DISTRIBUTION OF SOIL SALINITY IN DRY BEAN (*PHASEOLUS VULGARIS* L.) FIELDS: ASSESSMENT AND IMPACT QUANTIFICATION

BY

ROBERT J. BROGAN

A Thesis
Submitted to the Faculty of Graduate Studies
In Partial Fulfillment of the Requirements for the Degree of

MASTER OF SCIENCE

Department of Plant Science
University of Manitoba
Winnipeg, Manitoba

THE UNIVERSITY OF MANITOBA

FACULTY OF GRADUATE STUDIES

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MASTER'S THESIS/PRACTICUM FINAL REPORT

The undersigned certify that they have read the Master's Thesis/Practicum entitled:

Distribution of Soil Salinity in Dry Bean (*Phaseolus vulgaris* L.) Fields:

Assessment and Impact Quantification

submitted by

ROBERT J. BROGAN

in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

The Thesis/Practicum Examining Committee certifies that the thesis/practicum (and oral examination if required) is:

Approved
(Approved or Not Approved)

☑ Thesis

☐ Practicum

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Date: August 12, 2005

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

Brogan, Robert John. M.Sc., The University of Manitoba, July, 2005. Distribution of Soil Salinity in Dry Bean (*Phaseolus vulgaris* L.) Fields: Assessment and Impact Quantification. Advising professor: Dr. Jane C. Froese.

Increased grower concern over the effect of soil salinity on dry bean crop production has precipitated the need for inexpensive but effective methods of assessing soil salinity in the field and measuring its impact on dry bean crops. The objectives of this study were to, firstly, assess the extent and severity of soil salinity in dry bean fields in southern Manitoba and to develop methods of mapping soil salinity utilizing the Veris 3100, and secondly, to evaluate the impact of soil salinity on dry bean crop productivity within these same fields. These two main objectives were approached in two separate, but simultaneous experiments.

Four dry bean fields in southern Manitoba were included in this study, three in 2003 and one in 2004. In the first experiment, ordinary kriged prediction surfaces were created from apparent electrical conductivity (EC_a) surveys and then correlated to the electrical conductivity of a saturated soil past extract (EC_e) of soil samples collected from the same location using multivariate linear regression. Soil salinity assessment using depth weighted measurements of EC_a were found to be extremely effective. Highly significant correlations between EC_a and EC_e were obtained, with r^2 (coefficient of determination) values of approximately 0.9.

In the second experiment, a 10-ha evaluation zone was selected out of each field from the EC_a surveys collected in the first experiment, in which five treatments of salinity were delineated and established. Across all site-years, average root-zone salinity (EC_e) values ranged from a low of 0.78 dS m^{-1} to a high of 11.16 dS m^{-1}. The lowest salinity

treatments resulted in significantly greater crop biomass, grain yield, and harvested seed size than the highest salinity treatments. Salinity treatment did not have a marked impact on crop emergence and seedling survival or grain protein content. The concentration of root-zone salinity that resulted in a 50% decrease in relative crop yield (C_{50}) ranged between 4.88 and 8.35 dS m^{-1}.

This project successfully assessed soil salinity using measurements of EC_a collected with the Veris 3100, and established C_{50} levels for edible beans in select Manitoba fields.

FORWARD

This thesis is written in manuscript style, with each manuscript having it's own abstract, introduction, materials and methods, and results and discussion sections. There is a general introduction and review of the literature prior to the manuscripts, followed by the general discussion and conclusions, and the literature cited.

1 INTRODUCTION

Dry beans (*Phaseolus vulgaris* L.) are an excellent source of dietary protein, and for that reason it is one of the most important grain legume crops grown around the globe (Salunkhe et al., 1989). Manitoba is Canada's leading producer of dry beans, annually representing approximately half of national production (Manitoba Agriculture and Food, 2003). Over the last decade, the expansion of dry beans in particular, and pulse crops in general, has provided sound economic returns for many Manitoba producers, rendering it one of the great success stories of the agricultural industry in this province. However, this expansion has resulted in an increased concern over the sustainability of growing these crops because of their interaction with soil salinity.

Dry beans are classified as glycophytes, and are particularly sensitive to salinity stress (Maas, 1990; Steppuhn et al., 2005b). Soil salinity adversely affects dry bean production during germination and emergence (Bayuelo-Jimenez et al., 2002a), vegetative growth (Nieman and Bernstein, 1959; Cordivilla et al., 1995; Bayuelo-Jiménez et al., 2003), and results in severely reduced crop yield at relatively low levels of salinity (Magistad et al., 1943; Bernstein and Ayers, 1951; Nieman and Bernstein, 1959; Osawa, 1965; Hoffman and Rawlins; 1970). Crop salt tolerance is most often assessed using a two-piece linear yield response model, proposed by Maas and Hoffman (1977). Recent work by Steppuhn et al. (2005a) suggests that salinity tolerance modelling based on a non-linear response function of crop growth to increasing salinity would most closely reflect agricultural crop response to root-zone salinity.

Soil salinity is an important factor limiting crop production in the prairie provinces of Canada, and indeed around the world. At last report, most prairie farmland

(62%) has less than 1% of its area affected by salinity; 36% has 1-15% of its lands affected; and 2% has more than 15% of its lands affected (Eilers et al., 1995). In order to monitor the risk of increasing soil salinity, and allow producers to better manage their agricultural land base under saline conditions, rapid and cost-effective methods of determining the extent and severity of soil salinity are required.

Soil salinity is most often assessed on a field basis using apparent electrical conductivity (EC_a), a measurement that reflects the ability of the bulk soil to carry an electrical current, a relationship that has been shown to relate strongly to soil salinity (Rhoades et al., 1999). Since the early 1980s, the standard method of measuring soil salinity from field measurements of EC_a has been using electromagnetic induction techniques with the EM38 (Geonics Ltd, Mississauga, ON). However, this method does have disadvantages in terms of the difficulty and time associated with making mobile geo-referenced field measurements of EC_a. A recently developed technology for measuring soil EC_a directly, called the Veris 3100 (Veris Technologies, Salina, KS), possesses a number of more user friendly and time-saving innovations in comparison to the EM38. However, there have, as yet, been no published studies using this particular technology for soil salinity assessment.

This research project examined soil salinity and its impact on dry bean crops in southern Manitoba. The research effort included two main experiments encompassing the following objectives: Firstly, to assess the extent and severity of soil salinity in selected dry bean fields in southern Manitoba and to develop methods of mapping soil salinity utilizing the Veris 3100, and secondly, to evaluate the impact of soil salinity on dry bean crop productivity within these same fields, modelling the salt tolerance of dry

beans using methods proposed by Steppuhn et al. (2005a). The effect of soil salinity on dry bean crop yield in a field environment is a relationship that has not been evaluated in previous studies and could allow Manitoba producers to effectively predict and manage the impact of soil salinity on their dry bean crops.

2 LITERATURE REVIEW

2.1 Soil Salinity

Through ancient times to the present, soil salinity has been one of the most limiting crop production factors in the world. It is said that when Hun Attila's Asian warriors moved westward, he cowed his enemies by threatening to throw salt on their lands (Jenny, 1980). According to Munns (2005), over 6% of the world's land surface is salt-affected (i.e., influenced by either soil salinity or sodicity), covering some 831 million hectares (Mha). Much of the world's land surface is not cultivated, but a significant proportion of cultivated land is salt-affected. Of the current 230 Mha of irrigated land, 45 Mha (19.5 %) are salt-affected and of the 1,500 Mha under dryland agriculture, 32 Mha (2.1%) are salt-affected to varying degrees (Munns, 2005).

With ever increasing global population and world food demand, more drylands will be put into agricultural production. This expansion will be achieved mainly with irrigation, such that the area of salt-affected land will likely increase (Metternicht and Zinck, 2003). The importance of improving our overall crop production cannot be understated, and it is the driving force behind an intensive research initiative to increase our understanding of the effects of soil salinity on crop production, as well as to develop methods to reduce its impact.

The term salinity refers to the major dissolved inorganic solutes (primarily Na^+, Mg^{2+}, Ca^{2+}, K^+, Cl^-, SO_4^{2-}, HCO_3^-, NO_3^-, and CO_3^{2-}) in aqueous samples. When applied to soils, it includes the soluble plus readily dissolvable salts in the soil (Rhoades et al., 1999). In a general sense, a saline soil can be defined as one having a high enough concentration of solutes in the plant root-zone to adversely affect plant growth (Eilers et

al., 1995; Munns, 2005). It must be noted, however, that some level of dissolved salts is highly desirable in the plant root zone as many of them are nutrients essential for plant growth.

2.1.1 Extent and Distribution of Saline Soils in Canada

Over 79% of the agricultural land-base in Canada is located in the prairie provinces: 36.3 Mha as cultivated or tame land and 17.2 Mha as permanent pastures, with the vast majority of soil salinity found in this region. Of this agricultural land, it is estimated that salinity affects 12.2 Mha, whilst 2.3 Mha has been estimated to be severely saline, indicating that non-irrigated crop yields would be lowered by 25% or more. An estimate of the prairie agricultural land showing slight to moderate salinity indicated that low level salinity across the Canadian prairies covers about seven Mha of arable land and three Mha of permanent pasture (Munns, 2005). Figure 2.1 shows the estimated location and extent of salinized soils in the prairie provinces, created and verified in 1991 from existing salinity information (Eilers et al., 1995).

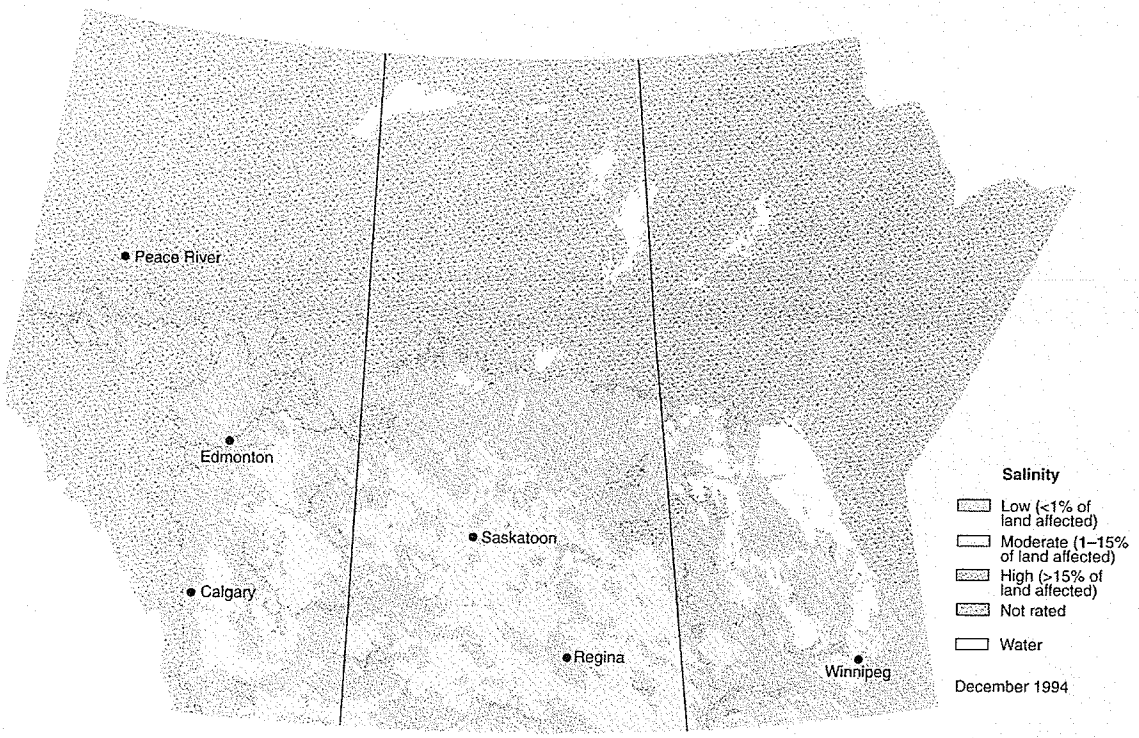

Figure 2.1. Surface salinity of prairie agricultural soils (from Eilers et al., 1995)

2.1.2 Risk of Increasing Soil Salinization on the Canadian Prairies

Eilers et al. (1995) created a salinity risk index (SRI) that was used to rank individual land areas on the Canadian prairies according to the likelihood that the salinity level will change within each area. The risk of salinity increasing in a given area was based on current extent of salinity, slope of land (representing topography), soil drainage, aridity (representing precipitation and evaporation), and surface cover (representing land use and land management practices). Using the SRI, Figure 2.2 displays the risk (based on 1991 farming practices) of increasing salinization for the prairie provinces. Under 1991 farming practices, there is little or no risk of a change in salinity levels on about 61% of the agricultural land of Manitoba, 59% of Saskatchewan, and 80% in Alberta, with the remaining farmland in each province displaying a moderate-to-high risk of increasing salinity (Eilers et al., 1995). Areas that display moderate-to-

high risk of increasing salinity do not mean that salinity has increased on these lands, but rather that there is considerable risk of increase under 1991 farming practices (Eilers et al., 1995).

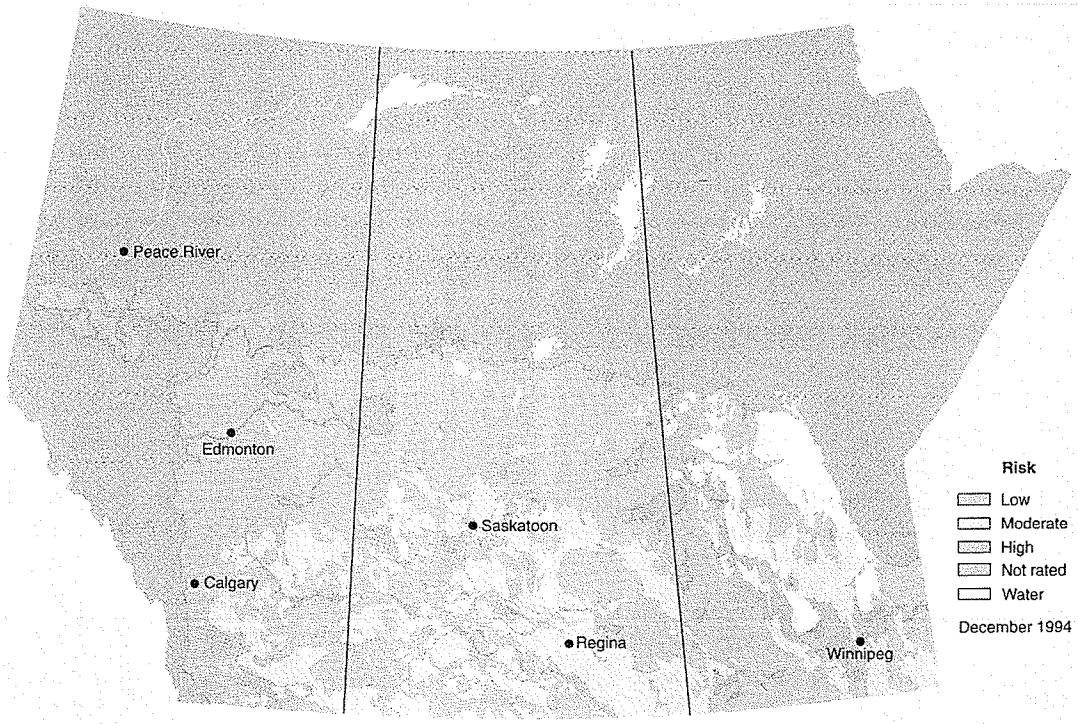

Figure 2.2. Risk of salinization in prairie agricultural soils (from Eilers et al., 1995)

2.1.3 Measuring Soil Salinity

During the first half of the 20th century, soluble salt contents of soils were estimated from the electrical conductivity (EC) of saturated soil-pastes (EC_p), a methodology first described in a publication by Whitney and Means (1897). EC is a numerical expression of the inherent ability of a medium to conduct electricity, and since water itself is a very poor conductor of electricity, the EC of aqueous samples is a result of the contributions of electrolytes dissolved in it. As the understanding of saline soils progressed, it was found that plant response to salinity was much more highly related to

the salt concentration of the soil solution than to the total dissolved salt content of the soil (EC of a saturated paste, EC_p). For this reason, the electrical conductivity of the saturated soil-paste-extract (EC_e) was advocated as the preferred universal index of soil salinity (U.S. Salinity Laboratory Staff, 1954), and is the conventional method of defining and measuring soil salinity today. This soil/water ratio is used because it is the lowest reproducible ratio for which enough extract can be readily removed from the soil with pressure or vacuum and because it is often related in a predictable manner to field soil water contents (Rhoades, 1996). Ayers and Westcot (1985) found that the electrolyte concentration resulting from the saturated soil-paste-extract procedure equals approximately one-half of the soil-pore water at field capacity.

Besides EC_e, salinity can be quantified in terms of the total concentration of dissolved solutes (C_s) and osmotic potential (Ψ_o) of the soil extracts. For many soil extracts:

$$EC_e \approx (C_s)/640 \text{ for } EC_e < 5.0 \text{ dS m}^{-1}, \quad [1]$$

$$EC_e \approx (C_s)/800 \text{ for } EC_e > 5.0 \text{ dS m}^{-1}, \quad [2]$$

$$\text{and } \Psi_o \approx -36.47\ (EC_e) \quad [3]$$

where EC_e, C_s, and Ψ_o are expressed in deciSiemens per meter (dS m^{-1}), parts per million (ppm), and kilopascals (kPa), respectively (Maas, 1990).

The collection of a saturated soil-paste-extract according to Rhoades (1996) is itself quite a tedious and time-consuming process. Therefore, more rapid extraction ratios, which can be related back to the standard salinity index value of EC_e, have been adopted (Hogg and Henry, 1984; Al-Gosaibi and Al-Shater, 1997; Triantafilis et al., 2000). Extracts at soil/water ratios of 1:1, 1:2, and 1:5 have become common methods of

assessing salinity (Rhoades, 1996) and if EC is the only parameter being measured, the suspensions of soil and water need not be even filtered to collect an extract; an EC meter can be placed directly in the soil-water suspension (Henry et al., 1985).

2.1.4 Development of Saline Soils

The origin and direct source of all of the salt constituents (i.e., ionic compounds) are the primary minerals found in soils and in the exposed rocks of the earth's crust. During the processes of chemical and physical weathering, these constituents are gradually released and made soluble. Although the weathering of primary minerals is the direct source of nearly all soluble salts, there are probably few instances where sufficient salts have accumulated *in situ* from this source alone to form a saline soil (U.S. Salinity Laboratory Staff, 1954). Saline soils usually develop in areas that receive salts from other locations with water as the main mode of transportation. The ocean is one source of salts, as in soils where the parent material consists of marine deposits that were laid down during earlier geologic periods and have since been uplifted or redistributed by the movement of glaciers, mixing the underlying marine shales with deposits closer to the surface (Henry et al, 1987). More commonly, however, the direct sources of salts in the soil profile are surface and ground waters. Both of these water sources contain dissolved salts, and their concentration depends upon the salt content of the soil and geologic materials with which the water has been in contact. Essentially, soil salinization occurs in areas where groundwater or surface water carrying dissolved salts discharges or is deposited at or near the soil surface (Stein and Schartwz, 1990). In other words, salinization develops in areas where evapotranspiration (ET) exceeds infiltration at or

near the soil surface. Shannon et al. (1994) provides an interesting description of the development of soil salinity:

> "Our world is dissolving around us. As a consequence of rain, the earth's mantle is slowly being solubilized and washed into the oceans. Salts of sodium, calcium, magnesium, chloride, sulphate, carbonate, and numerous other elements are formed as water flows from soils into rivers, lakes, and finally, the sea. The water and dissolved salts are essential to plant growth, but water reuse and high evaporation rates in arid or semiarid regions concentrate the salt as the general phenomenon of salinization occurs."

There are two general types of soil salinity that can develop: natural (a.k.a. primary) soil salinity and secondary soil salinity. Natural soil salinity results from the accumulation of salts in the soil profile over long periods. Secondary salinization is the result of anthropogenic activities. The soil salinity conditions we see today often result from contributions of both salinization processes, although the principles behind them are equivalent, which are the distribution and management of water within a landscape.

2.1.4.1 Natural Salinization Processes

There are three processes of natural salinization: artesian (a.k.a. regional) discharge, evaporitic rings, and side-hill seeps.

Artesian discharge salinization occurs where the pressure in an aquifer is sufficient to force groundwater up to or near the soil surface. The mechanism of soil salinization by artesian discharge is shown in Figure 2.3. Water entry into the aquifer occurs in an upland area that can be great distances away from the saline soil. If the

permeable material in the aquifer ends abruptly, then the water entering the aquifer is confined and pressure builds up. At this point, water and dissolved solutes are forced upward through the soil profile into the plant rooting-zone, where deposition of solutes may occur following evaporation.

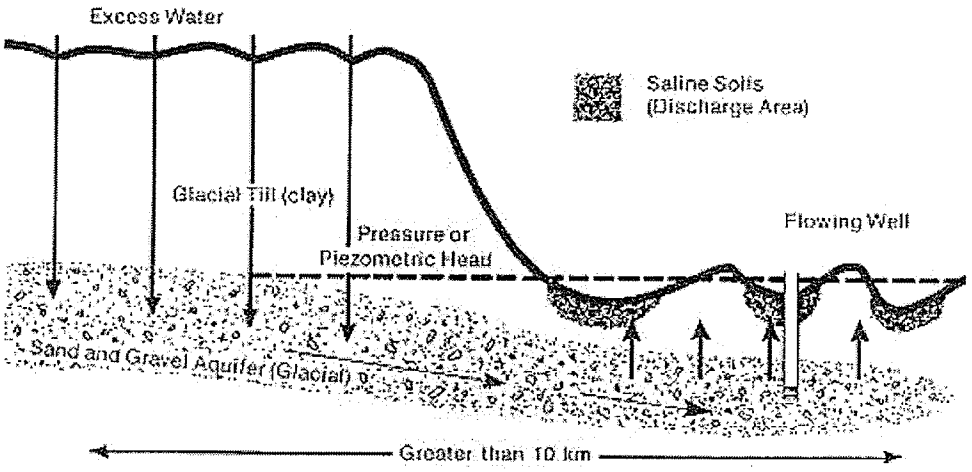

Figure 2.3. Regional artesian discharge mechanism of salinization (Henry et al., 1987)

Evaporitic ring salinity is associated with undrained potholes or sloughs and dugouts that occur in low-lying areas where deep drainage is limited. Runoff collects from the local surrounding uplands, which causes the water table to mound under the slough and cause salinization (Figure 2.4). As there is a continual supply of water for evaporation at the soil surface due to upward movement from the shallow water table through capillary action, salinization occurs in a ring around the perimeter of the slough.

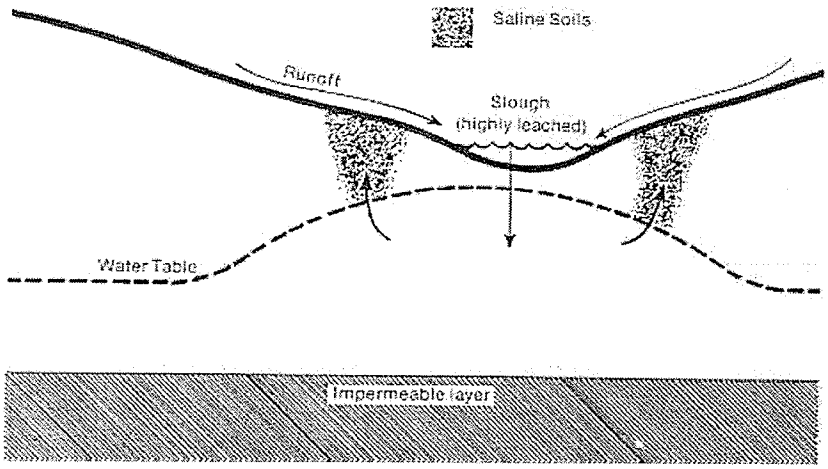

Figure 2.4. Evaporatic ring mechanism of salinization (Henry et al., 1987)

In locations where the soil is underlain by impermeable bedrock, lateral movement of water along the impermeable surface can cause soil salinity (Figure 2.5). The water eventually emerges at the soil surface along a sidehill and produces salinity at this point, referred to as sidehill seep salinity. Usually the scale of salinization in this case is reasonably small, and can even occur within a field. This type of salinity development can be both natural and anthropogenic, and is a common salinization process in Alberta.

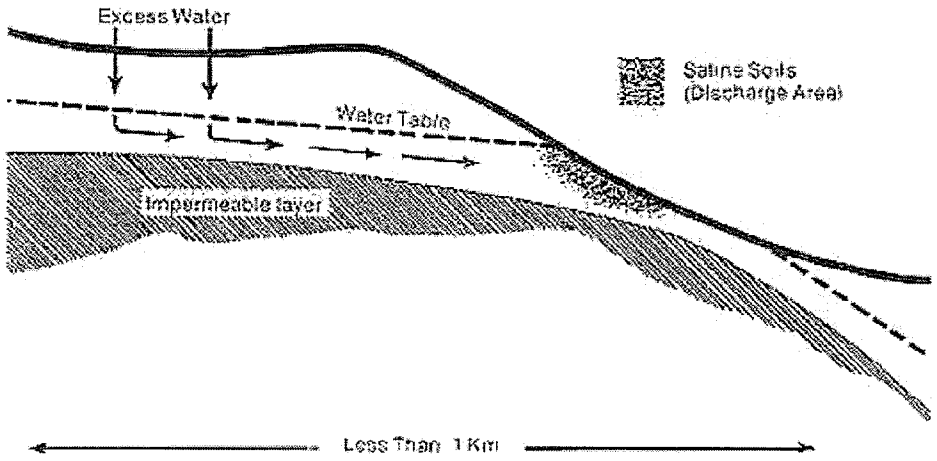

Figure 2.5. Sidehill seep mechanism of salinization (Henry et al., 1987)

2.1.4.2 Secondary Salinization

There are two processes of secondary salinization: ditch salinity and irrigation salinity.

Ditch salinity is a common form of salinity found in extremely flat regions, such as the Red River Valley of Manitoba and North Dakota. Salinity along surface drainage ditches is due to lateral movement of water from ditches to adjacent fields (Figure 2.6). The low grade on most drainage ditches can allow water to stand for long periods, providing ample opportunity for a continual supply of water for evaporation at the soil surface by upward movement from the shallow water table through capillary action. This is similar to the processes involved in evaporitic ring salinity. The point of maximum salt concentration is not directly adjacent to the edge of the ditch, but generally some distance inward away from the ditch (Figure 2.7).

