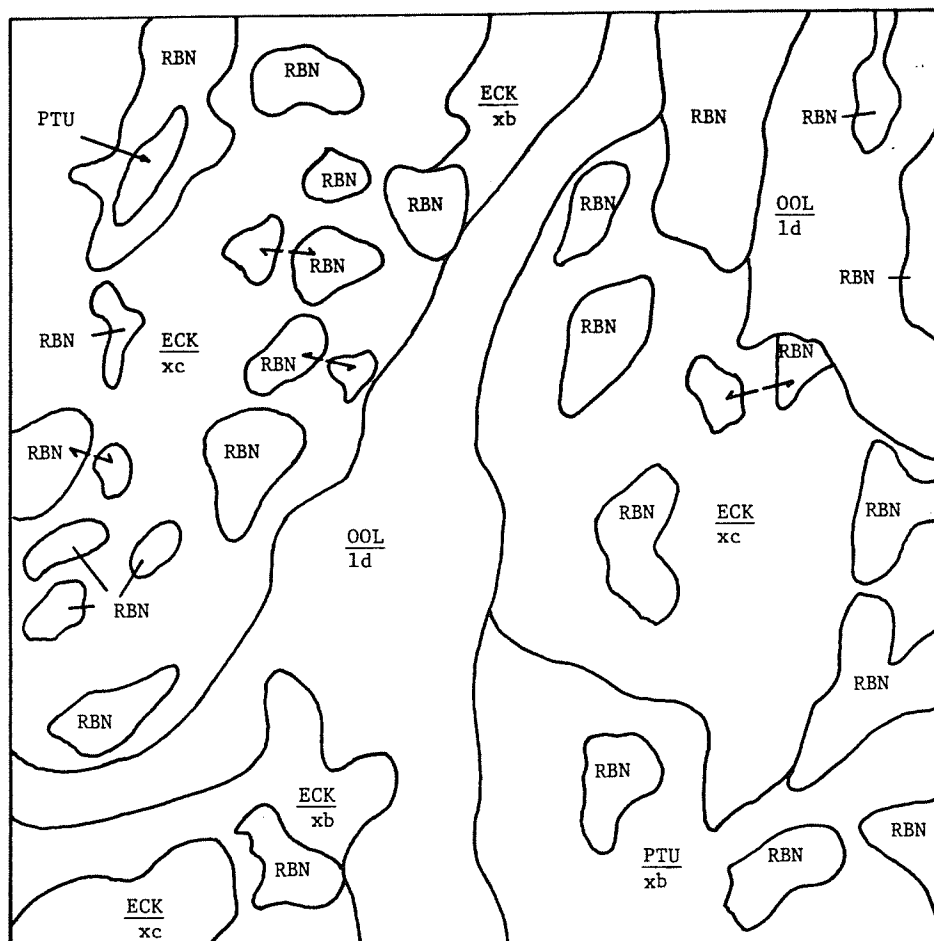


Fig. 3.3 Soil Series Map (1:6560) SW 1/4 20-25-28W *

Map Symbol	Series Name	Dominant Texture	Soil Drainage	Classification
ECK/ _b	Erickson nearly level	Clay loam	Good	Orthic Dark Gray Chernozem
ECK/ _c	Erickson very gently sloping	Clay loam	Good	Orthic Dark Gray Chernozem
OOL/ _{1d}	Onanole slightly eroded, gently sloping	Loam	Good	Orthic Dark Gray Chernozem
PTU/ _b	Petlura nearly level	Clay loam	Imperfect	Gleyed Dark Gray Chernozem
RBN	Roblin	Clay	Imperfect to poor	Humic Luvic Gleysol

* Reproduced from the Preliminary Soil Survey Report for the Roblin Wastewater Irrigation Project (by R. G. Eilers), Canada-Manitoba Soil Survey, 1980.

Note: x - A symbol of erosion

3.4 PLANNING THE EXPERIMENT

3.4.1 Treatment Selection

A greenhouse model study was designed with the Roblin (RBN) and the Erickson (ECK/c) soils. Similar treatments were applied for both the Roblin and the Erickson soils. Each soil group was subdivided into two sub-groups, one cropped with brome grass and the other uncropped. Each sub-group was under two simulated rainfall regimes and corresponding levels of effluent application. The first level of effluent application simulated irrigation in an average year where the rainfall expected at a probability level of 50 percent was the minimum assured value. The second level of effluent application simulated irrigation in a dry year for which rainfall expected at a probability of 90 percent was assumed to be the minimum assured value. Thus each soil group had received four different treatments. There were five replications in each treatment, therefore, a total of 40 soil columns in both soils. The allotment of individual replications to each treatment as well as the sub-group within each soil type was done completely at random. A complete sketch of the experimental layout is shown in Fig. 3.4.1.

3.4.2 Handling the Soil

With respect to the normal seasonal root length of brome grass, the depth of the soil columns was limited to 100 cm. As the columns had to be weighed periodically and bigger columns would be too difficult to handle, this depth was considered to be acceptable. The vertical space in the greenhouse was another limiting factor in the selection of the depth of the columns. The cross sectional area of each column was 20 cm

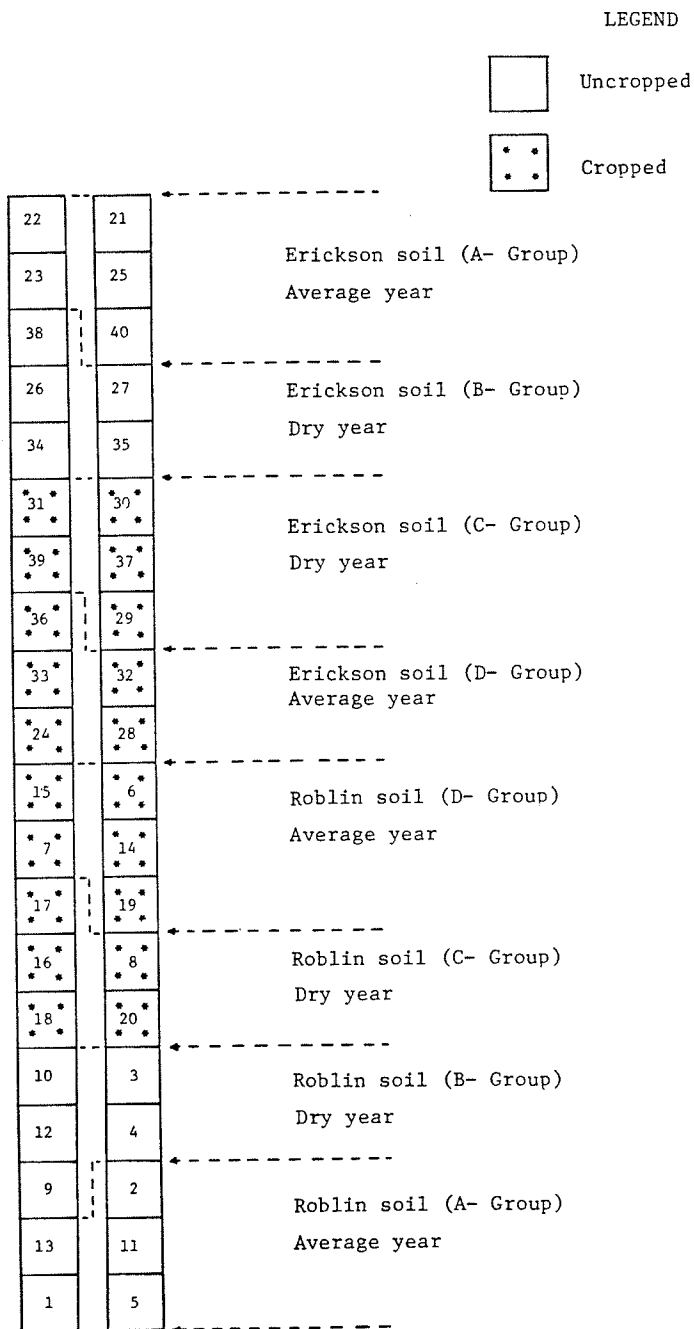


Fig. 3.4.1 Arrangement of the individual boxes in the greenhouse.

by 20 cm square. Due to the size and large number of columns, taking of undisturbed soil columns and transferring them to Winnipeg was not possible. It was, therefore, decided to bring disturbed soil from distinct horizons of the two soils and to reconstruct the profile in Winnipeg.

The Roblin and the Erickson soils were identified in the field and based on the color and the texture (judged by the feel method), the depth of distinct horizons in the top 100 cm depth were determined. No consideration was given to the surface organic horizons due to their very shallow depth.

Roblin soil had two distinct horizons in the top 100 cm of soil depth. The first horizon was approximately 40 cm deep and the thickness of the lower horizon was 60 cm. They represent roughly the A and the B horizons. To the same depth, the Erickson soil showed 3 distinct horizons. The first horizon was 20 cm deep, the second horizon was 40 cm thick and the third one was also 40 cm. This stratification is slightly different from the average values obtained in the earlier soil survey.³ A front-end loader was used to dig separately the distinct horizons of the two soils and to load them on a truck in five separate compartments for transportation from the field to the university campus. The soil was then air-dried separately. Excess organic matter such as plant stems and roots were eliminated from the first horizons of both the soils by sieving. From the other horizons only the bigger stones were removed. The moisture content of the air-dry soil of each horizon was then determined (Appendix B, Table B-4).

³ Unpublished report of soil survey of the Roblin experimental site by R. G. Eilers, Canada-Manitoba Soil Survey.

At the same time the field bulk densities of different soil horizons were determined (Appendix B, Table B-5).

3.4.3 Soil Holding Boxes

Soil holding boxes were made of five-ply 12.5 mm (0.5 inch) Douglas Fir plywood (Fig. 3.4.3). The total depth of the boxes was 113 cm. To secure good drainage of the soil columns an inclined grooved board of average thickness of 1.0 cm was placed on the bottom of each box with an approximately 6.0 cm of gravel on top for a total depth of approximately 7.0 cm. The 100-cm deep soil column followed the gravel allowing an approximately 6.0 cm of freeboard to facilitate irrigation and to prevent water and soil spills. The horizontal cross section of the boxes was 20 cm by 20 cm inside and 22.5 cm by 30.0 cm outside due to the wall-thickness and reinforcing wooden constructional members in the corners.

A small hole was drilled near the bottom of each box and fitted with a spout (short tube) for collecting the leachates. The inside surface of each plywood board directly facing the soil, was primed with an interior-exterior latex primer (specially used for plywood) and a coat of swimming pool enamel was applied on the primer in order to protect the plywood from water and to avoid chemical reactions between the plywood and the soil. All the jointing surfaces were glued with a water-proof urea formaldehyde glue and were nailed with 30-mm (1.25-in) ringed nails. All the corner and bottom lines inside each box were sealed with silicon sealant which is water-repellant and inert. In every box a 60-mm-long and 12.5-mm-(0.5-in-)diameter plastic tube was

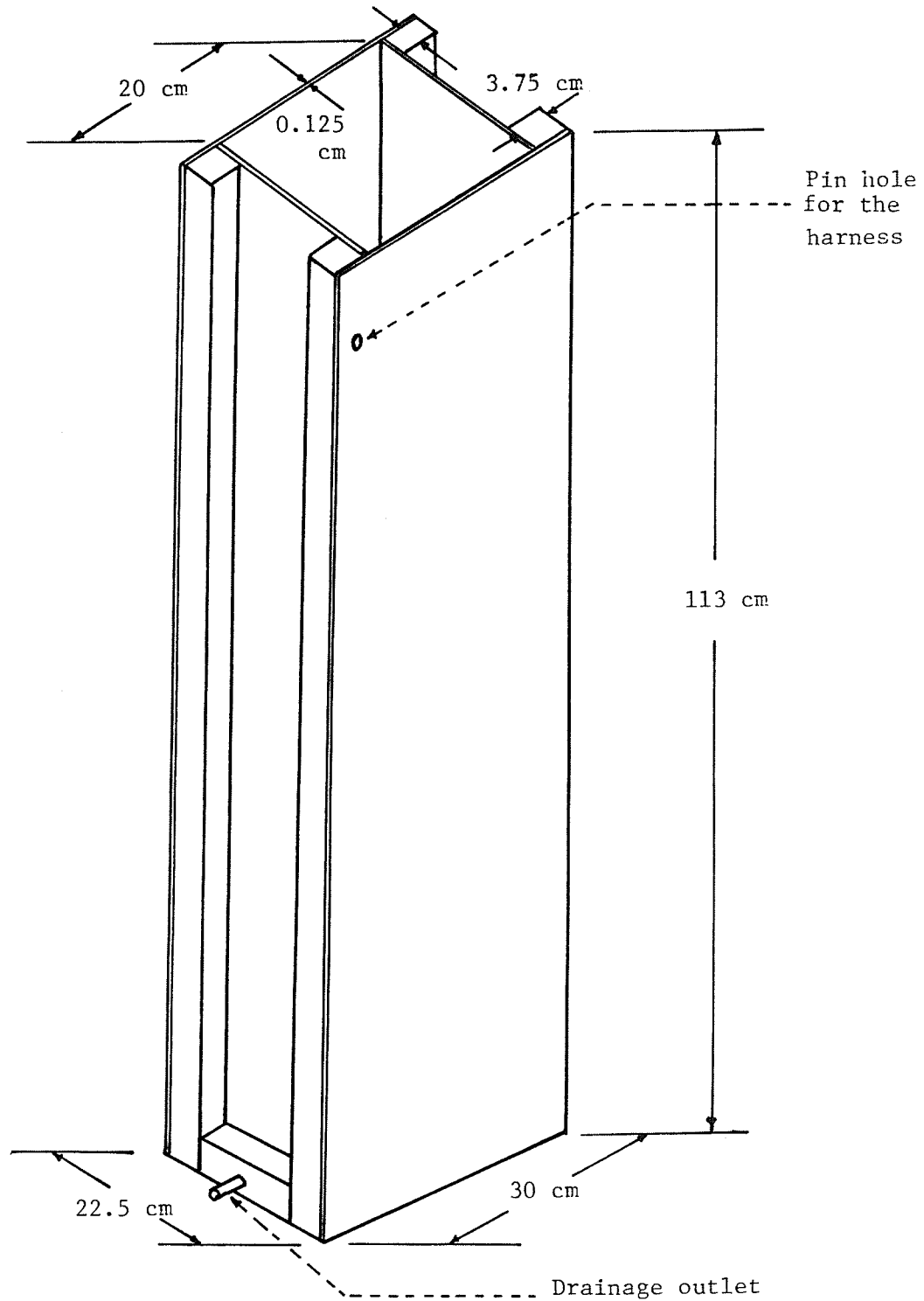


Fig. 3.4.3 Sketch of a of a plywood box for holding the soil

inserted at the bottom of the box through the side up to the lower edge of the inclined bottom plate as shown in Fig. 3.4.3. All the boxes were tested for watertightness.

3.4.4 Water and Effluent used for the Experiment

3.4.4.1 Rainwater

Rainwater collected from the roof tops was stored in big drums in order to have adequate supply for the entire duration of the experiment. Four 600-L drums painted inside with swimming pool enamel and covered with plywood boards at the top to prevent rust and dust contaminations, were used to collect and store the rainwater. The drums were installed in series. From each storm, rainwater was collected in the first drum and was subsequently siphoned to the next ones. The process of sedimentation was helpful in removing the dust and large suspended particles washed from the roof tops. The drums were hauled to the laboratory at the commencement of winter in order to protect the water from freezing.

3.4.4.2 Effluent

The effluent used in the study was brought from the secondary cells of the Roblin sewage lagoon. In the initial stages of the study, the effluent from the lagoon was brought in 20-L plastic containers. The containers were stored at low temperature before use. Later on, drums identical with those used for storing rainwater were used to bring the effluent from the lagoon because of the large volume of effluent needed, the long hauling distance and the impossibility of getting effluent from

a frozen-up lagoon in winter. The drums with the effluent were stored inside the laboratory.

3.4.5 Loading of the Boxes

The initial mass of each empty box was determined. Pea gravel was then poured into the boxes to a depth of 60 mm and the combined mass of each box with gravel was determined. The gravel layer was covered with a 20 cm by 20 cm fibreglass felt of negligible thickness. After that a total of 20 boxes were selected randomly for the Roblin soil and the rest were left for the Erickson soil.

All the boxes were then loaded with the appropriate kind of soil in the sequences and to the depths required to reconstruct the profiles of the two selected soils. Every effort was made to achieve the bulk densities of the individual horizons as measured in the field. To this end the moisture content of the air dry soil was determined and the dry mass content of the soil computed. Appropriate quantities of soil in terms of their dry mass were then compacted into specified volumes of the boxes in thin layers in order to achieve the correct bulk densities. This effort was not completely successful as it proved impossible to pack all the soils into the appropriate spaces and the resulting bulk densities were, therefore, lower than the bulk densities measured in the field. However, a very good uniformity in the bulk densities of comparable horizons has been achieved as shown in Tables 4.5.2.1 and 4.5.2.2.

The top 15 cm of the sodded soil columns were filled with the natural brome grass sod and the bulk densities of those top horizons were computed afterwards.

3.4.6 Instrumentation and Calibration

3.4.6.1 Mechanical Devices

The changes in the soil moisture content of the columns was determined on the basis of the changes in the mass of each box. The main device for the determination of the changes in the mass of boxes was a platform balance. The balance was capable of measuring the nearest 100 g which was accurate enough for this study. A hydraulic jack was used for loading the boxes on the balance (Fig. 3.4.6.1). The hydraulic jack was mounted on a small push cart and dead weights were used to counter balance it. The platform balance and the hydraulic jack were used for the entire duration of the experiment.

3.4.6.2 Strain Transducer

A special transducer was also designed and fabricated for measuring the changes in mass of the boxes. The calibration data are given in Appendix G. The transducer mounted between the steel harness (Fig. 3.4.6.2) and the hydraulic jack was connected each time to a strain indicator during the weighing operations. From the indicated strain the mass of each box was determined using one of the equations given in Appendix G. The transducer was only used towards the end of the experiment for faster measurements. However, the mass of a few boxes measured by the transducer was rechecked again by the help of the platform balance in order to detect any differences between the two measurements.

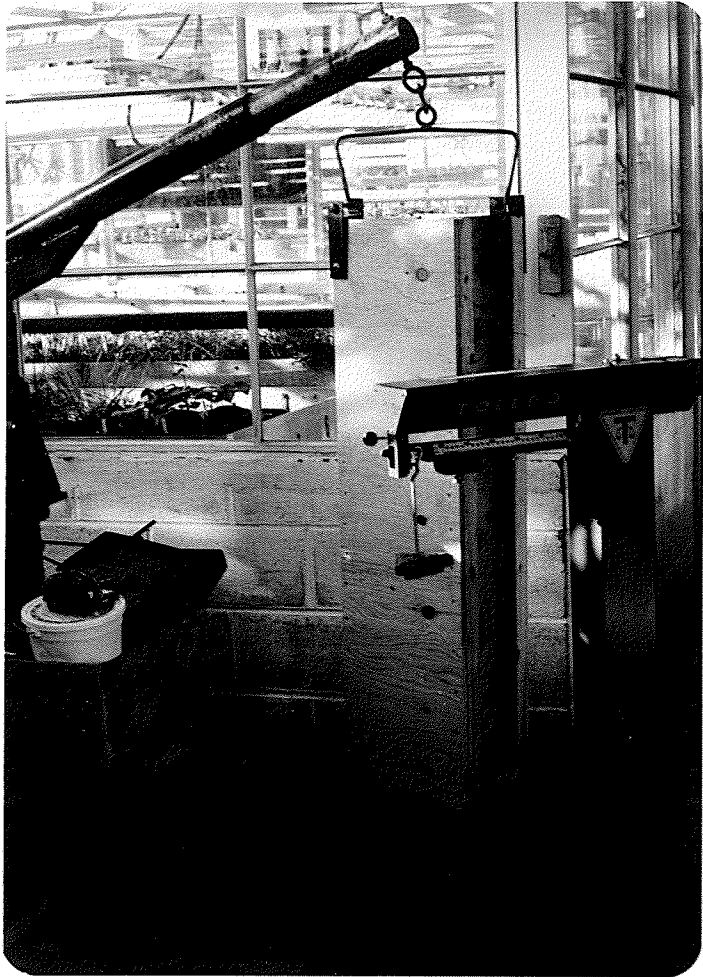


Fig. 3.4.6.1 Hydraulic jack and platform balance.

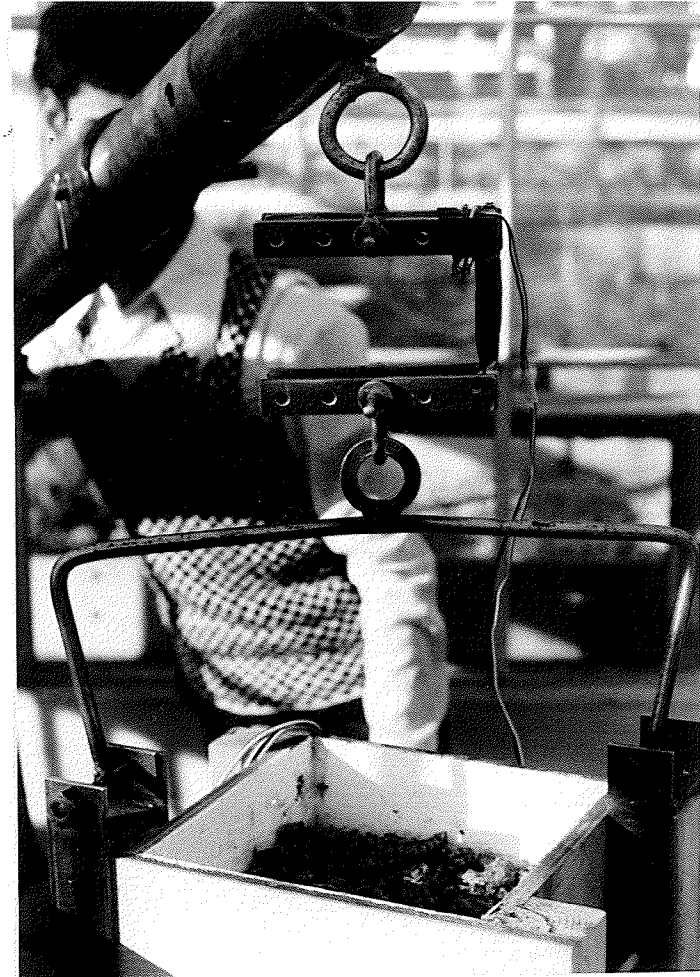


Fig. 3.4.6.2 Transducer.

3.4.6.3 Recording Devices

A hygrothermograph (Fig. 3.4.6.3) was used for recording the temperature and the humidity of air in the greenhouse. The hygrothermograph was placed inside the crop environment on top of the boxes. Weekly charts were used to record the temperature and relative humidity. At the beginning of each week the hygrothermograph was standardized with the help of a sling psychrometer. Towards the later part of the experiment, dry-bulb and wet-bulb temperatures at three different locations (middle portion and the two ends) of the greenhouse compartment were also measured once a day to determine the temperature and humidity variations within the compartment.

3.4.7 Experimental Setting in the Greenhouse

The greenhouse compartment in which the experiment took place had an usable floor space of about 7.40 m by 1.65 m. There was a 0.85-m concrete sidewalk along one of the longer sides of the usable space which was used for the operation and movement of the platform balance and hydraulic jack. The growth lights were suspended from the ceiling at a maximum vertical height of 1.70 m above the level of the sidewalk. The usable space was covered with a wooden floor to support the boxes holding the soil columns. As described in subsection 3.4.1, the allotment of individual boxes to different treatments was at random. Fig. 3.4.7 shows the arrangement of the boxes in the greenhouse.

Small 150-mL plastic containers were used to collect the leachates. Flexible tubes made of rubber balloons were used to convey the leachates from the drainage outlet to the plastic containers.

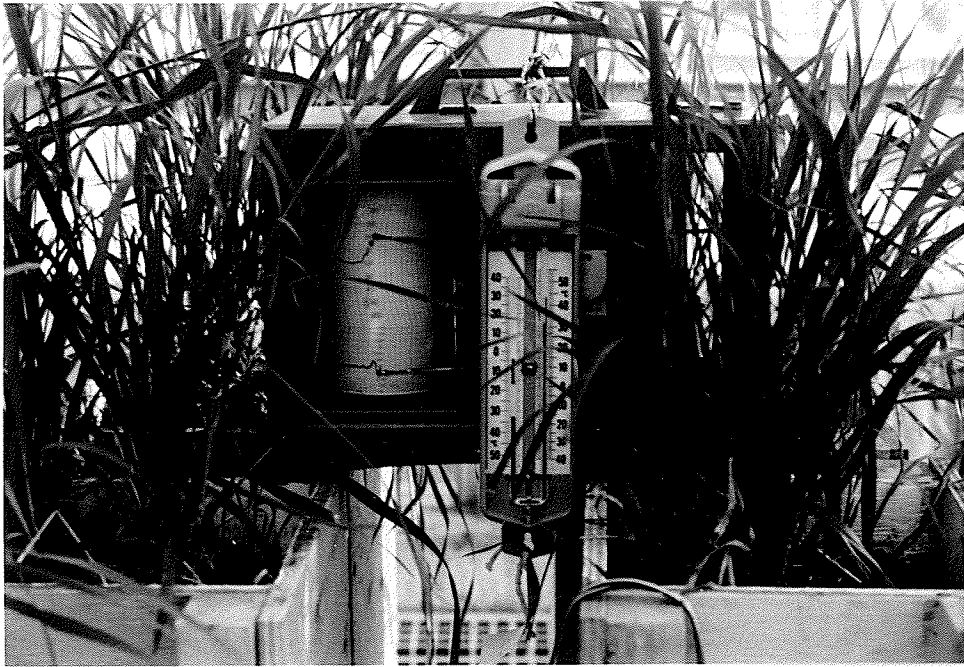


Fig. 3.4.6.3 Placement of hygrothermograph and maximum-minimum thermometer.



Fig. 3.4.7 Arrangement of the soil columns in the greenhouse.

3.4.8 Initiation of Irrigation

The boxes which were supposed to be cropped were placed in the center part of the greenhouse compartment. The brome grass had been closely cut prior to the start of the study. The average moisture content of the sods was determined by taking grab samples and found to be about 12 percent by mass. During the transport and construction phases, the sods were tightly covered with plastic sheets to check evaporation before they could be placed in the boxes. The bulk density of the top horizon in each column was then computed on the basis of the sod mass, its moisture content and the space it occupied. The values appear in Tables 4.5.2.1 and 4.5.2.2. At the same time appropriate amounts of top soil were added to the boxes which were supposed to be left uncropped, leaving a clear space of 6 cm at the top. Every effort was made during the packing of the soil in the uncropped boxes to keep the bulk densities as close as possible to those of corresponding cropped boxes.

The boxes were then saturated with rainwater from the top. Excessive ponding of water on the soil surface was avoided. The top surfaces of the boxes were covered with plastic sheets at all time excepting during the addition of rainwater to prevent evaporation losses from the saturated soil surface. When water started running from the bottom drains, it was presumed that the soils in the boxes reached saturation. Further addition of rainwater was stopped and the boxes were left to drain freely for about 24 hours in order that the soil columns could reach field capacity moisture level. The boxes were then weighed in order to determine the mass of each box with the soil column at field capacity which was important baseline information.

3.5 SIMULATION OF CLIMATIC VARIABLES

It was not possible to simulate in greenhouse all those climatic conditions which control evapotranspiration. In this study, only the theoretical daylight hours and the rainfall amounts for the Roblin-Russell area were simulated.

Artificial lighting is highly essential in greenhouse conditions for carbon assimilation. Fluorescent lamps are superior to incandescent lamps and, under fluorescent lamps of desired spectral density, normal carbon assimilation by plants can be achieved (Seemann, 1979). In this greenhouse experiment, 27 individual 75 W Sylvania fluorescent lamps each 2.4 m (8 ft) long were used to cover the experimental area.

The theoretical daylight hours for Roblin were computed from the Selected Tables and Conversions (Russelo et al., 1974) for the 15th day of each month from May to September. Fig. 3.5.1 shows the distribution of daylight hours for the growing season. Electrical clock-operated timers were used to regulate the hours of lighting. The timers had a minimum operating range of 15 min and were reset every 10 days to change the time of lighting.

Simulation of rainfall was one of the most important parameters in this study. Rainfall values⁴ for the Russell weather station were used because there is no weather station in Roblin and Russell is the nearest weather station to Roblin. Rainfall totals for periods of 10 days for the growing season were analysed in order to determine rainfall depths at 50 percent and 90 percent probability levels and to predict the expected rainfall in an average year and in a dry year respectively.

⁴ Unpublished work by C. F. Shaykewich, Department of Soil Science, University of Manitoba.

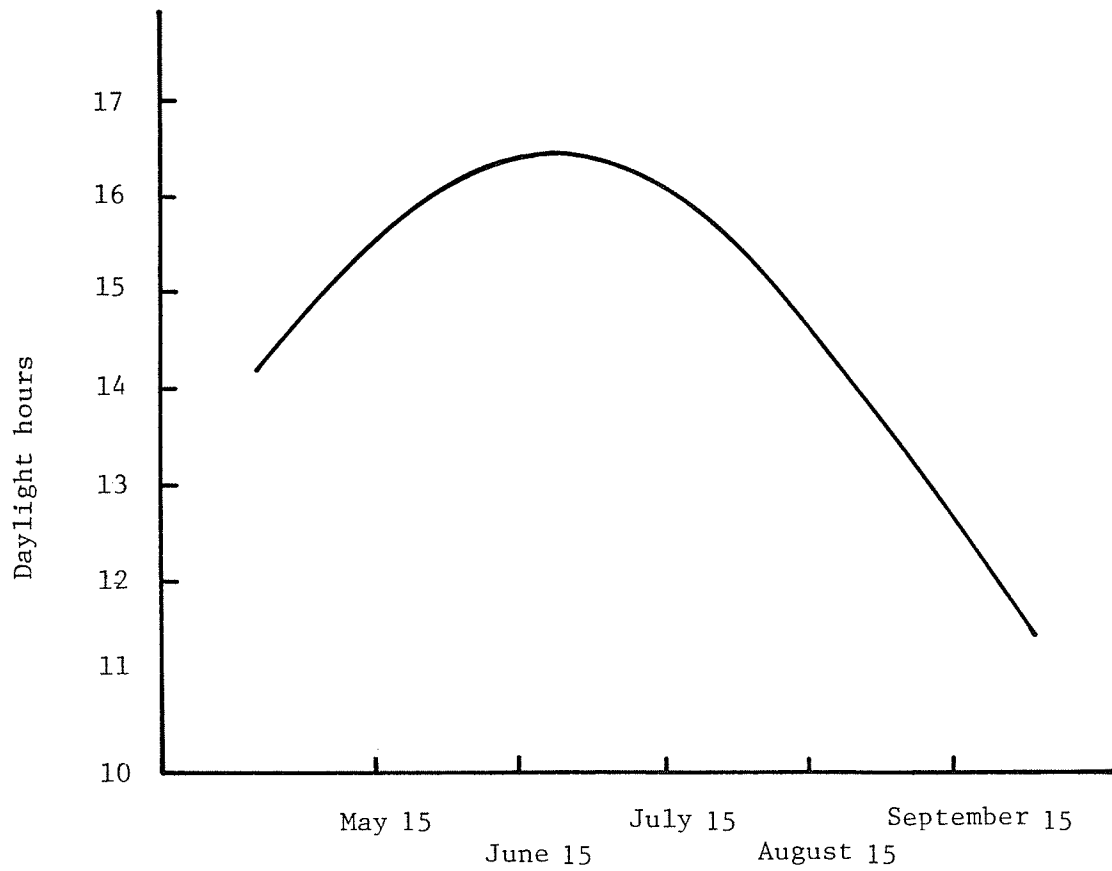


Fig. 3.5.1 Theoretical daylight hours for Roblin from May 15 to September 15.

Plotting positions were determined by using Weibull's formula as recommended by Benson (1962). Attempts were made to find out the rainfall values at the two probability levels by using theoretical frequency equations but in most of the cases, the extreme portions of the theoretical line deviated a lot from the observed values. This was done by graphical method. A sample plot has been presented in Fig. 3.5.2. Table 3.5 shows the expected rainfall values for each 10-day block of the entire growing season at the two different levels of probability. However, in this study, the expected rainfall on the first 10-day block was not simulated. This was done to avoid creating leachates before the addition of effluent as the boxes were already at field capacity level at that time.

3.6 IRRIGATION STUDY OVER THE GROWING SEASON

The greenhouse study started on October 2, 1981, simulating rainfall and daylight hours of the growing season, starting the first day of May. As for irrigation, it was decided to apply effluent to the soil columns when the average moisture depletion in a particular treatment group (whether cropped or uncropped) exceeded 50 mm. The depth of application to each soil column was equivalent to the amount of moisture needed to bring the soil moisture back to field capacity level. Thus, irrigation was solely dependent upon the actual water requirement of the crop with no allowance for a leaching fraction. The leachates collected from some of the boxes were not due to any intentional leaching but due to accidental combination of irrigation and simulated rainfall.

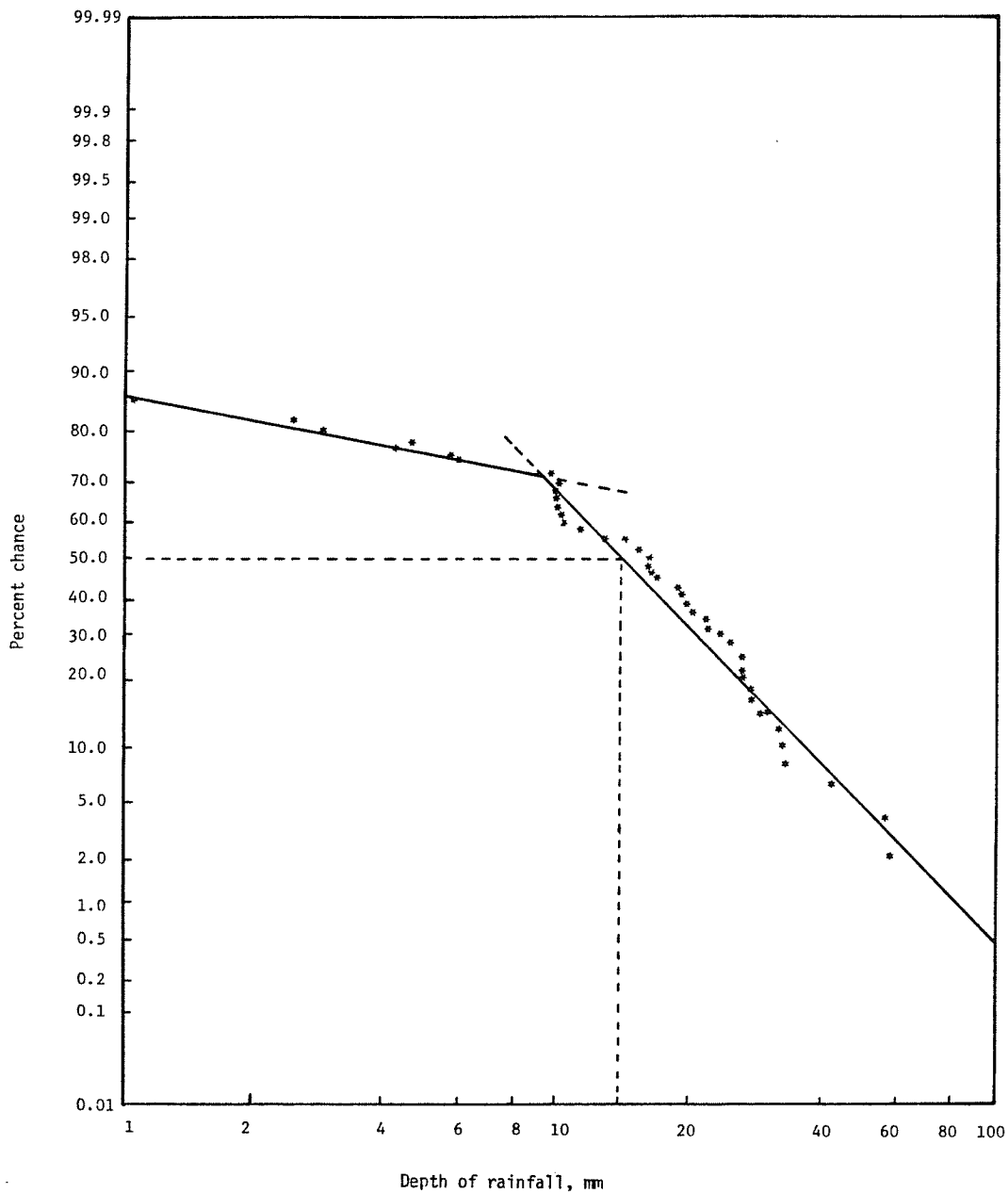


Fig. 3.5.2 A sample log-probability plot of the rainfall data for the period between July 29 and August 7 (9th block of simulation) to calculate expected rainfall at 50 percent probability.

Table 3.5 Expected Rainfall for Periods of Ten Days at Different Levels of Probability

Period Number	Date Starting	Expected Depth of Rainfall (mm) at Probability Levels of	
		50 percent	90 percent
1	May 1	7.3	0.0
2	May 11	8.0	1.7
3	May 21	8.6	1.7
4	May 31	18.0	2.2
5	June 10	14.0	2.4
6	June 20	18.0	2.5
7	June 30	17.5	2.8
8	July 10	10.0	2.2
9	July 20	14.0	0.0
10	July 30	15.0	0.0
11	August 9	12.8	0.8

For a particular application level, the expected rainfall for the entire 10-day period was applied on the first day of the period. In one case irrigation with effluent was interrupted because simulated rain was due before the irrigation could be completed. In that particular event, higher amounts of leachates were obtained from each box in that group.

The boxes in each group were weighed on an average once a week to measure the moisture depletion. The temperature and humidity in the greenhouse compartment were continuously monitored. Grasses from the C- and D- groups of both soils were cut twice during the simulated growing season. The first cut on the Roblin soil columns was after 55 days while the first cut on the Erickson soil columns was after 60 days. The second cut on both soils was on the 110th day.

3.7 ANALYTICAL PROCEDURES

3.7.1 Sampling

3.7.1.1 Soils

At the beginning of the study, air-dried soil samples of each horizon of the two soils were submitted for chemical analysis to the Provincial Soil Testing Laboratory (P. S. T. L.) in Winnipeg. Further, soil samples from each soil horizon were preserved for a later aggregate stability analysis and for the determination of the percentage of the particles bigger than 2 mm.

At the end of the study, the boxes were open and the soils from individual horizons of each of the 40 soil columns were sampled. The samples were taken from the center of the core uniformly along the length of the column. The samples were again submitted to the

Provincial Soil Testing Laboratory for chemical analysis. However, a portion of the samples were preserved for an aggregate stability study. At the same time, two undisturbed core samples were taken from each of the cropped boxes below the depth of 15 cm from the top for the determination of root mass. Using the same core (52.4 mm in diameter and 77.1 mm deep) undisturbed samples from each horizon were also taken for bulk density determination.

3.7.1.2 Plant Tissues

Plant samples were collected three times during the study period. The first sampling was done only one week after sodding before any effluent was applied. The second and third samplings were done during the first and the final cuts respectively. There was a time gap of 5 days between the samples collected from the two soils during the second sampling period.

The plant samples were initially weighed and subsequently air-dried. The air-dried mass of grass from each box of a particular group was recorded. Composite samples for each treatment group were made by taking proportionate amounts of dry material from each column. It was necessary to take proportionate amounts of dry matter from each column because the mass of harvested dry matter from different soil columns was different. The samples were mixed thoroughly and ground to small fractions. The ground samples were bagged, labelled and delivered to the Provincial Soil Testing Laboratory for nutrient analysis. Identical samples from each of the treatment groups were kept for determining the moisture content of the air-dried plant material.

3.7.1.3 Effluent

Sampling of the effluent from the Roblin sewage lagoon was done by using the specified bottles. The samples were taken 15 cm below the surface of the effluent in the lagoon. The bottles were delivered to the Ward Chemical Laboratories in Winnipeg for chemical analysis. At the end of the study, samples of the stored effluent were again submitted for chemical analysis.

3.7.1.4 Rainwater

Samples of rainwater for chemical analysis were taken from the storage drums at the beginning of the experiment and analysed by the Ward Chemical Laboratories in Winnipeg. Towards the end of the study, further sampling was done to recheck the concentration of certain elements.

3.7.1.5 Leachates

Leachates obtained from the soil columns were also submitted for chemical analysis. Because the amounts of leachates were very small, leachates collected from identical columns in the same treatment group had to be mixed to make a composite sample representative of the particular group. The samples were submitted for chemical analysis to the Ward Chemical Laboratories after determining their pH and conductivity in the laboratory of the the Department of Agricultural Engineering.

3.7.2 Physical Analysis

3.7.2.1 Soils

Effluent-treated soils were tested for the water stability index of the soil aggregates (group composite samples) and for bulk density (individual horizons in each column). Samples for the determination of bulk density of individual horizons of the Roblin soil were obtained by driving the core sampler into the soil horizons in a transverse plane. The bulk densities of the Erickson soil columns were measured with a surface nuclear moisture meter. The probe had a built-in processor to calculate the bulk density on a dry basis. As one of the walls of each box was removed and the boxes were laying flat on the floor, it was possible to use the surface probe even for the deep layers of the soil columns. Core samples of the Roblin soil were dried in an oven at 105 C for 48 hours to determine the oven-dry mass. The bulk densities were then calculated from the oven-dry mass and the volume of the core sampler.

Composite soil samples from each horizon were used for aggregate stability tests. The samples were analysed in a wet-sieving apparatus. The procedure followed was a modification of that reported by Shaykewich (1981). The samples were gently crushed and passed through a 4.76-mm sieve. Large pieces of rocks and roots were removed. Duplicate samples each weighing 50 g were placed on the top screens of the two submerged sieve nests consisting of 1.981-mm, 0.991-mm, 0.495-mm, and 0.246-mm sieves in order from the top. The samples were sieved for 10 min at 30 strokes per min with 37.5-mm-long strokes. The aggregates retained on each sieve in each sieve nest were transferred into separate beakers

using wash bottle and compressed air. The soil in each beaker was oven-dried at 110 °C for 48 hours and the mass of the oven dried soil from each sieve was determined. The mean weight-diameter (MWD) was calculated using the formula

$$\text{MWD} = \sum_{1}^{n} x_i \cdot w_i$$

where, MWD is an index of water stability of soil aggregates, x_i is mean diameter (mm) of each size fraction, w_i is the proportion of total mass (g) occurring in the corresponding size fraction and n is the number of sieves per nest. Final mean weight-diameter is the average of the values obtained from the two nests.

3.7.2.2 Root Mass

The amount of root mass was determined for the cropped soils at the two treatments. Two soil samples were taken from each column in those treatment groups using the previously mentioned core sampler. The samples were taken below a vertical depth of 15 cm on a transverse plane after one of the faces of each box had been opened. The samples were air-dried and gently crushed. Each sample was then soaked for 24 hours in a wetting solution containing 37.5 g of sodium metaphosphate (NaHPO_4), 7.94 g of sodium carbonate (Na_2CO_3) and 954 ml of distilled water. The wetting solution disperses the soil aggregates and facilitates root extraction. The samples were then passed through a 2.38-mm sieve followed by a 1.00-mm sieve. Roots retained on both sieves were removed by the help of compressed air and water jet and oven dried at 80 °C for 48 hours.

3.7.2.3 Plant Tissue

The air-dried plant samples were oven dried at 70 °C for 48 hours to determine the moisture content.

3.7.3 Chemical Analysis

3.7.3.1 Soils

Chemical analysis of all soil samples was carried out by the Provincial Soil Testing Laboratory. Nitrogen and phosphorus were determined by the sodium bicarbonate method using colorometric auto-analyser. Potassium was determined by the acetate-extractable method using flame photometry auto-analyser. Calcium, magnesium and sodium were determined by the ammonium-acetate method using atomic absorption apparatus. Nutrient analysis for the above soils were done in the routine soil test. Besides that, special tests were done for determining total nitrogen, total phosphorous, calcium carbonate, chlorides, and cation exchange capacity (CEC).

3.7.3.2 Plant Tissue

Total Kjeldahl Nitrogen was determined using the Kjeldahl apparatus. Phosphorus and sulphur were determined by the wet-ashing method using a colorimetric auto-analyser. Other tests were done by atomic absorption. The analysis was also carried out by the Provincial Soil Testing Laboratory.

3.7.3.3 Effluent, Rainwater and Leachates

All the tests for the chemical analysis of effluent and rainwater were carried out at the Ward Chemical Laboratories. The tests include the determination of exchangeable cations, common anions, major crop nutrients, heavy metals, pH and conductivity. The pH and the conductivity of the leachates were determined in the laboratory of the Agricultural Engineering Department. Exchangeable cations, some selected anions and major plant nutrients were determined at the Ward Chemical Laboratories. The procedure followed in analysis was similar to that followed in the Provincial Soil Testing Laboratory. In the above tests, organic and ammonia nitrogen were not determined.

The analysis of $\text{NH}_3\text{-N}$ of the effluent was not done during the experiment. It was obvious that the high-pH effluent stored in the laboratory would be free of $\text{NH}_3\text{-N}$ due to evaporation. Further, all the analyses were done according to the Ward Laboratory's routine Test No. 83 (Clean Environment Commission of Manitoba, 1979) which did not include $\text{NH}_3\text{-N}$ analysis. Only $\text{NO}_3\text{-N}$ was determined by that test. As the $\text{NO}_3\text{-N}$ concentration remained very low in all the tests, the total Kjeldahl Nitrogen (TKN) of the effluent used in the study was determined at the end of the study. The $\text{NO}_3\text{-N}$ concentration of the effluent was checked at the end to determine if there was any transformation of organic N to $\text{NO}_3\text{-N}$ due to mineralization followed by nitrification. Ammonia analysis was performed on some of the samples in the laboratory of the Civil Engineering Department using an ammonia analyser and the test showed the absence of ammonia.

3.7.4 Statistical Analysis

Statistical analysis (Statistical Analysis Systems, 1979) was carried out for the changes in bulk densities, and for the amount of dry matter and root mass produced. The analysis of variance procedure was followed in the above cases. A product moment correlation analysis was carried out to check the linear relation among the variables such as root mass, bulk density in the top horizon, amount of effluent added and the yield of dry matter. A regression analysis was done between the yield of dry matter and the amount of effluent added.

Chapter IV
RESULTS AND DISCUSSION

4.1 IRRIGATION WATER

4.1.1 Effluent

A typical chemical analysis of the effluent sampled over a period of six months (which covers the entire growing period) has been presented in Table 4.1.1. From the table it is apparent that the effluent contained insignificant amount of $\text{NO}_3\text{-NO}_2\text{-N}$. On the other hand, the pH and the Na content were relatively high compared to that suggested by the Clean Environment Commission of Manitoba (1979) for the quality of irrigation water. The electrical conductivity of the effluent was in the hazardous range of irrigation water as per their definitions. The Mn and Cl contents were also much higher than the suggested limits. The bicarbonate content of the effluent was about 370 mg L^{-1} and the carbonate content was a low 8.9 mg L^{-1} . As the concentration of both of these ions are pH-dependent, an effluent-pH of 8.34 might have converted all the carbonates to bicarbonates. The Sodium Adsorption Ratio (SAR) of the effluent was calculated using the following formula as suggested by the U.S. Salinity Laboratory Staff (1954):

$$\text{SAR} = \frac{\text{Na}}{\{ (\text{Ca} + \text{Mg})/2 \}^{0.5}}$$

Table 4.1.1. Quality of Effluent used for Irrigation

Items	Units	Value
pH	units	8.34
Electrical		
Conductivity (EC)	mS cm ⁻¹	2.312
Total Residue	mg L ⁻¹	1518.00
As	mg L ⁻¹	0.017
B	mg L ⁻¹	0.496
Cd	mg L ⁻¹	traces
Cu	mg L ⁻¹	0.085
Pb	mg L ⁻¹	traces
Ni	mg L ⁻¹	0.008
Zn	mg L ⁻¹	0.030
Cr	mg L ⁻¹	traces
Ca	mg L ⁻¹	85.70
Ca	meq L ⁻¹	4.28
Mg	mg L ⁻¹	78.70
Mg	meq L ⁻¹	6.47
Na	mg L ⁻¹	310.90
Na	meq L ⁻¹	13.52
K	mg L ⁻¹	30.00
K	meq L ⁻¹	0.77
Mn	mg L ⁻¹	0.254
Fe	mg L ⁻¹	0.303
F	mg L ⁻¹	0.676
Total Kjeldahl		
Nitrogen (TKN)	mg L ⁻¹	1.80
NO ₃ ⁻ -NO ₂ ⁻ -N	mg L ⁻¹	0.43
Total P	mg L ⁻¹	2.18
Cl	mg L ⁻¹	441.00
SO ₄ ⁻ -S	mg L ⁻¹	286.00
Alkalinity (HCO ₃)	mg L ⁻¹	370.00
Alkalinity (CO ₃)	mg L ⁻¹	8.88
Co	mg L ⁻¹	traces
Se	mg L ⁻¹	traces
Calculated:		
Sodium Adsorption		
Ratio (SAR)	-	5.83
Sodium Percentage	percent	54.00

where, Na, Ca, and Mg are the concentrations of the soluble ions in meq L^{-1} . The concentration of these ions are generally expressed in mg L^{-1} in the laboratory. For the above calculation, these ions were expressed in meq L^{-1} dividing their concentrations expressed in mg L^{-1} by respective equivalent masses.

The effluent used in this study had a Na concentration of 13.52 meq L^{-1} . The Ca and Mg concentrations were 4.28 and 6.47 meq L^{-1} respectively. The SAR calculated by the given formula was found to be 5.83 which is not fully safe as per the guidelines of the previously referenced Clean Environment Commission of Manitoba. It was apparent that the SAR value was low to some extent due to the higher concentrations of Ca and Mg in the effluent. The sodium percentage, which is the percentage of the concentration of Na out of total cations, including K, was found to be 54 percent. This value is in the range of questionable quality (Wilcox, 1948 cited by Sessing, 1961). The electrical conductivity (EC) and the Na content of the Roblin sewage effluent were similar to the sewage effluent of the city of Swift Current (Jame and Nicholaichuck, 1979), which was categorised as saline.