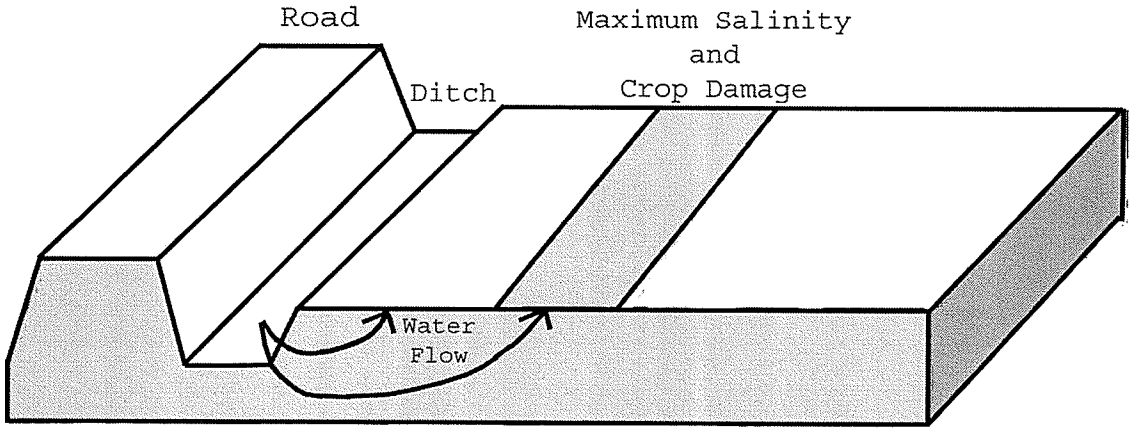

Figure 2.6. Schematic of the ditch mechanism of salinization (Seelig, 2000)

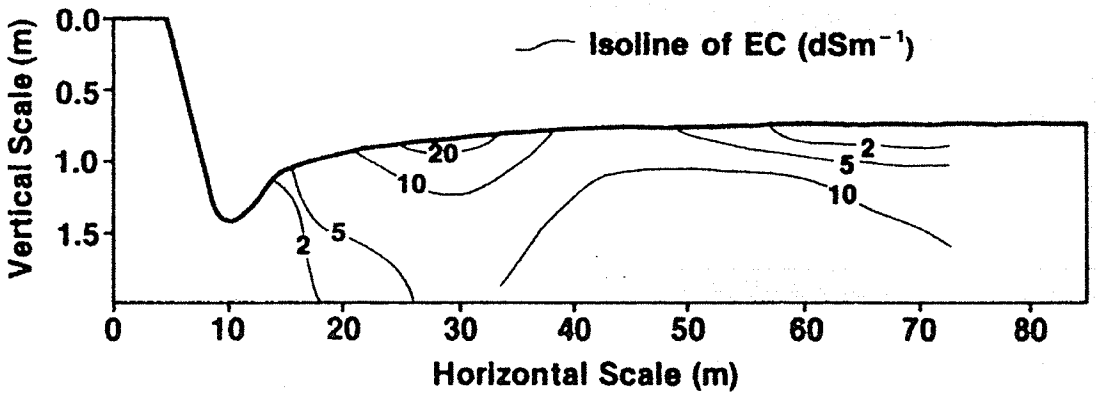

Figure 2.7. Isopleths of soil electrical conductivity shown in cross-section (Skarie et al., 1986)

All irrigation water contains some level of salts and these salts, regardless of their source, can salinize agricultural land if the mass of salts that moves out of the root zone is less than the mass of salts entering the root zone (Maas and Grattan, 1999). As irrigation water is used by crops and/or evaporated on the surface, salts are precipitated within the soil profile. This process may lead to saline conditions in which plant growth is adversely affected. The rate at which salinization occurs depends on the amount and the quality of the irrigation water used. Irrigation water with high levels of dissolved salts will likely cause rapid salinization.

2.2 Effect of Soil Salinity on Plant Growth

2.2.1 Plant Responses to Salinity Stress

Plant species vary widely in their response to salinity stress. Most species can be placed into one of two groups: halophytes or glycophytes. Halophytes are most often associated with the vegetation of saline environments (Poljakoff-Mayber and Lerner, 1999) and thrive in such conditions (Flowers et al., 1977). Glycophytes on the other hand, are not normally associated with saline environments and generally suffer reduced

growth under saline soil conditions, although the relative degree of salinity tolerance within species of this group is extensive, sometimes to the point where distinguishing a plant as glycophytic or halophytic can be quite difficult (Greenway and Munns, 1980). Most crop species, with the exception of the coconut and date palm, and perhaps sugar beet (*Beta vulgaris* L.), are classified as glycophytes (Läuchli and Epstein, 1990).

Plants sense salt stress through both ionic (e.g., Na^+) and osmotic stress signals (Chinnusamy et al., 2005). Excess Na^+ can be sensed either on the surface of the plasma by transmembrane protein or within the cell by membrane proteins or Na^+ sensitive enzymes (Zhu, 2003). Cell volume decreases because of turgor loss under salinity-induced hyperosmotic stress may lead to retraction of the plasma membrane from the cell wall, which is probably sensed by both stretch-activated channels and transmembrane protein kinases (Urao et al., 1999; Kreps et al., 2002).

The effects of soil salinity on plant growth may be mediated by osmotic effects such as osmotic inhibition of water uptake (osmotic effects, i.e., function of total ion concentration) and/or by specific ion effects of the saline constituents (i.e., function of ion composition) (Bernstein and Hayward, 1958). Both can operate simultaneously, but since saline soils in the field generally consist of a mixture of different salts (with the major exception of saline-sodic soils), specific ion effects are minimal, and osmotic effects dominate. This relationship is particularly true with annual crops, as they often do not have tissues that survive long enough to accumulate toxic levels of harmful ions (Bernstein, 1974; Maas and Grattan, 1999). However, Munns (2002) states that while plant growth is primarily limited by the osmotic effects of salinity stress, in species that have a high rate of salt uptake or cannot compartmentalize salt effectively in vacuoles,

salt-specific effects develop with time and impose an additional stress on the plant through failing capacity to produce photoassimilate. When specific ion effects occur, the effects on yield are generally complementary with the growth suppressive effects of osmotic stress (Bernstein, 1974; Maas and Grattan, 1999). In the following sections, osmotic and specific ion effects will be discussed separately, although the two may frequently operate simultaneously, such that any specific examples of crop response should not, in general, be attributed solely to one or the other.

2.2.1.1 Osmotic Effects

Water comprises over 80% of the weight of most plant tissues and is required as a physiological solvent, a transport medium for nutrients, an evaporative coolant, and a pressure source to support form and function (Shannon et al., 1994). The amount of water inside a plant at any given time is relatively small compared to the quantities that pass from root to shoot throughout its life cycle (Shannon et al., 1994). Water and selected solutes move from the bulk soil into the plant roots in response to an ever decreasing total water potential on opposite sides of root and other cellular membranes, i.e., down energy gradients, all the way through the vascular tissues of the plant, ultimately leaving the plant via the stomata into the atmosphere (Taiz and Zeiger, 1998b). Water potential is symbolized by Ψ_w, the Greek letter psi, and the water potential of solutions can be separated into individual components, described by the following equation:

$$\Psi_w = \Psi_s + \Psi_p + \Psi_g + \Psi_m \qquad [4]$$

The terms Ψ_s, Ψ_p, Ψ_g, and Ψ_m denote the effects of solutes, pressure, gravity, and when referring to soil water, matric potential, respectively, on the free energy of water (Taiz and Zeiger, 1998a). When dissolved salt concentrations in soil-water increase, the total water potential of soil-water decreases, such that water gradients from the soil into root tissue decrease, making it more difficult for the plant to uptake water and nutrients (Volkmar et al., 1998). Osmotic inhibition as a result of salinity stress is nearly identical to the problem faced by plants under water stress (Munns, 2002), even when actual soil-water contents may be quite high, leading, over 100 years ago, to the still useful observation that salt stress is a form of physiological drought stress (Glenn et al. 1997, citing Schimper, 1898).

2.2.1.2 Specific Ion Effects

Specific ion effects of soil salinity generally refer to and result in one of two possible outcomes in terms of plant function: (i) ion toxicities and/or nutrient imbalances through the effect of salinity on nutrient availability, uptake and/or distribution of a nutrient within the plant, and/or; (ii) increasing the internal plant requirement for a nutrient element resulting from physiological inactivation (Bernstein, 1964; Grattan and Grieve, 1999). According to Grattan and Grieve (1999), nutrient availability and uptake by plants grown in saline soil conditions are a function of the following:

1. The activity of the nutrient ion in the soil solution, which depends on pH, pE (the negative log of the activity of the electron), concentration, and composition.
2. The concentration and ratios of accompanying elements that influence the uptake and transport of this nutrient by roots.

3. Numerous environmental factors, e.g., soil temperature.

Unless the salinizing ions are nutrients (e.g., Ca^{2+}, Mg^{2+}, SO_4^{2-}), increasing salinity generally decreases nutrient availability (Grattan and Grieve, 1999). For example, the presence of other salinizing ions in soil solutions may reduce Ca^{2+} activity and limit the availability of calcium to the plant (Suarez and Grieve, 1988; Willumsen et al., 1996; Grieve et al., 2001). Janzen and Chang (1987) attributed an apparent calcium deficiency in salinity treated barley (*Hordeum vulgare* L.) plants to reduced activity of Ca^{2+} in the soil solution because of precipitation with SO_4^{2-}. Cations such as Na^+ and Mg^{2+} may displace Ca^{2+} from its extracellular binding sites within plant organs to further disrupt Ca^{2+} acquisition, uptake, and transport (Grieve et al., 1999). Given that calcium is required for plant membrane integrity, deficiencies can lead to disruption of membrane function (Cramer et al., 1989; Rengel, 1992).

A high K^+/Na^+ ratio in the cytosol is essential for normal cellular functions of plants (Chinnusamy et al., 2005). Na^+ competes with K^+ uptake through Na^+-K^+ contransporters, and may block the K^+ specific transporters of root cells under salt-stress (Zhu, 2003), such that Na^+-induced potassium deficiency can develop on crops under salinity stress by sodium salts (Janzen and Chang, 1987). Cl^- soil salinity has been shown to inhibit NO_3^- uptake (Munns and Termaat, 1986). Aslam et al. (1984) found that SO_4^{2-} and, to a greater extent Cl^-, reduce the rate of NO_3^- absorption in the roots of barley seedlings.

Na^+ and Cl^- ions may accumulate in leaf tissue and cause necrotic tips and/or leaf margins (Bernstein et al., 1956; 1969). NaCl salinity stress in soybeans (*Glycine max* L.) was found to increase leaf concentrations of Na^+ and Cl^-, while decreasing leaf

accumulations of K^+, Ca^{2+}, and Mg^{2+} (Essa, 2002). Flowers and Yeo (1986) found that the supply of Na^+ and Cl^- ions from salinity treatments to leaf cells of rice (*Oryza sativa* L.) plants was greater than that required for osmotic adjustment, resulting in either excessive apoplastic ion concentrations in the leaves and death through dehydration or excessive symplastic concentrations and death through ion toxicity. Salinity may cause physiological inactivation of phosphate, thereby increasing the plant's internal requirement for this nutrient (Awad et al., 1990). In general, ionic effects often result in leaf and/or meristem damage or as symptoms typical of specific nutrient deficiencies (Steppuhn et al., 2005a).

2.2.1.3 Integration in the Whole Plant

Salt-stress, including other abiotic stresses, induce accumulations of reactive oxygen species that are detrimental to plant cells at high concentrations as they cause oxidative damage to membrane lipids, proteins, and nucleic acids (Hernandez et al., 2001). Salinity generally decreases plant growth at low concentrations and is lethal at higher concentrations. Salt-affected plants often appear darker green than normal and are stunted, with shorter and fewer internodes (Shannon et al., 1994).

The effect of salinity on the germination of glycophytes is usually negative. For example, chickpea (*Cicer arietinum* L.) (Esechie et al., 2002), barley, wheat (*Triticum aestivum* L.), and mustard (*Brassica juncea* L.) (Mer et al., 2000), cowpea (*Vigna unguiculata* L.) (Murillo-Amador et al., 2002), and soybean (Wang and Shannon, 1999) all show reduced germination under salinity stress. Salinity may also affect germination by facilitating the intake of toxic ions, which may change certain enzymatic or hormonal

activities of the seed (Smith and Comb, 1991). Murumkar and Chavan (1987) also observed decreases in the germination of chickpea seeds. In their study, salinity caused an inhibition of the enzymes α-amylase, acid phosphatase, and peroxidase in seedlings at different germination stages, and dehydrogenase activity in embryo axis was also suppressed by salinity, while activity of enzymes protease and catalase were stimulated due to salt stress. They postulated that the salt sensitivity of chickpea during germination may be due to these metabolic disturbances.

The overall adverse affects of soil salinity on plant growth, in particular crop yield, are extremely well documented on virtually every crop grown in the world today (Maas and Hoffman, 1977; Steppuhn et al., 2005b). It is generally accepted that in most plants, stress, including salinity, induces biosynthesis and accumulation of abscisic acid (ABA) (Poljakoff-Mayber and Lerner, 1999; Jia et al., 2002). As a growth inhibitor, ABA acts as a negative regulator of growth and stomatal opening (Taiz and Zeiger, 1998c). A reduction in stomatal conductance to reduce water loss also reduces CO_2 entry, causing CO_2 to be rate-limiting for photosynthesis (Downtown et al., 1985; Kriedmann, 1986; Brugnoli and Lauteri, 1991; Belkhodja et al., 1999).

One of the earliest responses of glycophytes to salinity stress is that their leaves grow more slowly because of reduced cell enlargement, rates of metabolism (Bernstein and Hayward, 1958; Munns and Termaat, 1986), and rates of leaf elongation (Munns et al., 2000). Wang et al. (2001) found that salinity reduced the cumulative absorption of photosynthetically active radiation and radiation use efficiency in soybean plants. The observed smaller plant leaf sizes and darker green leaves under salt-stress were attributed to reductions to leaf area index and increases in unit leaf chlorophyll, respectively. Root

growth is almost always less affected by salinity than either vegetative shoot growth or fruit and seed production (Maas and Neiman, 1978), and in some cases may even increase, with the overall response being an increase in root/shoot ratio (Munns and Termaat, 1986; Shannon et al., 1994; Essa, 2002). Maas and Grieve (1990) and Grieve et al. (1994) reported that salinity stress accelerated development of wheat shoot apex on the main stem by as much as 18 days and decreased time to initiation of reproductive structures, as well as a shorter time to flowering. The phenological response of crops to salt stress are clearly complex, but appear to produce less but higher quality seed in as short a time as possible (Volkmar et al., 1998).

Salinity can adversely affect the quality of some crops while improving the quality of others (Maas and Grattan, 1999). By decreasing the size and/or quality of fruits, tubers, or other edible organs, salinity reduces the market value of many vegetable crops, e.g., carrot (*Daucus carota* L.), celery (*Apium graveolens* L.), cucumber (*Cucumis sativus* L.), pepper (*Capsicum annuum* L.), potato (*Solanum tuberosum* L.), head cabbage (*Brassica oleracea* L. (Capitata Group)) and lettuce (*Lactuca sativa* L.), and yam (*Dioscorea alata* L.) (Maas and Grattan, 1999). Conversely, salinity can improve vegetable quality, with, for example, increased sugar content of carrot (Bernstein and Ayers, 1953) and asparagus (*Asparagus officinalis* L.) (Francois, 1987). Rye (*Secale cereale* L.) grown on saline soils produces grain with poorer baking quality (Francois et al., 1989), while Francois et al. (1986) observed an increase in the grain quality of durum wheat (*Triticum turgidum* L. var. *durum* Desf.) under salt-stress.

2.2.2 Mechanisms of Salt Tolerance

Water and salts can enter plant roots through either symplastic or apoplastic pathways. The symplast is the interconnected cytoplasmic compartments of root cells leading from the epidermis inward to the steele, interconnected by plasmodesmata between adjacent cells; the apoplast is the interconnected cell wall channels of the same cells (Taiz and Zeiger, 1998b). Water entering the symplast must cross the plasmalemma of an epidermal or cortical cell, at which point the ionic composition may be altered. Entry into the symplast is the most fundamental control point for salt entry into the plant (Glenn et al., 1997). Water entering the apoplast is much more representative of the external solution than the water in the symplast, although the salt concentration of apoplast water can be modified by uptake into cells along the apoplastic pathway and by the ion exchange capacity of cell walls (Pitmann, 1984). If salts could enter the xylem vessel elements through the apoplast pathway alone, the shoots could be flooded with salts; however, the casparian strip of suberized cells require that salts and water cross the endodermis by entering the symplasm (Glenn et al., 1997). As compared to glycophytes, which often have thin casparian strips, halophytes often have thick layers of suberin or double layers of suberized cells at the endodermis (Poljakoff-Mayber, 1975; Kramer, 1984). As the effects of soil salinity on plant growth are often attributed to osmotic inhibition of water absorption and/or by specific ion effects of the saline constituents (Bernstein and Hayward, 1958), it is sensible to expect mechanisms of salt tolerance in plants to focus on these aspects of soil salinity.

2.2.2.1 Osmotic Adjustment

A decrease in water potential due to soil salinity causes osmotic stress that leads to loss of turgor (Chinnusamy et al., 2005). Plants have evolved an osmotic adjustment (active solute accumulation) mechanism that maintains water uptake and turgor under osmotic stress conditions by increasing the water potential gradient from the soil, ultimately into shoot tissue (Chinnusamy et al., 2005). For osmolyte, plants use inorganic ions such as Na^+ and K^+ and/or synthesize organic solutes such as proline, betaine, polyols, and soluble sugars (Volkmar et al., 1998; Chinnusamy et al., 2005). Halophytes adjust their solute content mainly with inorganic ions, whereas glycophytes primarily rely on organic osmolyte (Jacoby, 1999).

The production of organic compounds for osmotica in the cytoplasm is energetically expensive, depriving the cell of significant quantities of carbon that could otherwise be used for growth (Greenway and Munns, 1980). Greenway (1973) calculated that for plants with highly vacuolated cells, adaptation to 100 mM external NaCl with hexoses, would require 20-30% of the total plant biomass. The energetic cost of using inorganic ions for osmotica is much lower, however this solution presents another problem for plant cells as high concentrations of inorganic ions may interfere with normal biochemical reactions within the cell (Poljakoff-Mayber, 1975; Jacoby, 1999). Thus, osmotic adjustment with mineral ions is limited in the cytoplasm and largely confined to the vacuoles (Jacoby, 1999; Chinnusamy et al., 2005).

Glycine betaine, trehalose, mannitol, and proline, as well as being organic solutes for osmotic adjustment, are known as osmoprotectants for their beneficial contributions to cell health during salt stress (Bohnert and Jensen, 1996; Chen and Murata, 2002).

Their role as osmoprotectants has been attributed more strongly in conferring salt tolerance than their capacity for osmotic adjustment (Chinnusamy et al., 2005).

2.2.2.2 Exclusion, Efflux, and Compartmentation

There is a wealth of knowledge linking exclusion of salt from the leaf with salt tolerance (Volkmar et al., 1998). Exposed to moderate salinities, glycophytes tend to exclude salt and to sequester what salt they absorb in the roots and stems, minimizing exposure to leaf cells and protecting the photosynthetic apparatus from salt damage (Läuchli and Epstein, 1990). Examples of glycophytic crops that often demonstrate this mechanism of salt tolerance include: wheat and barley (Gorham, 1993), corn (*Zea mays* L.) (Alberico and Cramer, 1993), chickpea (Lauter and Munns, 1986), and beans (Awada et al., 1995). Jacoby (1964) demonstrated that bean plants exclude Na^+ by retention in the basal parts of the plants but readily translocate Cl^- to the tops. Cl^- is also known to be excluded by some glycophytes (Läuchli, 1984), although this is a mechanism less common than Na^+ exclusion (Lessani and Marschner, 1978). Na^+, as opposed to Cl^- exclusion, would seem to be more important for conferring salt tolerance in both halophytes and glycophytes. Halophytes can accumulate extremely high levels of Cl^- in their cytoplasm when exposed to high levels of NaCl salinity stress, but do not accumulate Na^+ to similar levels (Jacoby, 1999). The capacity of salt exclusion in a plant has its limits, such that above a threshold level of salt in the external medium, that capacity becomes saturated and the salt exclusion mechanism breaks down, leading to high rates of transport of Na^+ and/or Cl^- to the shoot (Läuchli, 1984).

Sodium retranslocation from the leaves also contributes to maintaining Na^+ at low levels in leaves (Läuchli, 1984). Marschner and Ossenberg-Neahaus (1976, cited by Läuchli, 1984), Levi (1970), and Lessani and Marschner (1978) demonstrated, by applying ^{22}Na to the tip of a bean leaf, significant Na^+ retranslocation through the phloem to the root followed by Na^+ efflux into the rooting medium. In a similar experiment, Jacoby (1979) applied ^{22}Na to the upper roots of bean plants and found that Na^+ moved upwards in the stem, then downward to the main roots, from where it was lost into the rooting medium. Although the above cases present interesting evidence of Na^+ retranslocation, the actual benefit in terms of salt tolerance may be minimal (Läuchli, 1984; Flowers and Yeo, 1986; Munns et al., 1986). The experiments presented above were conducted in non-saline conditions such that the processes involved might not operate under salinity stress, particularly in bean plants, and Na^+ efflux from one area of the root might result in uptake elsewhere, thus net loss may actually be quite small (Läuchli, 1984).

Sodium efflux from root cells can prevent accumulation of toxic levels of Na^+ in the cytosol and transport of Na^+ to the shoot (Chinnusamy et al., 2005). Sodium efflux may also be vital for salt tolerance of meristem cells such as growing root tips and shoot apex, as these cells do not have large vacuoles for sodium compartmentalisation (Shi et al., 2002). A structure many halophytes have adapted is the presence of epidermal glands on their leaves and stems, which secrete both salt ions and minerals, structures referred to as salt glands (Thomson, 1975).

Many essential enzymes are severely inhibited when exposed in vitro to high levels of Na^+ (Flowers et al., 1977), such that in halophytic plants, salts are occluded in

the vacuole, aiding in turgor regulation (Jacoby, 1999). Many halophytes regulate turgor pressure by NaCl accumulation to a higher concentration than that in the saline medium (Jacoby, 1999). Glycophytes are unable to cause the sharp asymmetrical intracellular compartmentation of inorganic and organic solutes that is central in the adaptation of halophytes to their saline habitats (Läuchli and Epstein, 1990). See Table 2.1 for examples of the salinity tolerance mechanisms employed by many plants.

Table 2.1. Salt tolerance and diversity of tolerance mechanisms among some vascular plants. Tolerance level is the NaCl salinity level that causes 50% reduction in dry matter production. Adapted from Glenn at al., 1997

Plant	Tolerance Level (mM)	Tolerance Mechanisms	References
Bean	40	Na exclusion Na retransport leaf to root	Maas, 1987; Lauchli, 1984
Rice	40	Na exclusion Na storage in older leaves	Maas, 1987; Yeo & Flowers, 1986
Maize	60	Na exclusion	Maas, 1987; Cramer et al., 1994
Wheat	140	Partial Na exclusion, storage in leaf vacuoles	Maas, 1987; Schachtman & Munns, 1992
Barley	200	Controlled Na uptake, storage in leaf vacuoles	Maas, 1987; Jeschke & Wolfe, 1993
Brown beetle grass	313	Controlled Na uptake, storage in leaf vacuoles Salt glands	Warwick & Halloran, 1994

2.2.3 Modelling Crop Salt Tolerance

2.2.3.1 Methods of Evaluating Crop Salinity Tolerance

Plant tolerance to salinity is usually appraised in one of three ways: (i) the ability of a plant to survive on saline soils, (ii) the absolute plant growth or yield, and (iii) the relative growth or yield on saline soil compared with that on nonsaline soil (Maas, 1987). The yield of an agricultural crop grown in saline media relative to the growth of the same

crop under nonsaline conditions is the primary criterion in which to indicate a crop's level of salt tolerance in contrast to other crops (U.S. Salinity Laboratory Staff, 1954; Ayers and Westcot, 1985; Katerji et al., 1992). There have been many studies, for virtually all crop species, to evaluate decreases in yield in response to increasing root-zone salinity, summarized and tabulated in articles by Bernstein (1964), Maas and Hoffman (1977), Maas (1987, 1990), Francois and Maas (1999), Maas and Grattan (1999), and Steppuhn et al., (2005b), as well as many others. The work of Maas and Hoffman (1977), with updates by Maas (1990) and Maas and Grattan (1999), is of particular importance as, from that point on (and perhaps until recently), it has been the standard reference for evaluating and classifying the relative salt tolerance of crops grown around the globe.

2.2.3.2 Yield Response to Salinity Models

Yield-response functions indicate that most crops tolerate salinity up to a threshold level, beyond which, yields decrease approximately linearly as salinity increases (Francois and Maas, 1999). In reality, the response of crops to environmental influences such as salinity stress or soil fertility is rarely linear in nature, but more often non-linear or sigmoidal; however, for the purposes of modelling, factors leading to non-linear growth response are often ignored (Maas, 1990). Maas and Hoffman (1977) proposed a two-piece linear response model to characterize the curved crop yield response to salinity. Qualitatively, crops have most commonly been classified as either tolerant (T), moderately tolerant (MT), moderately sensitive (MS), or sensitive (S), in terms of their response to increasing levels of salinity (Francois and Maas, 1999). Recent

work by Steppuhn et al. (2005a) suggests that a salinity tolerance index (STI) based on a non-linear response function of crop growth to increasing salinity would most closely reflect agricultural crop response to root-zone salinity and be more useful in making comparisons between crops in terms of their relative salt tolerance.

2.2.3.2.1 Two piece linear model

The piecewise linear response model proposed by Maas and Hoffman (1977) contains two independent parameters: the salinity threshold (C_t), the maximum allowable salinity level without a reduction in yield as compared to the yield under nonsaline control conditions, and the slope (s), the fractional yield decrease per unit increase in salinity beyond a threshold (van Genuchten and Hoffman 1984; Francois and Maas, 1999). This relationship in equation form:

$$Y_r = \begin{cases} 1 & 0 \le C \le C_t \\ 1 - s(C - C_t) & C_t < C \le C_0, \\ 0 & C > C_0 \end{cases} \qquad [5]$$

where Y_r is the relative yield, C is the average root-zone salinity, C_t is the threshold salinity concentration, C_0 is the salinity concentration beyond which the yield is zero, and s is the absolute value of the slope of the response function between C_t and C_0 (van Genuchten and Hoffman, 1984). This piecewise linear model, coupled with a number of nonlinear models, are packaged together by the U.S. Salinity Laboratory in a freely available software program called SALT (van Genuchten, 1983). Maas and Hoffman (1977) used least squares linear regression for values beyond C_t, as well as some manual adjustments, to fit the threshold slope function to data from salinity tolerance experiments in which crops were grown while subjected to two or more levels of salinity, plus a

nonsaline control. Table 2.2 includes crop tolerance data evaluated and tabulated by Maas and Hoffman (1977), Maas (1990), and Maas and Grattan (1999) for many common agricultural crops. Division boundaries for the salt tolerance ratings in Table 2.2 were defined using Figure 2.8, chosen to approximate the family of linear curves that represent the majority of the crops reported (Maas and Hoffman, 1977).