At the end of the study it was determined that the average $\text{NO}_3\text{-N}$ concentration of the effluent reached 1.35 mg L^{-1} as compared with the mean value of 0.43 mg L^{-1} . It showed that some transformation among the nitrogen forms took place during the transportation and storage of the effluent. However, due to numerous difficulties, attempts were not made to determine the TKN of the effluent in the lagoon itself.

4.1.2 Rainwater

The chemical composition of the rainwater used in this study has been presented in Table 4.1.2. The pH was almost neutral and the concentrations of Na, Ca, and Mg were almost negligible. The $\text{NO}_3\text{-N}$ content averaged 0.44 mg L^{-1} which was similar to that of the effluent.

4.2 BASELINE ANALYSIS OF THE SOIL

Baseline soil samples from each horizon of both the Roblin and the Erickson soils up to a depth of 100 cm were analysed for their chemical and physical properties. The results of the analysis have been compiled in Tables B-1 and B-2 of Appendix B. A detailed textural analysis of each horizon of both soils was also completed (Table B-3, Appendix B). From the results of the textural analysis, it was revealed that with the exception of the top horizon of the Roblin soil which was classified as silt loam, all the remaining horizons were loam. A sieve analysis of the soils of all involved horizons was done to determine the percentage of primary particles having diameter greater than 2.0 mm (Table B-6, Appendix B).

Table 4.2 shows the contents of major nutrients in each of the soil horizons and the recommended applications of N, P, K, and S for growing brome grass as suggested by the Provincial Soil Testing Laboratory. It is apparent that the original soils were seriously deficient in $\text{NO}_3\text{-N}$. In general, the deeper horizons had negligible amounts of $\text{NO}_3\text{-N}$, while the surface horizons of both soils had a $\text{NO}_3\text{-N}$ content of 1.2 ppm. This can be expected under continuous cropping without fertilization.

Table 4.1.2. Quality of Rainwater used for Rain Simulation

Items	Units	Value
pH	units	7.15
Electrical		
Conductivity (EC)	mS cm ⁻¹	0.063
Total Residue	mg L ⁻¹	59.00
As	mg L ⁻¹	0.001
B	mg L ⁻¹	traces
Cd	mg L ⁻¹	traces
Cu	mg L ⁻¹	traces
Pb	mg L ⁻¹	0.005
Ni	mg L ⁻¹	0.005
Zn	mg L ⁻¹	0.240
Cr	mg L ⁻¹	0.005
Ca	mg L ⁻¹	10.00
Ca (calculated)	meq L ⁻¹	0.50
Mg	mg L ⁻¹	5.00
Mg (calculated)	meq L ⁻¹	0.42
Na	mg L ⁻¹	traces
K	mg L ⁻¹	traces
Mn	mg L ⁻¹	0.025
Fe	mg L ⁻¹	0.060
F	mg L ⁻¹	traces
Total Kjeldahl		
Nitrogen (TKN)	mg L ⁻¹	traces
NO ₃ ⁻ -NO ₂ ⁻ -N	mg L ⁻¹	0.44
Cl	mg L ⁻¹	traces
SO ₄ ⁻ -S	mg L ⁻¹	2.75
Co	mg L ⁻¹	traces
Se	mg L ⁻¹	traces
Alkalinity (HCO ₃)	mg L ⁻¹	36.60
Calculated:		
Sodium Adsorption		
Ratio (SAR)	-	0.00
Sodium Percentage	percent	0.00

Table 4.2 Major Nutrient Content of Individual Horizons of the Roblin and the Erickson Soils Before Effluent Application and the Recommended N-P-K-S Fertilizer Applications ¹

Soil Type and Horizons	Nutrients, kg ha ⁻¹			
	N	P	K	S
Roblin				
First	6.70	215.00	1260.00	13.40
Second	1.80	388.30	1206.00	17.60
Recommended	110.00	0.00	0.00	0.00
Erickson				
First	3.40	29.10	722.00	7.30
Second	2.20	22.40	896.00	11.20
Third	3.50	22.00	812.00	15.00
Recommended	110.00	20.00	0.00	15.00

¹ Recommended by the Provincial Soil Testing Laboratory

Analysis of soil samples taken in the summer of 1980 by the Department of Agricultural Engineering gave similar results. Only the top horizons of a few soil samples collected from the depressions had a higher $\text{NO}_3\text{-N}$ concentration.

Phosphorus content of the Roblin soils was much higher than of the Erickson soils and the concentration of K was high in both soils. The cation exchange capacity of the surface horizons of both soils were higher than the lower horizons possibly due to high content of organic matter.

4.3 ANALYSIS OF THE LEACHATES

The amounts of collected leachates as the percentage of the amount of applied water (both effluent and rainwater) were almost insignificant. Tables 4.4.1 and 4.4.2 presented in the next section show the amounts from each group of both soils.

The leachates were analysed for their chemical composition. Extremely small volumes of the leachates collected in some cases imposed limitations in a full-range analysis of chemicals. However, the concentration of nitrogen, major cations and anions, the pH, electrical conductivity, and filtrable residues were determined in each case as presented in Tables C-1 and C-2 of Appendix C. The amounts of nutrients (expressed in kg ha^{-1}) leached out of the two soils are presented in Tables 4.3.1 and 4.3.2.

Appendix C shows that the pH of the leachates in the Erickson soil groups were similar to that of the applied effluent. However, in the Roblin soil columns, in average-year conditions (A- and D- groups) the

Table 4.3.1 Mass of Chemicals Leached out of Roblin Soil

Chemicals (kg ha ⁻¹)	Treatment Group			
	A	B	C	D
Na	3.15	4.36	2.31	1.85
Ca	8.88	9.95	6.58	3.03
Mg	2.34	2.66	1.87	0.71
Total Kjeldahl Nitrogen (TKN)	0.11	0.18	0.08	0.03
NO ₃ -NO ₂ -N	0.30	0.09	0.09	0.09
SO ₄ -S	16.53	14.92	12.88	5.19
Cl	3.53	6.48	2.20	4.31
B	0.02	0.12	0.02	0.02
HCO ₃	9.78	30.69	N. A.	N. A.
Filtrable Residue	45.30	65.55	46.93	18.33

Table 4.3.2 Mass of Chemicals Leached out of Erickson Soil

Chemicals (kg ha ⁻¹)	Treatment Group			
	A	B	C	D
Na	0.81	1.05	1.05	1.90
Ca	3.07	5.73	3.12	6.38
Mg	1.28	3.37	1.21	2.80
Total Kjeldahl Nitrogen (TKN)	0.07	0.12	0.05	0.08
NO ₃ -NO ₂ -N	0.38	0.65	0.08	0.03
SO ₄ -S	2.16	3.45	1.75	2.98
Cl	1.58	2.14	0.36	8.84
B	0.02	0.08	0.01	0.07
HCO ₃	7.60	22.20	10.61	13.65
Filtrable Residue	16.13	33.45	14.88	36.32

NOTE: N. A. - Information not available because of small amount of leachates collected

pH of the leachates was lower than that in others. In these groups the ratio of the depth of simulated rainwater to the depth of the applied effluent was much higher than the corresponding groups in the Erickson soil. Lower ion concentrations in the rainwater might have caused some dilution in the stored soil water and leachates.

The Na content of the leachates in general was much smaller as compared to that of the effluent. Besides the previously mentioned dilution effect at the low application levels, Na could have been retained in exchange complexes. The Ca concentration of the leachates was higher than that of the effluent. This was possibly due to the liberation of Ca from the exchange sites resulting from the retention of Na. Magnesium concentration in the leachates was lower than that in the effluent by a small margin. The calculated SAR values for the leachates of all the groups of the Erickson soil were less than 1.0. For the Roblin soil these values ranged between 1.07 and 2.49. The EC values for all groups of both soils were less than 1.25 mS cm^{-1} except for a high value of 2.2 mS cm^{-1} for the D- group of the Roblin soil for which the SAR was 2.49. This was the only sample collected from that particular group. In this case over irrigation could have been caused by the addition of a small quantity of effluent beyond the field capacity level whereas in other cases this could have been due to the addition of rainwater after field capacity was reached. Further, it was observed that the depth of leachates in this group was only 0.98 mm.

The concentration of $\text{NO}_3\text{-NO}_2\text{-N}$ in the leachates was much higher as compared to their concentration in the irrigation water. However, even those higher values were below the drinking water limits of 10 mg L^{-1} .

The concentrations of $\text{SO}_4\text{-S}$ and Cl concentrations in the leachates under both soils were lower than those of the effluent. It was also observed that in addition to the above ions, the concentrations of B and filtrable residues in the Roblin soil were higher than the Erickson soil. Because of the short duration of study it was difficult to make any firm conclusion.

The effluent had a boron concentration of about 0.5 mg L^{-1} . In the leachates this value reached a peak of 2.4 mg L^{-1} . The extremely high boron concentration in the leachates collected from both soils may impose problems in future, if the process continues like this in the same manner.

It was difficult to assess the source of this unaccountable boron in the leachates, because in ordinary conditions soils do not release boron. An explanation based on the handling of the leachates is however, possible. The leachates were stored for some time in glass containers in a refrigerator before they were sent to the laboratory. The U. S. Salinity Laboratory Staff (1954) instructions suggest not to use pyrex containers in boron analysis. It could not be determined whether the glassware was pyrex. Berger (1972a) says that boron can be released from soil organics due to microbial activity and can be leached out easily as nitrate-nitrogen. Another possible explanation exists in this connection. According to Cho,⁵ at high pH, release of boron from soil is possible. However, analysis for boron was not included in the soil analysis to determine the changes in boron content of the soil.

⁵ C. M. Cho, Department of Soil Science, University of Manitoba - verbal communication.

4.4 IRRIGATION WATER AND NUTRIENT LOADING

The amounts of nutrients applied to the soil columns are shown in Tables 4.4.1 and 4.4.2. They were naturally directly related to the amounts of effluent applied in irrigation which, in turn, was dependent upon the evapotranspiration demand of the cropped soil columns and upon evaporation from the soil surface in the uncropped soil columns. One of the intentions of this greenhouse study was to create conditions in which the water consumption would be at least equal to water consumption observed in actual field conditions during the growing period.

The modified Blaney-Criddle formula (U. S. Department of Agriculture, 1970) was used to calculate the evapotranspiration demand of growing grass for the geographic location of Roblin for a growth period of 110 days starting May 1 (Appendix D). Based upon the climatic records of the past 26 years, the consumptive use (or evapotranspiration) calculated for the above mentioned period was 372 mm. In the greenhouse study, the average consumptive use of brome grass was 768 mm (Tables 4.4.3 and 4.4.4) that is roughly two times higher. The causes were higher temperature, lower humidity (Fig. 4.4.1) and probably also higher plant population resulting in larger leaf areas.

In this study an attempt was made to study the plant population in different boxes (Table 4.4.5). Except for the D- group of the Roblin soil plant population in other groups of both soils were alike. In this study no attempt was made to measure the leaf surface area of each plant in conjunction with the plant population study.

Table 4.4.1 Mass of Nutrients Added to the Roblin Soil
through Irrigation (Effluent plus Rainwater)

Nutrient Loading	Treatment Group			
	A	B	C	D
Major Nutrients				
kg ha ⁻¹				
NO ₃ -N	1.21	1.58	3.40	3.92
Total Kjeldahl Nitrogen (TKN)	1.71	4.11	12.63	8.46
Total P	2.07	4.98	15.30	10.24
SO ₄ -S	267.72	655.37	2009.60	1349.96
K	28.50	68.55	210.54	140.98
Ca	99.68	202.58	610.26	424.32
Mg	74.76	179.83	552.32	369.84
Na	295.45	710.63	2082.63	1461.51
Cl	418.95	1007.68	3095.00	2073.43
HCO ₃	418.36	751.37	2628.95	1817.78
Trace Elements				
g ha ⁻¹				
As	17.98	39.52	120.19	82.05
B	471.20	1133.36	3480.97	2330.90
Cd	traces	traces	traces	traces
Cu	80.75	182.80	561.45	399.45
Pb	9.13	11.42	35.09	24.00
Ni	16.73	16.82	42.05	41.27
Zn	466.98	248.00	422.10	659.02
Cr	9.52	3.38	4.40	9.52
Co	traces	traces	traces	traces
Se	traces	traces	traces	traces
Mn	286.78	597.29	1804.63	1247.61
Fe	397.47	732.90	2179.37	1553.42
F	642.20	1544.66	4744.23	3176.79

Table 4.4.2 Mass of Nutrients Added to the Erickson Soil
through Irrigation (Effluent plus Rainwater)

Nutrient Loading	Treatment Group			
	A	B	C	D
Major Nutrients				
<u>kg ha⁻¹</u>				
NO ₃ -N	1.19	1.13	3.29	3.63
Total Kjeldahl Nitrogen (TKN)	1.78	3.81	12.00	11.55
Total P	1.80	4.55	14.52	13.98
SO ₄ -S	241.27	598.50	1844.33	1840.55
K	26.65	63.16	199.87	192.48
Ca	89.74	184.23	571.07	570.01
Mg	69.69	165.35	524.33	504.95
Na	266.01	651.34	2073.95	1995.40
Cl	365.73	920.85	2938.12	2829.50
HCO ₃	374.94	683.33	2974.68	2905.26
Trace Elements				
<u>g ha⁻¹</u>				
As	15.93	36.02	120.90	111.08
B	409.20	1035.40	3304.55	3182.38
Cd	traces	traces	traces	traces
Cu	70.12	177.44	566.30	545.36
Pb	9.52	2.67	4.86	10.08
Ni	16.12	19.36	101.90	61.40
Zn	481.71	190.50	433.22	676.08
Cr	9.52	2.67	4.86	10.08
Co	traces	traces	traces	traces
Se	traces	traces	traces	traces
Mn	257.15	543.55	1716.55	1680.00
Fe	364.22	664.49	2077.05	2064.98
F	557.70	1411.15	4503.80	4337.28

Table 4.4.3 Evapotranspiration Study for Roblin Soil Columns

Treatment Group and Number	Gain(+) or Loss(-) due to:				
	Rainwater +(mm)	Effluent +(mm)	Drainage -(mm)	Change in Soil Moisture +(mm)	Evapotrans- piration ¹ (mm)
A- Group					
Box No.					
1	135.9	95.0	0.00	36.3	267.2
2	135.9	95.0	11.38	47.5	267.0
5	135.9	95.0	3.75	45.0	272.1
11	135.9	95.0	0.00	47.5	278.0
13	135.9	95.0	7.50	57.5	280.9
Mean	135.9	95.0	4.53	46.8	273.2
B- Group					
Box No.					
3	16.3	235.0	5.38	52.5	298.4
4	16.3	222.5	9.75	52.5	281.6
9	16.3	228.8	5.00	52.5	292.6
10	16.3	238.8	9.38	57.5	303.2
11	16.3	224.8	7.25	56.3	290.1
Mean	16.3	228.5	7.85	54.3	293.2
C- Group					
Box No.					
8	16.3	662.1	3.75	62.5	737.1
16	16.3	784.0	0.00	97.5	897.8
17	16.3	636.0	3.00	70.5	719.8
18	16.3	689.0	11.26	61.3	755.3
20	16.3	737.8	0.00	67.5	821.6
Mean	16.3	701.8	3.61	71.9	786.4
D- Group					
Box No.					
6	135.9	582.8	0.00	98.8	763.5
7	135.9	527.5	3.88	91.3	750.8
14	135.9	290.0	0.00	53.3	479.2
15	135.9	377.6	0.00	70.5	584.0
19	135.9	624.5	1.00	86.0	845.4
Mean	135.9	469.9	0.98	80.0	684.8

¹ Only evaporation for A- and B- groups

Table 4.4.4 Evapotranspiration Study for Erickson Soil Columns

Treatment Group and Number	Gain(+) or Loss(-) due to:				
	Rainwater +(mm)	Effluent +(mm)	Drainage -(mm)	Change in Soil Moisture +(mm)	Evapotrans- piration ¹ (mm)
A- Group					
Box No.					
21	135.9	82.5	6.26	52.5	264.6
22	135.9	82.5	1.63	62.5	279.3
23	135.9	82.5	0.00	56.3	274.7
25	135.9	82.5	5.50	48.8	261.7
40	135.9	82.5	1.00	52.5	269.9
Mean	135.9	82.5	2.88	54.5	270.0
B- Group					
Box No.					
26	16.3	221.3	0.63	37.5	274.5
27	16.3	215.0	21.00	43.8	254.1
34	16.3	188.8	0.00	35.0	240.1
35	16.3	192.5	13.50	33.8	229.1
38	16.3	226.3	2.63	35.0	275.0
Mean	16.3	208.8	7.55	37.0	254.5
C- Group					
Box No.					
29	16.3	581.4	2.25	76.3	671.7
30	16.3	733.3	0.25	87.5	836.8
31	16.3	797.5	1.88	98.3	910.2
37	16.3	460.1	1.75	50.5	525.1
39	16.3	759.0	5.88	92.3	862.7
Mean	16.3	666.2	2.40	81.0	761.1
D- Group					
Box No.					
24	135.9	839.5	5.50	77.5	1047.4
28	135.9	515.2	0.63	67.5	718.0
32	135.9	525.7	6.75	55.0	709.8
33	135.9	733.4	7.63	64.5	926.2
36	135.9	594.3	2.38	63.5	791.3
Mean	135.9	641.6	4.58	65.6	838.5

¹ Only evaporation for A- and B- groups

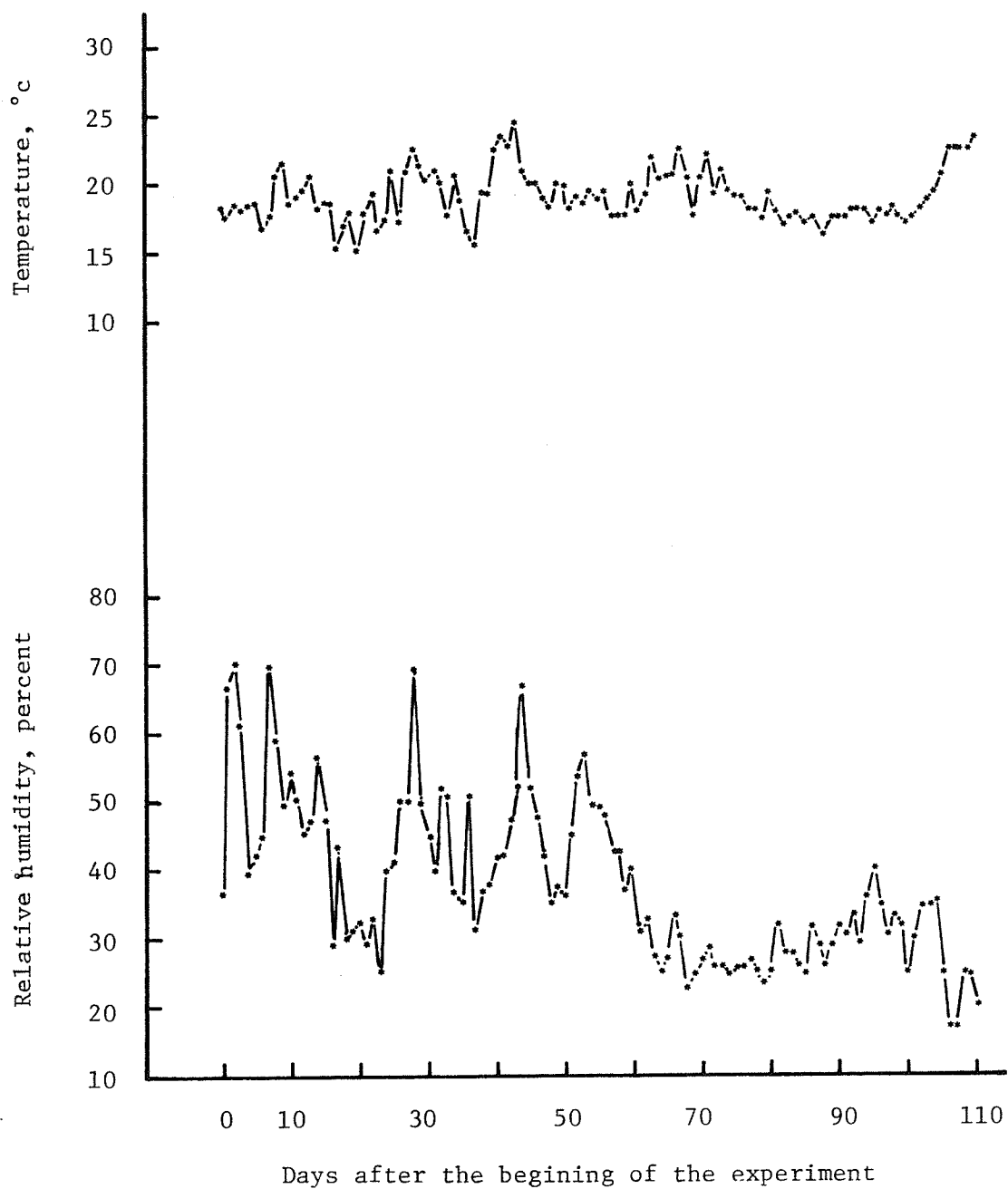


Fig. 4.4.1 Temperature and humidity conditions in the greenhouse during the experiment.

Table 4.4.5 Plant Population Study

Treatment Group and Number	Plant Population (stems/Box)		
	Cut 1	Cut 2	Average
Roblin Soil			
C- Group			
Box No.			
8	24	32	28
16	27	35	31
17	12	25	19
18	29	32	31
20	26	30	28
Mean Value			27
Standard Deviation			4.93
D- Group			
Box No.			
6	24	33	28
7	26	28	27
14	10	12	11
15	14	17	16
19	30	28	29
Mean Value			22
Standard Deviation			8.17
Erickson Soil			
C- Group			
Box No.			
29	23	21	22
30	23	26	25
31	27	29	28
37	19	18	19
19	35	27	31
Mean Value			25
Standard Deviation			4.74
D- Group			
Box No.			
24	36	34	35
28	20	21	21
32	21	19	20
33	30	29	30
36	26	32	28
Mean Value			27
Standard Deviation			6.36

The precipitation of an average year for the 110-day growing period is about 136 mm. Looking at the consumptive use of grass in the Roblin area an additional 236 mm of irrigation water would be needed for crop growth without causing a change in stored soil-water. However, the depth of applied effluent in a simulated average year to soil columns was more than two times the above estimated value. Similarly for a dry year, the expected seasonal rainfall was only about 16 mm therefore calling for irrigation of about 356 mm. However, the actual effluent application in this case was also about two times higher. From Table D of Appendix D, the evapotranspiration for growing grass in Roblin area from May to September was estimated to be 471 mm. This value was still far below the applied level.

4.5 CHANGES IN PHYSICAL PROPERTIES OF SOIL COLUMNS

4.5.1 Bulk Density and Porosity

Porosity and bulk density of a soil are related as expressed by the formula:

$$\theta = \left\{ 1 - \frac{d_b}{d_p} \right\} \cdot 100$$

In the formula θ is the total porosity (percent), d_b is the bulk density (g cm^{-3}) and d_p is the particle density (g cm^{-3}). As the particle density of a particular soil is almost a constant, changes in total porosity will be reflected by changes in bulk density. In this study, no attempt was made to measure the capillary and non-capillary porosities. Tables 4.5.1.1 and 4.5.1.2 show the changes in bulk density

Table 4.5.1.1 Changes in Bulk Density for the Roblin Soil

Treatment Group and Number	Bulk Density (g cm^{-3}) for Horizon			
	First		Second	
	Initial	Final	Initial	Final
A- Group				
Box No.				
1	1.20	1.21	1.70	1.64
2	1.23	1.15	1.72	1.66
5	1.22	1.21	1.71	1.72
11	1.25	1.25	1.70	1.69
13	1.24	1.25	1.73	1.70
Mean	1.23	1.21	1.71	1.68
B- Group				
Box No.				
3	1.19	1.22	1.74	1.72
4	1.22	1.19	1.70	1.65
9	1.21	1.21	1.68	1.68
10	1.21	1.23	1.69	1.69
12	1.23	1.26	1.73	1.71
Mean	1.21	1.22	1.71	1.69
C- Group				
Box No.				
8	1.20	1.15	1.65	1.63
16	1.24	1.31	1.73	1.64
17	1.22	1.17	1.73	1.67
18	1.24	1.21	1.73	1.72
20	1.23	1.23	1.71	1.71
Mean	1.23	1.21	1.71	1.67
D- Group				
Box No.				
6	1.23	1.22	1.71	1.61
7	1.24	1.21	1.68	1.57
14	1.23	1.24	1.71	1.68
15	1.27	1.35	1.73	1.57
19	1.22	1.11	1.72	1.69
Mean	1.24	1.23	1.71	1.62

Table 4.5.1.2 Changes in Bulk Density for the Erickson Soil

Treatment Group and Number	Bulk Density (g cm ⁻³) for Horizon					
	First		Second		Third	
	Initial	Final	Initial	Final	Initial	Final
A- Group						
Box No.						
21	1.22	1.24	1.53	1.54	1.46	1.42
22	1.20	1.19	1.53	1.53	1.48	1.53
23	1.21	1.13	1.51	1.47	1.46	1.43
25	1.21	1.21	1.53	1.49	1.50	1.52
40	1.19	1.20	1.51	1.52	1.48	1.47
Mean	1.20	1.19	1.52	1.51	1.48	1.47
B- Group						
Box No.						
26	1.22	1.14	1.53	1.49	1.45	1.44
27	1.22	1.29	1.51	1.41	1.44	1.42
34	1.24	1.29	1.49	1.45	1.44	1.45
35	1.20	1.21	1.50	1.44	1.44	1.37
38	1.29	1.23	1.51	1.42	1.48	1.39
Mean	1.24	1.23	1.51	1.44	1.45	1.41
C- Group						
Box No.						
29	1.29	1.27	1.55	1.57	1.43	1.37
30	1.22	1.21	1.55	1.51	1.50	1.49
31	1.22	1.21	1.53	1.49	1.49	1.40
37	1.28	1.24	1.51	1.43	1.47	1.43
39	1.19	1.18	1.53	1.57	1.47	1.46
Mean	1.24	1.22	1.53	1.51	1.47	1.43
D- Group						
Box No.						
24	1.21	1.18	1.50	1.45	1.46	1.50
28	1.22	1.20	1.51	1.36	1.47	1.38
32	1.21	1.22	1.49	1.39	1.45	1.37
33	1.20	1.14	1.52	1.47	1.49	1.43
36	1.26	1.28	1.51	1.39	1.48	1.40
Mean	1.29	1.20	1.51	1.41	1.47	1.42

of each soil horizon of individual boxes for both the Roblin and the Erickson soils. From the analysis of variance (Table E-1, Appendix E) it was revealed that soil, crop, soil and crop interaction, and the effluent level within a particular soil did not have significant effect on the change in bulk densities of the individual horizons. Further, from Duncan's multiple range test (Table E-4, Appendix E) the mean values for the changes in bulk densities of the individual horizons of each of the two soils with and without crop cover were found to be statistically insignificant. The bulk density, according to this study under the specified conditions was found to be unaffected by effluent irrigation. However, it is possible that this was only due to the short duration of the experiment and some changes may occur if effluent irrigation continues for several seasons.

4.5.2 Aggregate Stability

The results of the water stability index of the soil aggregates for individual horizons of the Roblin and the Erickson soil are summarized in Tables 4.5.2.1 and 4.5.2.2. The results indicate that effluent irrigation significantly reduced the stability of the soil aggregates especially in the top horizons of both soils.

The uncropped group of the Erickson soil under dry year conditions (B- group) had the lowest aggregate stability value in the first horizon than other groups of the same soil. The reduction in the aggregate stability values in the second and the third horizons of all groups of the Erickson soil was less dramatic as compared to the top horizons. In these horizons, cropped soil columns had slightly higher values than

Table 4.5.2.1 Soil Aggregate Stability Index for the
Roblin Soil

Soil Samples	Horizon	
	First	Second
Original	16.959	14.361
Treated		
A- Group	9.016	11.721
B- Group	8.484	13.391
C- Group	9.503	14.529
D- Group	9.294	14.844

Note: Original - Samples collected before effluent application

Table 4.5.2.2 Soil Aggregate Stability Index for the
Erickson Soil

Soil Samples	Horizon		
	First	Second	Third
Original	21.085	24.240	25.561
Treated			
A- Group	13.050	16.273	14.418
B- Group	9.836	15.319	14.433
C- Group	15.714	17.417	19.408
D- Group	14.931	16.340	17.331

Note: Original - Samples collected before effluent application

uncropped ones. In all of the second horizons of the cropped columns of the Roblin soil there was slight increase in the aggregate stability values. For the uncropped columns the reductions were not appreciable. Further, in most of the cases, there were not appreciable changes in the aggregate stability values for similar horizons under different levels of effluent application within each soil.

From the results it is apparent that crop had a significant effect in maintaining higher aggregate stability values. The reduction in these values could have been due to the soil deflocculating action of Na applied through effluent

Sessing (1961) showed that a decrease in aggregate stability could be reflected in an increase in bulk density. However, in this study there was no appreciable increase in bulk density.

4.5.3 Root Mass

The amount of root mass obtained per core sample from the top horizons of individual boxes is shown in Table 4.5.3. There was slight variation in the group means. A significant variation was observed between the means of the two soils. The analysis of variance (Table E-2, Appendix E) also shows that soil type had a significant effect on the amount of roots produced. The level of effluent application within each soil did not have any significant effect on the amount of root mass. Duncan's multiple range test (Table E-5, Appendix E) indicated that the mean values of root mass produced in the two different soils were different. There was no correlation between root mass and initial bulk density nor between root mass and the amount of effluent applied.

Table 4.5.3 Analysis of Root Mass

Treatment Group and Number	Root Mass per Core Sampler [*] (g)
Roblin Soil	
C- Group	
Box No.	
8	0.0880
16	0.1034
17	0.0886
18	0.1746
20	0.1408
Mean	0.1191
D- Group	
Box No.	
6	0.1451
7	0.0918
14	0.0647
15	0.1086
19	0.1677
Mean	0.1156
Erickson Soil	
C- Group	
Box No.	
29	0.0777
30	0.1479
31	0.1220
37	0.0457
39	0.0663
Mean	0.0919
D- Group	
Box No.	
24	0.1192
28	0.0494
32	0.1041
33	0.0550
36	0.0705
Mean	0.0796

* Core sampler (52.4-mm diameter and 77.1-mm depth) used for taking undisturbed samples

4.6 CHANGES IN CHEMICAL PROPERTIES OF SOILS

4.6.1 Major Nutrients

4.6.1.1 Nitrate Nitrogen

Results shown in Figs. 4.6.1.1.1 and 4.6.1.1.2 indicate that in the cropped groups there was almost no change in the original $\text{NO}_3\text{-N}$ level in the soil. This was due to crop removal as explained in section 4.7.2. However, there was a general increase in the $\text{NO}_3\text{-N}$ content of both soils after effluent irrigation under no-crop conditions.

The A- group (average year, without crop) of the Roblin soil gained about 130 kg of $\text{NO}_3\text{-N}$ per ha in the top 100 cm profile. For the same group, the Erickson soil gained about 130 kg ha^{-1} for the same depth. The B- group (dry-year, without crop) of the Roblin soil gained about 120 kg ha^{-1} of $\text{NO}_3\text{-N}$ in the top 100 cm depth while the Erickson soil gained about 150 kg ha^{-1} for the same group for the same depth. The increase was, therefore, higher in both cases of the Erickson soil columns even though in the B- group of the Roblin soil the loading of effluent was higher than the loading in the corresponding group of the Erickson soil. The two figures also show that in general, the total $\text{NO}_3\text{-N}$ content in the first horizons of the non-cropped soil columns was much higher than that in the rest of the profiles although the first horizon had a shallower depth compared to the rest of the profile. Further, from Tables B-1 and B-2 of Appendix B the concentration of $\text{NO}_3\text{-N}$ in the first horizons of the non-cropped columns were much higher than that in the lower horizons. Sessing (1961) showed similar results in his lysimeter study.

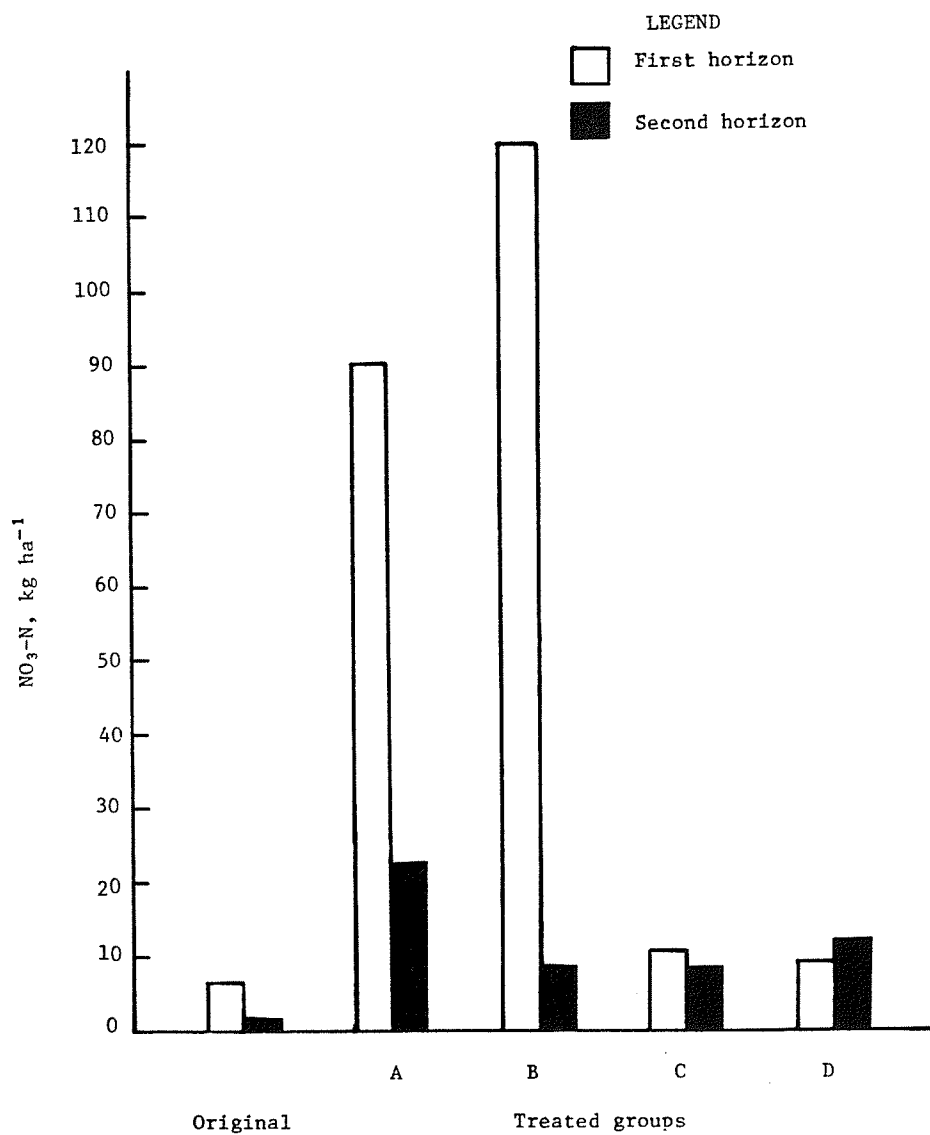


Fig. 4.6.1.1.1 Changes in the NO₃-N content of the saturation extracts of the Roblin soil after irrigation with municipal sewage effluent.

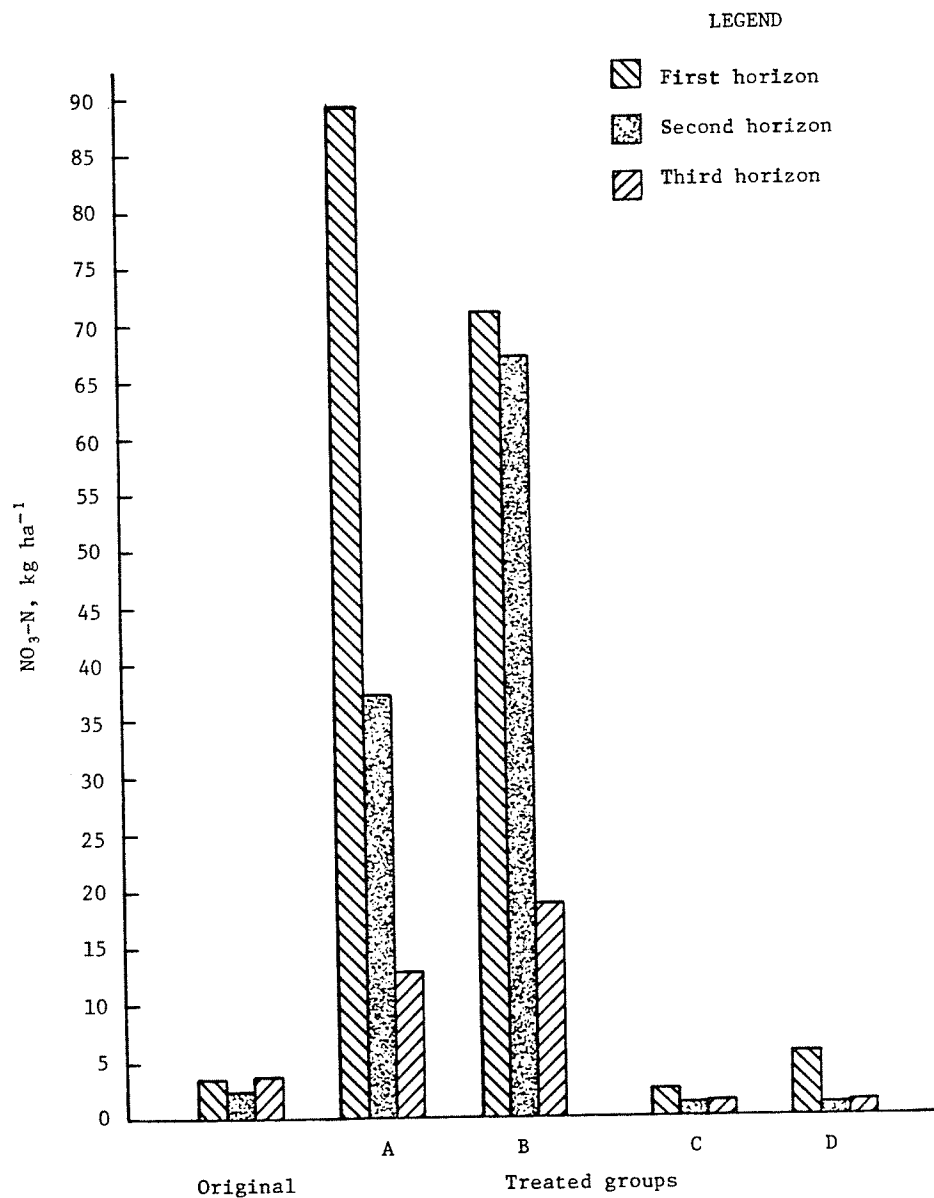


Fig. 4.6.1.1.2 Changes in the $\text{NO}_3\text{-N}$ content of the saturation extracts of the Erickson soil after irrigation with municipal sewage effluent.

4.6.1.2 Available Phosphorus

From Fig. 4.6.1.2.1 it is apparent that the available phosphorus content of the first horizons of the uncropped boxes of the Roblin soil increased in accordance with the amount of the effluent applied. In the entire 100-cm depth the A- group of the Roblin soil had about 50 kg ha^{-1} more available phosphorus than B- group in spite of the fact that the amount of effluent applied to the A- group was much smaller than that applied to the B- group. In the cropped Roblin columns (both C- and D-groups) there was almost no increase in the phosphorus concentration either in the first or in the second horizon.

The Erickson soil which is generally deficient in phosphorus did not show a similar tendency (Fig. 4.6.1.2.2). The phosphorus content of the first horizons increased whether there was a crop or not. In the second horizons of the Erickson soil, available phosphorus content, in general, did not change. However, there was a slight reduction in the available phosphorus content of the third horizons of all groups as compared to the original values and this reduction was maximum in the B- group. No such trend was observed in the second horizons of the Roblin soil. After only one season of irrigation with municipal effluent there was no phosphorus need in the Erickson soils, although the original soil had a phosphorus need of about 20 kg ha^{-1} .

There was a higher percentage of finer particles (Table B-3, Appendix B) in the first horizon of the Roblin soil than the same horizon of the Erickson soil. Further, the first horizon of the Erickson soil had a high percentage of particles (by mass) with diameter greater than 2.0 mm (Table B-6, Appendix B). The above two statements explain why the

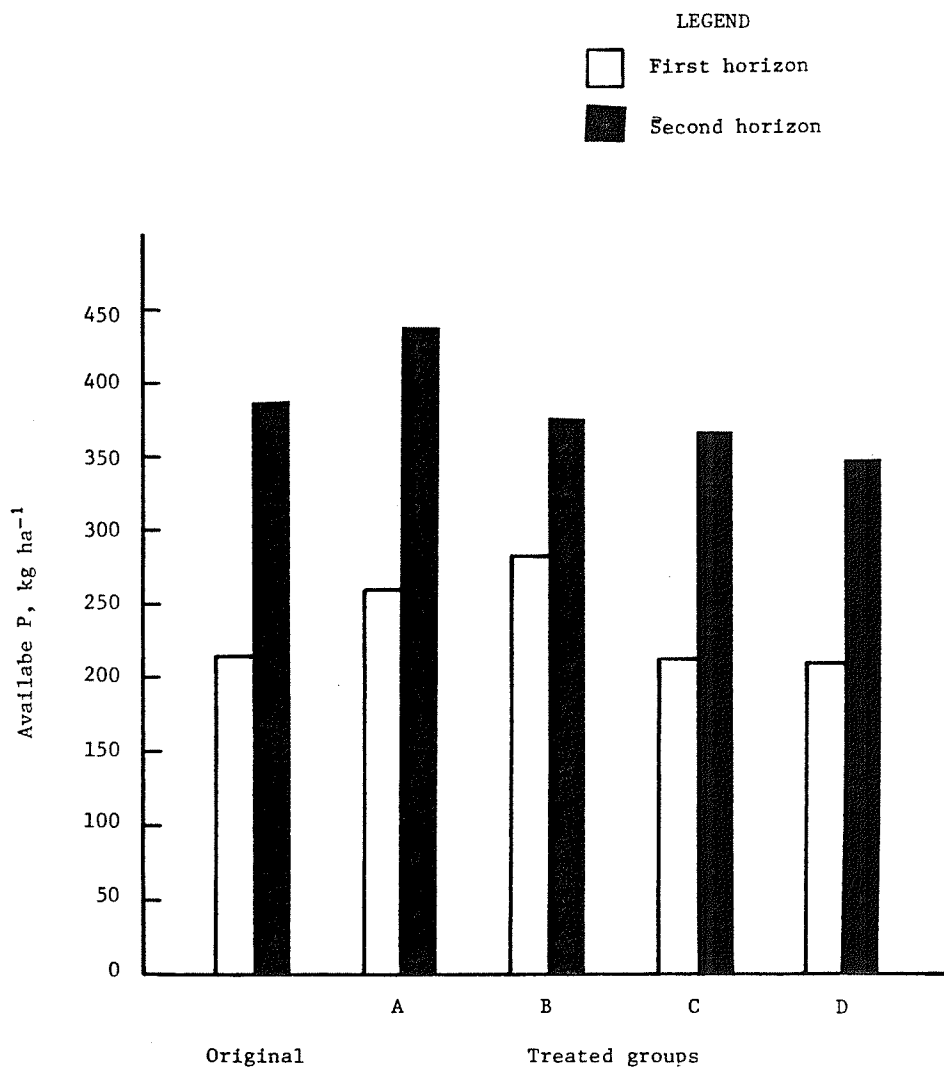


Fig. 4.6.1.2.1 Changes in the available P content of the saturation extracts of the Roblin soil after irrigation with municipal sewage effluent.

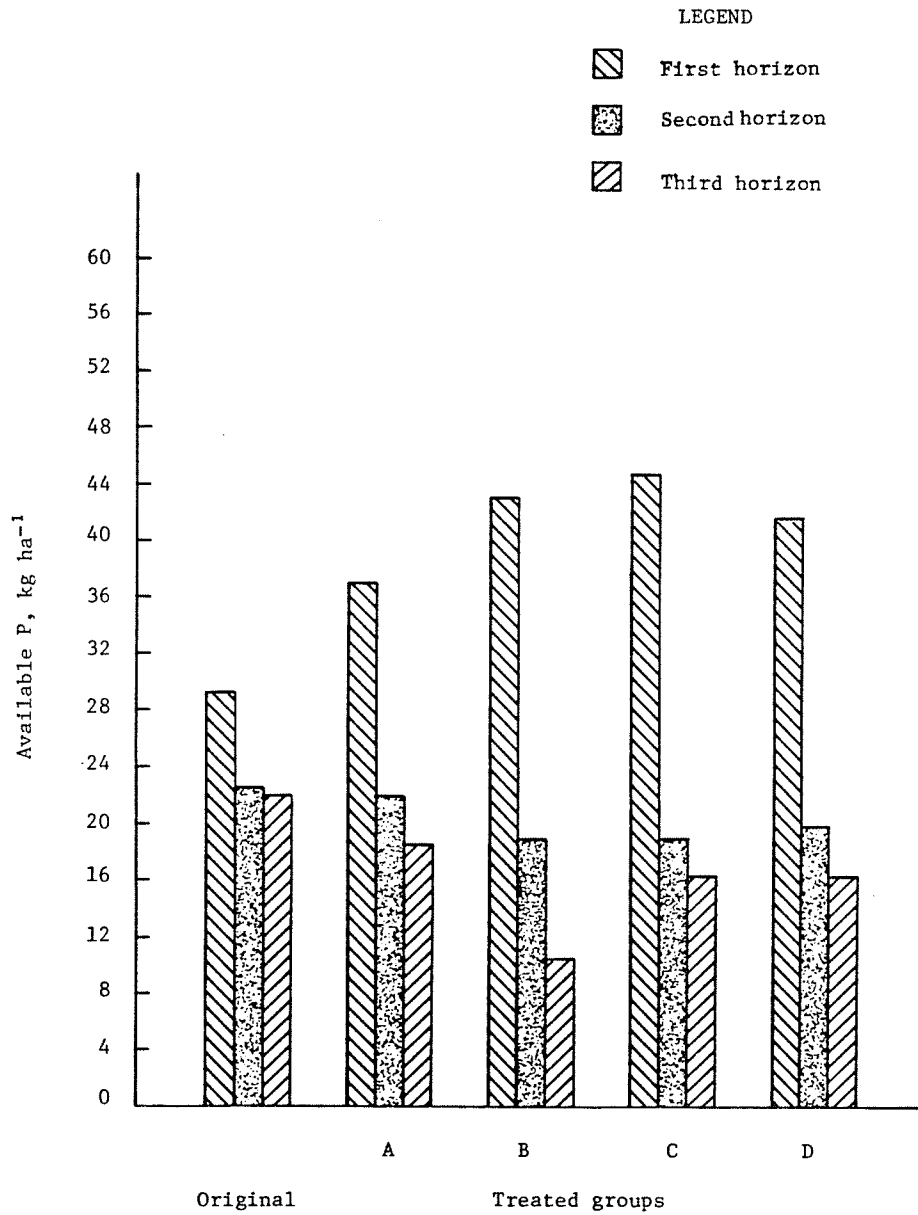


Fig. 4.6.1.2.2 Changes in the available P content of the saturation extracts of the Erickson soil after irrigation with municipal sewage effluent.

accumulation of available phosphorus was higher in the uncropped sections of the Roblin soil than the Erickson soil.

4.6.1.3 Available Potassium

The soil was originally rich in potassium and effluent irrigation added extra potassium to the individual horizons of both soils under crop as well as no-crop conditions. The amount of increase was substantially higher than that applied through irrigation. Figs. 4.6.1.3.1 and 4.6.1.3.2 give a comparison between the initial and the final values of the available potassium for the individual horizons of both soils.

The available K concentration in the first horizons of both A- and B- groups was identical. Although, the amount of effluent application to the A- group of the Roblin soil was lowest, accumulation of K in its second horizon was higher than that of the B- group. The available K content of the first 100 cm of the profiles of both C- and D- groups (dry- and average-years under crop respectively) were almost identical.

There was no appreciable increase in the available K content of the first horizons of all the groups of the Erickson soil. The second and third horizons of the A- group had higher concentrations of available K as compared to the similar horizons of the B- group. The total available K concentration in both C- and D- groups up to a depth of 100 cm were identical.

Loss of K through drainage cannot be taken as a major factor for the lower available K content of the first 100 cm of the profile of the B- group of the Roblin soil than that of the A- group. The reason being, the leachates in the B- group were not excessively high. In this study,

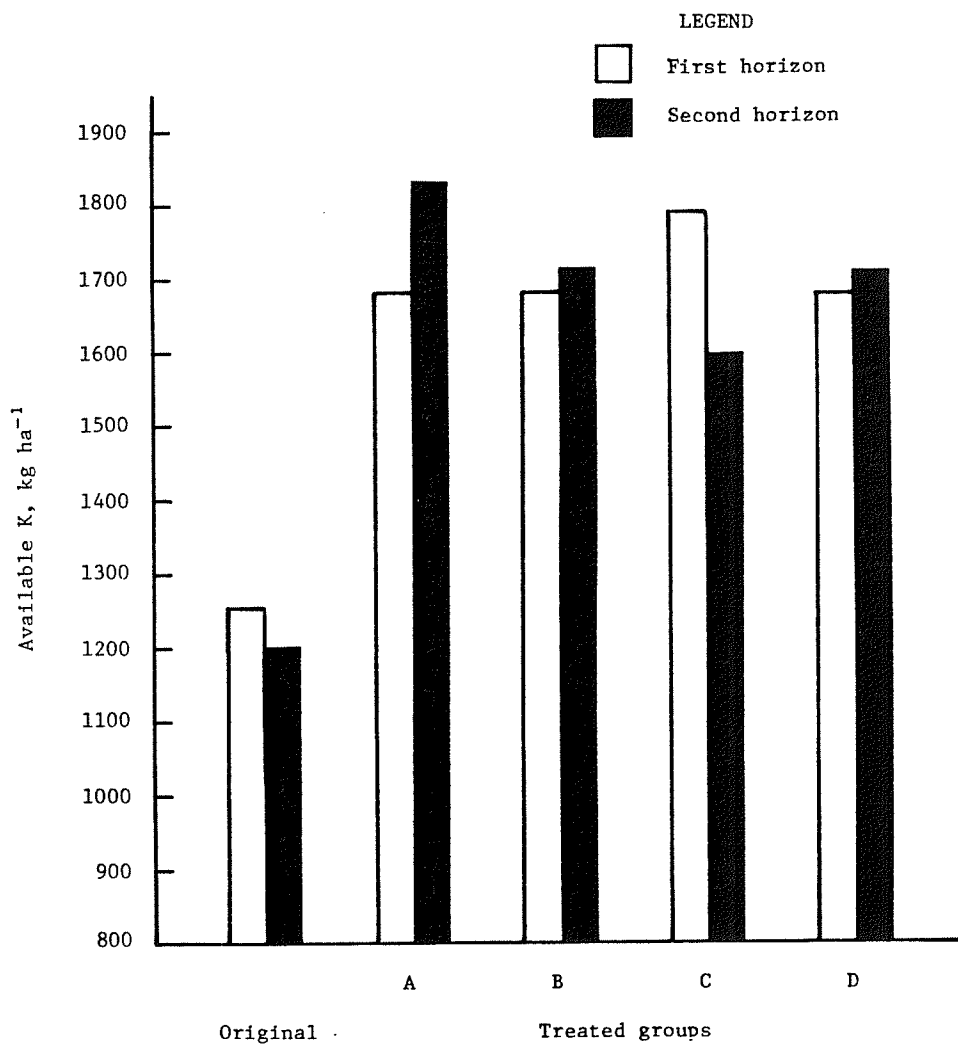


Fig 4.6.1.3.1 Changes in the available K content of the saturation extracts of the Roblin soil after irrigation with municipal sewage effluent.