Table 2.2. Salt tolerance of selected crops, assessed with a piecewise linear response model (from Maas and Grattan, 1999)

Common name	Botanical name†	Tolerance based on††	Salt Tolerance Threshold (C_t), EC_e (dS m^{-1})	Slope of response, s (% per dS m^{-1})	Qualitative salt tolerance rating‡
Alfalfa	*Medicago sativa* L.	Shoot DW	2.0	7.3	MS
Barley (irrigated)	*Hordeum vulgare* L.	Grain yield	8.0	5.0	T
Bean, common	*Phaseolus vulgaris* L.	Seed yield	1.0	19	S
Broadbean	*Vicia faba* L.	Shoot DW	1.6	9.6	MS
Canola or rapeseed	*Brassica napus* L.	Seed yield	11.0	13.0	T
Carrot	*Daucus carota* L.	Storage root	1.0	14.0	S
Corn	*Zea Mays* L.	Ear FW	1.7	12.0	MS
Cotton	*Gossypium hirsutum* L.	Seed cotton yield	7.7	5.2	T
Cowpea	*Vigna unguiculata* (L.) Walp.	Seed yield	4.9	12.0	MT
Flax	*Linum usitatissimum* L.	Seed yield	1.7	12.0	MS
Oat	*Avena sativa* L.	Grain yield	—	—	T
Onion (bulb)	*Allium cepa* L.	Bulb yield	1.2	16.0	S
Pea	*Pissum sativum* L.	Seed FW	3.4	10.6	MS
Peanut	*Arachis hypogaea* L.	Seed yield	3.2	29.0	MS
Potato	*Solanum tuberosum* L.	Tuber yield	1.7	12.0	MS
Rice, paddy	*Oryza sativa* L.	Grain yield	3.0	12.0	S
Rye	*Secale cereale* L.	Grain yield	11.4	10.8	T
Safflower	*Carthamus tinctorius*	Grain yield	—	—	MT
Sorghum	*Sorghum bicolor* (L.) Moench	Grain yield	6.8	16.0	MT
Soybean	*Glycine max* (L.) Merril	Seed yield	5.0	20.0	MT
Sugar beet	*Beta vulgaris* L.	Storage root	7.0	5.9	T
Sugarcane	*Saccharum officinarum* L.	Shoot DW	1.7	5.9	MS
Sunflower	*Helianthus annuus* L.	Seed yield	4.8	5.0	MT
Triticale	*x Triticosecale* Wittmack	Grain yield	6.1	2.5	T
Wheat, leavened bread (irrigated)	*Triticum aestivum* L.	Grain yield	6.0	7.1	MT
Wheat (semidwarf) (irrigated)	*Triticum aestivum* L.	Grain yield	8.6	3.0	T
Wheat, durum (irrigated)	*T. turgidum* L. var. *durum* Desf.	Grain yield	5.9	3.8	T

† Botanical and common names follow the convention of Hortus Third (Liberty Hyde Hortium Staff, 1976) where possible.

†† FW = fresh weight, DW = dry weight.

‡ Ratings are defined by the boundaries in Figure 2.8.

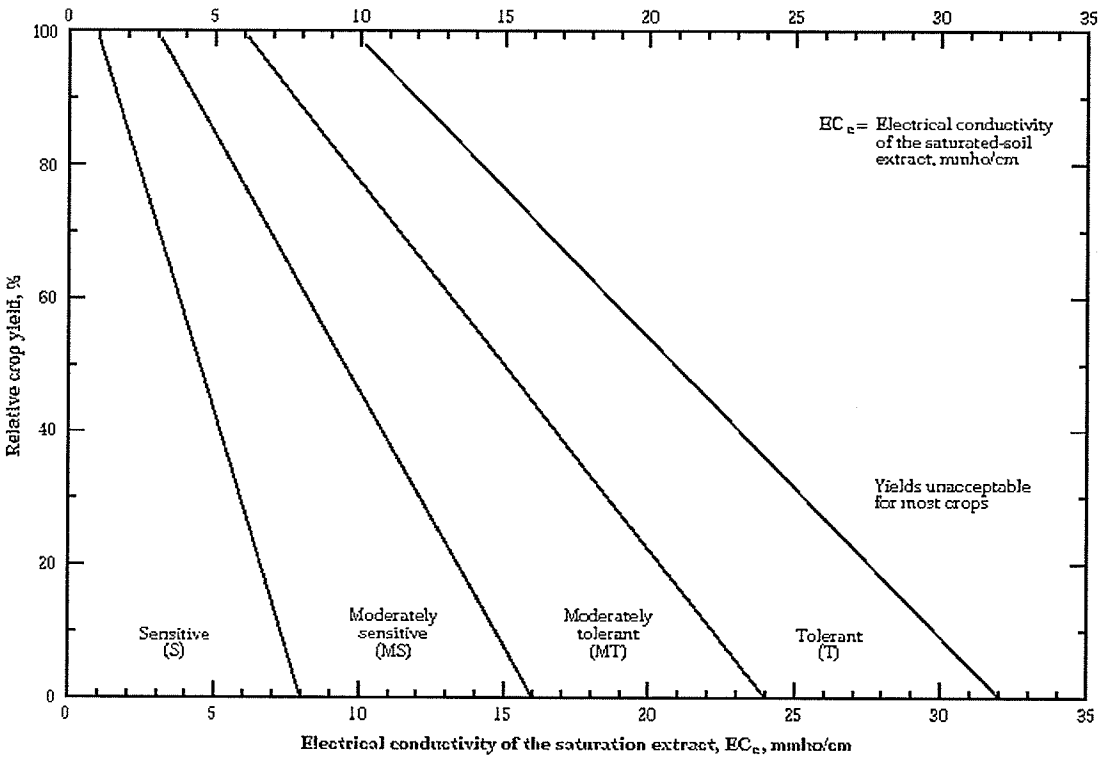

Figure 2.8. Divisions employed by Maas and Hoffman (1977), Maas (1990), and Maas and Grattan (1999) for classifying crop salt tolerance qualitatively (Note: mmho cm^{-1} are equivalent to dS m^{-1}) (From Maas, 1990)

2.2.3.2.2 Non-linear response function of crop growth

Steppuhn et al. (2005a) suggest that a sigmoidal shaped nonlinear modified compound discount function would better represent a given crop's growth or yield response to increasing root-zone salinity. Other researchers (van Genuchten, 1983; van Genuchten and Hoffman, 1984; van Genuchten and Gupta, 1993; Steppuhn et al., 1996) have made this suggestion of non-linear or sigmoidal shaped response functions, however until the work of Steppuhn et al. (2005b), this function has not been applied in a similar fashion as Maas and Hoffman (1977) did to a large number of crops (Table 2.3). The response function employed by Steppuhn et al. (2005b) can be represented in equation form as follows:

$$Y_r = 1/[1 + (C/C_{50})^{\exp(sC_{50})}] \quad [6]$$

where C_{50} defines C at Y_r = 0.5, and s represents the response curve steepness. The steepness parameter equals the average absolute value of the slope (dY_r/dC) of the equation through C_{50} and its steepest segments on either side of C_{50} (Steppuhn et al., 2005a). The effect of the steepness parameter, s, on the crop response to salinity is shown in Figure 2.9. As s increases, the reduction in crop yield in response to unit increases in salinity is greater (analogous with a greater negative slope of a linear model). If the term p is substituted for $[\exp(sC_{50})]$ in equation [6], a form of the modified discount results, which was introduced by van Genuchten (1983) and van Genuchten and Hoffman (1984) and used by van Genuchten and Gupta (1993) and Steuppuhn et al. (1996):

$$Y_r = 1/[1 + (C/C_{50})^p] \quad [7]$$

where p is a shape parameter with no biophysical characteristic (Steppuhn et al., 2005b).

Table 2.3. Salt tolerance of selected crops, assessed with a modified compound discount model (from Steppuhn et al., 2005b)

Common name†	Botanical name††	Tolerance based on	C_{50} (EC_e) dS m^{-1}	Shape, *p*	Steepness, *s*	Salinity tolerance Index
Alfalfa	*Medicago sativa* L.	Shoot DW	8.49	2.57	0.111	9.43
Alfalfa (dryland)*	*Medicago sativa* L.	Shoot DW	6.20	1.80	0.095	6.79
Barley (irrigated)	*Hordeum vulgare* L.	Grain yield	17.53	3.80	0.076	18.87
Barley (dryland)*	*Hordeum vulgare* L.	Grain yield	7.51	2.18	0.104	8.29
Bean, common	*Phaseolus vulgaris* L.	Seed yield	3.34	2.63	0.289	4.30
Broadbean	*Vicia faba* L.	Shoot DW	6.47	2.58	0.146	7.42
Canola or rapeseed	*Brassica napus* L.	Seed yield	14.42	13.50	0.198	17.27
Canola (dryland)*	*Brassica napus* L.	Seed yield	7.10	2.46	0.126	8.00
Carrot	*Daucus carota* L.	Storage root	4.26	2.48	0.213	5.17
Corn	*Zea Mays* L.	Ear FW	5.54	2.75	0.183	6.56
Cotton	*Gossypium hirsutum* L.	Seed cotton yield	16.86	3.80	0.079	18.19
Cowpea	*Vigna unguiculata* (L.) Walp.	Seed yield	8.71	4.91	0.183	10.30
Flax	*Linum usitatissimum* L.	Seed yield	5.54	2.75	0.183	6.56
Onion (bulb)	*Allium cepa* L.	Bulb yield	4.02	2.66	0.244	5.00
Pea	*Pissum sativum* L.	Seed FW	7.77	3.50	0.161	9.02
Peanut	*Arachis hypogaea* L.	Seed yield	4.61	7.67	0.442	6.65
Potato	*Solanum tuberosum* L.	Tuber yield	5.54	2.75	0.183	6.56
Rice, paddy	*Oryza sativa* L.	Grain yield	6.83	3.48	0.183	8.08
Rye	*Secale cereale* L.	Grain yield	15.84	5.76	0.111	17.59
Sorghum	*Sorghum bicolor* (L.) Moench	Grain yield	9.57	10.16	0.242	11.89
Soybean	*Glycine max* (L.) Merril	Seed yield	7.16	8.85	0.305	9.34
Sugar beet	*Beta vulgaris* L.	Storage root	15.04	3.86	0.090	16.39
Sugarcane	*Saccharum officinarum* L.	Shoot DW	9.80	2.41	0.090	10.68
Sunflower	*Helianthus annuus* L.	Seed yield	14.37	2.99	0.076	15.46
Triticale	*x Triticosecale* Wittmack	Grain yield	25.53	2.64	0.038	26.51
Wheat, leavened bread (irrigated)	*Triticum aestivum* L.	Grain yield	12.63	3.92	0.108	14.00
Wheat, leavened bread (dryland)*	*Triticum aestivum* L.	Grain yield	2.76	1.67	0.186	3.27
Wheat (semidwarf) (irrigated)	*Triticum aestivum* L.	Grain yield	24.71	3.09	0.046	25.84
Wheat, durum (irrigated)	*T. turgidum* L. var. *durum* Desf.	Grain yield	18.58	2.93	0.058	19.65
Wheat, durum (dryland)*	*T. turgidum* L. var. *durum* Desf.	Grain yield	5.36	3.67	0.243	6.66

† Crops in this column, marked with an (*) describe tolerance data that were not included in Maas and Grattan (1999), based on tests following dryland agriculture practices, where seeds are planted directly in saline beds.

†† Botanical and common names follow the convention of Hortus Third (Liberty Hyde Hortium Staff, 1976) where possible.

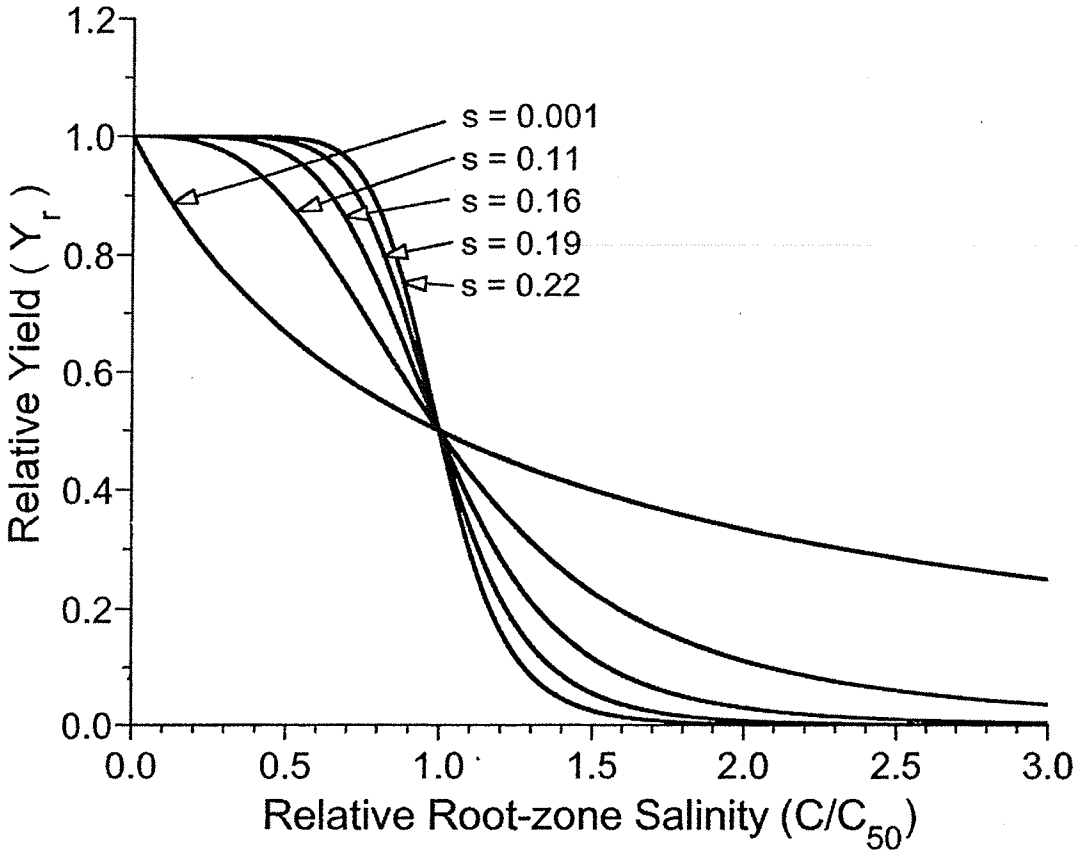

Figure 2.9. Relative crop yield from the modified discount function, with relative root-zone salinity for C_{50} = 10 dS m^{-1} and a wide range of values for s (from Steppuhn et al., 2005a)

The concept of using a single value index for assessing crop salinity tolerance is not a new idea; in the past, it was achieved by using the value of C_{50} as the index (Ayers et al., 1951; U.S. Salinity Laboratory Staff, 1954; Brown and Hayward, 1956). Steppuhn et al. (2005b) describe the STI as follows: If C_{50} and s are combined such that the salinity level associated with a 50% yield reduction (C_{50}) along with a measure of the tendency to maintain some product yield as the crop is subjected to increasing salinity levels approaching C_{50}, a comparative, single-value, STI is defined by the equation:

$$\mathrm{STI} = C_{50} + sC_{50} \qquad [8]$$

The shape of the function for salinity levels greater than C_{50} is not included in this index.

Steppuhn et al. (2005b) found only limited amounts of data available for the calculation of C_{50}, s, the STI, and for the generation of an associated crop-tolerance list (Table 2.3), and thus developed methods for converting the linear threshold-slope parameters of C_t and s (slope) to C_{50} and s (steepness) of the non-linear modified discount function to generate the data in Table 2.3.

2.2.3.3 Considerations of Crop Tolerance Modelling

Most of the data presented in Tables 2.2 and 2.3 were obtained where crops were grown under conditions simulating typical field production practices for commercial production of a given crop (Maas and Grattan, 1999). Thus, the data indicate relative tolerances of different crops grown under different conditions and not a standard set. There are a variety of literature sources used in the generation of the data for Tables 2.2 and 2.3, differing for each crop in terms of their number, their methods, their quality, and their date. This is important as the experiments used for a given crop tolerance may be decades old. The data in Tables 2.2 and 2.3, generally apply to soils where Cl^- is the predominant anion. When preparing saturated soil extracts, $CaSO_4$ has a tendency to precipitate out of solution, such that the EC_e of gypsiferous (nonsodic, low Mg^{2+}) soils will range from 1 to 3 dS m^{-1} higher than that of nongypsiferous soils having the same soil water conductivity at field capacity (Bernstein, 1962; Maas and Grattan, 1999). Therefore, plants grown in gypsiferous soils will tolerate EC_e values approximately two dS m^{-1} higher than those listed in Table 2.2 (Maas and Grattan, 1999), and about 5-10% higher than those listed in Table 2.3 (Steppuhn et al., 2005b). This is an important

consideration for western Canadian crop salt-tolerance modelling, as SO_4^{2-} is the predominant anion found in prairie soils (Chang et al., 1983; Curtin et al. 1993).

Some experiments included in the generation of Tables 2.2 and 2.3 would have been conducted in greenhouse environments; others would have been conducted in field environments. Both situations are subject to the many factors affecting crop growth other than root-zone salinity. The confounding effects of spatial (x, y, and z axes) and temporal variability of both soil water and salt content can have a dramatic effect on crop response to salinity treatments. Many other crop-environment interactions may cause variability in a crop's response to salinity, such as temperature (soil and ambient), radiation, humidity, and fertility (Shannon et al., 1994). For example, combinations of low humidity and high temperatures have been found to decrease a crop's salt-tolerance in comparison to those described for the same crop in either Tables 2.2 or 2.3 (Bernstein, 1974; Hoffman et al., 1978). It is therefore critical, regardless of the source, to be aware of the situations in which the salt-tolerance of a given crop was evaluated before applying that information directly to specific growing conditions.

2.3 *Phaseolus Vulgaris* L.

2.3.1 Origins and Classifications of the Common Bean

Common bean (*Phaseolus vulgaris* L.) is part of the *Leguminosae* family, and is thought to have originated from wild *Phaseolus* species in Mexico, Central America, and parts of northern South America (Gentry, 1968; Gepts and Debouck, 1991; Kaplan, 1996). Common bean has been cultivated in Mexico for at least 7,000 years (Kaplan, 1996). During its evolution under domestication, common bean has experienced a

widening of its ecological range (principally by adaptation to warmer temperatures and long-day photoperiods) and is grown on all continents except Antarctica (Gepts, 1998).

In the English language, the generic term "beans" is often used not only for *Phaseolus vulgaris* but also for other species, such as *Phaseolus coccineus*. For this reason, the following descriptive terms are used to distinguish *Phaseolus vulgaris* from other grain legumes: French beans, dry beans, food beans, field beans, beans, common beans, kidney beans, haricot beans, *Phaseolus* beans, and dry edible beans (Voysest and Dessert, 1991).

The principle products of *Phaseolus vulgaris* are dry beans (seeds harvested at complete maturity), shell beans (seeds harvested at physiological maturity, i.e., before the desiccation associated with complete maturity sets in), and green or snap beans (pods harvested before the seed development phase) (Gepts, 1998). Canada produces dry beans in many different colours, sizes, and shapes. The dry beans produced in Canada are classified as either white or coloured beans. The white pea bean or navy type is considered a white bean. Major coloured bean production in Canada includes such types as Great Northern, Black, Pink, Pinto, Dark Red Kidney, Light Red Kidney, White Kidney, Dutch Brown, Cranberry and Small Red (Pulse Canada, 2005).

2.3.2 Global and Regional Production

In 2004, the world production of dry beans was 18,724,766 metric tonnes (MT), with Brazil, India, and China having the largest production at 3,054,049 MT, 3,000,000 MT, and 2,009,000 MT, respectively (FAOSTAT data, 2004). Canada was the tenth largest global producer of dry beans in 2004, with production levels of 290,000 MT

(FAOSTAT data, 2004). In Manitoba, production of dry beans peaked in 2002 at 231,335 MT, with 56.8% of national production, but fell to 165,563 MT and only 47.8% of national production in 2003. Still, Manitoba remains Canada's leading producer of dry beans (Manitoba Agriculture, Food and Rural Initiatives, 2003).

Commercial production of dry beans began in Manitoba in 1963 when 40.5 ha were harvested, but increased dramatically, especially in the late 1990s and peaked in 2002 when 125,550 ha were harvested (Manitoba Agriculture, Food and Rural Initiatives, 2003).

The majority of dry beans produced in Manitoba are exported internationally to countries such as Cuba, the United States, Mexico, Brazil, Italy, Venezuela, and the Netherlands. Dry beans shipped within Canada are generally sent to eastern provinces where they are processed into products such as soups or pork and beans (Manitoba Agriculture, Food and Rural Initiatives, 2003).

2.3.3 Manitoba Production Practices

In Manitoba, dry beans are typically planted at the end of May and grown as a row-crop with seed rows spaced 76.2-91.4 cm apart. With row-planted beans, producers cultivate between the crop two to three times over the course of the growing season from planting until the rows fill in with the advancing dry bean crop. Row cultivation allows for reduced herbicidal weed control as well as reduced disease pressure due to improved aeration between crop rows.

Producers accustomed to growing crops such as canola (*Brassica napus* L.) and wheat have recently adapted their current production practices and equipment for these

crops to dry bean production by solid-seeding (narrow row) dry beans in rows from 12.7 to 22.9 cm (Manitoba Agriculture, Food and Rural Initiatives, 1998). However, not all dry bean varieties are suited to both row and solid planting practices. Dry beans can be generally classified as either bush or vine types. Bush-type varieties have determinate growth patterns making them suitable in solid-seeded production systems. Determinate growth means that the dry bean plants stop producing new leaves (growing vegetatively) once the flowers have developed. Vine-type dry bean varieties have indeterminate growth, meaning they continue to grow, flower, and set pods as long as temperature and moisture permit. Dry bean plants exhibiting indeterminate growth tend to have pods set close to the ground and are usually grown in row-crop situations (Manitoba Agriculture, Food and Rural Initiatives, 1998).

2.3.4 Effect of Salinity

2.3.4.1 Germination and Emergence

Beans are less affected by soil salinity during germination and emergence than during later stages of growth, a situation common among many crops. When compared to controls, Prisco and Leary (1970) found the germination of red kidney beans to be unaffected at an equivalent EC_e value of 5 dS m^{-1}, and observed 21 and 50% decreases in germination at equivalent EC_e values of 10 and 20 dS m^{-1}, respectively, with no germination occurring at an equivalent EC_e value of 30 dS m^{-1}. Bayuelo-Jimenez et al. (2002a) observed a 15% reduction in bean germination at an equivalent EC_e value of 16 dS m^{-1}, whereas Steppuhn et al. (2001) observed no germination and survival at an EC_e

value of 25 dS m^{-1}. Bayuelo-Jimenez et al. (2002a) and Steppuhn et al. (2001) observed no reduction in bean germination to an equivalent EC_e value of 11 dS m^{-1}.

2.3.4.2 Vegetative Growth

Many studies have reported decreases in bean dry-matter (DM) accumulation in response to increasing root-zone salinity stress (Figure 2.10), reflected by decreases in relative growth rate (Wignarajah, 1990; Bayuelo-Jiménez et al., 2003). The range in the degree of effect is quite broad, a result of the large number of distinctive experimental conditions imposed in the studies presented in Figure 2.11; including factors such as differences in cultivar selection, the length of time plants were exposed to salinity treatments, and the type of salinity stress. In general, bean shoot growth is more affected by salt-stress than root growth, with an increase in root/shoot ratio in response to elevated root-zone salinity (Nieman and Bernstein, 1959; Wignarajah, 1990; Cordivilla et al., 1995; Bayuelo-Jiménez et al., 2002b; Bayuelo-Jiménez et al., 2003). Bayuelo-Jiménez et al. (2003) found that after 20 days of salinity treatment, the root/shoot ratio of bean seedlings increased from 0.16 to 0.27 in salinity treatments of equivalent EC_e values of 0 and 7.3 dS m^{-1} respectively. Reductions in the shoot growth of beans in response to salinity stress are often associated with reductions in leaf area (Brugnoli and Lauteri, 1991; Bayuelo-Jiménez et al., 2003), most likely due to reductions in cell elongation and division (Nieman, 1965; Wignarajah et al., 1975).

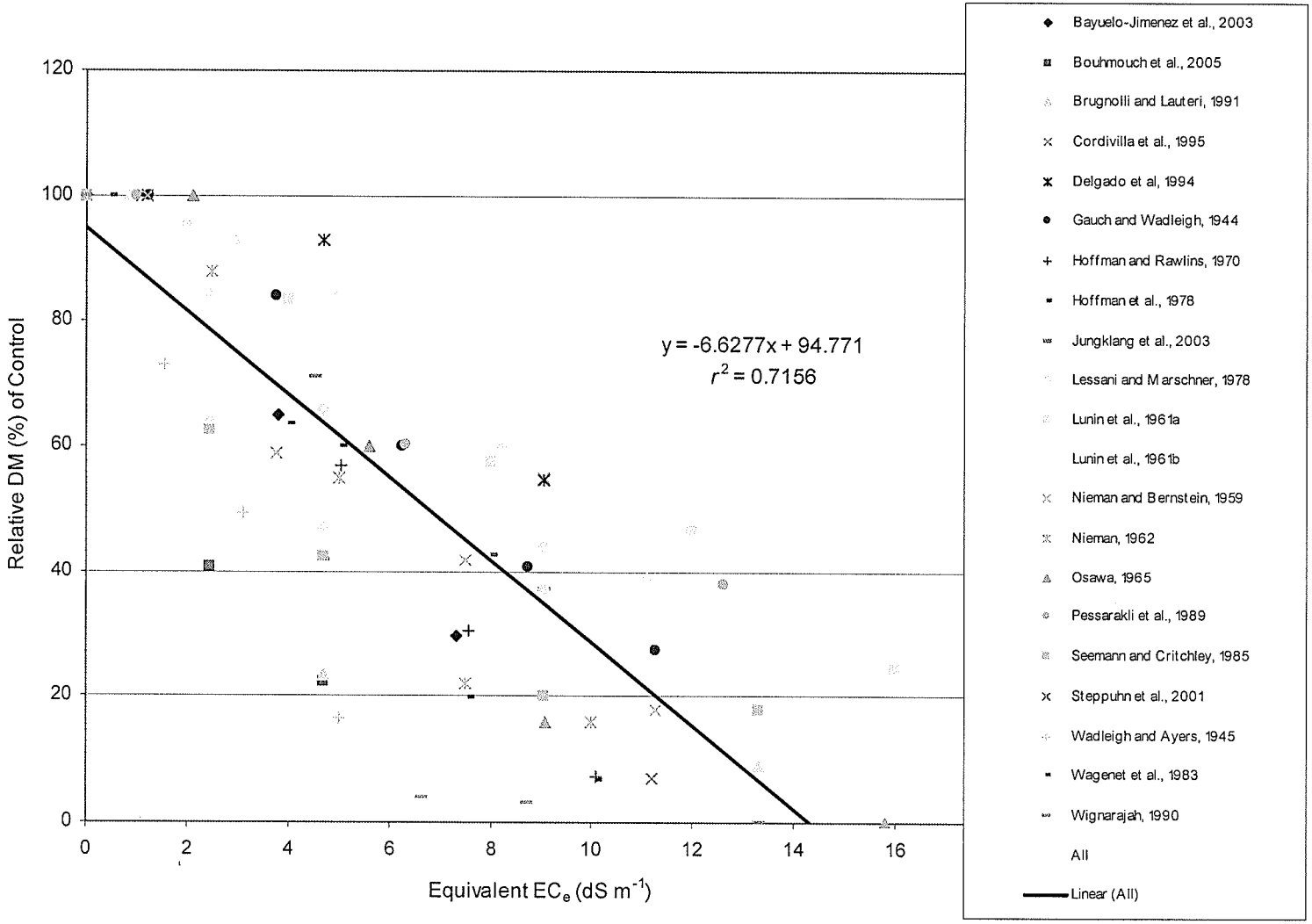

Figure 2.10. Literature summary of the effects of increasing root-zone salinity on the above-ground DM production of bean crops. Values of salinity other than EC_e were converted to an EC_e basis using Equations 1-3, depending on the original reference units.