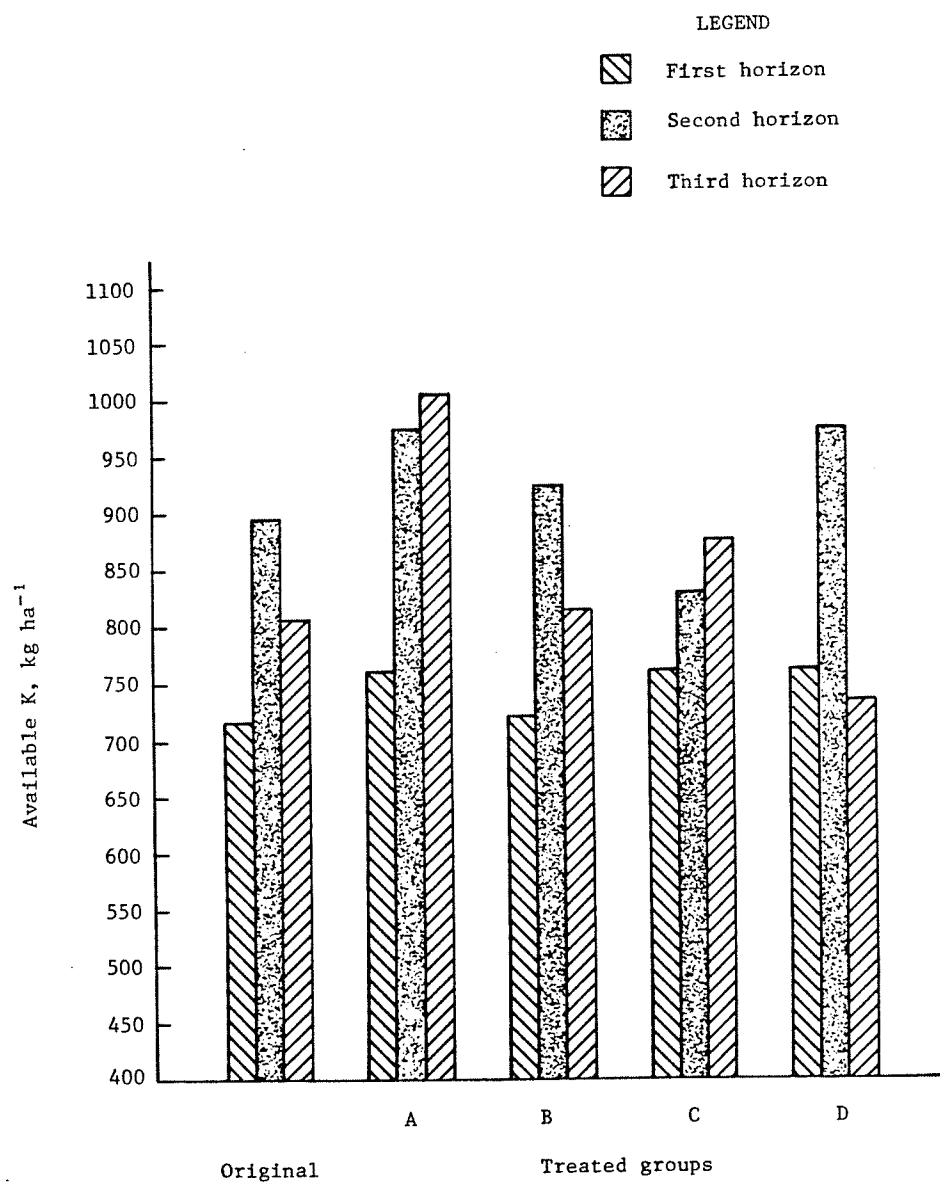


Fig. 4.6.1.3.2 Changes in the available K content of the saturation extracts of the Erickson soil after irrigation with municipal sewage effluent.

K was not determined in the leachates. The concentration of K in the effluent was less than 1 meq L⁻¹. This suggests that the concentration of K in the leachates can not be excessively high to cause such dramatic changes. Any such change can be expected in soil itself, because, clay particles are large storehouses of potassium.

4.6.1.4 Sulphate Sulphur

The SO₄-S content of both soils increased after irrigation with effluent (Figs. 4.6.1.4.1 and 4.6.1.4.2).

The concentration of SO₄-S was extremely high in the first horizons of all groups of the Roblin soil as compared to the second horizons. There was also an increasing tendency of SO₄-S accumulation in the second horizons of all groups of the Roblin soil. Maximum accumulation of SO₄-S was in the C- group where the amount of effluent application was maximum.

In the Erickson soil columns the first horizons of the A- and B- groups had higher levels of SO₄-S than the second and the third horizons. However, in the cropped groups (C- and D- groups), the SO₄-S content in the first horizons was not highest among the three horizons. In the C- group, the third horizon had the highest concentration of SO₄-S where as the second horizon of the D- group had the highest concentration. The concentration of SO₄-S in the first 100 cm of the profile of the C- group had the highest concentration of SO₄-S compared to all other groups in the soil. The depth of effluent application in this group was also the highest.

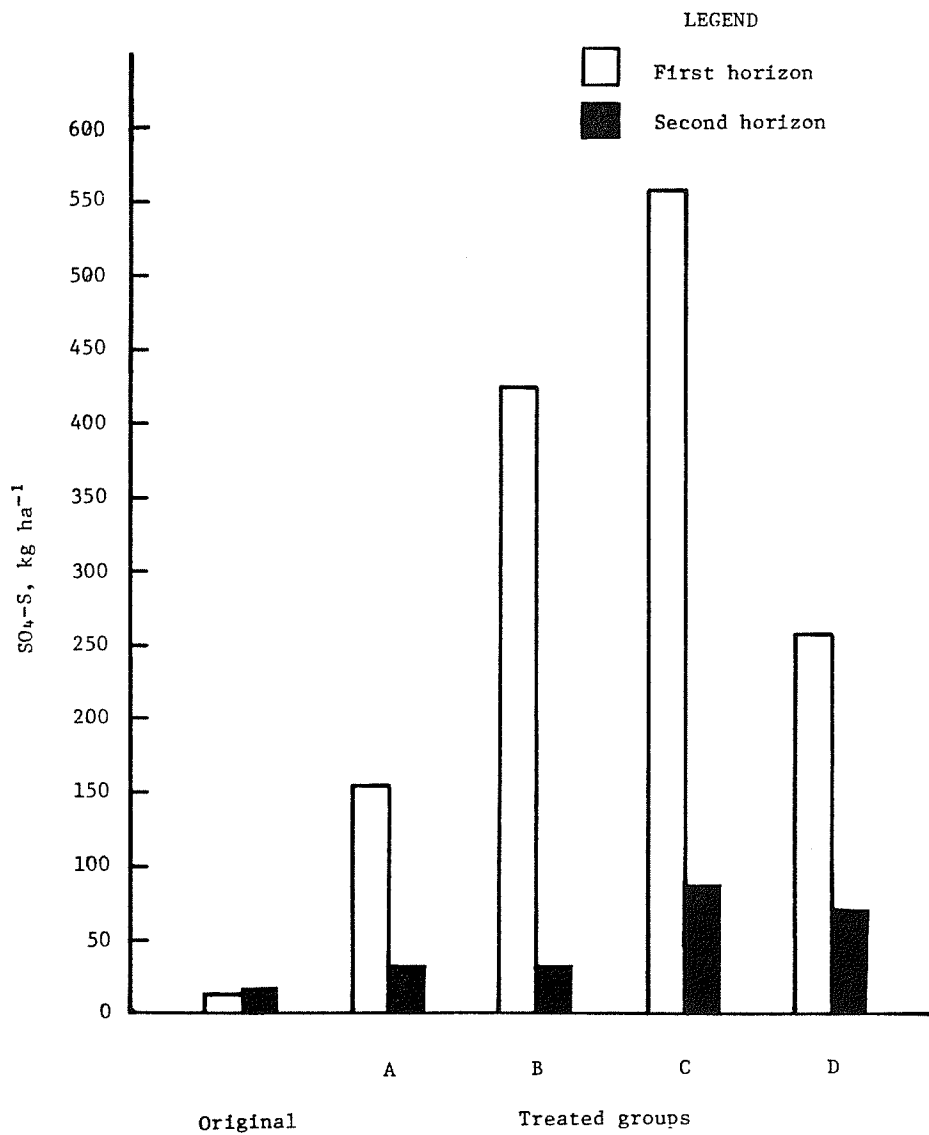


Fig. 4.6.1.4.1 Changes in SO₄-S content of the saturation extracts of the Roblin soil after irrigation with municipal sewage effluent.

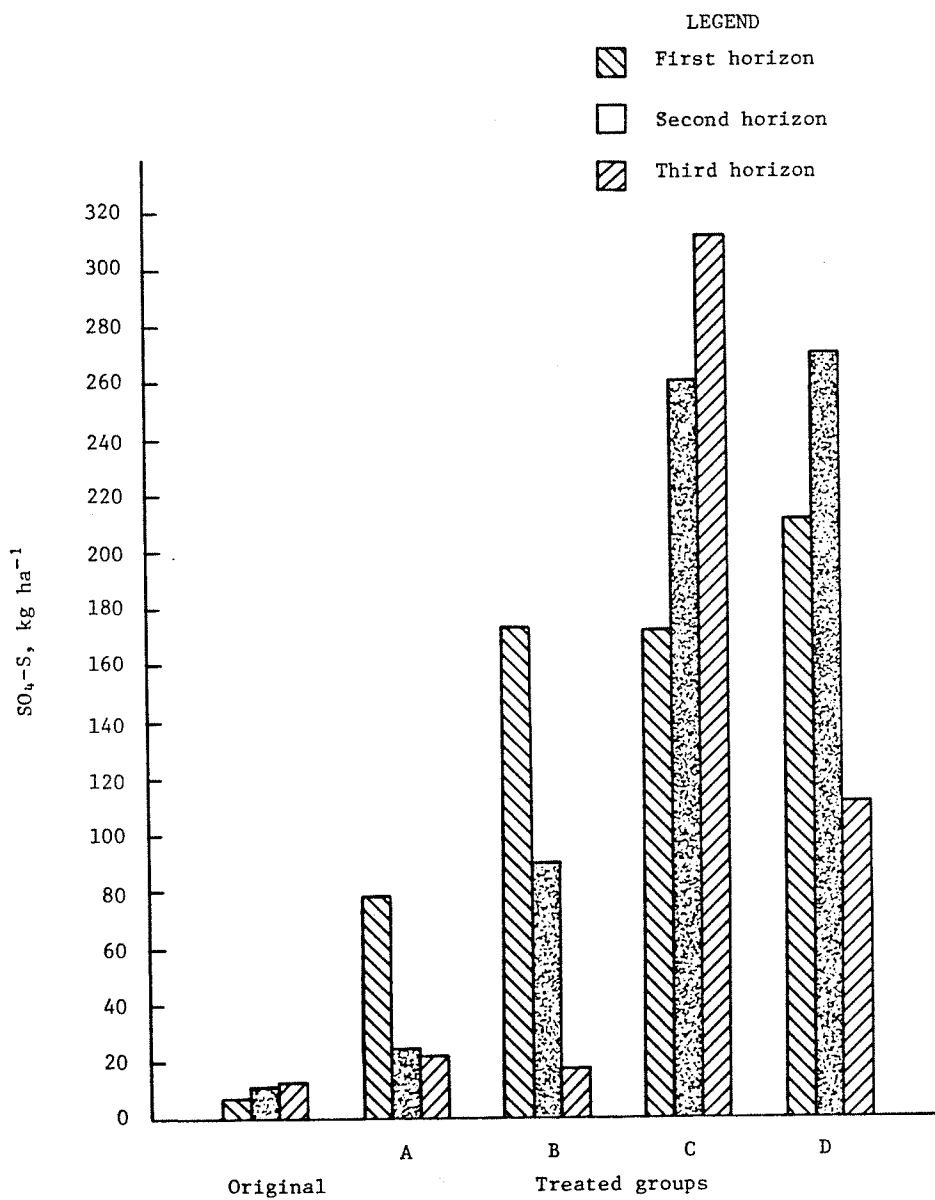


Fig. 4.6.1.4.2 Changes in the $\text{SO}_4\text{-S}$ content of the saturation extracts of the Erickson soil after irrigation with municipal sewage effluent.

The high concentration of $\text{SO}_4\text{-S}$ in the effluent was a major cause for such drastic increase in one irrigation season. It can be assumed that the accumulated sulphur can be leached down the profile as there was significant amount of $\text{SO}_4\text{-S}$ in the leachates. Berger (1972b) pointed out that in arid regions the leaching of sulphur from the root zone is usually low and it simply moves downward by the limited rainfall. He also suggested that the recurrent accumulation may reduce the growth of crops.

4.6.2 Exchangeable Cations

Except for K, other exchangeable cations such as Na, Ca, and Mg were determined from the soil analysis. The available K as described in the previous section was a combination of both exchangeable and water-soluble potassium. No separate test was done to determine the concentration of exchangeable K.

There was a significant increase in the exchangeable sodium concentration in the top horizons of both soils irrespective of cropping effect (Figs. 4.6.2.1 and 4.6.2.2). The Na concentration was directly dependent upon the level of effluent application. In the cropped columns of the Erickson soil, there was an increasing tendency for Na accumulation in the lower horizons as compared to the initial values. Further, referring to the section 4.5.2, the Na content was high for the horizons for which the aggregate stability index was low. The high sodium concentration in the effluent might have caused a breakdown in soil structure. The small decrease in bulk density shown in some of the columns of both soils (Tables 4.5.1.1 and 4.5.1.2) could be due to factors such as experimental errors or the addition of residues.

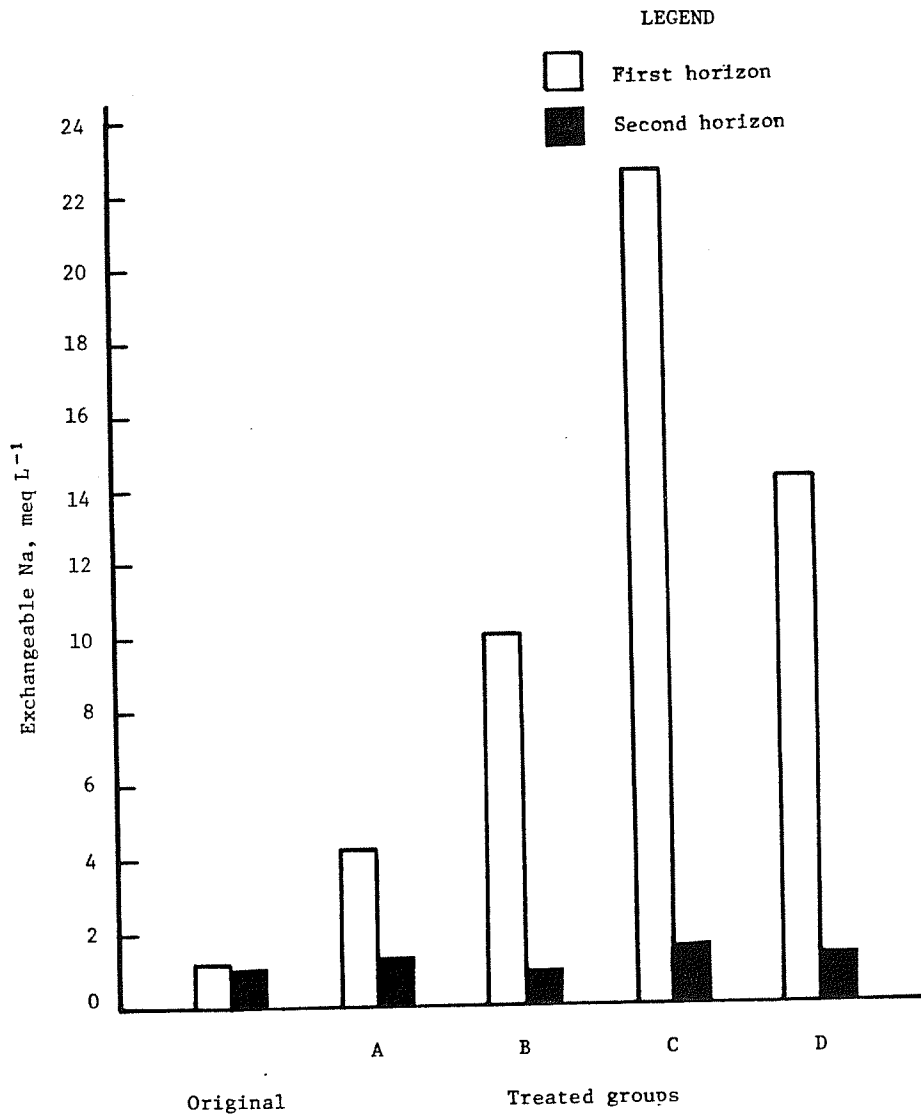


Fig. 4.6.2.1 Changes in exchangeable Na content of the saturation extracts of the Roblin soil after irrigation with municipal sewage effluent.

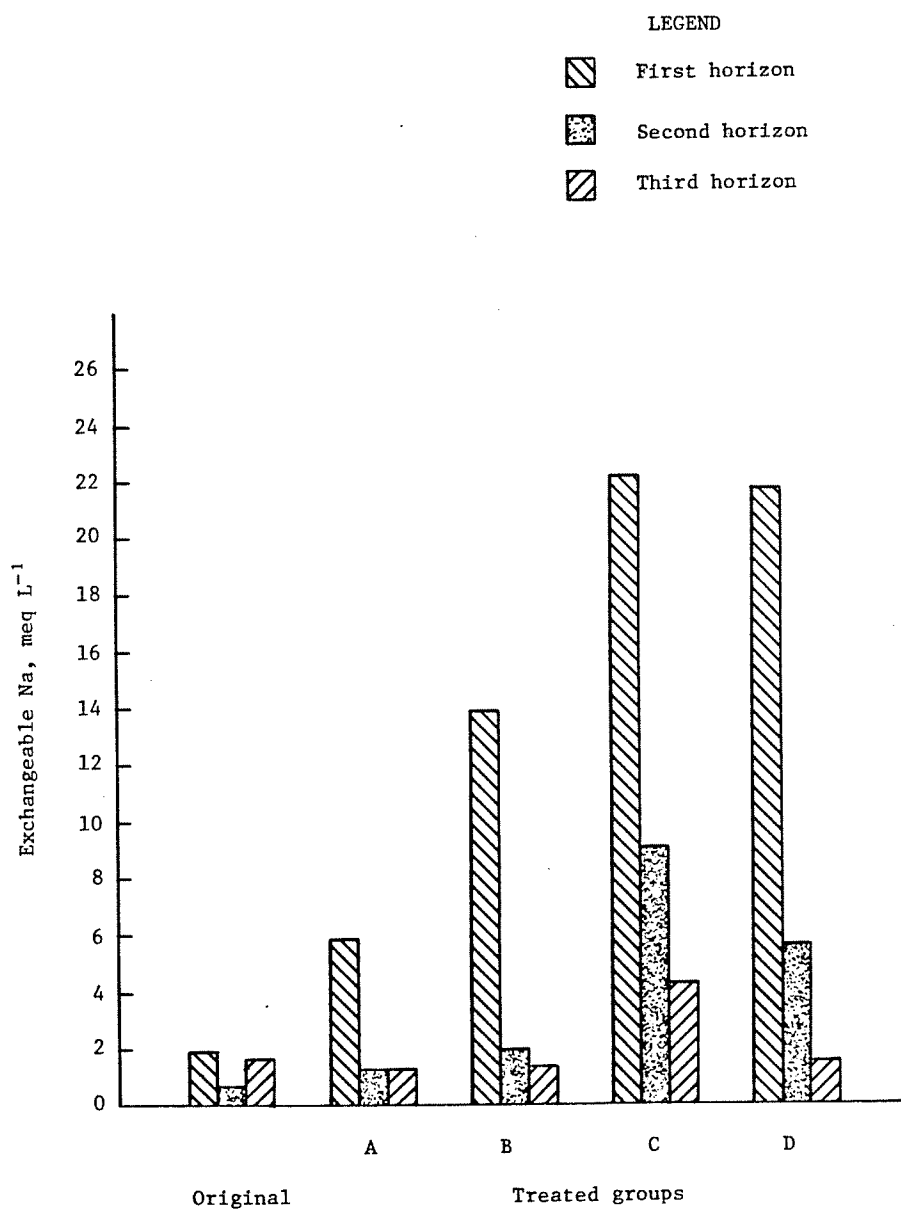


Fig. 4.6.2.2 Changes in the exchangeable Na content of the saturation extracts of the Erickson soil after irrigation with municipal sewage effluent.

Magnesium concentration increased in most of the horizons of both soils (Figs. 4.6.2.3 and 4.6.2.4). In the same way as described before, the increase in Mg concentration in the Roblin soil was correlated to the amount of application. Slight increase in Mg concentrations took place in the B-, C- and D- groups of the Erickson soil. The maximum increase in Mg concentration was observed in the first horizons of the C- groups of both soils. The amount of Mg lost through leachates was negligible. The crop removal (described later in this chapter) was low as compared to the amount of addition through irrigation. This element was retained in the exchange sites when Ca was lost from the soil.

The most peculiar thing observed was the pattern of loss of Ca from some soil horizons (Figs. 4.6.2.5 and 4.6.2.6). In the Roblin soil columns the concentration of Ca in the second horizons was low as compared to the original values. The concentrations in the top horizons changed slightly subject to a maximum increase of about 15 percent in the B- group. The concentration of Ca in the leachates was higher as compared to that of the effluent. However, the amount of Ca leached out in each group (Tables 4.3.1 and 4.3.2) was too low to justify this reduction.

In the Erickson soil, there was a slight reduction in the amount of exchangeable Ca in the first horizons. Crop removal of Ca could be one of the major reasons for such reductions in the C- and D- groups. In the same groups, there was an increase in Ca concentration in the lower horizons. Due to the extremely short duration of study, a firm conclusion on this point is not possible. A sufficiently long study is essential in this regard.

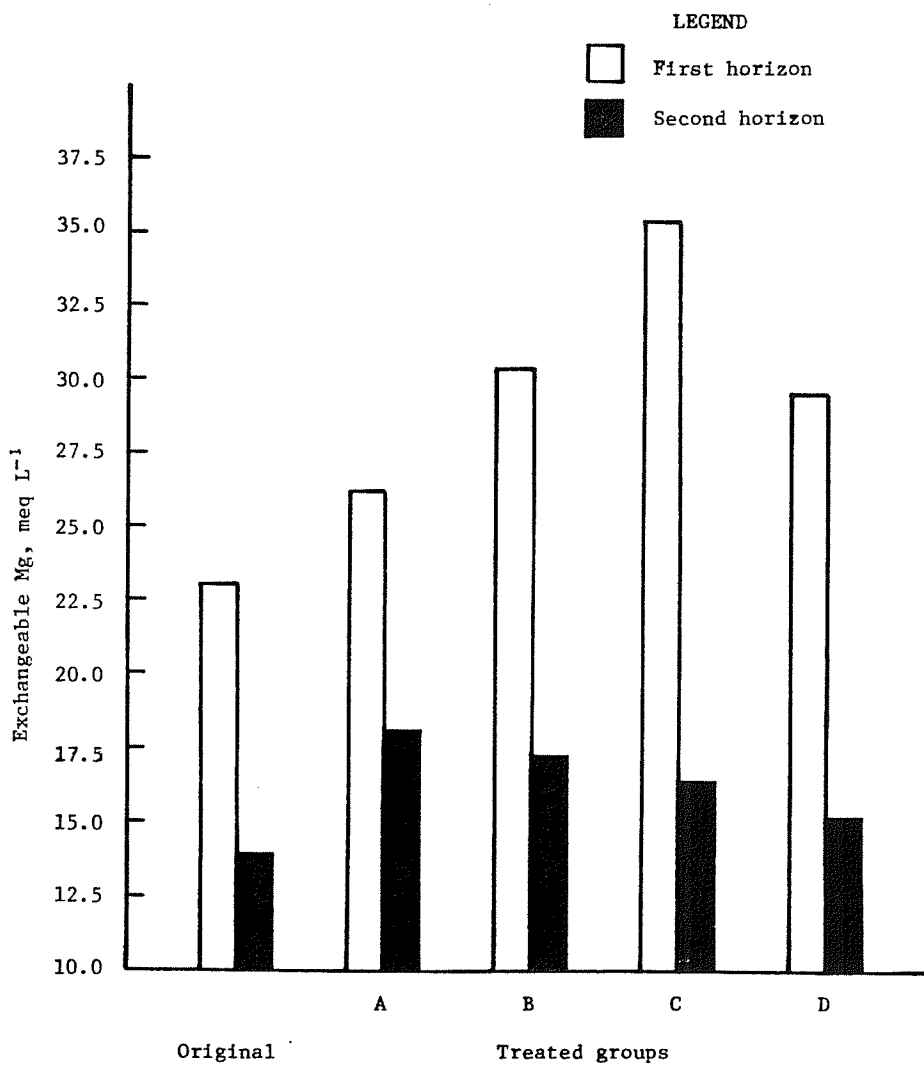


Fig. 4.6.2.3 Changes in the exchangeable Mg content of the saturation extracts of the Roblin soil after irrigation with municipal sewage effluent.

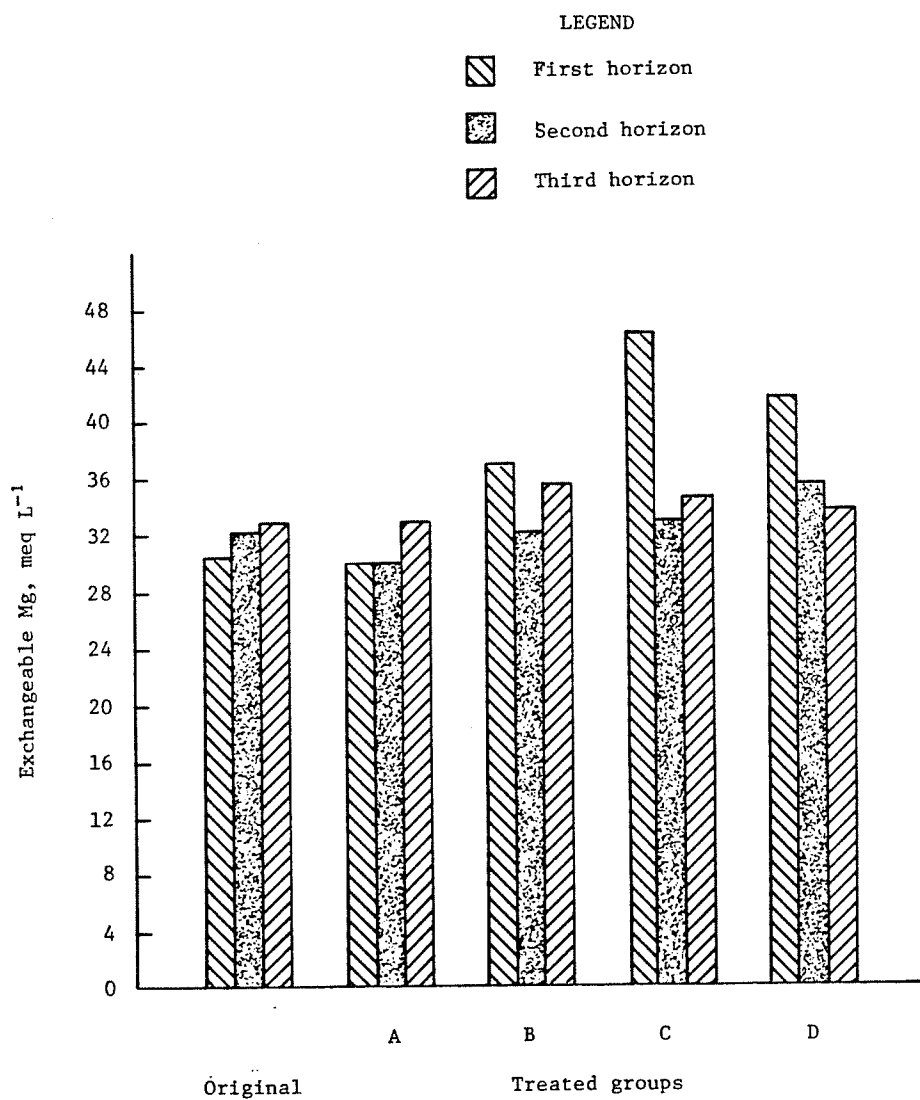


Fig. 4.6.2.4 Changes in the exchangeable Mg content of the saturation extracts of the Erickson soil after irrigation with municipal sewage effluent.

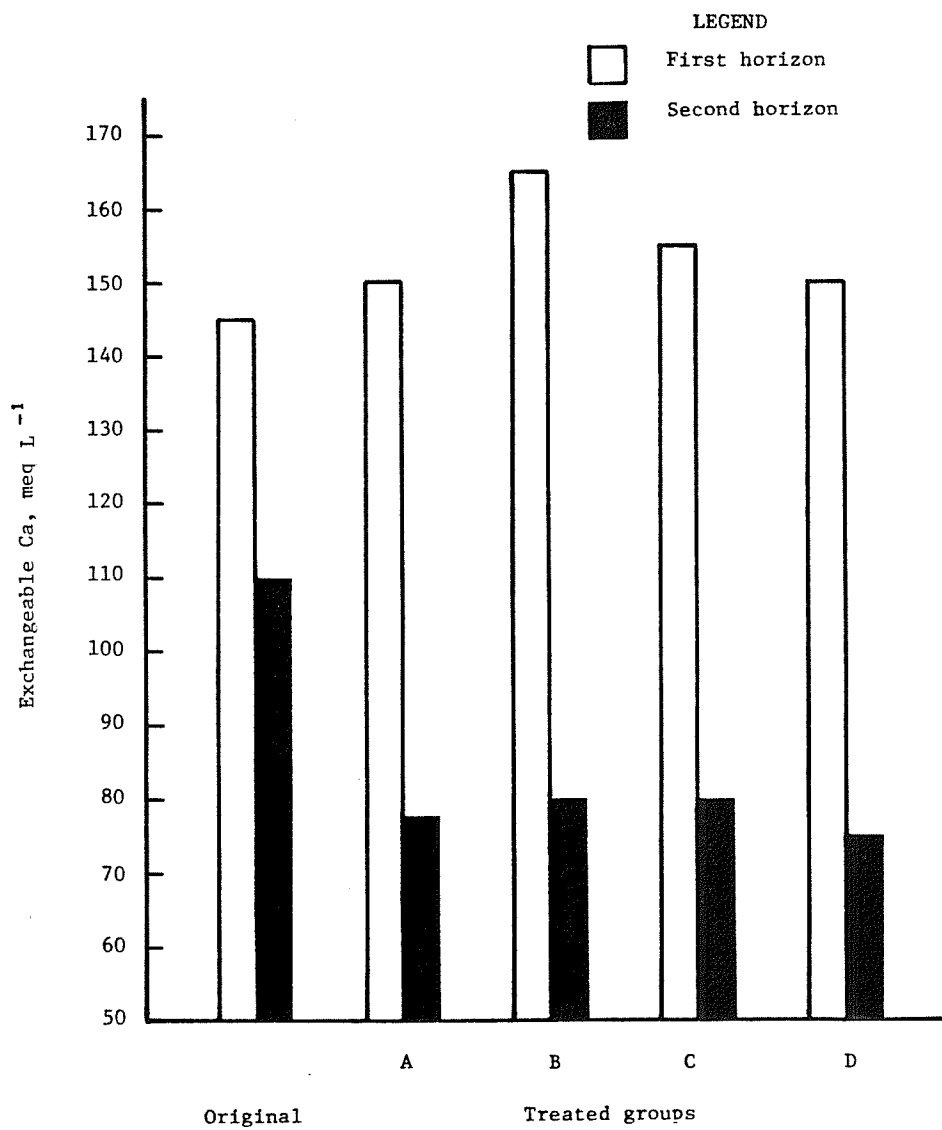


Fig. 4.6.2.5 Changes in the exchangeable Ca content of the saturation extracts of the Roblin soil after irrigation with municipal sewage effluent.

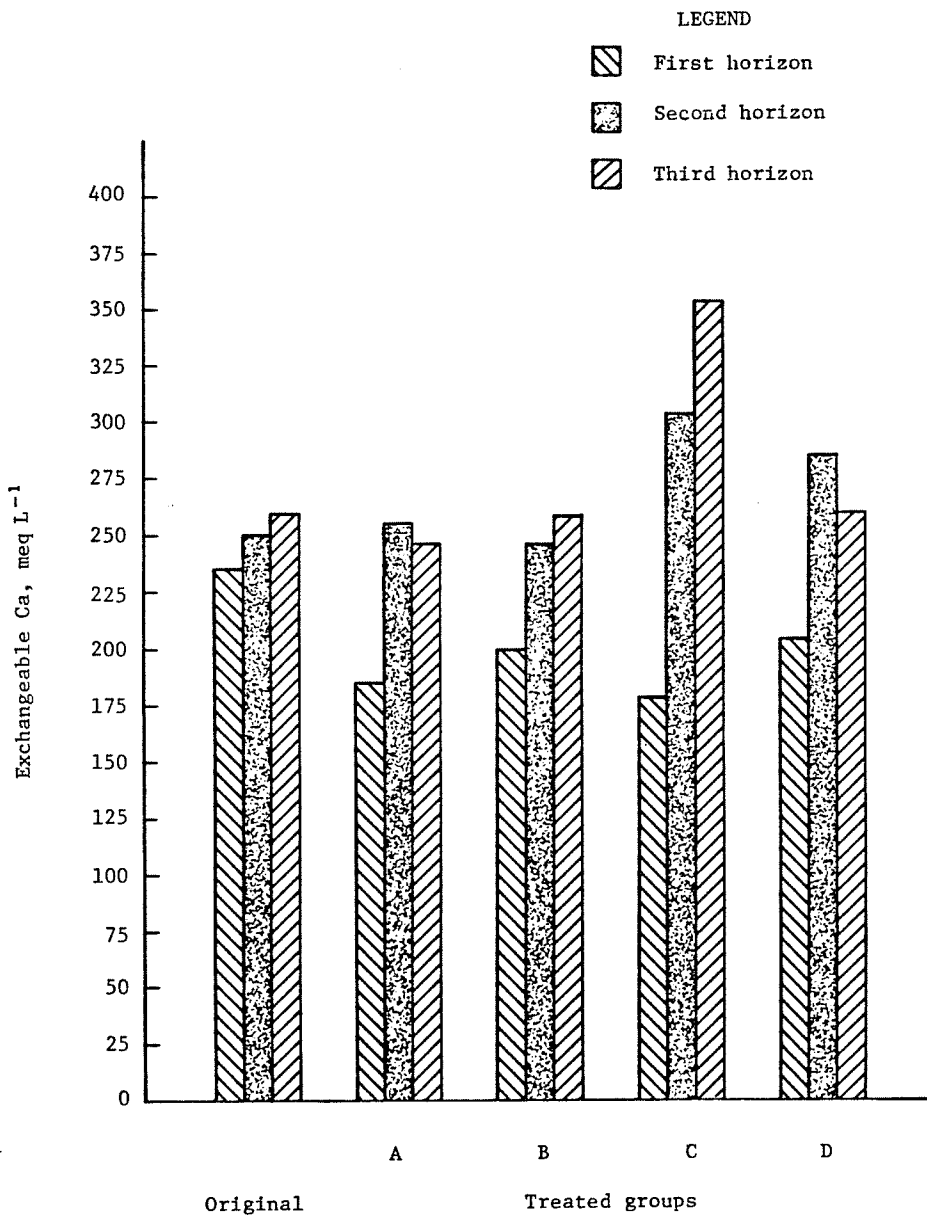


Fig. 4.6.2.6 Changes in the exchangeable Ca content of the saturation extracts of the Erickson soil after irrigation with municipal sewage effluent.

The SAR of the saturation extracts from the top horizons of both soils increased considerably as compared to the initial values (Figs. 4.6.2.7 and 4.6.2.8) while in the lower horizons the changes were either small or negligible. However, the SAR of the saturation extracts from all horizons were still well below the critical limits which would cause problems in crop growth.

4.6.3 Soil pH and Salinity

From Figs. 4.6.3.1 to 4.6.3.4 it can be observed that there was a general increase in the pH and in the salinity of the soils at the end of effluent irrigation. Both horizons of the Roblin soils were slightly acidic before effluent application (Fig. 4.6.3.1) but after the end of irrigation all the Roblin soil horizons turned to slightly alkaline. In the A- group of the Roblin soil a maximum rise of pH of 1.0 unit was observed although the amount of effluent added to the particular group was the lowest among all groups and the pH of the leachates under this group was substantially below that of the effluent.

Similar trends were observed in the Erickson soil columns (Fig. 4.6.3.2). Initially, the pH of the top horizon was almost neutral and the rest of the horizons were slightly alkaline. At the end of irrigation all horizons were in the alkaline range. The change in the pH values of the soils can be attributed to the addition of Ca and Mg through irrigation.

The changes in salinity (EC from Figs. 4.6.3.3 and 4.6.3.4) were appreciable in the first horizons of both soils after a single season of irrigation. A high EC value of 1.0 mS cm^{-1} was observed in the C- group

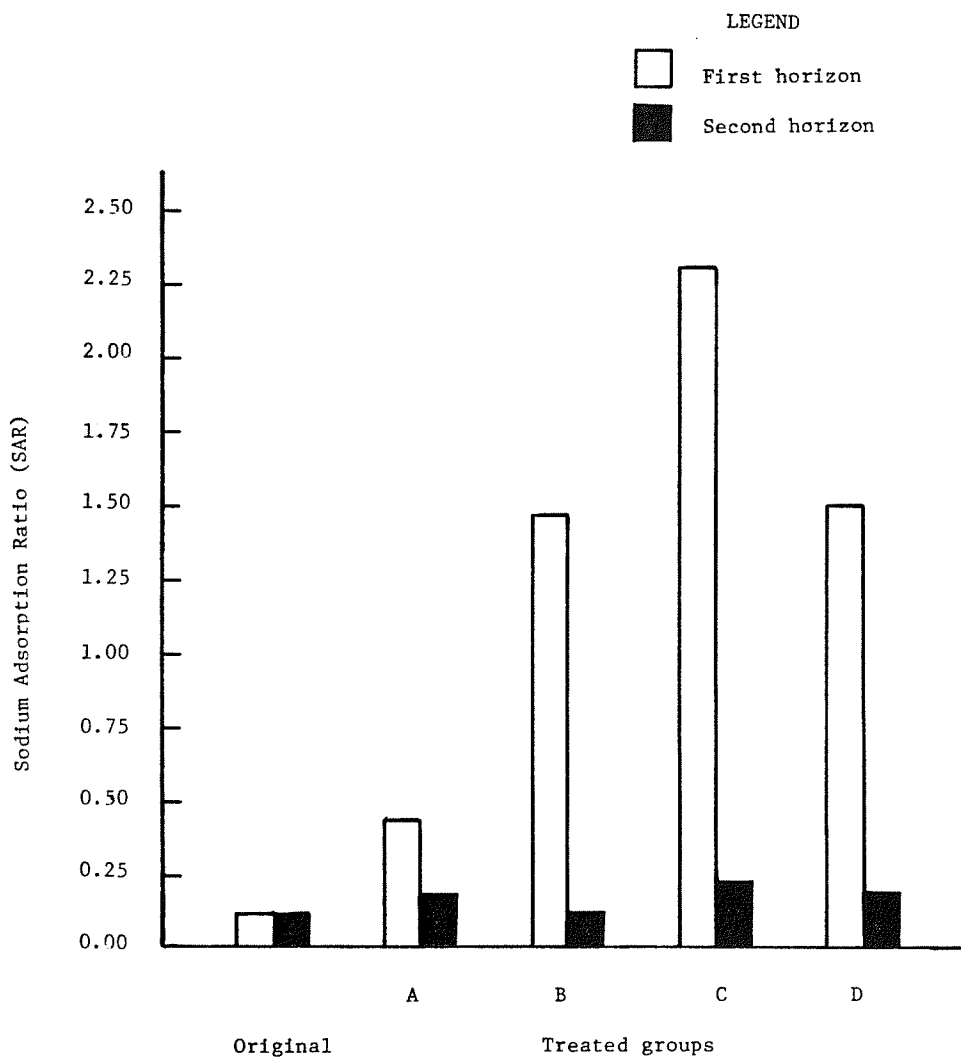


Fig. 4.6.2.7 Changes in the Sodium Adsorption Ratio (SAR) of the saturation extracts of the Roblin soil after irrigation with municipal sewage effluent.

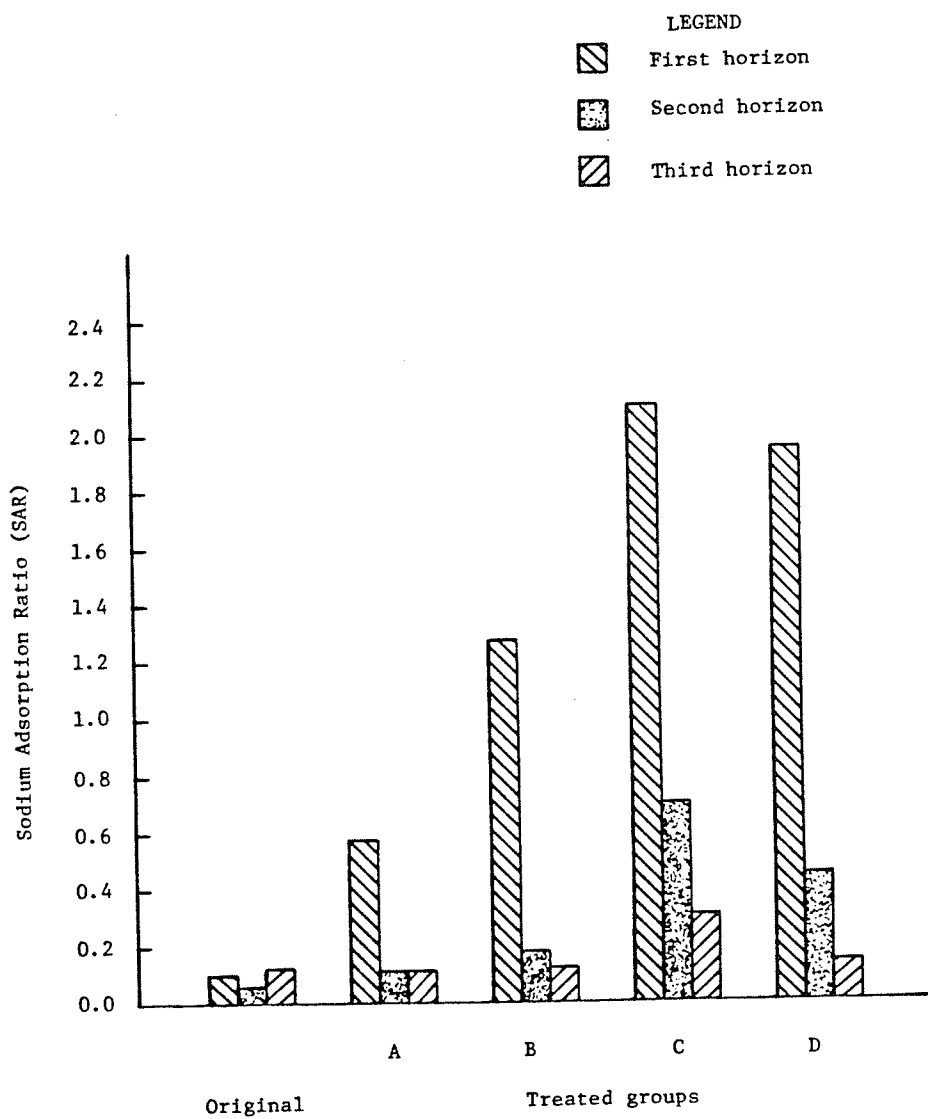


Fig. 4.6.2.8 Changes in the Sodium Adsorption Ratio (SAR) of the saturation extracts of the Erickson soil after irrigation with municipal sewage effluent.

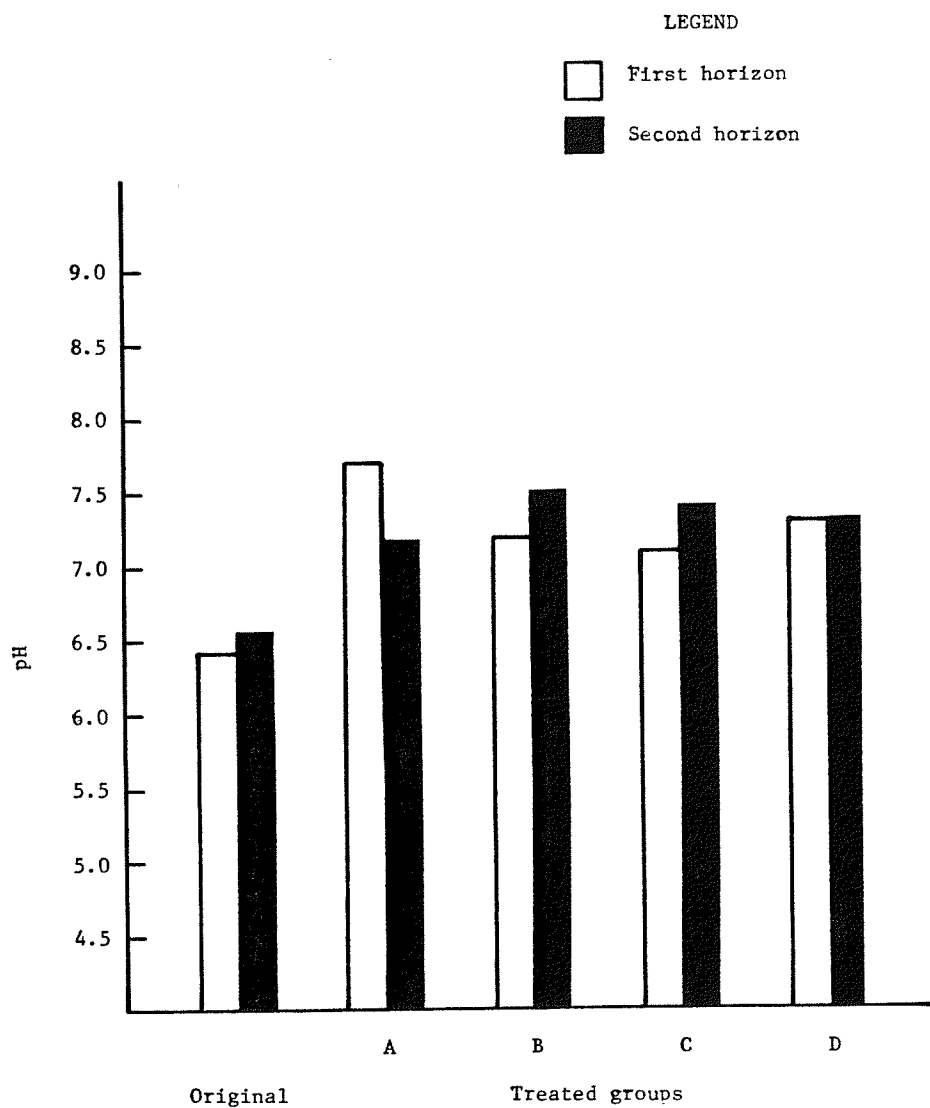


Fig. 4.6.3.1 Changes in pH of the saturation extracts of the Roblin after irrigation with municipal sewage effluent.