2.3.4.3 Yield

The adverse effect of increasing root-zone salinity on the yield of beans, whether the product be green beans or dry beans, has been documented by Mass and Hoffman (1977) (Table 2.2) and subsequently Steppuhn et al. (2005b) (Table 2.3). Steppuhn et al (2005b) simply adapted the data for beans presented by Mass and Grattan (1999) (same bean data as Mass and Hoffman (1977)), to their own salt-tolerance model, such that no new data were included. The original references included by Maas and Hoffman (1977) in their assessment of the salt-tolerance of beans were: Magistad et al. (1943), Bernstein and Ayers (1951), Nieman and Bernstein (1959), Osawa (1965), and Hoffman and Rawlins (1970). Figure 2.11 includes bean yield data for these five authors, as well as numerous others, and the bean response functions published by Maas and Hoffman (1977) and Steppuhn et al. (2005b). Maas and Hoffman (1977) found the value of C_t for beans to be equal to 1.0 dS m^{-1} and s to reflect a 19% unit yield decrease per unit increase in salinity. They rated beans as sensitive to salinity. Steppuhn et al. (2005b) found the value of C_{50} for beans to be 3.34 dS m^{-1}, p to be 2.63, s to be 0.289, and STI to be 4.30. The STI value of beans was found to be lower than all crops listed except for strawberry (*Fragaria* x *ananassa* Dutch.).

Salinity stress, coupled with environmental parameters such as humidity and temperature, are important to both the yield and the quality of bean crops. Hoffman and Rawlins (1970) found that with increasing salinity stress, hot and dry conditions reduced green bean yield and quality (with respect to the size of pods harvested per plant) more than cool and high humidity conditions. Bernstein and Ayers (1951) found similar results with an approximate 30% reduction in pod size from equivalent EC_e values of 0 to 7.5 dS

m^{-1}. Wagenet et al. (1983) found that with a salinity (EC_e) increase from 0 to 8 dS m^{-1}, the number of pods and seeds per plant decreased by approximately 70 and 92%, respectively. Protein content of bean plants is also significantly reduced under increasing salinity stress (Pessarakli, 1999).

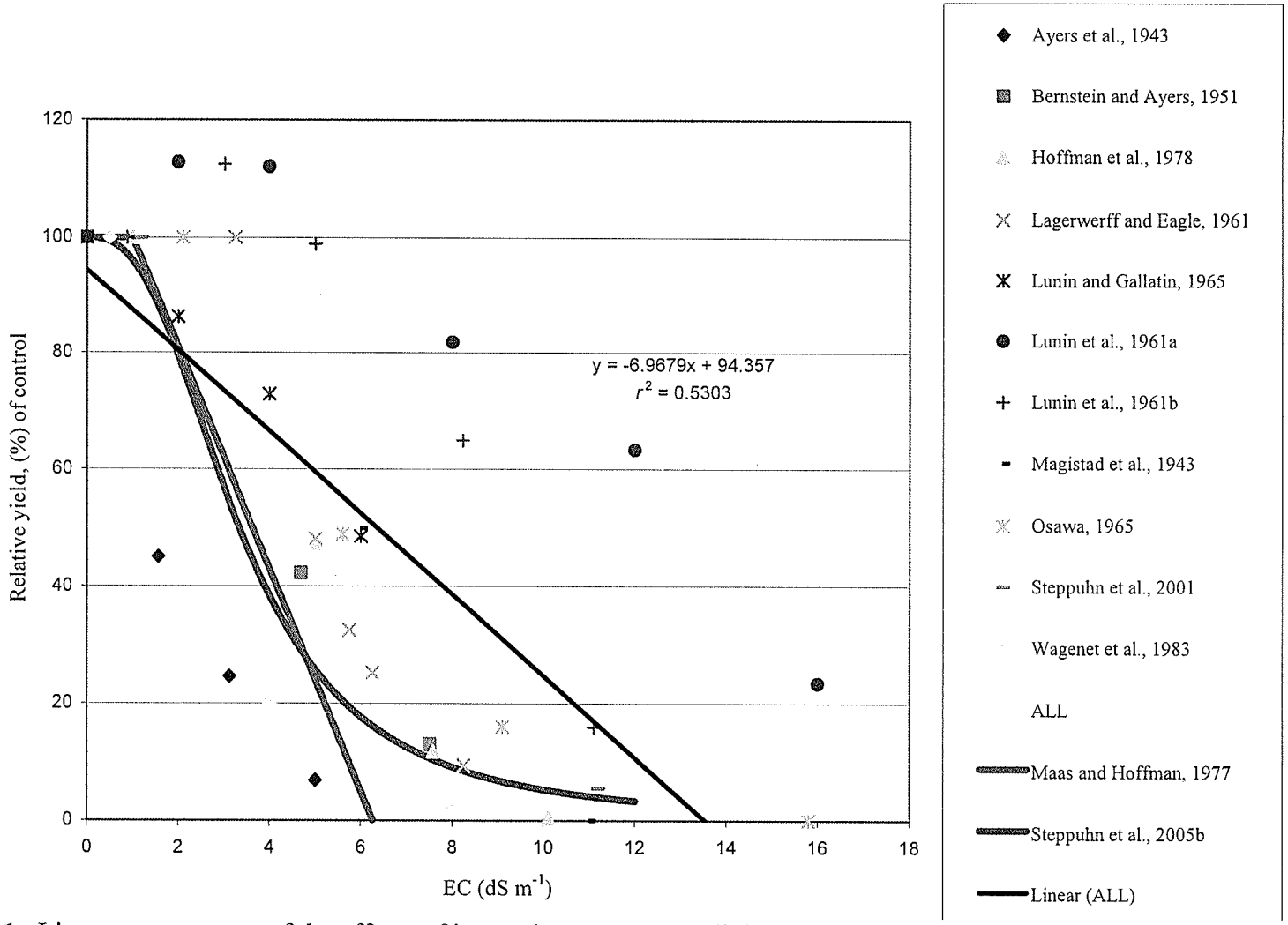

Figure 2.11. Literature summary of the effects of increasing root-zone salinity on the relative yield of bean crops. Values of salinity other than EC_e were converted to an EC_e basis using Equations 1-3, depending on the original reference units

2.3.4.4 Water Uptake

The most direct effect of soil salinity on soil water relations is an increased osmotic potential of the soil medium making it more difficult for plants to uptake water, such that, as one would expect, increasing levels of salinity reduce bean crop water uptake (Hoffman et al., 1978). Stomatal conductance, transpiration rate, and the rate of photosynthesis are also reduced in response to increasing salinity stress (Seemann and Critchley, 1985; Brugnoli and Lauteri, 1991; Cachorro et al., 1995).

2.3.4.5 Nitrogen Fixation

Fixation of atmospheric nitrogen (N_2) results from symbiosis between leguminous crops and *Rhizobium* bacteria, a particularly useful and energetically efficient source of mineral nitrogen for legume crop growth, although perhaps of less importance in beans than other grain legumes (Kimura et al., 2004). Salinity may adversely affect the *Rhizobium*-legume symbiosis indirectly by reducing plant growth and, therefore, net photoassimilate available for N-fixation (Brugnoli and Lauteri, 1991; Cachorro et al., 1995). Salinity may directly affect infection and nodule growth and development (Zahran and Sprent, 1986; Verdoy et al., 2004; Bouhmouch et al., 2005), and can also influence N-fixation capacity (Hafeez et al., 1988; Elsheikh and Wood, 1990). A salinity effect on N-fixation could explain, at least partially, the salt sensitivity of grain legumes (van Hoorn et al. 2001). Delgado et al. (1994) observed a 57% reduction in acetylene reduction activity and 55% reduction in nodule dry weight in bean plants treated with an equivalent EC_e value of 9.1 dS m^{-1} when compared to untreated plants. The strain of bacteria used in the previous experiment was *Rhizobium leguminosarum* bv. *phaseoli*, the

most common *rhizobium* species used to inoculate beans. Boncompagni et al. (1999) found that this strain of *rhizobium* cannot grow in culture at an equivalent EC_e of 9.1 dS m^{-1}, however, Bouhmouch et al. (2005) found that growth and viability of two other strains used to inoculate beans, *Rhizobium giardinii* strain RP161 and *Rhizobium tropici* strain RP163, were virtually unaffected to equivalent EC_e values of 15 dS m^{-1}, while still viable to 29 dS m^{-1}. In general, most *Rhizobium* species are quite tolerant of high levels of salt-stress, certainly to a greater extent than their symbiotic grain-legume partners (Bouhmouch et al., 2005).

2.4 Mapping Soil Salinity

2.4.1 Apparent Electrical Conductivity

The ability of the bulk soil to carry an electrical current, often termed apparent electrical conductivity (EC_a), is a characteristic of agricultural soils that has received much attention of late, particularly in a spatial context. Applications of EC_a have primarily focused on soil salinity assessment and there are many examples of this utilization including Halvorson and Rhoades (1976), Cameron et al. (1981), Williams and Baker (1982), McKenzie et al. (1989), Lesch et al. (1992, 1995a, 1995b), Mankin and Karthikeyan (2002), and Corwin et al. (2003). Other spatial applications include field characterizations of soil water content (Kachanoski et al., 1988; Morgan et al., 2000) and soil texture (Triantafillis et al., 2001; Sudduth et al., 2005).

Three pathways of current flow contribute to the EC_a of a soil: (1) a solid-liquid phase pathway via exchangeable cations associated with clay minerals and organic matter, (2) a liquid phase pathway via dissolved solids (i.e., electrolytes) contained in the

soil water occupying the large pores, and (3) a solid pathway via soil particles that are in direct and continuous contact with one another (Corwin and Lesch, 2005). These three pathways of electrical current flow are illustrated in Figure 2.12. As a result of the three conductance pathways, EC_a measurement is influenced by several soil physical and chemical properties including: soil salinity, water content, porosity, and clay and organic matter content (Corwin and Lesch, 2005). Another factor influencing EC_a is temperature, since electrolytic conductivity increases at a rate of approximately 1.9% per °C increase in temperature (Corwin and Lesch, 2005).

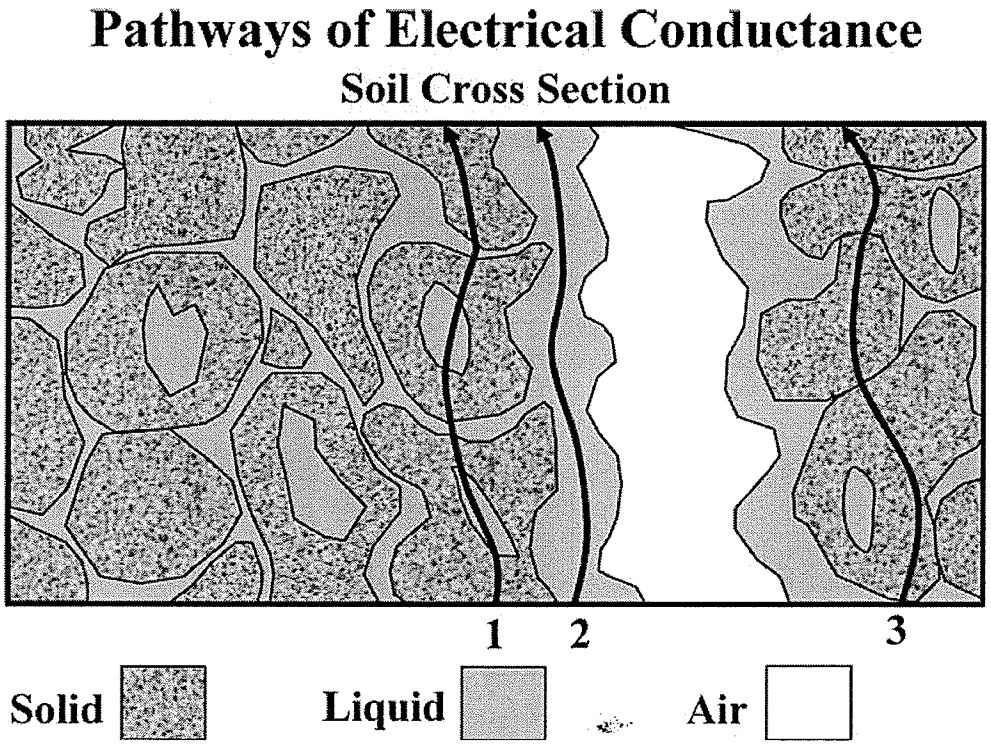

Figure 2.12. Three conductance pathways for EC_a measurement: (1) Solid-liquid phase pathway via cations associated with colloidal soil surfaces, (2) electrolytic liquid phase pathway, and (3) a solid continuous soil pathway. (From Corwin and Lesch, 2005, adapted from Rhoades et al., 1989)

2.4.2 History of Soil Salinity Assessment Utilizing Measurements of EC_a

Shea and Luthin (1961) were the first to advocate the use of EC_a for soil salinity assessment. Their work was based on earlier work of geophysicists who used resistivity (R, inverse of conductivity) to evaluate the depth to sub-surface strata and ore bodies. Shea and Luthin (1961) installed permanently buried four-electrode probes at different soil depths in a soil profile to monitor salt movement and assess salinity changes. Rhoades and Ingvalson (1971) proposed the first mobile adaptation of EC_a measurement to rapidly assess soil salinity. They used a Wenner electrode configuration method (i.e., R measurements taken using four equally spaced electrodes in a straight line), creating linear regression models relating EC_e to EC_a in artificially salinized irrigated field plots. They found very strong relationships between EC_e and EC_a, with coefficient of determination (r^2) values of approximately 0.95. Building on this earlier work of Rhoades and Ingvalson (1971), Halvorson and Rhoades (1974) created EC_e vs. EC_a calibration models, again using the four-probe Wenner electrode configuration for saline seeps in dryland agricultural soils of the northern Great Plains. Again, the relationship between EC_a and EC_e was found to be very strong ($r^2 \sim 0.95$). Following up on their earlier work, Halvorson and Rhoades (1976), created maps of EC_e for northern Great Plains soils, creating isolines from gridded measurements of EC_a and EC_e. Halvorson et al. (1977) suggested that an EC_e vs. EC_a calibration made for a soil textural class at one location would apply to another location of similar range in soil water, clay content, and salinity, as they found that geographic location had little effect on the EC_e vs. EC_a relationship for a number of northern Great Plains soils. This revelation marked the

advent of using spatial measurements of EC_a to create maps of soil salinity using previously created calibration models relating EC_e to EC_a for a given soil type.

As the four electrode technique requires direct soil contact and insertion of electrodes into the soil profile (a relatively time consuming process), more rapid non-contact methods of measuring soil EC_a were developed, specifically measuring electromagnetic induction of the bulk soil using the EM38 (Geonics Ltd, Mississauga, ON). In similar methods developed for calibrating EC_e vs. EC_a using the four electrode technique, numerous researchers (e.g., Cameron et al., 1981; Williams and Baker, 1982; McKenzie et al., 1989; Rhoades et al., 1989; Lesch et al., 1992, 1995a, 1995b; Triantafilis et al., 2000) have created such calibration models using EM38 measurements of EC_a, finding similarly strong linear relationships between EC_e and EC_a (r^2 ~0.9). Since the early 1980s, the standard method of measuring soil salinity from field measurements of EC_a has been the EM38. However this method does have disadvantages in terms of the difficulty and time associated with making mobile geo-referenced field measurements of EC_a.

2.4.3 Equipment Used to Measure Soil EC_a

Two types of portable field EC_a sensors are commercially available for agriculture, an electrode-based sensor based on the principles of the Wenner array or four-electrode technique (Griffiths and King, 1965; Rhoades and Ingvalson, 1971) requiring soil contact and a non-contact electromagnetic induction (EMI) sensor.

A device implementing the electrode-based approach is the Veris 3100 (Veris Technologies, Salina, KS), which uses six rolling coulters for electrodes configured to

provide both shallow and deep readings of EC_a (Lund and Christy, 1998) (Figure 2.13). One pair of electrodes emits an electrical current into the soil, while the other two pairs detect decreases in the emitted current (Johnson et al., 2001). The center pair, situated closest to the emitting (reference) coulter-electrodes, integrates resistance between depths of 0 and approximately 30 cm, while the outside pair integrate between 0 and approximately 90 cm (Johnson et al., 2001). The theoretical instrument response to soil conductivity varies as a nonlinear function of depth (Figure 2.14) so that the for the shallow reading, 90% of the response is obtained from the soil above the 30-cm depth, while for the deep measurement, 90% of the response is obtained from the soil above the 100-cm depth (Sudduth et al., 2005).

Figure 2.13. Photograph of the Veris 3100

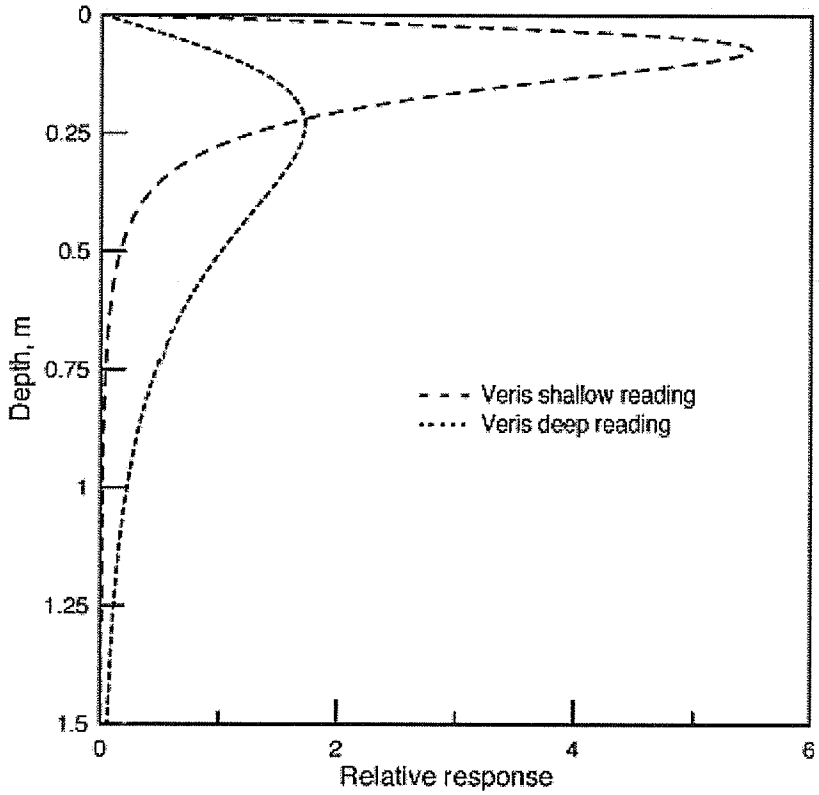

Figure 2.14. Relative response of the Veris 3100 EC_a sensor as a function of depth. Responses are normalized to yield a unit area under each curve. (modified from Sudduth et al., 2005)

The EMI-based EC_a sensor most often used in agriculture is the EM38 (Geonics Ltd., Mississauga, ON, Canada). The EM38 is a lightweight bar designed to be carried by hand and provide stationary EC_a readings (Figure 2.15). To implement mobile data acquisition with this unit, it is necessary to assemble a transport mechanism and data collection system (e.g., Cannon et al., 1994; Sudduth et al., 2001). The EM38 can be operated in two orientations, vertical dipole and horizontal dipole, with effective measurement depths of approximately 1.50 m and 0.75 m, respectively (McNeill, 1992).

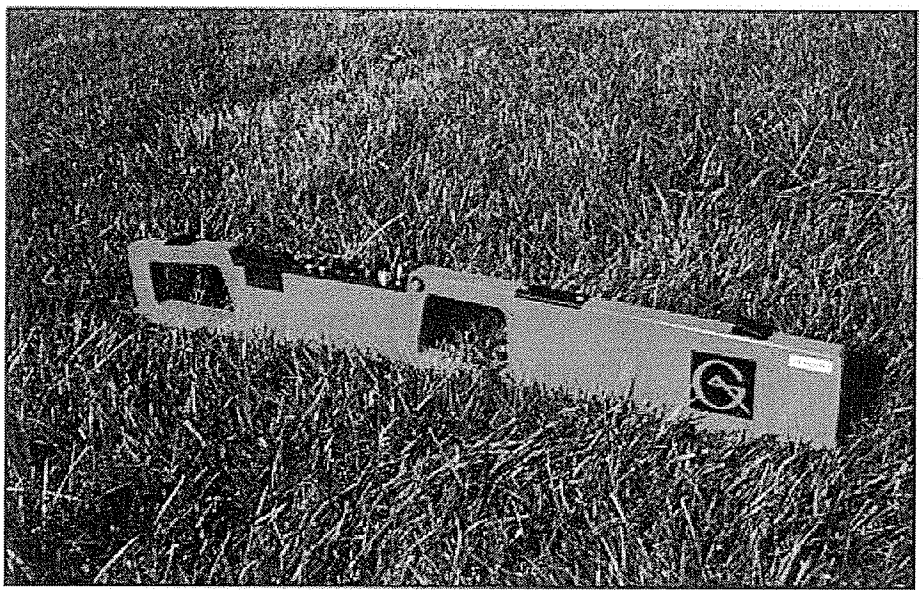

Figure 2.15. Photograph of the EM38

The theoretical depth response of either the Veris 3100 or the EM38 is based on equations that assume a homogeneous soil volume (Sudduth et al., 2005). The actual effective measurement depth will vary due to EC_a differences among soil layers, with a highly conductive surface layer reducing the response depth (Barker, 1989). Both systems can create geo-referenced data sets when coupled with a global positioning system (GPS), such that with the aid of a geographic information system (GIS) software application, a map of EC_a can be created.

2.4.4 Calibrating EC_a Measurements

To calibrate the relationship between spatial measurements of EC_a and EC_e (the standard index of soil salinity) in order to create a soil salinity map, a number of methods have been suggested. The simplest method (Rhoades et al., 1999) involves:

1. Collecting soil samples from several locations in a field where EC_a has been measured at depth intervals analogous with the predicted EC_a depth of measurement.
2. Analysing the value of EC_e for these samples.
3. Creating a simple linear regression model to estimate EC_e from EC_a and applying this function to the rest of the EC_a dataset from the field of interest.

A similar method has been used in the past by Halvorson et al. (1977), Cameron et al. (1981); McKenzie et al. (1989), and Triantafillis et al. (2000) among others. Shortcomings of this method when utilized in large area characterizations of soil salinity are:

1. The implications of random soil sampling locations for characterizing a parameter, soil salinity that by nature is not a random phenomenon.
2. The assumption that EC_e or salt content is the only spatially variable soil attribute of importance influencing EC_a measurements.

A method proposed by Lesch et al. (1995a, 1995b) addresses these concerns. With respect to random soil sampling, they created a spatial site selection algorithm that is designed to identify a minimal number of calibration sites while still selecting sites that are spatially representative of the entire survey area. In terms of EC_e being the only parameter influencing EC_a, the authors developed multiple-linear regression models that incorporate properties such as soil clay content, saturation percentage, and sodium absorption ratio into the calibration model. The statistics involved with the above mentioned methods are quite intensive and a software package called ESAP-95 (Lesch et al., 2000) was developed to take a user step by step through the process of calibrating

spatial EC_a measurements in terms of soil salinity. The correlation between EC_a and EC_e in comparison to other soil attributes is often strong, particularly in saline fields (Kaffka et al., 2005). For example, Rhoades and Ingvalson (1971) reported a linear reationship, $EC_e = 9.095(EC_a) - 0.274$, with a correlation coefficient (r) of 0.997.

Spatial measurements of EC_a can be collected at densities several orders of magnitude higher than what would be practical from direct soil sampling and measurement of EC_e. The rapid and relatively inexpensive collection of EC_a data sets is the rationale for using it to map and characterize soil salinity status in agricultural fields. However, the measurements are still collected from a point in space. To create a continuous map or surface, geostatistical methods of estimating unmeasured values are required.

2.4.5 Geostatistics and Salinity Mapping

Although measurements of EC_a can be collected at very high densities in the field, they still reflect a particular point in space. Similarly, values of EC_e are determined from discrete soil sample locations. Geostatistics provide a means of utilizing spatial continuity for estimating the value of a parameter such as EC_a at un-sampled locations (Kuhn et al., 1996). The techniques are powerful analytical tools that integrate numerical and statistical methods with scientific intuition and professional judgement to resolve conflicts between conceptual interpretation and direct measurement (Cromer, 1996).

The basic principle of geostatistics is that data values are not statistically independent (unlike classic statistics that assume they are) but rather spatially dependant: data values that are close together tend to be more similar than data values that are far

apart (Srivastava, 1996). However, spatial dependency need not be the same in every direction or axes, for example in two-dimensional space (north/south; east/west). If the dependency structures are the same in all directions, it is called an isotropic dependency structure; if it is not the same in every direction, it is called anisotropic (Haining, 2003).

Geostatistical methods involve two stages: modelling of the spatial correlation of the observed variable using semi-variogram analysis, and the estimation of variable values at unsampled locations using a technique known as kriging (Dowdall and O'Dea, 1999). Kriging is named in honour of D.G. Krige, a South African mining engineer who pioneered the use of weighted moving averages in the assessment of ore bodies. According to Myers (1997), kriging can be defined as a statistical prediction method that analyzes correlation of sample values in terms of their spatial proximity to each other and uses a mathematical representation of their spatial correlation to make predictions at locations where the values are not known.

The semi-variogram is created by plotting the semi-variance, $\gamma(h)$, in relation to the distance between sample points, h. The semi-variance is calculated according to the equation:

$$\gamma(h) = \frac{1}{2\,n(h)} \sum_{i=1}^{n-h} [\,z(x_{i+h}) - z(x_i)\,]^2 \qquad [9]$$

where $n(h)$ is the number of sample pairs separated by a distance, or lag, h and $[z(x_{i+h}) - z(x_i)]$ is the difference between variable values separated by a distance h (Dowdall and O'Dea, 1999). The resulting plot, termed the empirical semi-variogram, describes the spatial correlation of the data set, with the semi-variance typically increasing as the distance between samples increases (Figure 2.16). To describe the spatial correlation, it is necessary to fit a mathematical model to the empirical semi-variogram, with the most

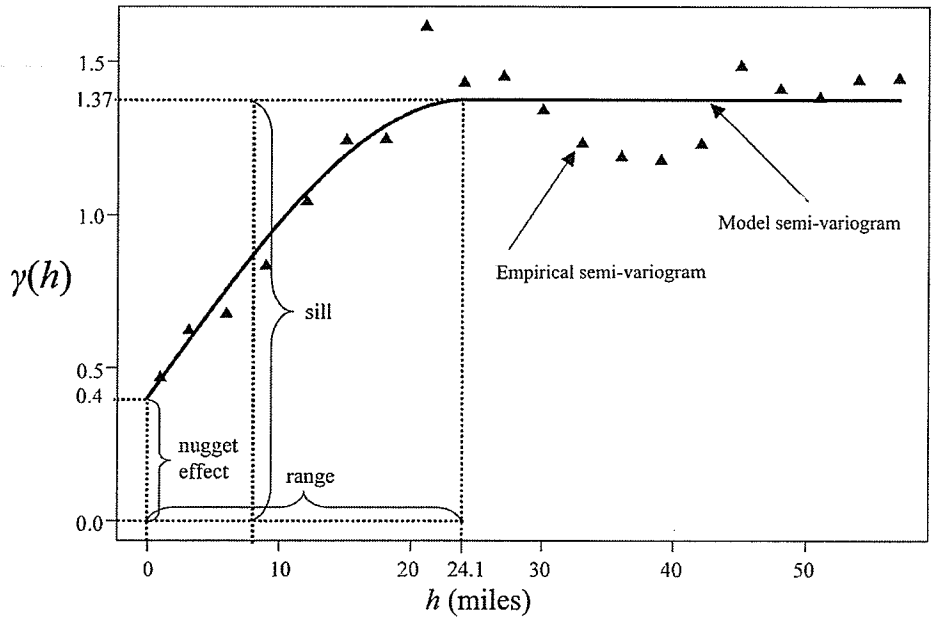

Figure 2.16. An example of a spherical semi-variogram model fit to an empirical semi-variogram (adapted from Watson et al., 2001)

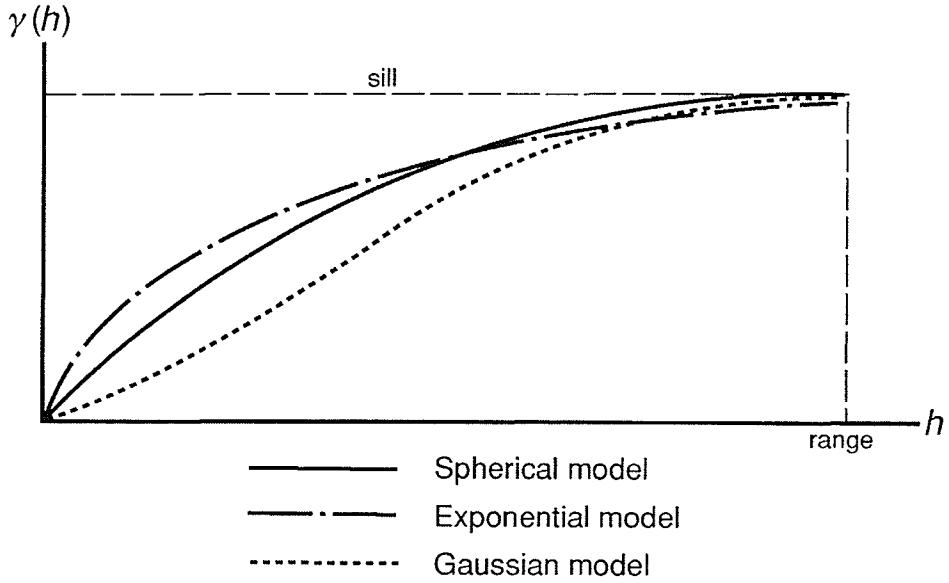

Figure 2.17. Illustration of spherical, exponential, and gaussian semi-variogram models (adapted from Haining, 2003)

common models employed being gaussian, exponential, or spherical functions (Figure 2.17) (Dowdall and O'Dea, 1999).

The distance where the model semi-variogram (Figure 2.16) first plateaus is known as the range. Sample locations separated by distances closer than the range are deemed spatially correlated, whereas locations farther apart than the range are not and are spatially independent (Cressie, 1991). The value at which the variogram model attains the range (the value on the y-axis) is called the sill. The partial sill is the sill minus the nugget. Theoretically, at zero separation distance, the semi-variogram value is zero, however, at an infinitely small separation distance, the semi-variogram often exhibits a nugget effect, which is some value greater than zero. If the variogram model intercepts the y-axis at 2, then the nugget is 2. The nugget effect can be attributed to measurement errors or spatial sources of variation at distances smaller than the sampling interval (or both) (Cressie, 1991).

There are a number of specific kriging techniques, but ordinary kriging (OK) is one of the most widely used spatial interpolators. Ordinary kriging assigns weights to samples according to information provided by the semi-variogram such that it ensures that the estimate produced is a best linear unbiased estimator (i.e., errors are as close to zero as possible). Ordinary kriging can be described in equation form as follows:

$$z^*(x_o) = \sum_{i=1}^{n} [\lambda_i z(x_i)] \qquad [10]$$

$z^*(x_o)$ being the kriged estimate, λ_i being the weight assigned to the known sample z at the location (x_i) (Dowdall and O'Dea, 1999). Sample weights are assigned according to the kriging system:

$$\sum_{j=1}^{n} \lambda_i \gamma(x_i, x_j) + \mu = \gamma(x_i, x_0), \quad 1 = 1,2,3,.....,n \qquad [11]$$

(x_i,x_j), (x_i,x_0) are the lag intervals separating the relevant points, x_0 is the location to be estimated, γ is the semi-variogram value for that lag distance, λ_i is the assigned weight and μ is a Lagrange multiplier (Dowdall and O'Dea, 1999).

3 SOIL SALINITY ASSESSMENT

3.1 Abstract

Increased grower concern over the effect of soil salinity on crop production in the province of Manitoba has precipitated the need for inexpensive but effective methods of assessing soil salinity in the field. The objectives of this study were to develop a rapid, simple, and yet accurate method of assessing soil salinity in fields of the Red River Valley of Manitoba, converting values of soil apparent electrical conductivity (EC_a) measured with the Veris 3100 to the electrical conductivity of a saturated soil past extract (EC_e), and to create continuous map surfaces of EC_e in order to estimate the extent and severity of soil salinity in study fields.

Ordinary kriged prediction surfaces were created from EC_a measurements and then correlated to the EC_e of soil samples collected from the same location using multivariate linear regression. Soil salinity assessment using depth weighted measurements of EC_a were found to be extremely effective. Highly significant correlations between EC_a and EC_e were obtained, with r^2 (coefficient of determination) values of approximately 0.9. Levels of soil salinity observed in study fields were highly variable spatially in x, y, and z directions. Soil salinity values (EC_e) observed in study fields ranged from 0.3 to 18.3 dS m^{-1}.

3.2 Introduction

Saline soils usually develop in areas that receive salts from other locations with water as the main mode of transportation (and wind as another mode transportation). The

ocean is one source of salts, as in soils where the parent material consists of marine deposits that were laid down during earlier geologic periods and have since been uplifted or redistributed by the movement of glaciers, mixing the underlying marine shales with deposits closer to the surface (Henry et al, 1987). More commonly, however, the direct sources of salts in the soil profile are surface and ground waters. Both of these water sources contain dissolved salts, and their concentration depends upon the salt content of the soil and geologic materials with which the water has been in contact. Soil salinization occurs in areas where groundwater or surface water carrying dissolved salts discharges or is deposited at or near the soil surface (Stein and Schartwz, 1990), in areas where evapotranspiration (ET) exceeds infiltration of water at or near the soil surface.

Soil salinity is an important factor limiting crop production in the prairie provinces of Canada, and indeed around the world. At last report (Eilers et al., 1995), most prairie farmland (62%) had less than 1% of its area affected by salinity; 36% has 1-15% of its lands affected; and 2% has more than 15% of its lands affected. A salinity risk index created by Eilers et al. (1995) showed that under 1991 farming practices, there is little or no risk of a change in salinity levels in about 61% of the agricultural land in Manitoba, 59% of Saskatchewan, and 80% in Alberta; however, the remaining farmland in each province exhibits a moderate-to-high risk of increasing salinity. In order to monitor the risk of increasing soil salinity, and allow producers to better manage their agricultural land base under saline conditions, rapid and cost effective methods of determining the extent and severity of soil salinity are required.

3.2.1 Principles of Soil Salinity Assessment

During the first half of the 20th century, soluble salt contents of soils were estimated from the electrical conductivity (EC) of saturated soil-pastes (EC_p), a methodology first described in a publication by Whitney and Means (1897). EC is a numerical expression of the inherent ability of a medium to conduct electricity, and since pure water is a very poor conductor of electricity, the EC of aqueous samples is a result of the contributions of electrolytes dissolved in it. As the understanding of saline soils progressed, it was found that plant response to salinity was much more highly related to the salt concentration of the soil solution than to the total dissolved salt content of the soil. For this reason, the electrical conductivity of the saturated soil-paste-extract (EC_e) was advocated as the preferred universal index of soil salinity (U.S. Salinity Laboratory Staff, 1954), and is the conventional method of defining and measuring soil salinity today. Manitoba Agriculture, Food and Rural Initiatives (2001) qualitatively characterizes soil salinity in terms of EC_e as follows: non-saline (0-2 dS m^{-1}), slightly saline (2-4 dS m^{-1}), moderately saline (4-8 dS m^{-1}), severely saline (8-16 dS m^{-1}), and very severely saline (> 16 dS m^{-1}).

The ability of the bulk soil to carry an electrical current, termed apparent electrical conductivity (EC_a), is a characteristic of agricultural soils that has received much attention of late, particularly in a spatial context. Applications of EC_a have primarily focused on soil salinity assessment and there are many examples of this utilization including Halvorson and Rhoades (1976), Cameron et al. (1981), Williams and Baker (1982), McKenzie et al. (1989), Rhoades et al. (1989), Lesch et al. (1992, 1995a, 1995b), Mankin and Karthikeyan (2002), and Corwin et al. (2003). Other spatial

applications include field characterizations of soil water content (Kachanoski et al., 1988; Morgan et al., 2000) and soil texture (Triantafillis et al., 2001; Sudduth et al., 2005). Spatial measurements of EC_a can be collected at densities several orders of magnitude higher than what would be practical from direct soil sampling and measurement of EC_e. The rapid and relatively inexpensive collection of EC_a data sets is the rationale for using it to map and characterize soil salinity status in agricultural fields.

The Veris 3100 (Veris Technologies, Salina, KS) is a commercially available technology of rapid measurement of soil EC_a that has been recently developed. This technology possesses a number of more user friendly and time saving innovations in comparison to the EM38 (see section 2.4.3). Measurement of EC_a using the Veris 3100 is based on the Wenner four-electrode probe technique, and uses six rolling coulters for electrodes configured to provide both shallow and deep readings of EC_a, denoted as $EC_{a\text{-}sh}$ and $EC_{a\text{-}dp}$ respectively (Lund and Christy, 1998). (For a more detailed description of the principles of EC_a measurement using the Veris 3100, see section 2.4.3.) Measurements of EC_a using the Veris 3100 have been found to relate very strongly to measurements of EC_a using the EM38 over similar soil response depths (Sudduth et al., 2005). However, calibration models of EC_e vs. EC_a measured using the Veris 3100 have yet to be created.

3.2.2 Objectives

The two main objectives of this study were to:

1. Develop a rapid, simple, and yet accurate method of assessing soil salinity in fields of the Red River Valley of Manitoba, converting values of soil EC_a measured with the Veris 3100 to standard soil salinity units of EC_e.
2. Create continuous map surfaces of EC_e in order to estimate the extent and severity of soil salinity in the selected study fields.

3.3 Materials and Methods

3.3.1 Study Fields

This experiment was part of a larger study initiated in 2003 comparing the effect of increasing root-zone salinity on the growth of dry bean crops on selected fields in southern Manitoba. Three row-cropped (76.2 cm row spacing) dry bean (*Phaseolus vulgaris* L.) fields were selected in the Winkler, Emerson and Portage la Prairie regions of southern Manitoba in the 2003 growing season and, again, Portage la Prairie in 2004 (Figure 3.1). These fields were denoted as Portage 03, Winkler 03, Emerson 03, and Portage 04, respectively. The sites were chosen from three selected producers who were willing to participate in the study and who believed there to be significant levels of soil salinity in their study fields. All four sites were imperfectly drained Black Chernozemic soils. The soil series at Winkler 03 and Emerson 03 were primarily Gnadenthal loam and Dencross loam, respectively, while both the Portage 03 and Portage 04 sites were primarily Neuhorst loams. For a more detailed edaphic description see Table 3.1, which also includes pertinent climatic data. Each selected field was suspected by the managing

producers of having a wide range of salinity within its boundaries. All sites had very little relief within their boundaries, outside of surface drainage ditches (see Figures 3.11, 3.12, 3.13, and 3.14). This observation was confirmed by topographical mapping operations. Topography data sets were collected for all four study fields, using Trimble AgGPS 214 RTK (real time kinematic) GPS equipment. Surveys were collected in the spring of 2003 for the Winkler 03 site, in the fall of 2003 for the Portage 03 site, in the spring of 2004 for the Portage 04 site, and in the fall of 2004 for the Emerson 03 site.

Table 3.1. Description of study sites

Field site	Field area (ha)	Predominant soil series	Soil series description	Textural class to ~ 90 cm	Mean annual precip. (mm)	Mean temp. May 1-Sept. 1 (°C)
Portage la Prairie, 2003 (Michalyna and Smith, 1972)	61.0	Neuhorst clay loam	Imperfectly drained Gleyed Carbonated Rego Black Chernozemic soils. Formed on moderately fine textured, moderately calcareous alluvial and lacustrine deposits.	Silty clay ~ 0-60 cm, silty loam ~ 60-90 cm.	514.5	16.6
		Plum Coulee clay	Imperfectly drained Gleyed Black Chernozemic soils. Formed on moderately fine textured, moderately calcareous alluvial and lacustrine deposits.	Clay		
		Gnadenthal loam	Imperfectly drained Gleyed Carbonated Rego Black Chernozemic soils. Formed on medium to moderately fine textured, moderately to strongly calcareous deltaic and lacustrine sediments.	Very fine sandy loam ~ 0-30 cm, very fine sandy clay loam ~ 30-60cm, very fine sandy loam ~ 60-90 cm.		
Winkler, 2003 (Smith and Michalyna, 1973)	32.1	Gnadenthal loam	See desciptrion above.	See desciptrion above	533.3	17.45
		Horndean clay	Imperfectly drained Gleyed Orthic Black Chernozemic soils. Formed in thin, fine textured, moderately to strongly calcareous lacustrine clay sediments overlying coarse to medium textured deposits.	Clay		
Emerson, 2003 (Peter Halushuk, personal communication)	32.7	Dencross loam	Imperfectly drained Gleyed Rego Black Chernozemic soils developed on (< 1 m) of moderately to strongly calcareous, shallow clayey, lacustrine deposits over very strongly to extremely calcareous, silty, lacustrine deposits	Clay ~ 0-30 cm, silty clay ~ 30-70 cm, silty clay loam 70-90 cm.	562.6	17.5
Portage la Prairie, 2004 (Michalyna and Smith, 1972)	35.4	Neuhorst clay loam	See desciptrion above.	See desciptrion above.	514.5	16.6
		Plum Coulee clay	Imperfectly drained Gleyed Orthic Black Chernozemic soils. Formed on moderately fine textured, moderately calcareous alluvial and lacustrine deposits.	Clay		

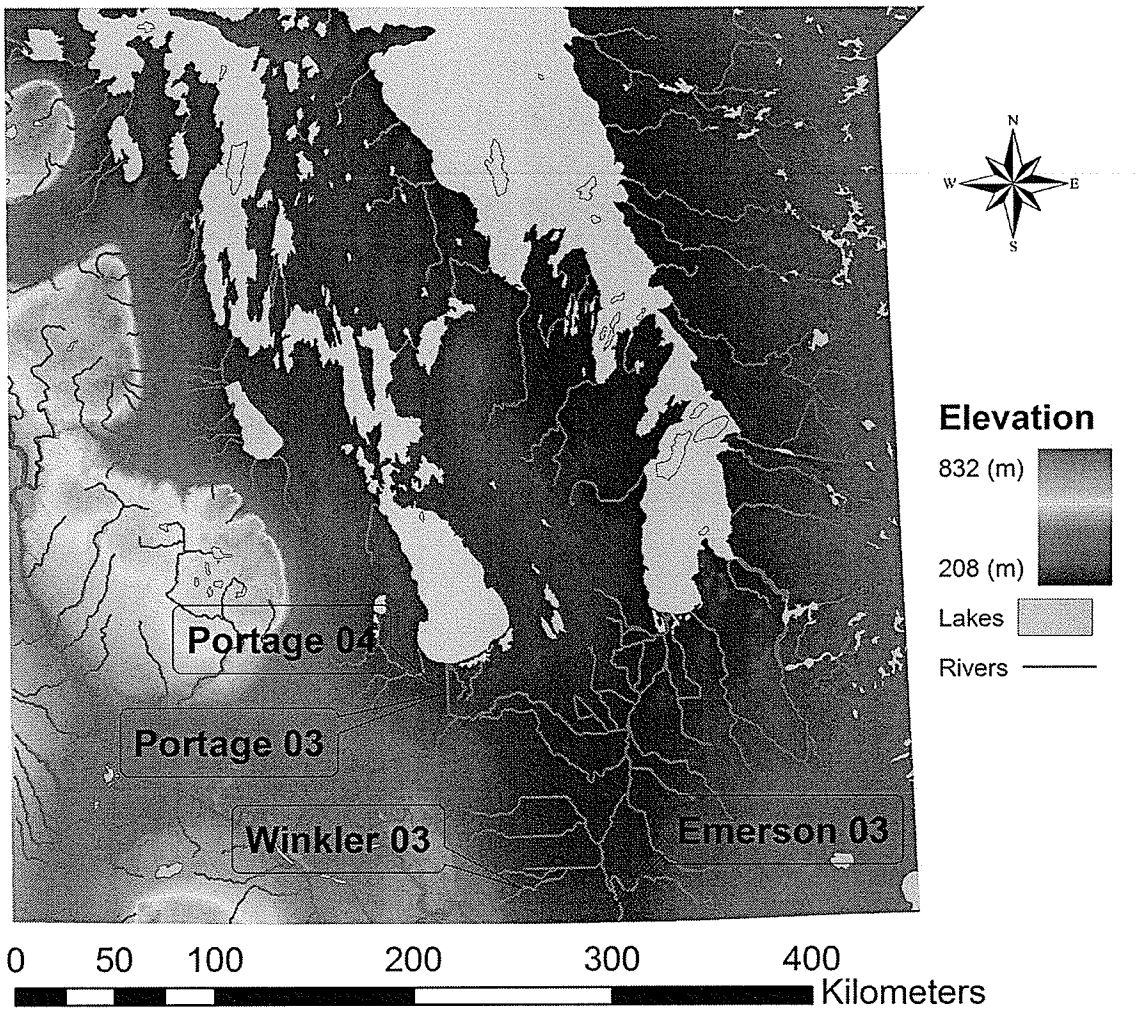

Figure 3.1. Elevation map (meters above sea level) of southern Manitoba, including the approximate location of study fields

3.3.2 EC_a Survey Collection

EC_a surveys were collected utilizing the Veris 3100. The Veris 3100 was towed with a pick-up truck through the field in the spring approximately three weeks before planting operations of the study site year, taking measurements at a speed of approximately 15 km h^{-1} and a transect width of approximately 10 m. $EC_{a\text{-}sh}$ and

$EC_{a\text{-}dp}$ (in units of mS m^{-1}) were recorded in conjunction with differential GPS data (in units of degrees, in coordinates of latitude and longitude, using the WGS (world geodetic survey) 84 datum, obtained using a Trimble AgGPS 114 (Trimble, Sunnyvale, CA) GPS antenna/receiver with a WAAS (wide area augmentation system) differential correction signal. Measurements were recorded at a rate of one reading per second, corresponding to a reading approximately every five meters along a transect. The GPS antenna was located either directly above the Veris 3100 or at the rear corner of the pick-up truck box (as near to the Veris 3100 sensor cart as possible). The Veris 3100 does not require a calibration before each mapping session; however, diagnostics tests of sensor function and of the coulters being electrically isolated from each other and the sensor cart were conducted before each survey operation.

To aide in the assessment of salinization processes, topography data sets were collected for all four study fields, using Trimble AgGPS 214 RTK (real time kinematic) GPS equipment. Surveys were collected in the spring of 2003 for theWinkler 03 site, in the fall of 2003 for the Portage 03 site, in the spring of 2004 for the Portage 04 site, and in the fall of 2004 for the Emerson 03 site. Surveys were collected on a transect width between 10-15 m. Topography and percent slope maps were created from the survey datasets using the ArcGIS Desktop version 9.0 (ESRI, Redlands, CA) geographical information (GIS) software platform. Geostatistical and surface analysis functions were conducted using the Geostatistical Analyst and Spatial Analyst Extensions of the same software program, respectively. Topography surfaces were created using ordinary kriging (OK) procedures. Topographical survey analysis was not a major component of

this project, but simply used to assist in the assessment of soil salinity development in our study fields.

3.3.3 Methods of Calibration

$EC_{a\text{-}sh}$ and $EC_{a\text{-}dp}$ map creation and visualization were conducted using the ArcGIS Desktop version 9.0 GIS software platform. Geostatistical analysis functions were conducted using the Geostatistical Analyst Extension of the same software program. Both omni- and multi-directional spherical, gaussian, and exponential semi-variogram models were compared in order to create the best possible $EC_{a\text{-}sh}$ and $EC_{a\text{-}dp}$ kriged surfaces (described further in Tables 3.3 and 3.4 of the Results and Discussion section). Omni-and multi-directional variogram were compared to evaluate the presence of anisotropism within the $EC_{a\text{-}sh}$ and $EC_{a\text{-}dp}$ datasets and whether accounting for its presence in the kriging model was of benefit. The best semi-variogram model was defined as having the smallest mean prediction error (MPE), root-mean-squared prediction error (RMSPE), and mean standard error (MSE), as well as values nearest to one for standardized mean prediction errors (SMPE), standardized root-mean-square prediction error (SRMSPE), and pseudo r^2 (~ coefficient of determination). All but the last summary statistic, pseudo r^2, were calculated in the Geostatistical Analyst Extension. Pseudo r^2 was determined by calculating the sum of the prediction errors (residuals) squared, divided by the corrected total sums of squares, added to negative one (Schabenberger, 1998). If a given dataset demonstrated a non-normal distribution, a log transformation of the dataset was conducted before kriging after which data values were

converted back to their original scale, a function available within the Geostatistical Analyst Extension.

Interpolated (using OK) point estimations of $EC_{a\text{-}sh}$ and $EC_{a\text{-}dp}$ were used in multivariate linear regression (MLR) analysis and ordinary least squares fitting techniques using the Proc Reg procedure in SAS version 8.0 (SAS Institute, Cary, NC) to establish the relationship between those parameters and EC_e for a given soil depth. The following MLR model was employed:

$$EC_z = m_1 EC_{a\text{-}sh} + m_2 EC_{a\text{-}dp} + b \qquad [4]$$

where EC_z is the value of EC_e for a given soil depth interval (z), m_1 and m_2 are regression coefficients relating EC_z to each of $EC_{a\text{-}sh}$ and $EC_{a\text{-}dp}$, and b is the intercept.

Following the creation of MLR models to estimate EC_e for various soil depths (z), soil salinity maps (on an EC_e basis) were created by using the original $EC_{a\text{-}sh}$ and $EC_{a\text{-}dp}$ survey data in the given MLR model, thus estimating EC_e for each surveyed location. OK surfaces were created using the same parameters employed in the creation of $EC_{a\text{-}sh}$ and $EC_{a\text{-}dp}$ prediction surfaces.

Following the creation of continuous $EC_{a\text{-}sh}$ and $EC_{a\text{-}dp}$ surfaces for each site, five ranges of EC_a were identified in each field, from which three sample sites located within 25 m of each other (to achieve a level of replication) were identified in each range. The EC_a range locations were chosen to encompass a broad spectrum of both $EC_{a\text{-}sh}$ and $EC_{a\text{-}dp}$ values.

3.3.4 Soil Sample Collection and Analysis

Soil samples within the five designated subplots were collected using a Dutch auger at depth increments of 0-15, 15-30, 30-60, and 60-90 cm. For the 0-15 and 15-30 cm depth increments, composites of four 7.5 cm diameter soil cores were collected; and for the 30-60 and 60-90 cm depth increments, composites of two 5 cm diameter soil cores were collected, all from a radial distance within 5 m of each soil sample location. Soil samples were stored in sealed plastic bags until they could be air-dried and crushed.

Soil salinity was determined for the collected samples using a 1:2 ratio electrical conductivity ($EC_{1:2}$). Fifteen g of air-dried soil was weighed into a pop-top centrifuge tube, diluted with 30 ml of deionised water, and shaken for 30-45 minutes and let stand for 15-30 minutes. The electrical conductivity of the solution was then measured directly, in units of dS m^{-1}. In addition, 66 samples that varied greatly in soil salinity were selected and prepared for determination of EC_e. Approximately 200 g of air-dried soil was weighed and made into a saturated soil paste according to Rhoades (1996) (Figure 3.2). The paste was left to stand for periods of up to 12 hours prior to extraction by suction. The electrical conductivity of the soil solution extract (EC_e) was then measured directly, again in units of dS m^{-1}. A regression analysis was conducted between EC_e and $EC_{1:2}$ as determined above, which showed a strong positive linear relationship, described by the following equation:

$$EC_e = 2.0916 * EC_{1:2} - 0.103 \quad [5]$$

This relationship (r^2 = 0.970, RMSE = 0.799) was then used to convert the measured values of $EC_{1:2}$ to EC_e. Values of EC_e were calculated for 0-15, 15-30, 30-60, and 60-90 cm soil depths, denoted as $EC_{0\text{-}15}$, $EC_{15\text{-}30}$, $EC_{30\text{-}60}$, and $EC_{60\text{-}90}$, respectively. As well,

averaged EC_e values were calculated using these values to get composite depth profiles from 0-30, 0-60, 0-90, 15-60, 15-90, and 30-90 cm, denoted as $EC_{0\text{-}30}$, $EC_{0\text{-}60}$, $EC_{0\text{-}90}$, and $EC_{15\text{-}60}$, $EC_{15\text{-}90}$, and $EC_{30\text{-}90}$, respectively.