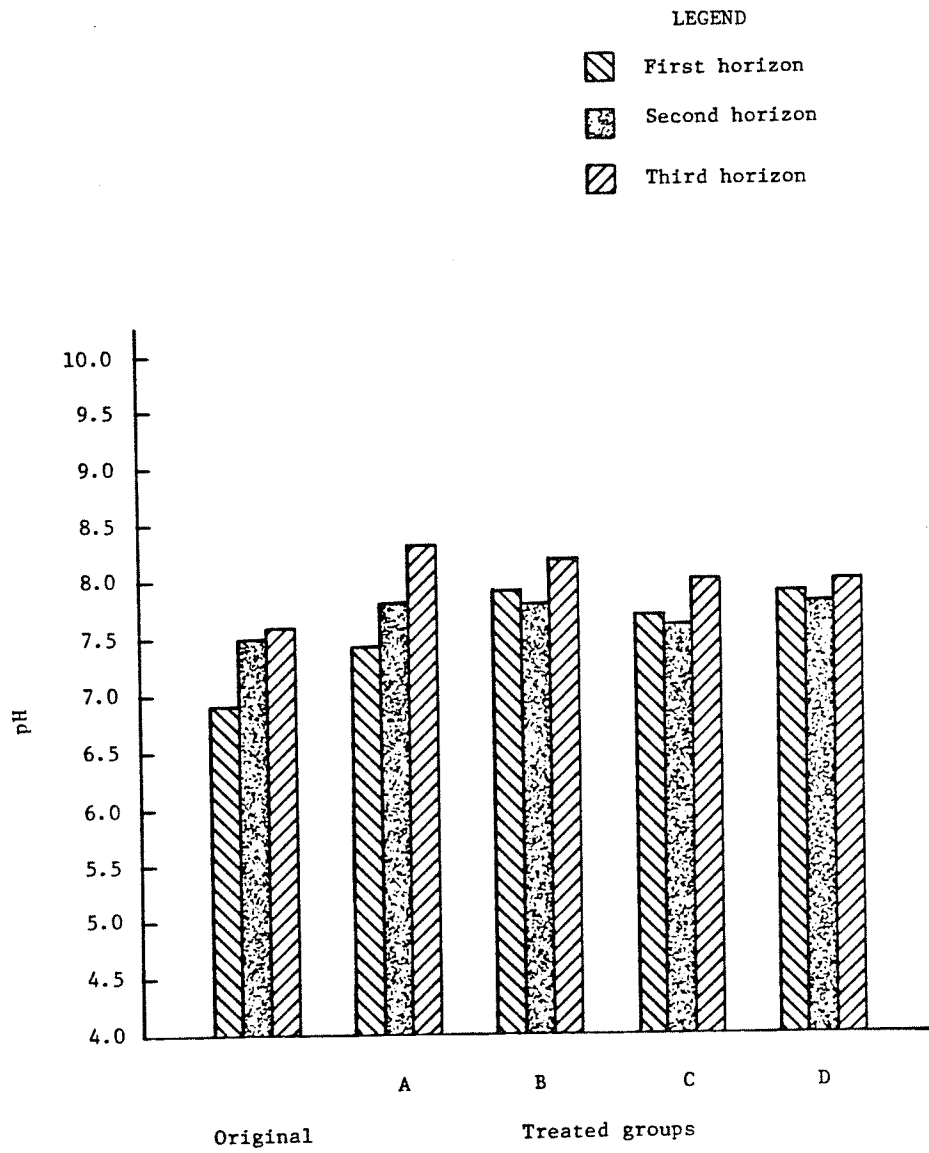


Fig. 4.6.3.2 Changes in pH of the saturation extracts of the Erickson soil after irrigation with municipal sewage effluent.

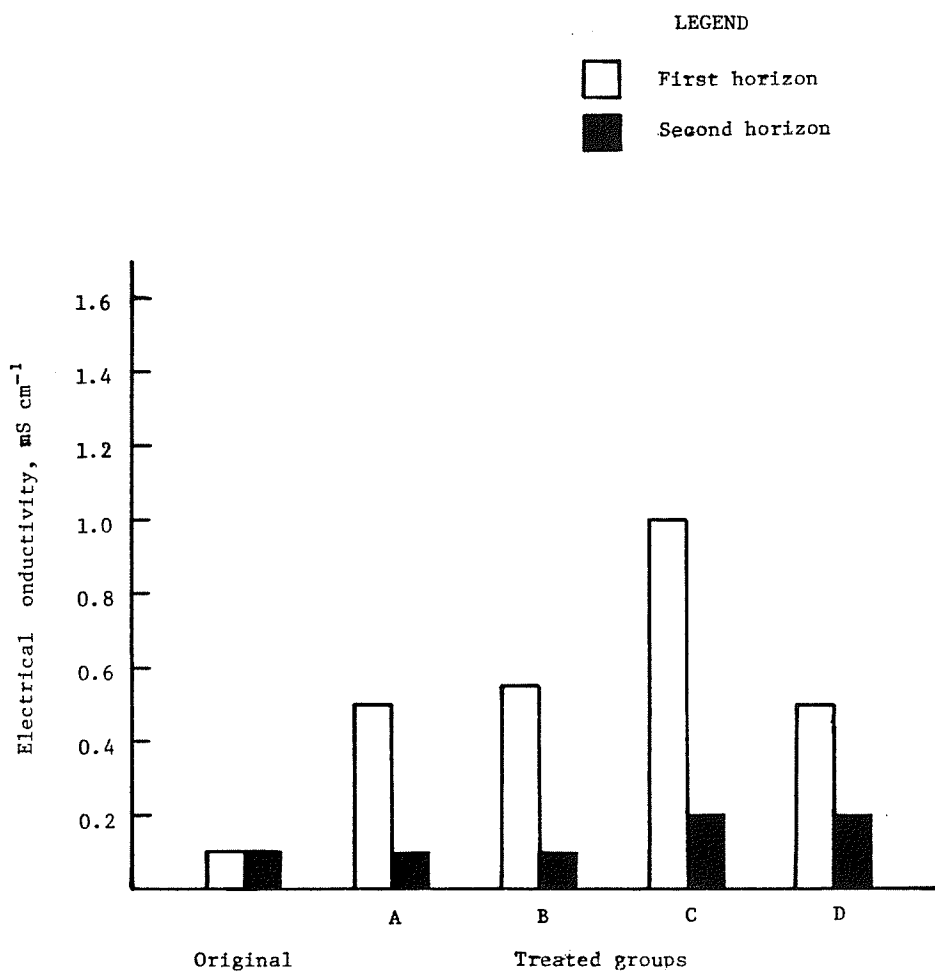


Fig. 4.6.3.3 Changes in the salinity (electrical conductivity) of the saturation extracts of the Roblin soil after irrigation with municipal sewage effluent.

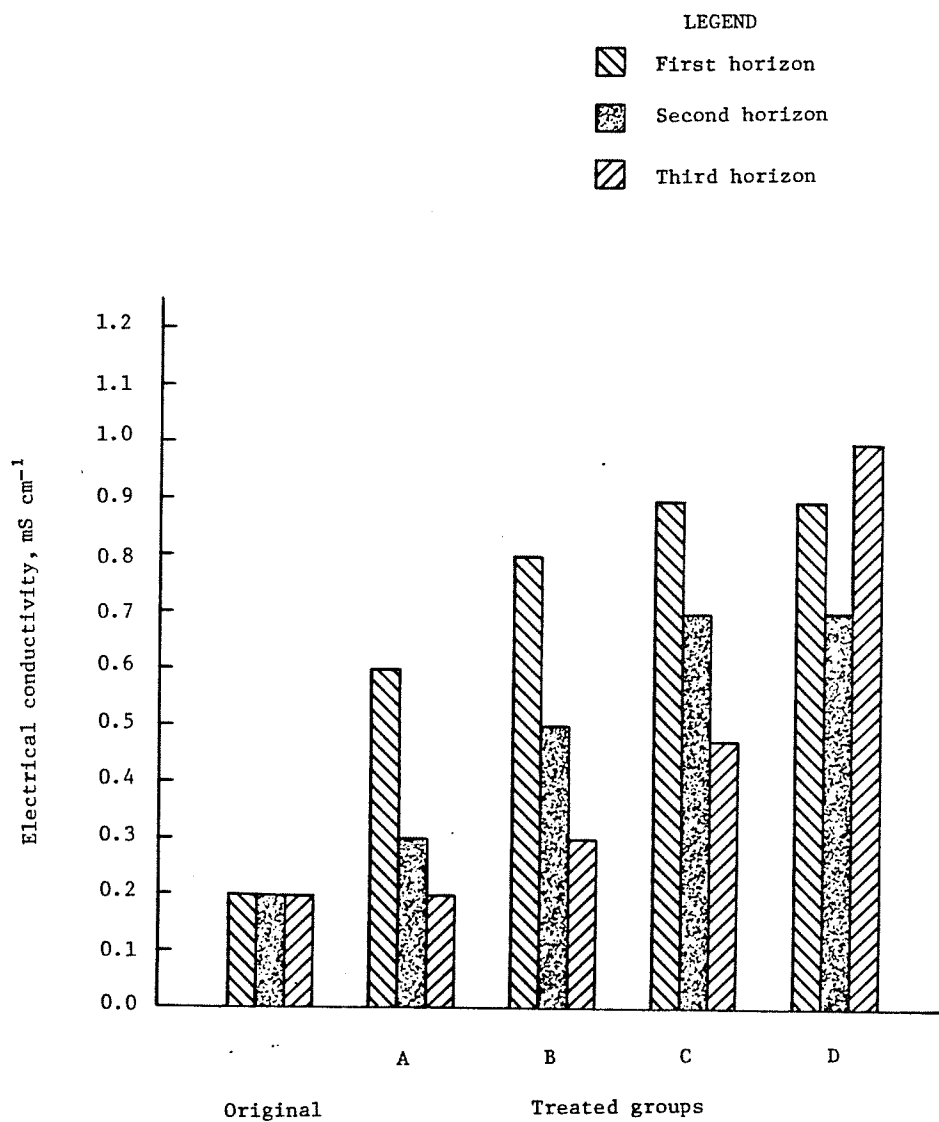


Fig. 4.6.3.4 Changes in salinity (electrical conductivity) of the saturation extracts of the Erickson soil after irrigation with municipal sewage effluent.

of the Roblin soil against an initial value of 0.1 mS cm^{-1} . The amount of effluent added to this group was the maximum. However, it was found that the increase in salinity was not proportional to the amount of effluent application. In the D- group, the amount of increase in salinity was lowest in the first horizon, although, the relative amount of effluent added was not the minimum. In the Erickson soil similar trends were also observed. The first horizons of A-, B-, and the C- groups had the highest levels of salinity. For the D- group, the third horizon had the highest salinity value. The salinity of the first horizon of the D- group was equally high as compared to the similar horizon of the C- group. The amount of effluent application to the D- group was also not the highest. There was no correlation between the increases in pH and salinity for individual groups.

Initially, the soil samples were free from chlorides as shown in Tables B-1 and B-2 of Appendix B. After the end of effluent irrigation the chloride concentration in the first horizons increased substantially. There was an increasing tendency for Cl accumulation in the lower horizons. The concentration of chlorides in the leachates was considerably low as compared to that of the effluent. As plants do not remove Cl, in this study no attempt was made to determine the Cl content of the plant tissues.

4.6.4 Trace Elements

From Tables B-1 and B-2 of Appendix B, it is clear that there were some changes in the concentration of extractable metals. The following elements were studied in the pre- and post- treatment analysis of the soils.

Copper: There was a general trend in the accumulation of Cu in the top horizons of the Roblin soil. In the second horizons there was no significant change. In the Erickson soil there was no appreciable change in the concentration of Cu in the top horizons but there was a slight change in Cu content of the lower horizons. The application levels did not have a significant effect on the amount of increase in Cu content. Loehr et al. (1979d) found that an increase in pH can greatly increase Cu adsorption in the soils. However, after the irrigation of one season with the effluent the Cu concentration was well below 1.5 ppm in all the soils even though there was a reasonably large increase in the soil pH. This is primarily due to low concentration of Cu in the effluent.

Zinc: There was a slight increase in the Zn concentration of the top horizons irrespective of the soils. In the non-cropped columns the concentration was related to the level of application. It should be recalled that the rainwater had a higher zinc concentration than the effluent. In the cropped columns a part of the applied Zn was removed by the plants as discussed in section 4.7. According to the findings of Olsen and Barber (1977) discussed in section 2.5, the phosphorus loading in this experiment was not high enough to induce Zn deficiency symptoms in plants.

Iron: There was a tendency of Fe accumulation in the top horizons. Inherently, the Erickson soils were low in Fe as compared to the Roblin soil and the Fe concentration remained proportionally low after irrigation with effluent.

Manganese: Mn concentration of the second horizons of the Roblin soil was lower than that of the first horizon before the application of effluent to the soil. At the end of the study, Mn concentration of both the horizons increased and the increase was higher in the second horizon than the first horizon. The Erickson soil responded differently to the applied Mn. There was a clear increase in the first horizon. The second and the third horizons showed a decrease.

Cadmium: There was apparently no change in the Cd concentration in both soils except a minor one in the Erickson soil. The Cd content in the effluent was virtually nil. Concern about Cd in this project will not likely arise.

Nickel: There was no significant increase in Ni content of the soils. In the Erickson soil there was a slight decrease in the Ni level in both the cropped and uncropped sections in the top horizon.

Lead: There was a slight increase in Pb concentrations of the top horizons. Probably this was due to its fixation to the organic matter.

4.6.5 Soil Organic Matter, Total Nitrogen and Total Phosphorus

From the results of the soil analysis it was observed that there was a slight increase in the percentage of organic matter in the top horizons of both soils at the end of effluent irrigation. A similar tendency was observed for the percentage of organic carbon. There was a negligibly small decrease in both organic matter and organic carbon percentage in both soils in the lower horizons.

The percentage of total N was almost stable in the soil profiles irrespective of crop cover and the level of application. The C:N ratio of the soil was about 12:1. Under aerobic conditions, the decomposition of organic matter is faster at a C:N ratio of about 10:1 (Loehr et al., 1979e). Temperature and moisture conditions of the soil also play important roles in this decomposition. The greenhouse conditions could have induced mineralization of organic nitrogen to NH_4 and NO_3 ions. This could be expected to be one of the major factors in increasing the NO_3 -N content of the soils. However, close monitoring of the amount of organic nitrogen added through irrigation was not possible.

There was an increase in the total P content in the top horizons of the Erickson soil in all groups. However, in the cropped groups of the Roblin soil the total P decreased in some horizons. Similar decreases in total P content of some horizons of the Roblin soil (without crop cover) were observed although there was no loss of P due to crop removal and loss of P in the leachates from these groups was not significant.

4.7 CROP RESPONSE

4.7.1 Yield of Dry Matter

Table H in Appendix H shows the dry matter yield from the individual boxes of both soils at the two different levels of effluent application. Table 4.7.1.1 shows the average yield of dry matter from each group of both soils in t ha^{-1} . The mass of dry matter in Table 4.7.1.1 refers to an average moisture content of 5.5 percent expressed on a wet basis. The fresh grass at the time of harvest had a moisture content of 75 percent expressed on a wet basis and the harvested mass per cut was more

than 12 t ha^{-1} which was about two times higher than that obtained in a subsequent field study without irrigation. In two cuts, the total amount of dry matter harvested ranged from 5.5 t ha^{-1} to 7.0 t ha^{-1} .

In the Roblin soil the yield of dry matter was higher at the high application level, in the Erickson soil higher yield was obtained at the lower level of effluent application, but the analysis of variance listed in Table E-3 of Appendix E shows that soil type had no particular effect on the yield of dry matter. The mean values of dry matter from both soils were not significantly different at the 0.05 level (Table E-5, Appendix E). A product moment correlation analysis (Table 4.7.1.2) was done to find out the relationship among bulk density, root mass, amount of effluent addition to individual boxes and the yield of dry matter. It was noticed that within the evapotranspiration requirements of the crop, a linear relationship existed between the yield of dry matter and the amount of effluent added. This has been common in most similar projects in the first few years of study.

A linear regression analysis between the yield of dry matter and the amount of effluent applied within the range of evapotranspiration gave a significantly high value for the coefficient of correlation. The prediction equation has the following form:

$$\text{DM} = 3.395 + 0.036 \text{ EFFL}$$

where, DM is the harvested amount of dry matter from each box expressed in g and EFFL was the depth in mm of effluent applied to the individual boxes. Initial bulk density had no impact upon the amount of dry matter harvested from each box.

Table 4.7.1.1 Yield of Dry Matter*

Soil and Treatment	Harvested Mass of Dry Matter (t ha ⁻¹)		
	Cut No.1	Cut No.2	Total
Roblin Soil			
C- Group	3.062	3.933	6.965
D- Group	2.710	2.808	5.538
Erickson Soil			
C- Group	3.315	3.147	6.462
D- Group	3.815	3.138	6.935

*

Determined at a moisture content of 5.5 percent

Table 4.7.1.2 Product Moment Correlation Analysis

Factor	Correlation between:			
	Bulk ^{**} Density	Root Mass	Dry Matter	Effluent Quantity
Bulk Density	1.0000	-0.1027	-0.2988	0.0937
Root Mass		1.0000	0.3987	0.3280
Dry Matter			1.0000	0.8513
Effluent Quantity				1.0000

**

Original bulk density of the soil in the top horizons of
of the columns

4.7.2 Nutrient Uptake

The results of plant tissue analysis of the grass harvested on the Roblin and the Erickson soils are shown in Tables F-1, and F-2 of Appendix F respectively. The first cut on the Roblin soil took place five days earlier than on the Erickson soil. The second cut was on the same day at the end of the study. It was apparent that in the first cut, plant tissues from the Roblin soil were slightly less mature than the plant tissues from the Erickson soil. In the second cut on the other hand the plant tissues from the Roblin soil were five days older than those of the Erickson soil.

The analysis of samples collected prior to the application of effluent was carried out to obtain the baseline information making it possible later to check whether effluent irrigation had any significant effect on the accumulation of certain elements in the plant tissues. These baseline samples were a mixture of stalks of the original sod and leaves which developed in the greenhouse in the period between planting and the first irrigation with effluent. In that particular analysis the concentrations of certain elements like N, Fe, and Mn were quite variable among the individual groups of each soil and between the similar groups of the two soils.

From the results of the two cuts after irrigation with effluent it was observed that the nutrient concentrations in all samples were different but within close limits. Concentration of N in the plant tissues of the Roblin soil between the two cuts were different although the concentration between the individual samples in each cut was not much different. There was an approximately 23-percent reduction in the

concentration of N in the plant tissues of the second cut as compared to the first cut. The concentration of N in the plant tissues of the Erickson soil during the first cut was slightly lower than that of the Roblin soil. In the second cut there was an 11-percent reduction in the concentration of N in the plant tissues. This concentration was slightly higher compared to the the concentration of N in the plant tissues in the second cut of the Roblin soil although, the grass in the Erickson soil grew for a relatively short period of time compared to that in the Roblin soil.

There was also wide variation in the Mn content in the plant tissues in individual groups of both soils between the two cuts. As there was a slight variation in the growth periods for each harvest, differences in maturity could have caused this unequal uptake. Another explanation of different nutrient uptake between the two cuts can be based upon the work of Palazzo (1981) who found that the uptake of nutrients was different in two separate cuts. According to him, the rate of uptake continued at a higher level for a particular growth period and then decreased.

It was further noticed that the N and P content of the plant tissues were in general lower than the minimum levels of plant nitrogen and phosphorus as suggested by the Provincial Soil Testing Laboratory. Although, the Erickson soil was deficient in phosphorus (Table 4.2) the Roblin soil had a substantially higher concentration of phosphorus in both horizons. Further, there was some addition of P through irrigation. Still then there was phosphorus deficiency in the plant tissues of the Roblin soil. On the other hand, both soils were

deficient in $\text{NO}_3\text{-N}$. Effluent application did not add any substantial amount of nitrogen in the form of $\text{NH}_4\text{-N}$ which constitutes a major portion of nitrogen in the sewage laggons located in the northern climates. The organic nitrogen which increased the $\text{NO}_3\text{-N}$ content of the uncropped soil columns can not be expected to be at similar concentrations in the storage drums as that in the sewage lagoons itself, because, organic nitrogen transforms to ammonia nitrogen at high temperature which finally escapes to atmosphere. However, such difficulties do not arise in field experiments.

Table 4.7.2.1 shows the amounts of nutrients removed by crop harvest. To calculate the uptake of the nutrients, the amount of nutrients removed by each cut was calculated separately and added to find the total uptake.

It was observed that the amount of K uptake was higher than the uptake of N. It is difficult to say whether it was luxury consumption.

Table 4.7.2.2 shows the major nutrient requirements of the individual treatment groups of both soils at the end of the experimental irrigation with municipal sewage effluent.⁶ Only nitrogen was needed in both soils for the cropped sections. The phosphorus and sulphur requirement of the Erickson soil was satisfied at the end of the season.

⁶ Recommended by the Provincial Soil Testing Laboratory

Table 4.7.2.1 Removal of Major Nutrients by the Crop

Soil and Treatment	Mass of Major Nutrients (kg ha ⁻¹)					
	N	P	K	S	Ca	Mg
Roblin Soil						
C- Group	144.3	18.2	181.0	12.6	42.0	13.3
D- Group	118.4	14.3	146.3	10.2	34.7	11.9
Erickson Soil						
C- Group	129.4	15.2	171.2	12.6	37.9	13.6
D- Group	157.5	18.1	187.0	14.5	42.5	15.3

Table 4.7.2.2 Recommended¹ Major Nutrient Application at the End of the Irrigation Season

Soil and Treatment	Mass of Major Nutrients (kg ha ⁻¹)			
	N	P	K	S
Roblin Soil				
A- Group	0	0	0	0
B- Group	0	0	0	0
C- Group	110	0	0	0
D- Group	110	0	0	0
Erickson Soil				
A- Group	0	0	0	0
B- Group	0	0	0	0
C- Group	110	0	0	0
D- Group	110	0	0	0

¹ Recommended by the Provincial Soil Testing Laboratory

4.8 FATE OF SELECTED NUTRIENTS

Changes in the status of the major nutrients in the soil columns after irrigation with effluent are presented in section 4.6 and shown in Appendix B, Tables B-1 and B-2. Crop removal of major nutrients is shown in Table 4.7.2.1 and Tables 4.3.1 and 4.3.2 show the amounts of selected chemicals leached out. Tables 4.4.4 and 4.4.5 show the amounts of nutrients added through effluent irrigation.

It is interesting to know the fate of different elements in a land treatment system because it gives an insight into pollution of soils and groundwater and into crop removal of essential and toxic elements. It can be accomplished by balance studies of the specified nutrients and chemicals.

For practical reasons such as limitations in time and resources in this study, no attempt has been made to carry out any nutrient balance studies. Phosphorus and potassium were not determined in the leachates and close monitoring of other forms of nitrogen in addition to $\text{NO}_3\text{-NO}_2\text{-N}$ in the irrigation water was not possible. Assuming that plant removal of Na was negligible, Na was not determined in the plant tissues. Above all, the study was of short duration as it was carried out to determine the basic changes in the physical and chemical properties of soils before the actual initiation of a larger field experiment.

Chapter V

CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS OF THE STUDY

1. The evapotranspiration of brome grass measured in the greenhouse was significantly higher than that expected in the Roblin area for the same duration with similar crops. Thus the soils were exposed to extremely harsh conditions.
2. Greenhouse irrigation water requirements of the grass under the simulated dry- and average- year rainfall were similar for both soil types and were not statistically significant at 5 percent level. Minor variations were caused by the differences in plant maturity and plant population.
3. The effluent was apparently free from heavy metals which impose serious environmental threats.
4. Changes in soil bulk densities after one season of irrigation with sewage effluent were not significant.
5. The water stability index of the soil aggregates was reduced considerably in the top horizons of both soils at the two treatment levels whether cropped or uncropped.
6. The root mass developed at a depth of 15 cm below the soil surface was not dependent upon the treatment level. The type of soil appeared to have an important influence on the development of root mass.

7. Although the chemical analysis of effluent did not show the presence of significant amount of $\text{NO}_3\text{-NO}_2\text{-N}$, the presence of nitrogen in other forms such as organic-N in the sewage effluent was evident from the soil and plant tissue analysis. Accumulation of N in plant tissues and the increase in $\text{NO}_3\text{-N}$ level in the uncropped soil columns showed the presence of N in the effluent in other forms.
8. The presence of phosphorus and $\text{SO}_4\text{-S}$ in the effluent replenished the P and S deficiency of the Erickson soil.
9. The accumulation of $\text{SO}_4\text{-S}$ after one season of irrigation was quite remarkable.
10. Increase in the Na content of the top horizons of both soils indicated that accumulation was proportional to the depth of application irrespective of crop cover.
11. Sodium Adsorption Ratio and electrical conductivity showed increasing trend after effluent application and the increase was higher in the top horizons.
12. The final levels of pH in the lower horizons were considerably higher than the original values.
13. Trace element concentration was not significantly different than the original values. However, in general a slightly increasing trend was observed.
14. Organic carbon, organic nitrogen and total phosphorus contents of the soil did not change significantly at the end of the study.
15. The accumulation of the above mentioned chemicals in the different horizons could be expected to be slightly different in

a field-scale study due to the method of water application. On an annual basis, their concentration in the soil will be considerably lower due to their leaching through spring runoff and intense storms.

16. Crop yield was substantially higher than that expected in the Roblin area without irrigation even though, the plant tissues were slightly deficient in nitrogen and phosphorus.

5.2 SUGGESTIONS FOR FUTURE WORK

1. A theoretical estimate of the maximum ammonium adsorption capacity of the soils by the exchange complexes should be carried out during a field-scale study to estimate the amount of ammonium nitrogen that can be retained by the soil. For this purpose, the $\text{NH}_4\text{-N}$, Ca and Mg contents of the effluent should be closely monitored preferably at the application site.
2. Phosphorus adsorption capacity of the soils should be determined in the laboratory at the beginning of a field-scale study to estimate the amount of P that can be adsorbed on the solid surfaces.
3. Groundwater samples from observation wells at the irrigation site should be analysed in regular intervals in conjunction with the samples drawn at or below the root zone using porous ceramic cups or lysimetric techniques.
4. A leaching percentage based upon the minimum reduction in crop yield and groundwater pollution should be determined.

5. Monitoring of the different forms of nitrogen present in the effluent should be given high priority.
6. A mass balance study of the applied major nutrients such as N, P, S and cations like Na, Cl should be done at the end of each season.
7. In case of excessive concentration of N in the effluent, measures supporting denitrification in soil should be explored.
8. Close monitoring is suggested for elements like B and Mn as their presence in the effluent is relatively high.
9. More research is recommended to find out the suitability of effluent irrigation for growing grain, fodder and vegetable crops using different methods of irrigation.