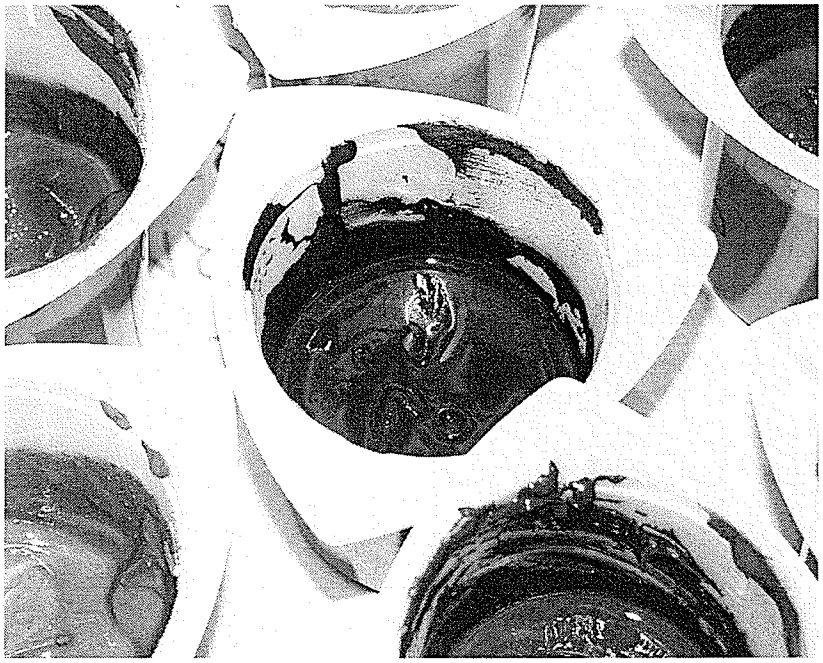

Figure 3.2. Photograph of a saturated soil paste, prepared according to Rhoades (1996)

3.4 Results and Discussion

3.4.1 Creation of $EC_{a\text{-}sh}$ and $EC_{a\text{-}dp}$ Prediction Surfaces

Table 3.2 includes a statistical summary of both $EC_{a\text{-}sh}$ and $EC_{a\text{-}dp}$ survey datasets. The density of survey measurements ranged from a low of 172.8 points ha^{-1} for the Portage 04 site, to a high of 267.0 for the Portage 03 site. $EC_{a\text{-}sh}$ and $EC_{a\text{-}dp}$ survey datasets for all sites contained high levels of variability, with a range of approximately 300 mS m^{-1}. The mean $EC_{a\text{-}sh}$ values for all four study sites were quite similar, ranging from 76.4 to 80.3 mS m^{-1}. The mean $EC_{a\text{-}dp}$ measurements, on the other hand, displayed much greater variability between study sites, ranging from 83.3 to 150.1 mS m^{-1},

Table 3.2. Statistical summary of EC_a survey data

Veris 3100 survey parameter	Survey collection date	N	Meas. Density (points ha^{-1})	Mean	Median	Min.	Max.	Range	S.D.	C.V. (%)	Skewness	*Kolmogorov-Smirnov P >D
				mS m^{-1}								
				Portage 03								
$EC_{a\text{-}sh}$	21-May-03	16288	267.0	77.9	68.3	23.3	451.0	427.7	39.0	50.1	2.3	<0.01
$EC_{a\text{-}dp}$	21-May-03	16288	267.0	106.0	99.8	21.7	362.4	340.7	49.0	46.2	0.7	<0.01
				Winkler 03								
$EC_{a\text{-}sh}$	27-May-03	7760	241.7	80.3	75.8	11.3	271.8	260.5	32.8	40.9	1.2	<0.01
$EC_{a\text{-}dp}$	27-May-03	7760	241.7	101.5	97.1	22.3	313.1	290.8	41.0	40.4	0.8	<0.01
				Emerson 03								
$EC_{a\text{-}sh}$	19-May-03	6584	201.3	78.6	70.0	30.5	326.7	296.2	31.2	39.7	2.2	<0.01
$EC_{a\text{-}dp}$	19-May-03	6584	201.3	83.3	73.0	29.7	269.8	240.1	36.7	44.0	1.1	<0.01
				Portage 04								
$EC_{a\text{-}sh}$	9-May-04	6117	172.8	76.4	59.6	30.4	309.6	279.2	40.2	52.7	2.0	<0.01
$EC_{a\text{-}dp}$	9-May-04	6117	172.8	150.1	137.3	59.1	362.1	303.0	53.1	35.4	0.8	<0.01

*Kolmogorov-Smirnov test for normality, $P < 0.05$ are considered non-normal

indicating more variability in soil salinity between study fields at deeper depths than near the soil surface. In all cases, the mean $EC_{a\text{-}dp}$ values were greater than the $EC_{a\text{-}sh}$ values. Greater mean than median values for $EC_{a\text{-}sh}$ and $EC_{a\text{-}dp}$, as well as positive skewness levels indicate that all datasets are positively skewed (i.e., a small proportion of relatively high EC_a values). Tests for normality showed highly significant non-normal conditions for all eight survey datasets, indicating that a log transformation before kriging interpolation would be appropriate. This log transformation was therefore performed as part of the OK process.

Tables 3.3 and 3.4 provide statistical summaries of the evaluation of kriging parameters used in the creation of $EC_{a\text{-}sh}$ and $EC_{a\text{-}dp}$ prediction surfaces, respectively. When comparing the three semi-variogram models used in OK of both $EC_{a\text{-}sh}$ and $EC_{a\text{-}dp}$ prediction surfaces, the exponential model was deemed the best in all of but one case; a spherical model was chosen for the $EC_{a\text{-}dp}$ surface at the Emerson 03 site. Accounting for the effects of anisotropism was found to be important in the creation $EC_{a\text{-}sh}$ surfaces at Portage 03 and Emerson 03 sites, and the $EC_{a\text{-}dp}$ surface at the Emerson 03 site, indicating directional trends in the spatial datasets.

Table 3.3. Summary of statistical results (mean prediction error (MPE), root-mean-squared prediction error (RMSPE), mean standard error (MSE), standardized mean prediction errors (SMPE), and standardized root-mean-square prediction error (SRMSPE)) from creation of $EC_{a\text{-}sh}$ prediction surfaces using either spherical, gaussian, or exponential semi-variogram models, as wells as accounting for the effects of anisotropism in surface prediction

Semi-variogram model	Direction of model semi-variogram	MPE	RMSPE	MSE	SMPE	RMSPES	Pseudo r^2	Chosen model
				Portage 03				
Spherical	Omni	-0.6589	14.86	16.25	0.00469	0.8082	0.9667	
	Multi	-0.1074	14.67	15.52	0.00122	0.8369	0.9675	
Gaussian	Omni	-0.0301	17.32	18.91	0.01056	0.8051	0.9542	
	Multi	-0.1813	17.19	17.73	-0.00762	0.8594	0.9547	
Exponential	Omni	-0.1114	13.58	13.50	0.00071	0.8972	0.9725	
	Multi	-0.1211	13.45	12.75	0.00019	0.9408	0.9731	x
				Winkler 03				
Spherical	Omni	0.1807	13.71	19.27	0.00311	0.7417	0.9730	
	Multi	0.1619	13.67	19.10	0.00246	0.7451	0.9732	
Gaussian	Omni	0.1253	16.71	21.51	-0.01466	0.8186	0.9593	
	Multi	0.1609	16.71	21.74	-0.01139	0.8075	0.9594	
Exponential	Omni	-0.0133	12.01	15.29	-0.00237	0.8231	0.9795	x
	Multi	-0.0212	12.00	15.29	-0.00358	0.8197	0.9795	
				Emerson 03				
Spherical	Omni	-0.0866	12.61	13.50	-0.00599	0.9299	0.9759	
	Multi	0.0258	12.58	14.63	-0.00160	0.8598	0.9760	
Gaussian	Omni	-0.1441	13.96	13.92	-0.00924	1.0040	0.9703	
	Multi	-0.0958	13.51	14.00	-0.00706	0.9648	0.9722	
Exponential	Omni	-0.0140	12.04	12.54	0.00169	2.4480	0.9782	
	Multi	-0.0004	11.45	10.77	-0.00134	2.9220	0.9804	x
				Portage 04				
Spherical	Omni	-0.2262	13.06	14.19	-0.01190	0.8625	0.9753	
	Multi	-0.2134	12.79	13.57	-0.01093	0.8892	0.9791	
Gaussian	Omni	-0.6986	17.02	17.42	-0.05273	0.9465	0.9562	
	Multi	-0.6542	16.24	16.28	-0.05990	0.9944	0.9603	
Exponential	Omni	-0.1129	12.14	11.18	-0.00618	1.0360	0.9791	x
	Multi	-0.1046	12.17	9.90	-0.00691	1.2520	0.9791	

Table 3.4. Summary of statistical results (mean prediction error (MPE), root-mean-squared prediction error (RMSPE), mean standard error (MSE), standardized mean prediction errors (SMPE), and standardized root-mean-square prediction error (SRMSPE)) from creation of $EC_{a\text{-}dp}$ prediction surfaces using either spherical, gaussian, or exponential semi-variogram models, as wells as accounting for the effects of anisotropism in surface prediction

Semi-variogram model	Direction of model semi-variogram	MPE	RMSPE	MSE	SMPE	RMSPES	Pseudo r^2	Chosen model
				Portage 03				
Spherical	Omni	0.0480	9.80	13.15	0.00441	0.7736	0.9922	
	Multi	0.0347	9.60	12.44	0.00395	0.8014	0.9926	
Gaussian	Omni	0.1004	13.11	17.75	-0.00745	0.7560	0.9860	
	Multi	-0.1253	12.48	14.99	-0.03893	0.8695	0.9873	
Exponential	Omni	0.0400	9.01	10.49	0.00370	0.9888	0.9934	x
	Multi	0.0759	9.00	10.71	0.00710	0.9607	0.9935	
				Winkler 03				
Spherical	Omni	0.2685	12.25	20.33	0.00439	0.6216	0.9867	
	Multi	0.1872	12.07	19.27	0.00246	0.6464	0.9871	
Gaussian	Omni	0.2034	17.15	24.20	-0.03484	0.7872	0.9735	
	Multi	0.1732	17.51	24.72	-0.02882	0.7748	0.9724	
Exponential	Omni	-0.0031	9.79	13.31	-0.00024	0.7714	0.9916	x
	Multi	0.0206	9.83	13.60	0.00238	0.7573	0.9915	
				Emerson 03				
Spherical	Omni	-0.0347	13.34	15.03	-0.00428	2.2880	0.9771	
	Multi	0.0122	12.81	14.43	-0.00353	2.4690	0.9790	x
Gaussian	Omni	-0.2270	14.39	14.01	-0.01605	1.0440	0.9733	
	Multi	-0.1499	13.89	14.20	-0.01205	0.9943	0.9752	
Exponential	Omni	0.3467	13.52	19.16	0.01747	1.7520	0.9765	
	Multi	0.3351	13.44	18.74	0.01639	1.7550	0.9768	
				Portage 04				
Spherical	Omni	0.0893	16.16	22.84	0.00017	0.7332	0.9892	
	Multi	-0.0722	15.62	19.51	-0.00726	0.8265	0.9899	
Gaussian	Omni	-0.1821	21.67	29.27	-0.02740	0.8012	0.9801	
	Multi	-0.1804	20.79	25.55	-0.04767	0.9152	0.9818	
Exponential	Omni	0.0060	14.76	16.91	0.00165	0.8906	0.9910	x
	Multi	0.0354	14.84	17.21	0.00310	0.8770	0.9909	

Figures 3.3, 3.4, 3.5, and 3.6 display the $EC_{a\text{-}sh}$ and $EC_{a\text{-}dp}$ kriged prediction maps along with the soil sample locations used in the MLR calibration of $EC_{a\text{-}sh}$ and $EC_{a\text{-}dp}$ to values of EC_e for the Portage 03, Winkler 03, Emerson 03, and Portage 04 study sites, respectively. All $EC_{a\text{-}sh}$ and $EC_{a\text{-}dp}$ kriged surfaces displayed high levels of spatial structure. In general, the spatial extent of larger EC_a values seemed to be greater for $EC_{a\text{-}dp}$ vs. $EC_{a\text{-}sh}$ prediction surfaces, for all study sites. Specific descriptions of spatial EC_a distributions and possible causes will be discussed in section 3.4.3 (i.e., following calibration of $EC_{a\text{-}sh}$ and $EC_{a\text{-}dp}$ measurements to EC_e and subsequent salinity map creation).

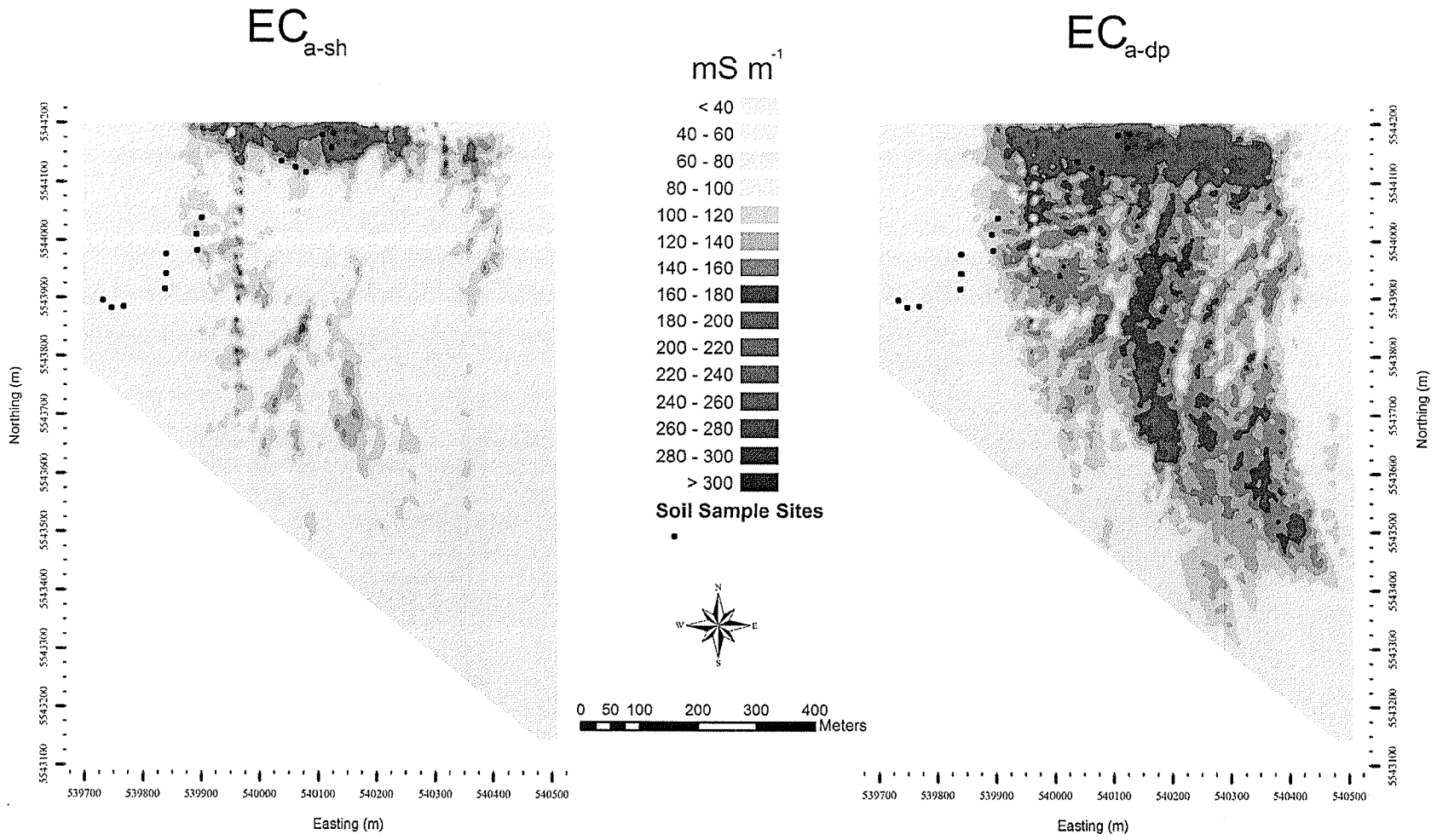

Figure 3.3. Maps of $EC_{a\text{-}sh}$ and $EC_{a\text{-}dp}$ kriged prediction surfaces for the Portage 03 study site

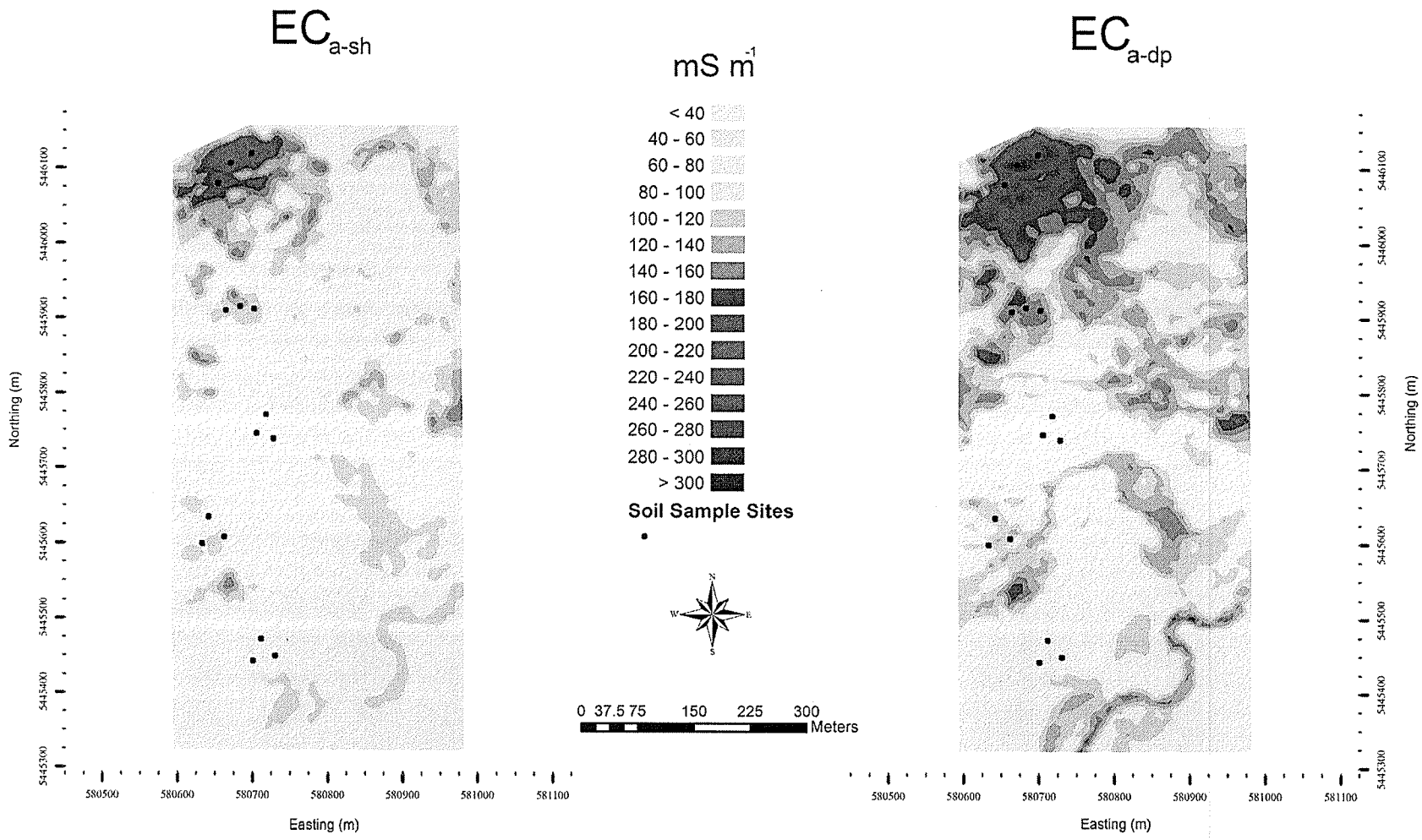

Figure 3.4. Maps of $EC_{a\text{-}sh}$ and $EC_{a\text{-}dp}$ kriged prediction surfaces for the Winkler 03 study site

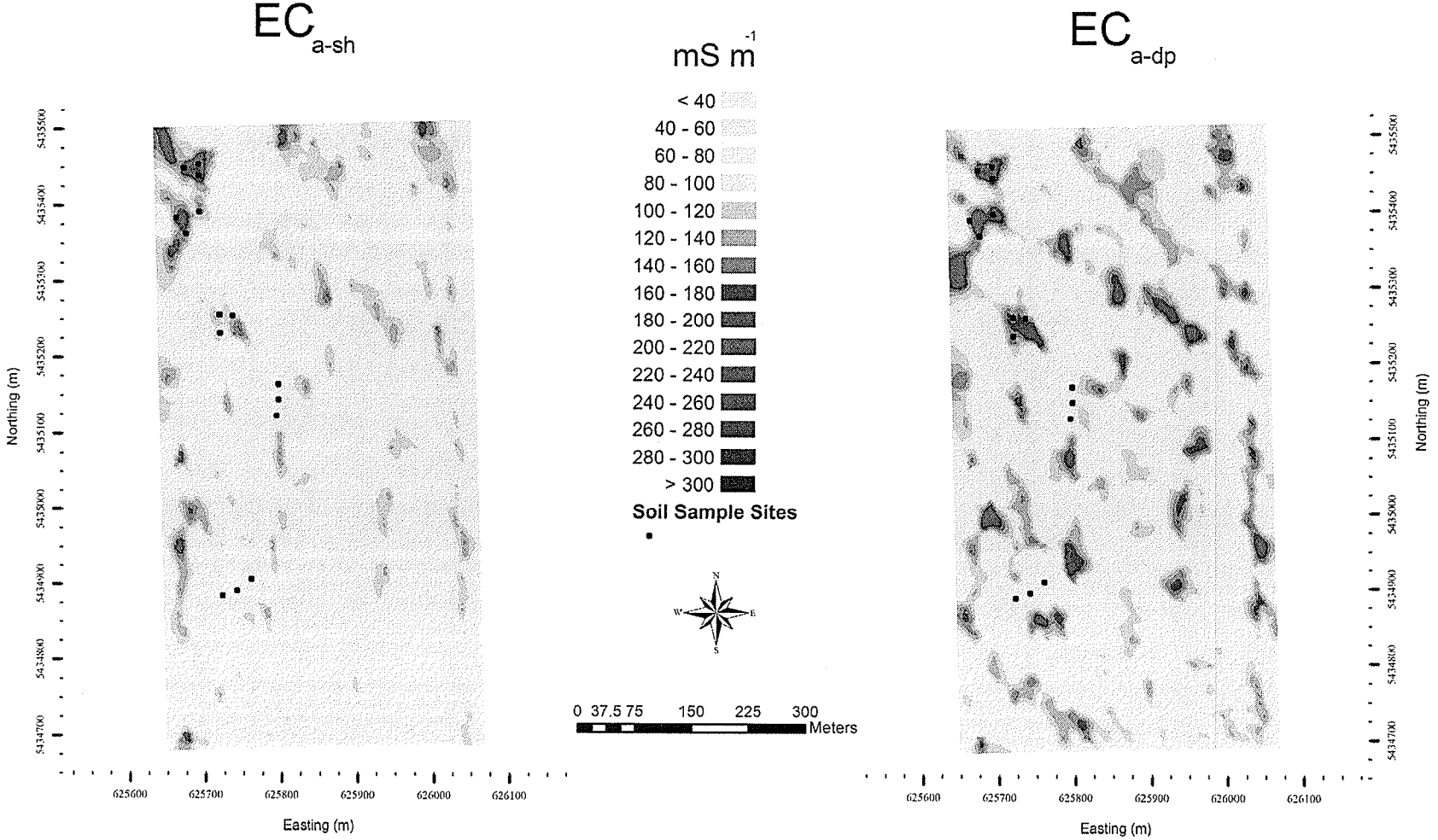

Figure 3.5. Maps of $EC_{a\text{-}sh}$ and $EC_{a\text{-}dp}$ kriged prediction surfaces for the Emerson 03 study site

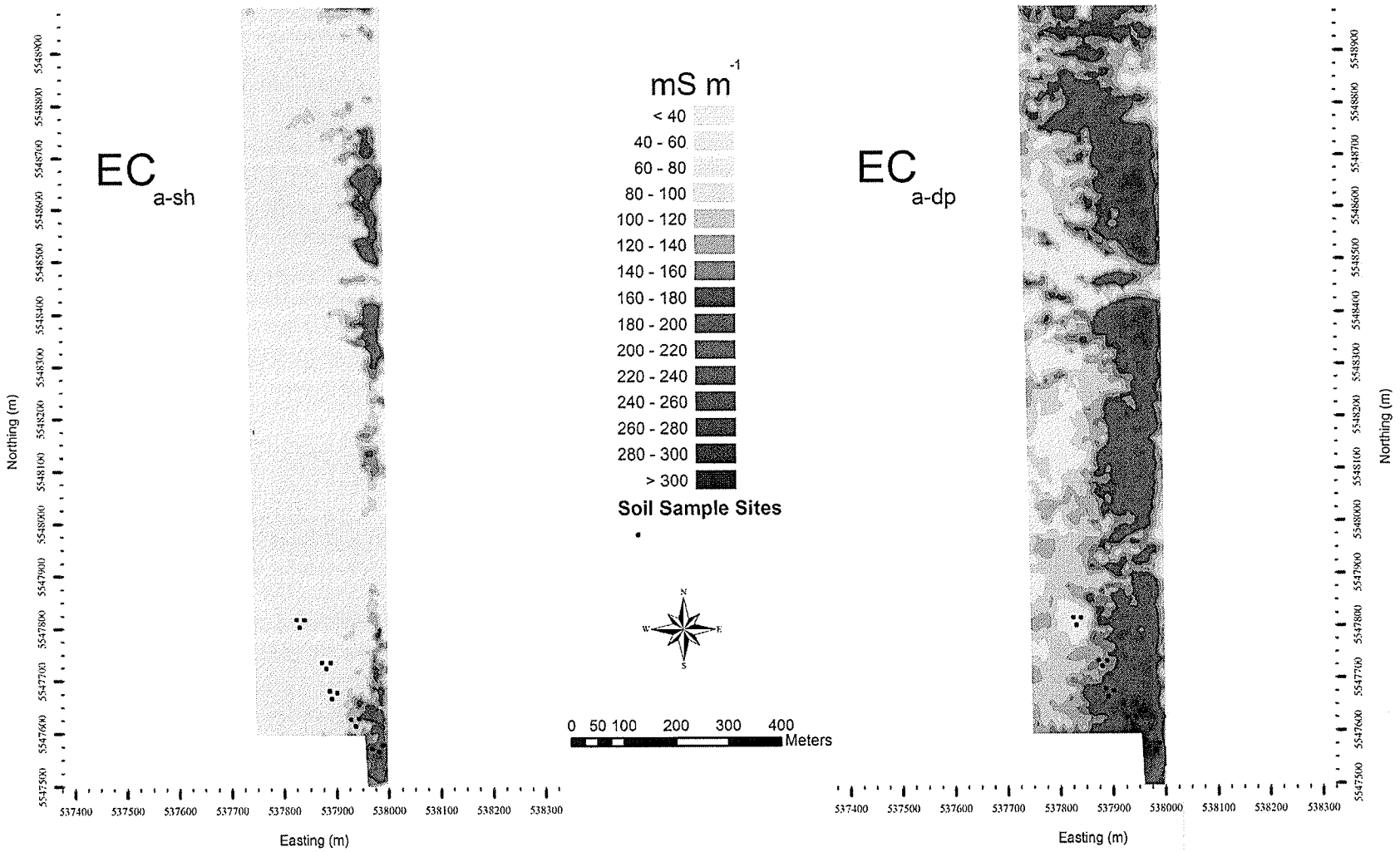

Figure 3.6 Maps of $EC_{a\text{-}sh}$ and $EC_{a\text{-}dp}$ kriged prediction surfaces for the Portage 04 study site

3.4.2 Calibration of $EC_{a\text{-}sh}$ and $EC_{a\text{-}dp}$ to EC_e

Table 3.5 includes summary statistics of $EC_{a\text{-}sh}$, $EC_{a\text{-}dp}$, and EC_z datasets used in MLR calibration procedures. Similar distributions were observed for the $EC_{a\text{-}sh}$ and $EC_{a\text{-}dp}$ calibration values as the original survey datasets. For the Portage 03, Winkler 03, and Emerson 03 EC_z datasets, mean EC_e values were approximately 4-6 dS m^{-1}, ranging from approximately 1 to 10-14 dS m^{-1} (i.e., non-saline to severely saline). Portage 04 calibration EC_e data had mean values from approximately 6-8 dS m^{-1}, with individual values ranging from approximately 1 to 11-18 dS m^{-1} (i.e., non-saline to very severely saline), relatively higher levels of salinity than the three 2003 study sites. Distribution of EC_e values with depth was not consistent between study sites, generally increasing from the surface to 30-60 cm in depth, but decreasing while migrating to the 60-90 cm depth interval (with the exception of the Winkler 03 dataset, which increased steadily with depth). The All Sites dataset had the lowest EC_e values in the 0-15 cm soil depth and the highest in the 15-30 cm depth, while decreasing slightly beyond this interval. Like the $EC_{a\text{-}sh}$ and $EC_{a\text{-}dp}$ survey datasets, the calibration data distributions also appeared to be significantly positively skewed, and again, tests for normality indicated overall non-normal distributions. Tests for normality following a natural log (ln) transformation of the calibration datasets was useful in producing normal distributions in some cases, however it functioned to reduce the normality of others. Therefore, both cases of either using an ln transformation of the dataset or not were included in MLR analysis calibration procedures.

Table 3.5. Statistical summary of data included in MLR calibration of $EC_{a\text{-}sh}$ and $EC_{a\text{-}dp}$ survey values to EC_z

EC Parameter	Sample collection date	N	Mean	Median	Min.	Max.	Range	S.D.	C.V. (%)	Skewness	*Shapiro-Wilk $P < W$	*Shapiro-Wilk $P < W$ after ln transf.
			dS m^{-1}									
						Portage 03						
$EC_{a\text{-}sh}$	21-May-03	15	1.08	1.05	0.36	2.67	2.31	0.70	65.07	1.14	0.0329	0.3104
$EC_{a\text{-}dp}$	21-May-03	15	1.39	1.25	0.35	3.00	2.65	0.90	64.70	0.48	0.1489	0.1971
$EC_{0\text{-}15}$	19-Jun-03	15	4.66	4.21	1.77	10.76	8.99	2.89	61.99	0.82	0.0581	0.1050
$EC_{15\text{-}30}$	19-Jun-03	15	5.69	5.65	1.52	11.73	10.21	3.83	67.32	0.18	0.0278	0.0091
$EC_{30\text{-}60}$	19-Jun-03	15	6.48	7.32	1.21	13.10	11.88	4.36	67.31	0.11	0.0442	0.0151
$EC_{60\text{-}90}$	19-Jun-03	15	5.97	7.11	0.84	11.30	10.46	3.82	63.93	-0.17	0.0297	0.0122
$EC_{0\text{-}30}$	19-Jun-03	15	5.18	4.93	1.64	11.24	9.60	3.32	64.16	0.39	0.0559	0.0244
$EC_{0\text{-}60}$	19-Jun-03	15	5.83	6.66	1.49	11.79	10.30	3.75	64.28	0.18	0.0325	0.0086
$EC_{0\text{-}90}$	19-Jun-03	15	5.88	7.23	1.39	11.62	10.24	3.72	63.35	0.01	0.0259	0.0062
$EC_{15\text{-}60}$	19-Jun-03	15	6.22	7.43	1.38	12.22	10.85	4.08	65.70	0.07	0.0252	0.0062
$EC_{15\text{-}90}$	19-Jun-03	15	6.12	7.59	1.31	11.80	10.49	3.93	64.30	-0.06	0.0188	0.0049
$EC_{30\text{-}90}$	19-Jun-03	15	6.23	7.42	1.26	11.93	10.68	4.04	64.93	-0.05	0.0257	0.0070
						Winkler 03						
$EC_{a\text{-}sh}$	27-May-03	15	1.02	0.92	0.26	2.26	2.00	0.64	62.97	0.73	0.1366	0.2721
$EC_{a\text{-}dp}$	27-May-03	15	1.22	1.18	0.29	3.10	2.81	0.86	70.41	0.78	0.0998	0.1354
$EC_{0\text{-}15}$	20-Jun-03	15	3.75	2.37	0.75	8.81	8.05	3.14	83.60	0.54	0.0094	0.0222
$EC_{15\text{-}30}$	20-Jun-03	15	3.94	1.40	0.67	9.71	9.04	3.77	95.71	0.63	0.0014	0.0071
$EC_{30\text{-}60}$	20-Jun-03	15	4.43	2.05	0.50	10.27	9.77	3.96	89.50	0.32	0.0041	0.0086
$EC_{60\text{-}90}$	20-Jun-03	15	4.40	3.58	0.44	10.92	10.48	3.88	88.28	0.28	0.0138	0.0049
$EC_{0\text{-}30}$	20-Jun-03	15	3.85	2.18	0.73	9.24	8.50	3.41	88.53	0.62	0.0041	0.0241
$EC_{0\text{-}60}$	20-Jun-03	15	4.14	1.70	0.70	9.75	9.06	3.62	87.41	0.51	0.0049	0.0197
$EC_{0\text{-}90}$	20-Jun-03	15	4.22	2.05	0.64	9.86	9.22	3.66	86.73	0.42	0.0071	0.0181
$EC_{15\text{-}60}$	20-Jun-03	15	4.27	1.78	0.66	10.07	9.41	3.85	90.34	0.45	0.0035	0.0076
$EC_{15\text{-}90}$	20-Jun-03	15	4.32	2.25	0.58	10.10	9.51	3.83	88.70	0.36	0.0059	0.0072
$EC_{30\text{-}90}$	20-Jun-03	15	4.41	2.51	0.48	10.23	9.75	3.89	88.24	0.28	0.0063	0.0060

*Shapiro-Wilk test for normality, $P < 0.05$ are considered non-normal

Table 3.5. Cont'd.

EC Parameter	Sample collection date	N	Mean	Median	Min.	Max.	Range	S.D.	C.V. (%)	Skewness	*Shapiro-Wilk $P < W$	*Shapiro-Wilk $P < W$ after ln transf.
			dS m^{-1}									
			Emerson 03									
$EC_{a\text{-}sh}$	19-May-03	15	1.27	0.92	0.44	3.08	2.63	0.85	66.60	1.04	0.0182	0.2771
$EC_{a\text{-}dp}$	19-May-03	15	1.33	1.41	0.31	2.55	2.24	0.73	54.51	0.18	0.4245	0.1755
$EC_{0\text{-}15}$	24-Jun-03	15	5.41	4.27	1.38	10.71	9.32	3.74	69.13	0.44	0.0103	0.0531
$EC_{15\text{-}30}$	24-Jun-03	15	6.27	5.23	1.28	14.71	13.43	4.92	78.39	0.64	0.0306	0.0675
$EC_{30\text{-}60}$	24-Jun-03	15	4.69	3.29	0.90	12.99	12.09	3.80	81.11	0.86	0.0472	0.2193
$EC_{60\text{-}90}$	24-Jun-03	14	5.67	5.15	0.75	11.63	10.88	4.20	74.02	0.29	0.0538	0.0434
$EC_{0\text{-}30}$	24-Jun-03	15	5.84	4.85	1.43	12.71	11.27	4.29	73.38	0.53	0.0245	0.0509
$EC_{0\text{-}60}$	24-Jun-03	15	5.27	4.70	1.18	12.85	11.67	3.85	73.08	0.62	0.0716	0.0628
$EC_{0\text{-}90}$	24-Jun-03	14	5.54	6.17	1.07	12.44	11.37	3.85	69.51	0.32	0.1425	0.0305
$EC_{15\text{-}60}$	24-Jun-03	15	5.22	4.85	1.05	13.56	12.51	4.03	77.14	0.75	0.0863	0.1150
$EC_{15\text{-}90}$	24-Jun-03	14	5.53	5.45	0.98	12.79	11.81	3.99	72.16	0.37	0.1637	0.0476
$EC_{30\text{-}90}$	24-Jun-03	14	5.27	4.62	0.86	12.31	11.45	3.92	74.42	0.39	0.1474	0.0851
			Portage 04									
$EC_{a\text{-}sh}$	9-May-04	15	1.08	0.74	0.52	2.43	1.91	0.67	61.98	1.16	0.0038	0.0286
$EC_{a\text{-}dp}$	9-May-04	15	2.11	2.22	0.87	3.46	2.59	0.92	43.34	-0.10	0.1194	0.0417
$EC_{0\text{-}15}$	22-Jun-04	15	5.66	4.69	1.17	14.27	13.09	4.49	79.40	0.63	0.0305	0.0555
$EC_{15\text{-}30}$	22-Jun-04	15	8.53	8.56	1.55	18.34	16.80	6.54	76.69	0.25	0.0234	0.0091
$EC_{30\text{-}60}$	22-Jun-04	15	7.61	5.84	1.28	17.17	15.90	5.44	71.53	0.32	0.1312	0.0535
$EC_{60\text{-}90}$	22-Jun-04	15	5.70	6.03	1.09	10.73	9.64	3.45	60.44	-0.18	0.1056	0.0052
$EC_{0\text{-}30}$	22-Jun-04	15	7.09	6.62	1.49	16.07	14.58	5.46	77.00	0.38	0.0263	0.0131
$EC_{0\text{-}60}$	22-Jun-04	15	7.35	6.23	1.38	15.16	13.77	5.29	71.91	0.19	0.0285	0.0258
$EC_{0\text{-}90}$	22-Jun-04	15	6.80	6.52	1.31	13.46	12.15	4.50	66.14	0.01	0.0491	0.0162
$EC_{15\text{-}60}$	22-Jun-04	15	7.92	6.74	1.40	17.09	15.69	5.66	71.51	0.16	0.0470	0.0226
$EC_{15\text{-}90}$	22-Jun-04	15	7.03	6.88	1.30	14.28	12.98	4.61	65.64	0.00	0.0838	0.0144
$EC_{30\text{-}90}$	22-Jun-04	15	6.66	6.46	1.21	13.62	12.40	4.31	64.79	0.09	0.1460	0.0204

*Shapiro-Wilk test for normality, $P < 0.05$ are considered non-normal

Table 3.5. Cont'd.

EC Parameter	Sample collection date	N	Mean	Median	Min.	Max.	Range	S.D.	C.V. (%)	Skewness	*Shapiro-Wilk $P < W$	*Shapiro-Wilk $P < W$ after ln transf.
			dS m^{-1}									
			All Sites									
$EC_{a\text{-}sh}$	NA	60	1.11	0.92	0.26	3.08	2.82	0.71	63.59	1.04	<0.0001	0.2825
$EC_{a\text{-}dp}$	NA	60	1.51	1.39	0.29	3.46	3.17	0.90	59.69	0.39	0.0051	0.0021
$EC_{0\text{-}15}$	NA	60	4.87	4.17	0.75	14.27	13.51	3.60	74.00	0.70	<0.0001	0.0055
$EC_{15\text{-}30}$	NA	60	6.11	5.31	0.67	18.34	17.67	5.05	82.63	0.72	<0.0001	0.0003
$EC_{30\text{-}60}$	NA	60	5.80	5.26	0.50	17.17	16.67	4.52	77.93	0.53	0.0001	0.0004
$EC_{60\text{-}90}$	NA	59	5.43	6.07	0.44	11.63	11.19	3.79	69.76	0.06	0.0001	<0.0001
$EC_{0\text{-}30}$	NA	60	5.49	4.61	0.73	16.07	15.33	4.27	77.72	0.69	<0.0001	0.0009
$EC_{0\text{-}60}$	NA	60	5.65	5.47	0.70	15.16	14.46	4.24	75.03	0.52	<0.0001	0.0003
$EC_{0\text{-}90}$	NA	59	5.61	6.52	0.64	13.46	12.82	3.96	70.55	0.23	0.0001	<0.0001
$EC_{15\text{-}60}$	NA	60	5.90	5.23	0.66	17.09	16.43	4.56	77.21	0.52	0.0001	0.0002
$EC_{15\text{-}90}$	NA	59	5.75	6.14	0.58	14.28	13.70	4.12	71.65	0.21	0.0002	<0.0001
$EC_{30\text{-}90}$	NA	59	5.65	6.06	0.48	13.62	13.14	4.04	71.53	0.18	0.0001	<0.0001

*Shapiro-Wilk test for normality, $P < 0.05$ are considered non-normal

Tables 3.6, 3.7, 3.8, 3.9, and 3.10 include the results of the MLR calibration procedures for Portage 03, Winkler 03, Emerson 03, Portage 04, and All Sites combined, respectively. All MLR analysis results were significant at probability levels less than 0.001.

The non-ln transformed MLR models for the Portage 03 study (Table 3.6) produced strong relationships between EC_z and $EC_{a\text{-}sh}$ and $EC_{a\text{-}dp}$, with r^2 values ranging from 0.79 to 0.90. Greater regression coefficients were assigned to $EC_{a\text{-}sh}$ than $EC_{a\text{-}dp}$ for shallower soil depth estimations (~ 0-30 cm) of EC_e, and vise versa for deeper soil depth estimations of EC_e (~ 30-90 cm). This relationship would be expected given the estimated non-linear depth response function of Veris 3100 measurements that are predicted by Sudduth et al. (2005) to be approximately 0-30 cm for $EC_{a\text{-}sh}$ and 0-90 cm for $EC_{a\text{-}dp}$. Overall performance of the non-ln transformed regression models indicate that estimation of EC_e at shallower soil depths (less than 60 cm) was better than deeper estimations as the lowest r^2 value was obtained for the estimation of $EC_{60\text{-}90}$ ($r^2 = 0.79$), whereas the highest ($r^2 = 0.9$) was obtained for the $EC_{0\text{-}60}$ estimation. When comparing the non-ln transformed MLR models against the ln-transformed MLR models, the latter proved to explain more of the variability in EC_z as the r^2 values was greater in all cases ranging from 0.88 to 0.94. In the ln-transformed MLR models it is difficult to ascertain any advantage in predicting EC_z at shallower depths over deeper depths.

The non-ln transformed MLR models for the Winkler 03 study site (Table 3.7) also produced strong relationships between EC_z and $EC_{a\text{-}sh}$ and $EC_{a\text{-}dp}$, with r^2 values ranging from 0.71 to 0.94. Greater regression coefficients were assigned to $EC_{a\text{-}sh}$ than $EC_{a\text{-}dp}$ for shallower soil depth estimations (i.e., less than or equal to the 30-60 cm depth

interval) of EC_e, and vise versa for deeper soil depth estimations of EC_e (i.e., 60-90 cm). The ln-transformed MLR models in this case proved to explain less of the variability observed in EC_z vs. the non-ln transformed models, especially at shallower soil depths. The r^2 for prediction of $EC_{0\text{-}15}$ and $EC_{0\text{-}30}$ with the non-ln MLR models was 0.71 and 0.80 respectively, vs. 0.47 and 0.59 with the ln transformed MLR models, respectively. Poor performance of shallow EC_e prediction in this case is likely a factor of the soil condition during the original Veris 3100 survey operations. The Winkler 03 site had been much more heavily cultivated prior to Veris 3100 survey operations than the other study fields, producing a very fluffy and deep plough layer (~ 20-25 cm), which likely reduced current transmission through the soil due to poor soil water continuity within soil pores with reduced volumetric soil water contents. This relationship was observed upon careful inspection of the EC_a survey data for this site, which revealed in some cases very low values of $EC_{a\text{-}sh}$ in comparison with higher values of $EC_{a\text{-}dp}$ recorded at the same location. Halvorson and Rhoades (1974) recommended that EC_a measurements be recorded as near to field capacity soil water content as possible, as this will be more closely related to EC_e (i.e., EC of a saturated soil paste extract) as compared to measurements taken under lower soil water contents. They found much stronger correlations of spring vs. late summer measurements of EC_a to EC_e (r^2 of 0.95 vs. 0.8, respectively).

The non-ln transformed MLR models for the Emerson 03 study site (Table 3.8) produced strong relationships between EC_z and $EC_{a\text{-}sh}$ and $EC_{a\text{-}dp}$, with r^2 values ranging from 0.76 to 0.91. The results of MLR analysis were quite similar for Emerson 03 as for Portage 03, however the greater performance of ln-transformed MLR was less apparent

than that of Portage 03 where ln transformed MLR models performing better in all cases vs. only seven out of ten comparisons for the Emerson 03 study site.

The non-ln and ln transformed MLR models for the Portage 04 study site (Table 3.9) both produced very strong relationships between EC_z and $EC_{a\text{-}sh}$ and $EC_{a\text{-}dp}$, with r^2 values ranging from 0.91 to 0.96. The improved performance of MLR analysis for the Portage 04 study site in comparison to the other three study sites is likely a function of the greater influence of soil salinity affecting EC_a measurements in this field, which had a greater range in EC_e values, as well as a greater extent and proportion of higher EC_a values in comparison to other fields.

The MLR analysis results produced from all sites (Table 3.10) were quite similar to the individual study site MLR analysis results in terms of r^2 (ranging from 0.69 to 0.88). A general observation of the RMSE values for the non-ln MLR analysis indicate that EC_e values could be predicted to within approximately, 1.5 dS m^{-1} (estimated from actual RMSE values or converted from ln-MLR regression analysis) of those observed in the field for MLR models developed for each study site, and 1.5 to 2.0 dS m^{-1} when the results are pooled between study sites. These results would seem to suggest that location has a strong impact on the accuracy of model used to convert EC_a to EC_e values, such that using the model developed from data nearest to your area of interest would be ideal, otherwise the pooled results could be used.

Table 3.6. Multiple linear regression (MLR) calibration results for the Portage 03 study site

N	EC_z (mS m^{-1})	MLR equation	r^2	RMSE
15	EC_{0-15}	$= 3.86 * EC_{a-sh} + 0.00 * EC_{a-dp} + 49.17$	0.8813	107.45
15	EC_{15-30}	$= 3.92 * EC_{a-sh} + 0.79 * EC_{a-dp} + 37.74$	0.8007	184.88
15	EC_{30-60}	$= 0.10 * EC_{a-sh} + 4.49 * EC_{a-dp} + 11.94$	0.8890	156.95
15	EC_{60-90}	$= 0.64 * EC_{a-sh} + 3.30 * EC_{a-dp} + 69.66$	0.7920	188.06
15	EC_{0-30}	$= 3.89 * EC_{a-sh} + 0.40 * EC_{a-dp} + 43.46$	0.8540	137.06
15	EC_{0-60}	$= 2.00 * EC_{a-sh} + 2.45 * EC_{a-dp} + 27.70$	0.9032	125.89
15	EC_{0-90}	$= 1.54 * EC_{a-sh} + 2.73 * EC_{a-dp} + 41.68$	0.8862	135.63
15	EC_{15-60}	$= 1.37 * EC_{a-sh} + 3.26 * EC_{a-dp} + 20.54$	0.8941	143.59
15	EC_{15-90}	$= 1.08 * EC_{a-sh} + 3.28 * EC_{a-dp} + 40.18$	0.8727	151.63
15	EC_{30-90}	$= 0.37 * EC_{a-sh} + 3.90 * EC_{a-dp} + 40.80$	0.8626	161.84
		ln-MLR equation		
15	$\ln(EC_{0-15})$	$= 1.24 * \ln(EC_{a-sh}) - 0.26 * \ln(EC_{a-dp}) + 1.63$	0.9379	0.17
15	$\ln(EC_{15-30})$	$= 1.21 * \ln(EC_{a-sh}) - 0.01 * \ln(EC_{a-dp}) + 0.67$	0.8878	0.30
15	$\ln(EC_{30-60})$	$= 0.53 * \ln(EC_{a-sh}) + 0.66 * \ln(EC_{a-dp}) + 0.69$	0.9006	0.30
15	$\ln(EC_{60-90})$	$= 0.30 * \ln(EC_{a-sh}) + 0.87 * \ln(EC_{a-dp}) + 0.63$	0.8821	0.33
15	$\ln(EC_{0-30})$	$= 1.22 * \ln(EC_{a-sh}) - 0.13 * \ln(EC_{a-dp}) + 1.14$	0.9155	0.23
15	$\ln(EC_{0-60})$	$= 0.81 * \ln(EC_{a-sh}) + 0.33 * \ln(EC_{a-dp}) + 0.93$	0.9237	0.24
15	$\ln(EC_{0-90})$	$= 0.65 * \ln(EC_{a-sh}) + 0.49 * \ln(EC_{a-dp}) + 0.87$	0.9238	0.24
15	$\ln(EC_{15-60})$	$= 0.72 * \ln(EC_{a-sh}) + 0.47 * \ln(EC_{a-dp}) + 0.70$	0.9112	0.27
15	$\ln(EC_{15-90})$	$= 0.57 * \ln(EC_{a-sh}) + 0.61 * \ln(EC_{a-dp}) + 0.72$	0.9168	0.27
15	$\ln(EC_{30-90})$	$= 0.44 * \ln(EC_{a-sh}) + 0.73 * \ln(EC_{a-dp}) + 0.71$	0.9140	0.27

Table 3.7. Multiple linear regression (MLR) calibration results for the Winkler 03 study site

N	EC_z (mS m^{-1})	MLR equation	r^2	RMSE
15	$EC_{0\text{-}15}$	$= 4.49 * EC_{a\text{-}sh} - 0.30 * EC_{a\text{-}dp} - 47.59$	0.7081	183.03
15	$EC_{15\text{-}30}$	$= 6.10 * EC_{a\text{-}sh} - 0.56 * EC_{a\text{-}dp} - 160.86$	0.9370	164.61
15	$EC_{30\text{-}60}$	$= 4.91 * EC_{a\text{-}sh} + 0.54 * EC_{a\text{-}dp} - 125.15$	0.8341	174.37
15	$EC_{60\text{-}90}$	$= -1.09 * EC_{a\text{-}sh} + 4.99 * EC_{a\text{-}dp} - 58.72$	0.8625	155.42
15	$EC_{0\text{-}30}$	$= 5.29 * EC_{a\text{-}sh} - 0.43 * EC_{a\text{-}dp} - 104.22$	0.7997	164.66
15	$EC_{0\text{-}60}$	$= 5.10 * EC_{a\text{-}sh} + 0.06 * EC_{a\text{-}dp} - 114.69$	0.8476	152.63
15	$EC_{0\text{-}90}$	$= 3.04 * EC_{a\text{-}sh} + 1.70 * EC_{a\text{-}dp} - 96.03$	0.8649	145.46
15	$EC_{15\text{-}60}$	$= 5.31 * EC_{a\text{-}sh} + 0.17 * EC_{a\text{-}dp} - 137.05$	0.8546	158.75
15	$EC_{15\text{-}90}$	$= 2.75 * EC_{a\text{-}sh} + 2.10 * EC_{a\text{-}dp} - 105.72$	0.8651	151.97
15	$EC_{30\text{-}90}$	$= 1.91 * EC_{a\text{-}sh} + 2.77 * EC_{a\text{-}dp} - 91.94$	0.8536	160.92
		ln-MLR equation		
15	$\ln(EC_{0\text{-}15})$	$= -0.35 * \ln(EC_{a\text{-}sh}) + 1.14 * \ln(EC_{a\text{-}dp}) + 1.89$	0.4725	0.77
15	$\ln(EC_{15\text{-}30})$	$= 0.37 * \ln(EC_{a\text{-}sh}) + 0.86 * \ln(EC_{a\text{-}dp}) - 0.08$	0.7356	0.61
15	$\ln(EC_{30\text{-}60})$	$= -0.96 * \ln(EC_{a\text{-}sh}) + 2.20 * \ln(EC_{a\text{-}dp}) - 0.21$	0.8488	0.50
15	$\ln(EC_{60\text{-}90})$	$= -1.51 * \ln(EC_{a\text{-}sh}) + 2.89 * \ln(EC_{a\text{-}dp}) - 0.86$	0.9280	0.38
15	$\ln(EC_{0\text{-}30})$	$= -0.23 * \ln(EC_{a\text{-}sh}) + 1.17 * \ln(EC_{a\text{-}dp}) + 1.25$	0.5856	0.70
15	$\ln(EC_{0\text{-}60})$	$= -0.64 * \ln(EC_{a\text{-}sh}) + 1.69 * \ln(EC_{a\text{-}dp}) + 0.71$	0.7616	0.56
15	$\ln(EC_{0\text{-}90})$	$= -1.01 * \ln(EC_{a\text{-}sh}) + 2.13 * \ln(EC_{a\text{-}dp}) + 0.35$	0.8500	0.46
15	$\ln(EC_{15\text{-}60})$	$= -0.47 * \ln(EC_{a\text{-}sh}) + 1.70 * \ln(EC_{a\text{-}dp}) - 0.11$	0.8410	0.49
15	$\ln(EC_{15\text{-}90})$	$= -0.91 * \ln(EC_{a\text{-}sh}) + 2.19 * \ln(EC_{a\text{-}dp}) - 0.34$	0.8979	0.41
15	$\ln(EC_{30\text{-}90})$	$= -1.29 * \ln(EC_{a\text{-}sh}) + 2.58 * \ln(EC_{a\text{-}dp}) - 0.46$	0.9058	0.41

Table 3.8. Multiple linear regression (MLR) calibration results for the Emerson 03 study site

N	EC_z (mS m^{-1})	Multiple linear regression	r^2	RMSE
15	EC_{0-15}	= 3.38 * EC_{a-sh} + 0.80 * EC_{a-dp} + 4.44	0.8317	165.87
15	EC_{15-30}	= 4.01 * EC_{a-sh} + 1.88 * EC_{a-dp} - 133.21	0.9111	158.41
15	EC_{30-60}	= -0.72 * EC_{a-sh} + 5.39 * EC_{a-dp} - 155.84	0.7732	195.77
14	EC_{60-90}	= -3.14 * EC_{a-sh} + 8.28 * EC_{a-dp} - 159.99	0.7648	221.23
15	EC_{0-30}	= 3.69 * EC_{a-sh} + 1.34 * EC_{a-dp} - 64.38	0.8932	151.43
15	EC_{0-60}	= 1.48 * EC_{a-sh} + 3.36 * EC_{a-dp} - 110.11	0.8943	134.93
14	EC_{0-90}	= -0.05 * EC_{a-sh} + 4.99 * EC_{a-dp} - 125.47	0.8777	145.91
15	EC_{15-60}	= 0.85 * EC_{a-sh} + 4.22 * EC_{a-dp} - 148.29	0.8640	159.98
14	EC_{15-90}	= -0.75 * EC_{a-sh} + 5.86 * EC_{a-dp} - 154.12	0.8550	165.08
14	EC_{30-90}	= -1.96 * EC_{a-sh} + 6.88 * EC_{a-dp} - 162.37	0.8025	189.53
		ln MLR		
15	$\ln(EC_{0-15})$	= 1.16 * $\ln(EC_{a-sh})$ - 0.05 * $\ln(EC_{a-dp})$ + 0.88	0.8415	0.34
15	$\ln(EC_{15-30})$	= 0.96 * $\ln(EC_{a-sh})$ + 0.39 * $\ln(EC_{a-dp})$ - 0.20	0.8815	0.34
15	$\ln(EC_{30-60})$	= 0.19 * $\ln(EC_{a-sh})$ + 1.06 * $\ln(EC_{a-dp})$ - 0.11	0.8173	0.42
14	$\ln(EC_{60-90})$	= -0.36 * $\ln(EC_{a-sh})$ + 1.75 * $\ln(EC_{a-dp})$ - 0.63	0.8975	0.36
15	$\ln(EC_{0-30})$	= 1.06 * $\ln(EC_{a-sh})$ + 0.17 * $\ln(EC_{a-dp})$ + 0.34	0.8699	0.33
15	$\ln(EC_{0-60})$	= 0.68 * $\ln(EC_{a-sh})$ + 0.57 * $\ln(EC_{a-dp})$ + 0.11	0.8762	0.33
14	$\ln(EC_{0-90})$	= 0.32 * $\ln(EC_{a-sh})$ + 0.96 * $\ln(EC_{a-dp})$ - 0.05	0.8898	0.33
15	$\ln(EC_{15-60})$	= 0.52 * $\ln(EC_{a-sh})$ + 0.79 * $\ln(EC_{a-dp})$ - 0.19	0.8760	0.34
14	$\ln(EC_{15-90})$	= 0.13 * $\ln(EC_{a-sh})$ + 1.19 * $\ln(EC_{a-dp})$ - 0.31	0.8931	0.34
14	$\ln(EC_{30-90})$	= -0.12 * $\ln(EC_{a-sh})$ + 1.44 * $\ln(EC_{a-dp})$ - 0.35	0.8718	0.38

Table 3.9. Multiple linear regression (MLR) calibration results for the Portage 04 study site