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Appendix A

CHARACTERISTICS OF DOMINANT SOILS

Table A Characteristics of the Dominant Soils at the Roblin Wastewater Irrigation Project

Parameters	Soil Type	
	Roblin (RBN)	Erickson (ECK/C)
No. of sites	31	186
Dominant texture		
Horizons		
A	Loam	Loam
B	Clay	Clay loam
C	Clay loam	Clay loam
Average thickness (cm)		
A	27.9	18.7
A+B	68.6	41.6
Dominant class		
Drainage	Poorly drained	Moderate to well drained
Surface runoff	Very slow	Moderate
Perviousness	Medium	Medium to slow
Erosion		
Water	nil	Slight
Stoniness	nil	Slight
Dominant slopes		
Type	Complex	Complex
Range, %	Less than 2	2 to 9
Position	Depression	Midslope
Land use	Crops	Crops
Soil class	Orthic Dark Gray	Humic Luvic
	Chernozem	Gleysol
Parent material	Morain till	Morain till

Appendix B
RESULTS OF SOIL ANALYSIS

Table B-1 Results of Soil Analysis for the Roblin Soil at the Conclusion of the Experiment

Parameters	Treated Soil									
	Original Soil		Cropped				Non-Cropped			
			C-Group		D-Group		A-Group		B-Group	
	First	Second	First	Second	Horizons		First	Second	First	Second
pH (units)	6.4	7.1	7.1	7.4	7.3	7.3	7.2	7.7	7.2	7.5
EC (mS cm ⁻¹)	0.1	0.1	1.0	0.2	0.5	0.2	0.5	0.1	0.6	0.1
NO ₃ -N (ppm)	1.2	0.2	1.8	1.0	1.6	1.4	16.2	2.6	21.4	1.0
(kg ha ⁻¹)	6.7	1.8	10.1	8.8	9.0	12.3	90.7	22.9	119.8	8.8
Avail. P (ppm)	38.4	38.8	38.2	41.8	37.6	39.6	48.8	49.8	50.8	42.8
(kg ha ⁻¹)	215.0	388.3	213.9	367.8	210.6	348.5	273.3	438.2	284.5	376.6
Avail. K (ppm)	225.0	137.0	320.0	182.0	300.0	195.0	300.0	208.0	300.0	195.0
(kg ha ⁻¹)	1260	1206	1792	1602	1680	1711	1680	1830	1680	1716
SO ₄ -S (ppm)	2.4	2.0	100.0	10.0	46.0	8.0	28.0	4.0	76.0	4.0
(kg ha ⁻¹)	13.4	17.6	560.0	88.0	258.0	70.4	156.8	35.2	425.6	35.2
Exchangeable ions (meq L ⁻¹)										
Cl	0.00	0.00	22.20	2.50	17.00	1.80	10.00	0.00	20.00	0.00
Cation Exchange Capacity (CEC) (meq 100 g ⁻¹)	23.0	12.4								
Ca	149.7	109.8	154.7	79.8	149.7	74.8	159.7	89.8	164.7	79.8
Mg	23.0	14.0	35.5	16.4	29.6	15.6	26.3	18.1	30.4	17.3
Na	1.17	1.04	22.6	1.60	14.30	1.30	4.22	1.35	9.57	0.95
DPTA extractable (ppm)										
Cu	0.85	0.56	0.71	0.38	0.98	0.48	1.30	0.58	1.30	0.70
Zn	5.30	1.20	6.00	1.40	7.1	1.70	6.10	1.40	6.70	2.30
Fe	130	88	120	71	130	72	140	91	140	100
Mn	11.0	2.5	14.0	22.0	39.0	22.0	32.0	35.0	44.0	58.0
Cd	0.24	0.08	0.22	0.04	0.19	0.06	0.24	0.08	0.16	0.04
Ni	1.80	0.68	1.40	0.21	2.30	0.13	3.10	0.58	1.80	0.52
Pb	1.10	0.53	1.20	0.55	1.60	1.00	1.90	0.74	1.70	0.92
% Organic Matter	5.1	1.7	5.4	1.2	5.7	0.7	6.1	1.3	5.4	1.2
% Organic Carbon	3.0	1.0	3.6	0.7	3.4	0.4	3.6	0.8	3.6	0.7
% CaCO ₃	0.60	0.73	0.73	0.84	0.32	0.48	0.27	0.45	0.66	1.40
% Total N	0.23	0.08	0.25	0.07	0.25	0.07	0.25	0.01	0.25	0.07
Total P (ppm)	495	495	472	497	445	345	330	215	535	420

Table B-2 Results of Soil Analysis for the Erickson Soil at the Conclusion of the Experiment

Parameters	Treated Soil														
	Original Soil			Cropped									Non-Cropped		
				C-Group			D-Group			A-Group			B-Group		
	First	Second	Third	First	Second	Third	First	Second	Third	First	Second	Third	First	Second	Third
pH (units)	6.9	7.5	7.6	7.7	7.6	8.0	7.9	7.8	8.0	7.4	7.8	8.3	7.9	7.8	8.2
EC (mS cm ⁻¹)	0.2	0.2	0.2	0.9	0.7	0.5	0.9	0.7	1.0	0.6	0.3	0.2	0.8	0.5	0.3
NO ₃ -N (ppm)	1.2	0.4	0.6	0.8	0.2	0.2	2.2	0.2	0.2	31.8	7.4	2.2	25.4	13.4	3.2
(kg ha ⁻¹)	3.4	2.5	3.5	2.2	1.0	1.2	5.7	1.0	1.2	89.0	37.0	12.9	71.1	67.0	18.7
Avail. P (ppm)	10.4	4.0	3.8	16.0	3.6	2.8	16.0	4.0	2.8	13.2	4.4	3.2	15.4	3.8	1.8
(kg ha ⁻¹)	29.1	22.4	22.0	44.8	18.0	16.4	41.6	20.0	16.4	37.0	22.0	18.7	43.1	19.0	10.5
Avail. K (ppm)	258	160	140	273	167	150	295	195	125	274	195	172	258	185	140
(kg ha ⁻¹)	722	896	812	764	835	878	767	975	732	767	975	1007	722	925	819
SO ₄ -S (ppm)	2.6	2.0	2.2	62.0	52.0	50.0	82.0	54.0	19.0	28.0	6.0	3.6	62.0	18.0	3.0
(kg ha ⁻¹)	7.3	11.2	12.8	173.6	260.0	292.6	213.2	270.0	111.2	78.4	30.0	21.1	173.6	90.0	17.6
Exchangeable ions (meq L ⁻¹)															
Ca	184.6	249.5	259.5	179.6	304.4	354.3	204.6	284.4	259.5	184.6	254.5	244.5	199.6	244.5	259.5
Mg	30.4	32.1	32.9	46.1	32.9	34.6	41.9	35.4	33.7	30.1	30.1	32.9	37.0	32.1	35.4
Na	1.87	0.70	1.57	22.20	9.10	4.30	21.70	5.70	1.70	5.90	1.30	1.30	13.90	2.00	1.40
Cl	0.0	0.0	0.0	13.8	8.8	6.8	24.5	12.5	5.3	6.8	1.0	0.0	15.8	3.0	0.0
Cation Exchange Capacity (meq 100g ⁻¹)	26.6	21.7	18.7												
DPTA extractable (ppm)															
Cu	0.77	1.10	1.00	0.72	0.87	1.00	0.56	0.83	1.20	0.56	0.84	0.99	0.59	0.83	1.10
Zn	1.4	0.4	0.6	3.8	0.9	0.8	3.2	0.6	0.5	3.0	0.6	0.4	4.1	0.8	0.7
Fe	31	17	11	95	21	15	54	16	10	29	15	10	39	22	16
Mn	2.4	8.8	5.2	8.1	5.4	3.8	8.7	4.8	3.5	7.8	4.8	4.9	7.5	5.3	8.6
Cd	0.16	0.06	0.11	0.25	0.19	0.18	0.13	0.03	0.05	0.14	0.13	0.05	0.14	0.09	0.10
Ni	2.00	1.60	0.66	1.20	1.20	0.35	1.00	1.30	0.41	0.96	1.00	0.44	0.85	1.40	0.56
Pb	0.56	0.52	0.64	1.60	1.70	1.00	0.01	1.20	1.10	1.00	1.00	0.75	1.30	1.60	1.30
% Organic Matter	4.8	2.2	1.4	5.4	2.1	1.0	5.1	2.1	0.80	4.1	1.7	1.1	5.2	2.2	1.3
% Organic Carbon	2.8	1.3	0.8	3.2	1.2	0.6	3.0	1.2	0.5	2.4	1.0	0.6	3.1	1.3	0.8
% CaCO ₃	0.95	4.00	20.10	0.11	2.7	19.50	0.30	3.60	19.60	0.80	4.10	20.80	0.10	1.40	19.00
% Total N	0.22	0.11	0.07	0.23	0.11	0.07	0.22	0.11	0.07	0.21	0.11	0.07	0.23	0.12	0.07
Total P (ppm)	190	140	155	280	155	130	240	130	130	205	155	140	215	130	155

Table B-3 Detailed Textural Analysis

Sample Description	Sand (%)				Very Fine	Total Sand (%)	Silt (%)	Clay (%)	Texture
	Very Coarse	Coarse	Medium	Fine					
Roblin Soil									
First horizon (0 to 40 cm)	2	3	6	8	6	25	54	21	Silt Loam
Second horizon (40 to 100 cm)	2	5	10	14	11	42	42	16	Loam
Erickson Soil									
First horizon (0 to 20 cm)	4	8	11	11	6	40	34	26	Loam
Second horizon (20 to 60 cm)	2	7	12	12	8	41	33	26	Loam
Third horizon (60 to 100 cm)	4	6	9	9	9	36	38	26	Loam

Table B-4 Gravimetric Moisture Content of the Air-dried Soil

Sample Description	Sample No.1 (percent)	Sample No.2 (percent)	Mean (percent)
Roblin Soil			
First horizon (0 to 40 cm)	5.18	5.38	5.28
Second horizon (40 to 100 cm)	2.47	2.42	2.45
Erickson Soil			
First horizon (0 to 20 cm)	4.34	4.36	4.35
Second horizon (20 to 60 cm)	4.17	4.21	4.19
Third horizon (60 to 100 cm)	3.43	3.41	3.42

Table B-5 Field-measured Soil Bulk Densities

Sample Description	Bulk Density of Samples (g cm ⁻³)				
	No.1	No.2	No.3	No.4	Mean
Roblin Soil					
First horizon (0 to 40 cm)	1.34	1.62	1.55	1.62	1.53
Second horizon (40 to 100 cm)	1.92	1.82	1.91	1.61	1.81
Erickson Soil					
First horizon (0 to 20 cm)	1.52	1.72	1.68	1.55	1.62
Second horizon (20 to 60 cm)	1.82	1.66	1.45	1.46	1.60
Third horizon (60 to 100 cm)	1.44	1.58	1.49	1.53	1.51

Table B-6 Percentage of Particles Greater than 2.0 mm

Sample Description	Sample No.1	Sample No.2	Mean
Roblin Soil			
First horizon (0 to 40 cm)	2.4	3.5	2.95
Second horizon (40 to 100 cm)	2.3	4.1	3.20
Erickson Soil			
First horizon (0 to 20 cm)	9.5	6.6	8.05
Second horizon (20 to 60 cm)	3.5	2.8	3.15
Third horizon (60 to 100 cm)	4.3	3.9	4.10

Appendix C

RESULTS OF LEACHATE ANALYSIS

Table C-1 Quality of Leachates Collected under the Roblin Soil

Parameter	Treatment Group			
	A	B	C	D
pH	7.70	8.36	8.07	7.53
Electrical Condu- ctivity (mS cm ⁻¹)	1.25	1.20	1.22	2.20
Na (mg L ⁻¹)	69.50	55.50	63.93	189.00
Ca (mg L ⁻¹)	196.0	126.7	182.3	309.0
Mg (mg L ⁻¹)	51.7	33.9	51.8	72.5
Total Kjeldahl Nitrogen (mg L ⁻¹)	2.4	2.3	2.2	2.9
NO ₃ -NO ₂ -N (mg L ⁻¹)	6.60	1.11	2.54	8.70
SO ₄ -S (mg L ⁻¹)	365.0	190.0	356.7	530.0
Cl (mg L ⁻¹)	78.0	82.5	61.0	440.0
B (mg L ⁻¹)	0.52	1.55	0.60	2.40
HCO ₃ (mg L ⁻¹)	216	391	N.A.	N.A.
Total CaCO ₃ (mg L ⁻¹)	177	321	N.A.	N.A.
Filtrable Residue (mg L ⁻¹)	1000	835	1300	1870
Calculated Sodium Adsorption Ratio (SAR)	1.13	1.12	1.07	2.49

Note: N.A. - Information not available because of small amount of leachates collected

Table C-2 Quality of Leachates Collected under the Erickson Soil

Parameter	Treatment Group			
	A	B	C	D
pH	8.30	8.27	7.80	8.22
Electrical Conductivity (mS cm ⁻¹)	0.86	0.64	1.00	1.16
Na (mg L ⁻¹)	28.0	13.9	43.6	41.4
Ca (mg L ⁻¹)	106.7	75.9	130.0	139.2
Mg (mg L ⁻¹)	44.4	49.6	50.5	61.2
Total Kjeldahl Nitrogen (mg L ⁻¹)	2.25	1.53	2.10	1.67
NO ₃ -NO ₂ -N (mg L ⁻¹)	13.30	8.60	3.40	0.72
SO ₄ -S (mg L ⁻¹)	75.0	45.7	73.0	65.0
Cl (mg L ⁻¹)	55.0	28.3	15.0	193.0
B (mg L ⁻¹)	0.64	1.07	0.38	1.53
HCO ₃ (mg L ⁻¹)	264	294	442	298
Total CaCO ₃ (mg L ⁻¹)	216	241	362	244
Filtrable Residue (mg L ⁻¹)	560	443	620	793
Calculated Sodium Adsorption Ratio (SAR)	0.57	0.30	0.82	0.73

Appendix D

ESTIMATION OF EVAPOTRANSPIRATION FOR ROBLIN AREA

Blaney-Criddle Formula for Determining Evapotranspiration:

$$U = \sum u = KF$$

$$u = kf$$

where,

U = Consumptive use of the crop for the entire growing period

K = Empirical consumptive use crop coefficient for the season

F = Sum of monthly/periodic consumptive use factors for the growing season (sum of the products of mean monthly temperature and monthly percentage of day light hours of the year)

u = Periodic consumptive use

k = Empirical consumptive use coefficient for the particular growing period

f = Periodic consumptive use factor

$$f = (t.p)/100$$

where,

t = Mean monthly or periodic air temperature, °F

Modifications:

$$k = k_t \cdot k_c$$

where,

k_t = A climatic coefficient which is related to mean air temperature

$$k_t = 0.0173t - 0.314$$

k_c = A coefficient reflecting the growth stage of crop

Note: The following table shows the detailed calculations as per the U. S. Department of Agriculture Technical Release No. 21.

Table D Evapotranspiration of Grass in the Roblin Area (Blaney-Criddle Method)

Month or Period	Midpoint of Period	Accumulated Days to Midpoint	Accumulated Percent of Growing Season	Mean Period Air Temperature, t (°F)	Daylight Hours, p (percent)	Consumptive Use Factor, f	Climatic Coefficient, k _t	Growth Stage Coefficient, k _c	Consumptive Use Coefficient, k=k _c .k _t	Consumptive Use, u u = k.f (inch)	Consumptive Use (mm)
May 1	May 15	15	13.4	49.4	10.76	5.32	0.54	0.90	0.49	2.61	66.3
June 1	June 15	46	41.8	57.7	11.02	6.36	0.69	0.92	0.63	4.01	101.9
July 1	July 15	76	69.1	64.0	11.09	7.10	0.80	0.92	0.74	5.25	133.4
August 1	August 9	101	91.8	63.5	6.10	3.87	0.78	0.91	0.71	2.75	69.9
May 1 to August 18										14.62	371.5
August 1	August 15	107		62.7	10.05	6.30	0.77	0.91	0.70	4.41	112.0
Sept. 1	Sept. 15	138		51.9	8.47	4.40	0.59	0.87	0.51	2.25	57.2
May 1 to Sept. 30										18.53	470.7

Appendix E
STATISTICAL ANALYSIS

Table E-1 Analysis of Variance for Changes in Bulk Density

Items	Source	Degree of freedom	Sum of square	Mean square	F value ¹
First horizon					
	Soil	1	0.00012	0.00012	0.20
	Crop	1	0.00097	0.00097	2.70
	Soil*Crop	1	0.00006	0.00006	0.15
	Effluent (Soil)	2	0.00119	0.00059	1.66
	Effluent (Soil*Crop)	2	0.00072	0.00036	0.19
	Error	32	0.06166	0.00206	
	Total	39	0.06472		
Second horizon					
	Soil	1	0.00054	0.00054	0.05
	Crop	1	0.00804	0.00804	2.89
	Soil*Crop	1	0.00080	0.00080	0.29
	Effluent (Soil)	2	0.02197	0.01099	3.95
	Effluent (Soil*Crop)	2	0.00557	0.00279	1.87
	Error	32	0.04754	0.00149	
	Total	39	0.08446		
Third horizon					
	Soil	0	0.00000	N.A.	N.A.
	Crop	1	0.00359	0.00359	9.27
	Soil*Crop	0	0.00000	N.A.	N.A.
	Effluent (Soil)	1	0.00328	0.00328	8.46
	Effluent (Soil*Crop)	1	0.00039	0.00039	0.21
	Error	16	0.02952	0.00184	
	Total	19	0.03678		

¹ F values not associated with any symbol are insignificant
N.A. - Not determined due to zero degree of freedom

Table E-2 Analysis of Variance for Root Mass

Source	Degrees of freedom	Sum of squares	Mean Squares	F value
Soil	1	0.00498	0.00498	24.42*
Effluent(Soil)	2	0.00041	0.00021	0.14
Error	16	0.02329	0.00146	
Total	19	0.02867		

* Significant at 0.05 level

Table E-3 Analysis of Variance for Dry Matter

Source	Degrees of freedom	Sum of squares	Mean squares	F value ²
Soil	1	13.0896	13.0896	0.26
Effluent(Soil)	2	100.2897	50.1448	1.30
Error	16	617.1703	38.5713	
Total	19	730.5496		

² F Values not associated with any symbol are insignificant

Table E-4 Duncan's Multiple Range Test for Mean Values of the Changes in Bulk Density

Parameters	Changes in Bulk Density (g cm^{-1})		
	First horizon	Second horizon	Third horizon
Soil type			
Roblin	0.008 ^a	0.042 ^b	N.A.
Erickson	0.012 ^a	0.049 ^b	0.034
Crop type			
With crop	0.015 ^c	0.060 ^d	0.048 ^e
Without crop	0.005 ^c	0.031 ^d	0.021 ^e

N.A. - Third horizon does not exist

a, b, c, d, and e

Mean values are not significantly different at 0.05 level

Table E-5 Duncan's Multiple Range Test for Mean Values of Root Mass¹ and Dry Matter²

Soil type	Root Mass (g)	Dry Matter (g)
Roblin	0.117 ^a	25.01 ^a
Erickson	0.086 ^b	26.63 ^a

¹ Mass of root mass per sample

² Mass of dry matter harvested per box

a or b Means with different letter are significantly different at 0.05 level

Appendix F

RESULTS OF PLANT TISSUE ANALYSIS

Table F-1 : Results of Plant Tissue Analysis for the Roblin Soil

Item	Before Effluent Irrigation		After Application			
	D	C	First Cut		Second Cut	
			Treatment Group		D	C
Major Nutrients (% of dry matter)						
N	2.1	1.6	2.4	2.4	1.9	1.8
P	0.21	0.19	0.26	0.19	0.26	0.25
K	2.1	1.9	2.6	2.7	2.5	2.5
S	0.18	0.17	0.19	0.18	0.18	0.18
Ca	0.49	0.74	0.67	0.64	0.59	0.57
Mg	0.17	0.22	0.22	0.19	0.21	0.19
Major Nutrients (ppm)						
Zn	31	37	24	24	21	20
Cu	10.0	11.0	5.8	6.3	6.5	5.3
Fe	53	111	69	50	44	56
Mn	77	114	95	79	110	80
Cd	0.8	0.7	1.5	0.3	0.7	0.9
Ni	N.A.	0.4	0.6	2.5	1.8	0.7
Pb	N.A.	2.7	0.4	1.2	0.7	0.2
Mb	N.A.	4.4	1.3	1.3	0.7	0.7

N.A. - Information not available due to smaller size of sample

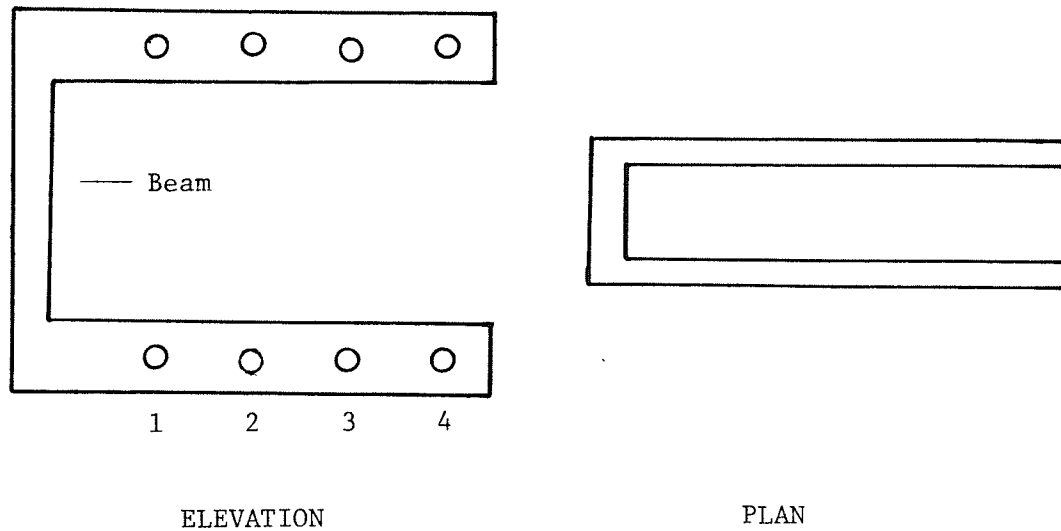
Table F-2 Results of Plant Tissue Analysis for the Erickson Soil

Item	Before Effluent Irrigation		After Application			
	D	C	First Cut		Second Cut	
			Treatment Group		D	C
Major Nutrients (% of dry matter)						
N	2.6	1.3	2.4	2.1	2.1	1.9
P	0.26	0.21	0.26	0.22	0.26	0.25
K	2.9	1.7	2.6	2.6	2.8	2.7
S	0.27	0.23	0.19	0.20	0.23	0.19
Ca	0.67	0.57	0.67	0.62	0.54	0.55
Mg	0.20	0.20	0.22	0.22	0.22	0.20
Minor Nutrients (ppm)						
Zn	42	42	24	23	21	24
Cu	11.0	11.0	5.8	6.7	6.5	6.0
Fe	153	173	69	65	62	230
Mn	114	121	95	115	140	139
Cd	0.4	0.4	1.0	1.0	1.0	1.1
Ni	1.0	0.1	0.1	0.1	0.9	2.3
Pb	0.9	1.9	0.9	0.2	1.7	1.2
Mb	N.A.	4.2	1.3	1.1	0.7	0.5

N.A. -- Information not available due to smaller size of sample

Appendix G
CALIBRATION OF TRANSDUCER

Calibration Details for the Transducer



Scale 1:2

Calibration Equations:

1.

$$y_2 = 2.109 + 14.521 x_2$$

$$r^2 = 0.999939$$

Linearity = 0.57 percent

2.

$$y_3 = 10.024 + 20.732 x_3$$

$$r^2 = 0.999983$$

Linearity = 0.27 percent

Note:

1. x and y refer to applied load (kg) and indicated strain (micro-strain) respectively.
2. Suffix 2 and 3 refer to the second and third hole from the beam.
3. 'r' is the coefficient of correlation.

Appendix H
YIELD OF DRY MATTER

Table H Yield of Dry Matter for Brome grass*

Treatment Group and Number	Yeild of Dry Matter(g) per Box		
	Cut No.1	Cut No.2	Total
Roblin Soil			
D- Group			
Box No.			
6	13.40	14.00	27.40
7	14.30	14.46	28.76
14	4.65	5.77	10.42
15	8.10	8.27	16.37
19	13.75	13.66	27.41
Mean	54.20	56.16	110.36
C- Group			
Box No.			
8	11.00	15.65	26.50
16	12.61	18.38	30.99
17	8.50	12.60	21.10
18	17.08	16.56	33.64
20	12.05	15.46	27.51
Mean	61.24	78.65	139.89
Erickson Soil			
D- Group			
Box No.			
24	19.60	16.14	35.74
28	11.85	9.82	21.67
32	11.80	9.67	21.47
33	18.25	13.46	31.71
36	14.80	13.66	28.46
Mean	76.30	62.75	139.05
C- Group			
Box No.			
29	12.60	13.21	25.81
30	13.25	12.63	25.88
31	15.35	14.13	29.48
37	8.50	8.54	17.04
39	16.60	14.42	29.02
Mean	66.30	62.93	129.23

* Determined at a moisture content of 5.5 percent