N	EC_z (mS m^{-1})	MLR equation	r^2	RMSE
15	$EC_{0\text{-}15}$	$= 4.71 * EC_{a\text{-}sh} + 1.56 * EC_{a\text{-}dp} - 274.43$	0.9515	106.86
15	$EC_{15\text{-}30}$	$= 4.75 * EC_{a\text{-}sh} + 3.86 * EC_{a\text{-}dp} - 475.81$	0.9448	165.95
15	$EC_{30\text{-}60}$	$= -0.17 * EC_{a\text{-}sh} + 5.78 * EC_{a\text{-}dp} - 442.79$	0.9149	171.10
15	$EC_{60\text{-}90}$	$= -3.32 * EC_{a\text{-}sh} + 5.20 * EC_{a\text{-}dp} - 170.13$	0.9139	109.19
15	$EC_{0\text{-}30}$	$= 4.73 * EC_{a\text{-}sh} + 2.71 * EC_{a\text{-}dp} - 375.12$	0.9621	114.84
15	$EC_{0\text{-}60}$	$= 2.28 * EC_{a\text{-}sh} + 4.25 * EC_{a\text{-}dp} - 408.95$	0.9621	111.15
15	$EC_{0\text{-}90}$	$= 0.42 * EC_{a\text{-}sh} + 4.56 * EC_{a\text{-}dp} - 329.35$	0.9584	99.08
15	$EC_{15\text{-}60}$	$= 1.47 * EC_{a\text{-}sh} + 5.14 * EC_{a\text{-}dp} - 453.80$	0.9515	134.63
15	$EC_{15\text{-}90}$	$= -0.44 * EC_{a\text{-}sh} + 5.16 * EC_{a\text{-}dp} - 340.33$	0.9497	111.76
15	$EC_{30\text{-}90}$	$= -1.74 * EC_{a\text{-}sh} + 5.49 * EC_{a\text{-}dp} - 306.46$	0.9330	120.55
		ln-MLR equation		
15	$\ln(EC_{0\text{-}15})$	$= 0.99 * \ln(EC_{a\text{-}sh}) + 0.74 * \ln(EC_{a\text{-}dp}) - 2.38$	0.9160	0.29
15	$\ln(EC_{15\text{-}30})$	$= 0.62 * \ln(EC_{a\text{-}sh}) + 1.33 * \ln(EC_{a\text{-}dp}) - 3.45$	0.9269	0.30
15	$\ln(EC_{30\text{-}60})$	$= -0.01 * \ln(EC_{a\text{-}sh}) + 1.83 * \ln(EC_{a\text{-}dp}) - 3.25$	0.9387	0.25
15	$\ln(EC_{60\text{-}90})$	$= -0.80 * \ln(EC_{a\text{-}sh}) + 2.34 * \ln(EC_{a\text{-}dp}) - 2.58$	0.9057	0.29
15	$\ln(EC_{0\text{-}30})$	$= 0.75 * \ln(EC_{a\text{-}sh}) + 1.10 * \ln(EC_{a\text{-}dp}) - 2.96$	0.9441	0.24
15	$\ln(EC_{0\text{-}60})$	$= 0.33 * \ln(EC_{a\text{-}sh}) + 1.49 * \ln(EC_{a\text{-}dp}) - 3.07$	0.9636	0.19
15	$\ln(EC_{0\text{-}90})$	$= 0.01 * \ln(EC_{a\text{-}sh}) + 1.74 * \ln(EC_{a\text{-}dp}) - 2.92$	0.9505	0.20
15	$\ln(EC_{15\text{-}60})$	$= 0.20 * \ln(EC_{a\text{-}sh}) + 1.66 * \ln(EC_{a\text{-}dp}) - 3.31$	0.9484	0.23
15	$\ln(EC_{15\text{-}90})$	$= -0.14 * \ln(EC_{a\text{-}sh}) + 1.89 * \ln(EC_{a\text{-}dp}) - 3.05$	0.9520	0.21
15	$\ln(EC_{30\text{-}90})$	$= -0.37 * \ln(EC_{a\text{-}sh}) + 2.06 * \ln(EC_{a\text{-}dp}) - 2.94$	0.9501	0.21

Table 3.10. Multiple linear regression (MLR) calibration results for all study sites combined

N	EC_z (mS m^{-1})	MLR equation	r^2	RMSE
60	EC_{0-15}	$= 3.28 * EC_{a-sh} + 1.20 * EC_{a-dp} - 59.46$	0.8192	155.91
60	EC_{15-30}	$= 2.71 * EC_{a-sh} + 3.21 * EC_{a-dp} - 177.47$	0.8304	211.56
60	EC_{30-60}	$= 0.38 * EC_{a-sh} + 4.32 * EC_{a-dp} - 115.39$	0.8307	189.37
59	EC_{60-90}	$= 0.84 * EC_{a-sh} + 2.91 * EC_{a-dp} + 4.76$	0.6861	216.12
60	EC_{0-30}	$= 2.99 * EC_{a-sh} + 2.21 * EC_{a-dp} - 118.47$	0.8420	172.56
60	EC_{0-60}	$= 1.69 * EC_{a-sh} + 3.26 * EC_{a-dp} - 116.93$	0.8815	148.40
59	EC_{0-90}	$= 1.41 * EC_{a-sh} + 3.14 * EC_{a-dp} - 76.11$	0.8744	142.81
60	EC_{15-60}	$= 1.16 * EC_{a-sh} + 3.95 * EC_{a-dp} - 136.08$	0.8727	165.48
59	EC_{15-90}	$= 1.03 * EC_{a-sh} + 3.53 * EC_{a-dp} - 79.57$	0.8573	158.44
59	EC_{30-90}	$= 0.61 * EC_{a-sh} + 3.61 * EC_{a-dp} - 55.17$	0.8075	180.35
		ln-MLR equation		
60	$\ln(EC_{0-15})$	$= 0.93 * \ln(EC_{a-sh}) + 0.18 * \ln(EC_{a-dp}) + 0.81$	0.6899	0.48
60	$\ln(EC_{15-30})$	$= 0.67 * \ln(EC_{a-sh}) + 0.69 * \ln(EC_{a-dp}) - 0.39$	0.8010	0.46
60	$\ln(EC_{30-60})$	$= 0.26 * \ln(EC_{a-sh}) + 1.06 * \ln(EC_{a-dp}) - 0.33$	0.8176	0.44
59	$\ln(EC_{60-90})$	$= 0.23 * \ln(EC_{a-sh}) + 1.11 * \ln(EC_{a-dp}) - 0.51$	0.8057	0.47
60	$\ln(EC_{0-30})$	$= 0.75 * \ln(EC_{a-sh}) + 0.46 * \ln(EC_{a-dp}) + 0.31$	0.7508	0.46
60	$\ln(EC_{0-60})$	$= 0.51 * \ln(EC_{a-sh}) + 0.75 * \ln(EC_{a-dp}) + 0.06$	0.8200	0.40
59	$\ln(EC_{0-90})$	$= 0.42 * \ln(EC_{a-sh}) + 0.86 * \ln(EC_{a-dp}) - 0.06$	0.8416	0.38
60	$\ln(EC_{15-60})$	$= 0.42 * \ln(EC_{a-sh}) + 0.92 * \ln(EC_{a-dp}) - 0.34$	0.8427	0.40
59	$\ln(EC_{15-90})$	$= 0.35 * \ln(EC_{a-sh}) + 1.00 * \ln(EC_{a-dp}) - 0.38$	0.8545	0.39
59	$\ln(EC_{30-90})$	$= 0.24 * \ln(EC_{a-sh}) + 1.09 * \ln(EC_{a-dp}) - 0.39$	0.8362	0.42

When comparing the effects of a ln-transformation in terms of r^2, it was not clear whether one method was better than the other. Given that a ln-transformation of the calibration datasets was useful in producing normal distributions in some cases, but functioned to reduce the normality of others (see Table 3.5) and that EC_{a-sh}, EC_{a-dp}, and EC_z datasets tended to be skewed in the same direction, it makes sense that the strength of the non-ln-transformed MLR functions in terms of r^2 would be similar to ln transformed MLR models. However, that does not mean that there is not an advantage of using one method over the other. Tables 3.11 and 3.12 include hypothetical determinations of EC_{0-90} using both the ln-transformed and non-ln-transformed MLR models, respectively, for all four sites, as well as all sites combined, from low, medium, and high values of EC_{a-sh} and EC_{a-dp}. Hypothetical low, medium, and high values of EC_{a-sh} and EC_{a-dp} were

determined as the mean values between all sites of minimum, median, and maximum survey values of $EC_{a\text{-}sh}$ and $EC_{a\text{-}dp}$ (from Table 3.5), respectively. The most interesting observation from Table 3.11 in comparison to Table 3.12 is that for low values of EC_a, the non-ln MLR model for Portage 04 resulted in a negative estimation of EC_e over the 0-90 cm soil depth increment. This illustrates a fundamental advantage of using ln transformation in calibration of $EC_{a\text{-}sh}$ and $EC_{a\text{-}dp}$ to EC_e: that it is extremely unlikely that EC_e predictions will ever be negative given rational measurements of EC_a (i.e., greater than one). This table (Table 3.12), also illustrates that predictions of EC_e using the MLR model created using all sites was very similar to those determined from the MLR models determined for each site, such that given similar soil types and moisture contents one could reasonably estimate soil salinity from measurements of EC_a collected using the Veris 3100 for a given field without taking any calibration soil samples.

Table 3.11. Example of hypothetical, non-ln MLR model predictions

		Low		Medium		High	
		$EC_{a\text{-}sh}$	$EC_{a\text{-}dp}$	$EC_{a\text{-}sh}$	$EC_{a\text{-}dp}$	$EC_{a\text{-}sh}$	$EC_{a\text{-}dp}$
Soil depth	study Site	39.5	45.5	90.75	151.5	205.065	302.75
$EC_{0\text{-}90}$	Portage 03	2.3		6.0		11.8	
	Winkler 03	1.0		4.4		10.4	
	Emerson 03	1.0		6.3		13.7	
	Portage 04	-1.1		4.0		11.4	
	All Sites	1.2		5.3		11.6	

Table 3.12. Example of hypothetical, ln MLR model predictions

		Low		Medium		High	
		$EC_{a\text{-}sh}$	$EC_{a\text{-}dp}$	$EC_{a\text{-}sh}$	$EC_{a\text{-}dp}$	$EC_{a\text{-}sh}$	$EC_{a\text{-}dp}$
Soil depth	Study site	39.5	45.5	90.75	151.5	205.065	302.75
$EC_{0\text{-}90}$	Portage 03	1.7		5.2		12.5	
	Winkler 03	1.2		6.6		12.6	
	Emerson 03	1.2		5.0		12.6	
	Portage 04	0.4		3.5		11.8	
	All Sites	1.2		4.7		12.0	

3.4.3 Soil Salinity Mapping and Assessment

Using the ln-transformed MLR models for each site, values of $EC_{0\text{-}30}$ and $EC_{30\text{-}90}$ were calculated from the $EC_{a\text{-}sh}$ and $EC_{a\text{-}dp}$ survey results for each study site. Kriged surfaces of both $EC_{0\text{-}30}$ and $EC_{30\text{-}90}$ and were created using the same models parameters of $EC_{a\text{-}sh}$ and $EC_{a\text{-}dp}$ maps, respectively. Figures 3.7, 3.8, 3.9, and 3.10 display $EC_{0\text{-}30}$ and $EC_{30\text{-}90}$ maps in units of EC_e (dS m^{-1}) for Portage 03, Winkler 03, Emerson 03, and Portage 04 sites respectively. Figures 3.11, 3.12, 3.13, and 3.14 display topographical and percent slope maps for Portage 03, Winkler 03, Emerson 03, and Portage 04, sites respectively. Table 3.13 includes summary data of the estimated proportions of $EC_{0\text{-}30}$ and $EC_{60\text{-}90}$ for each field that display EC_e ranges from 0-2, 2-4, 4-8, 8-16, and greater than 16 dS m^{-1}.

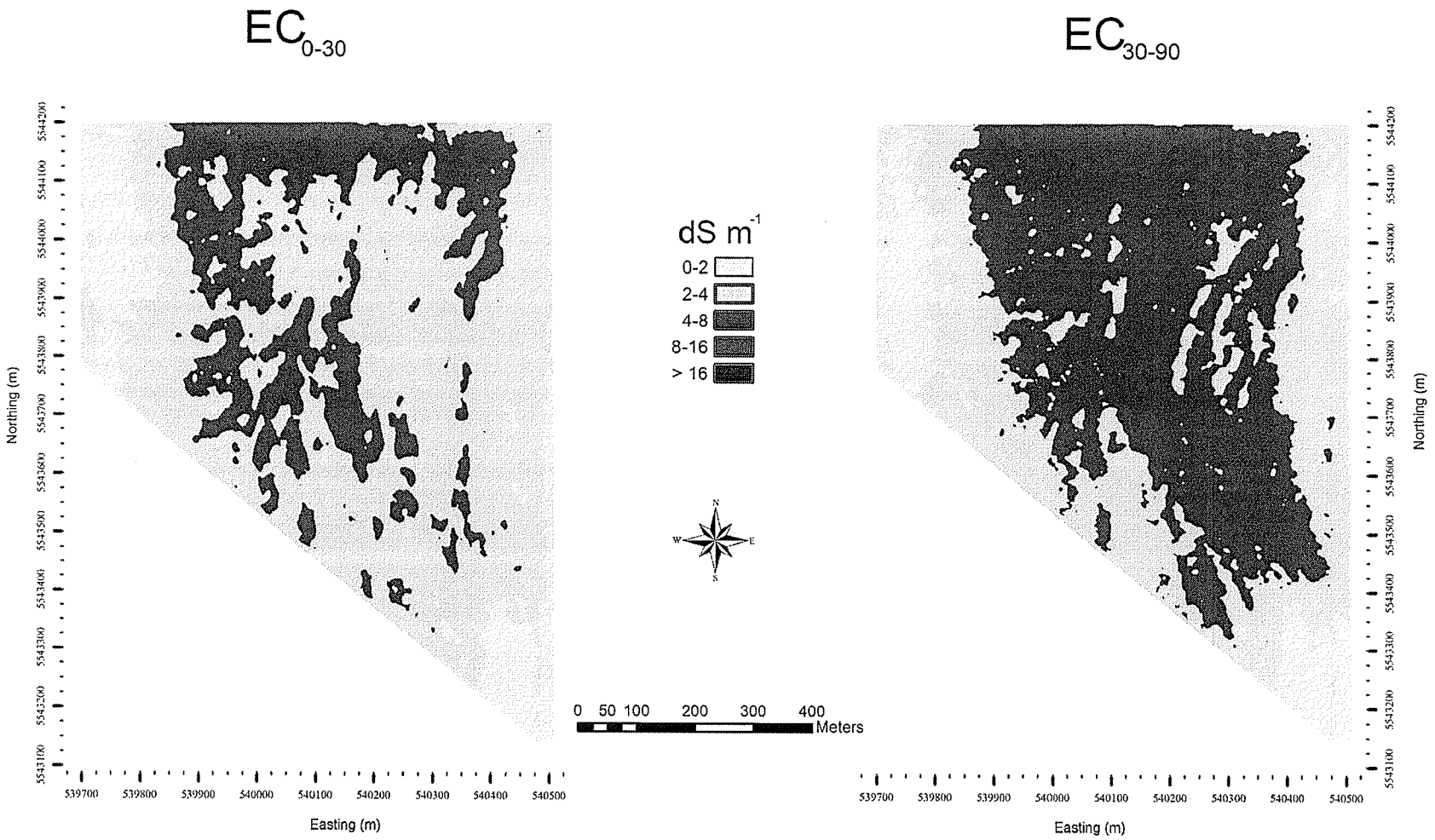

Figure 3.7. Maps of $EC_{0\text{-}30}$ and $EC_{30\text{-}90}$ from the Portage 03 study site

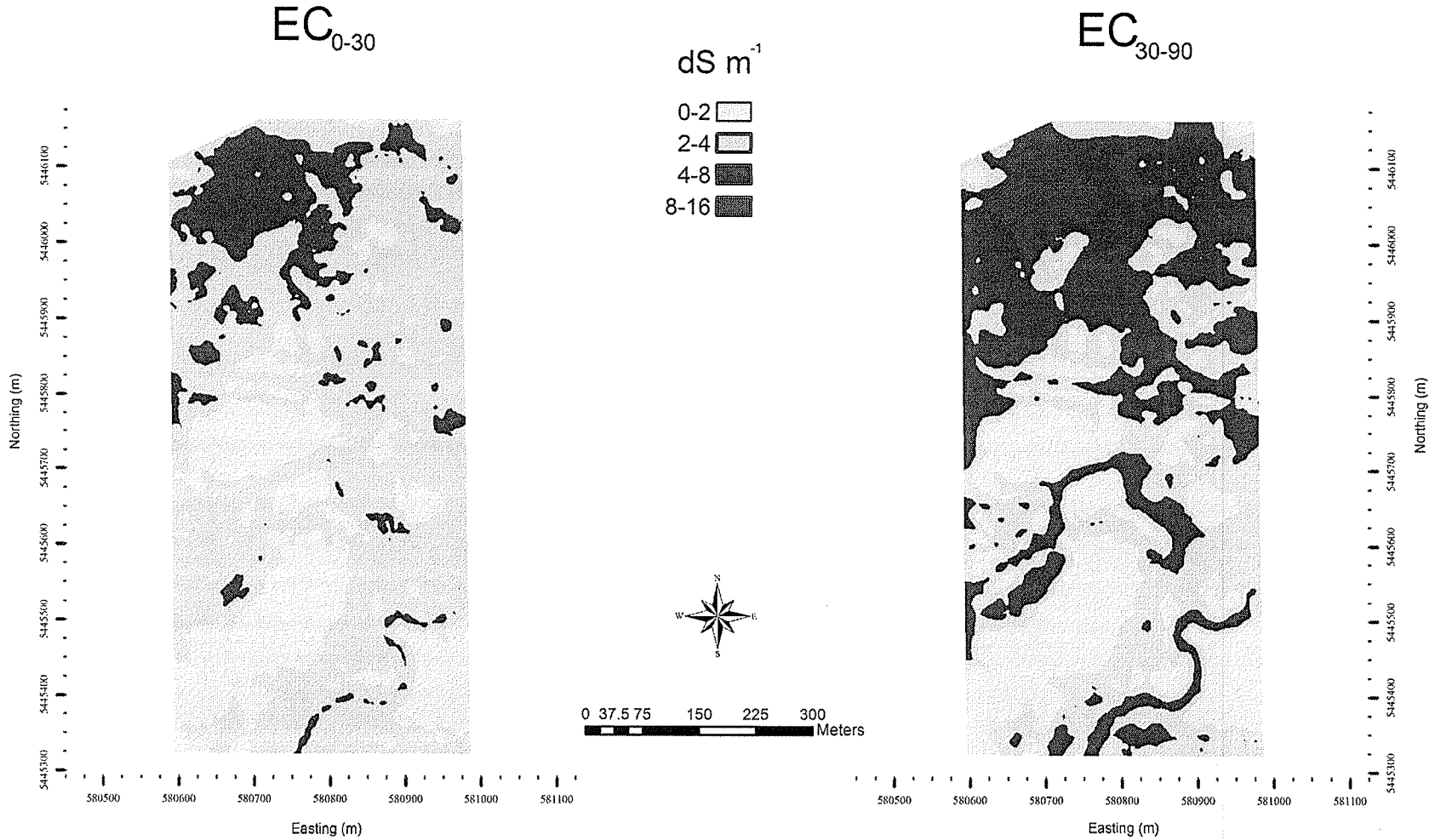

Figure 3.8. Maps of $EC_{0\text{-}30}$ and $EC_{30\text{-}90}$ from the Winkler 03 study site

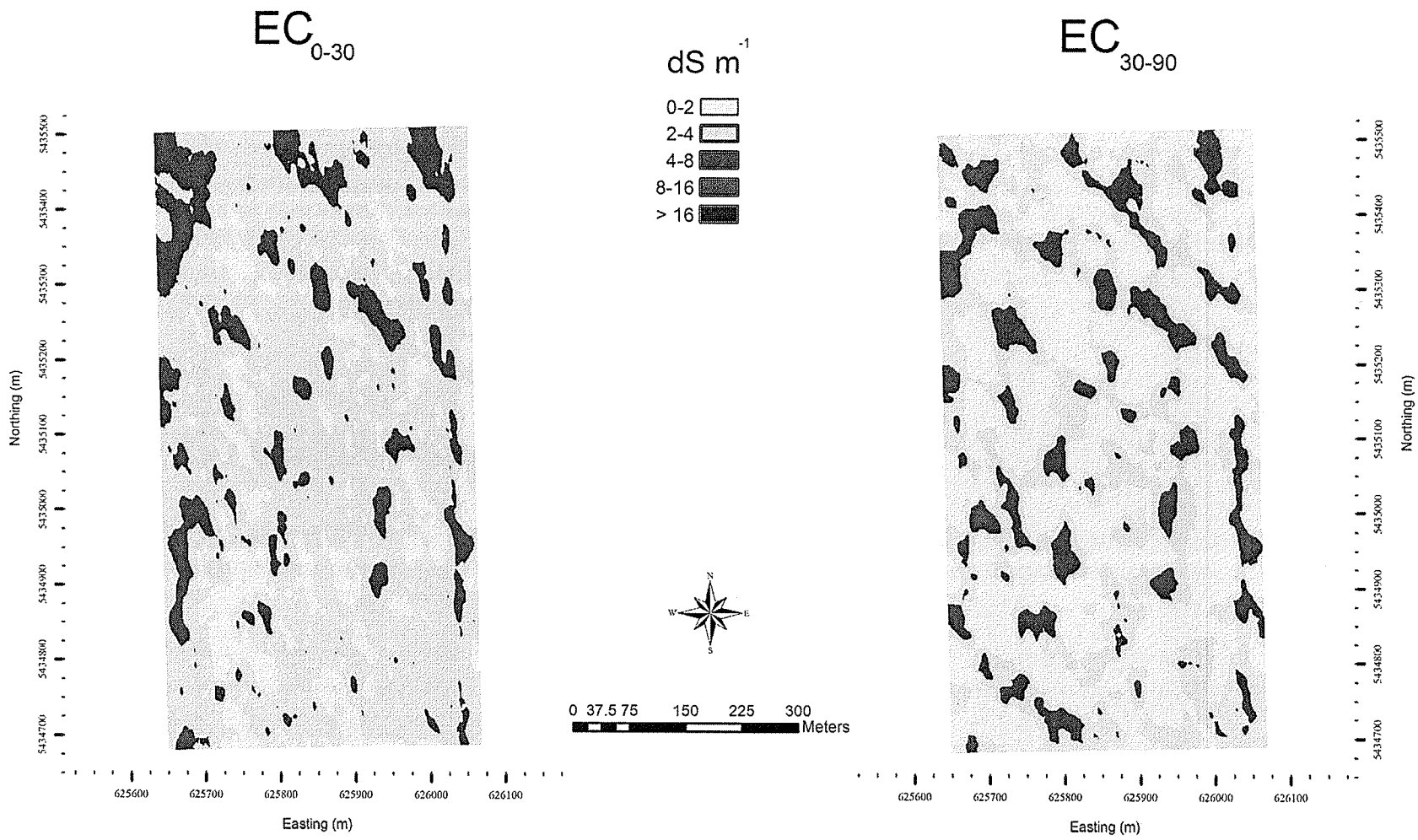

Figure 3.9. Maps of $EC_{0\text{-}30}$ and $EC_{30\text{-}90}$ from the Emerson 03 study site

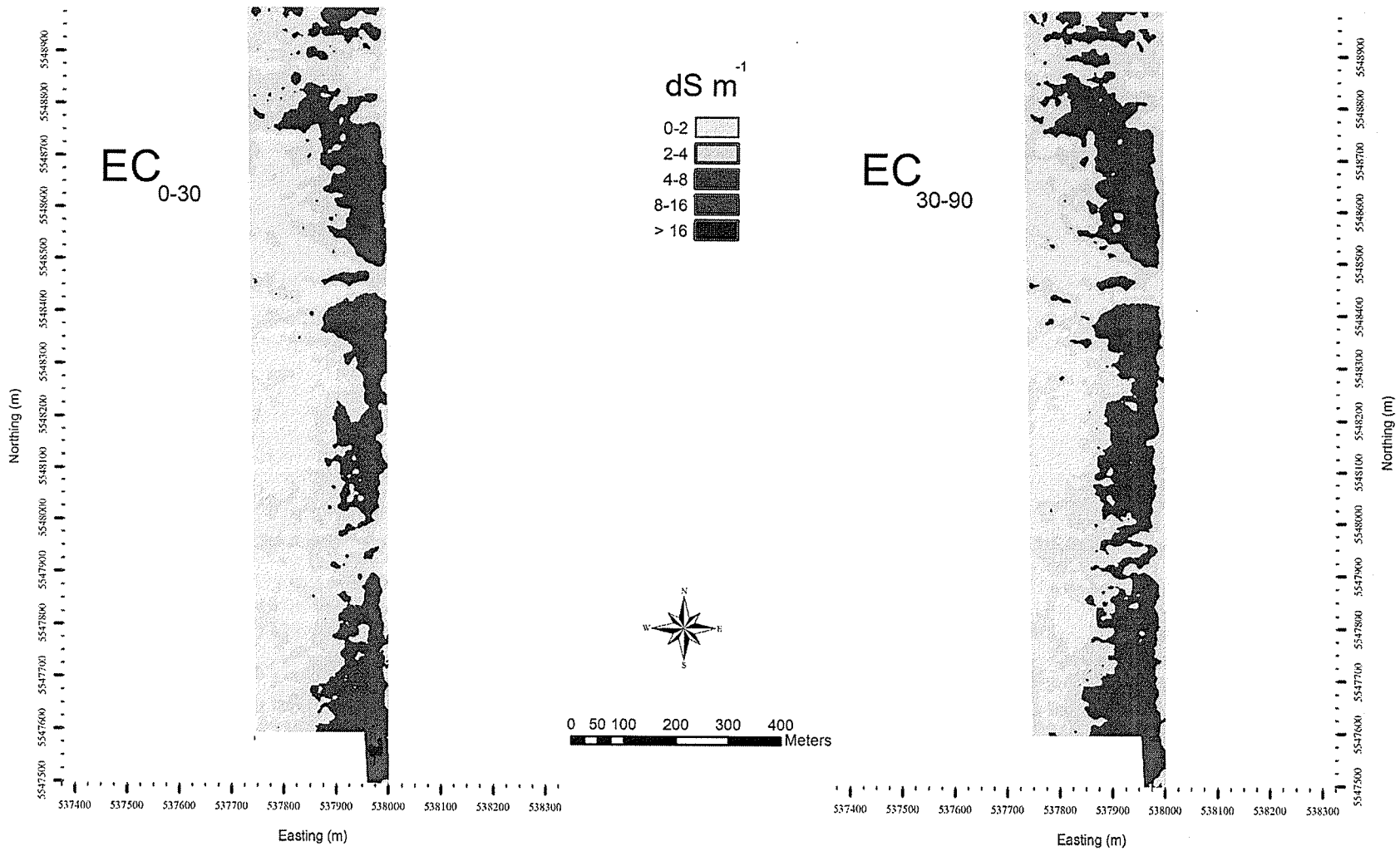

Figure 3.10. Maps of $EC_{0\text{-}30}$ and $EC_{30\text{-}90}$ from the Portage 04 study site

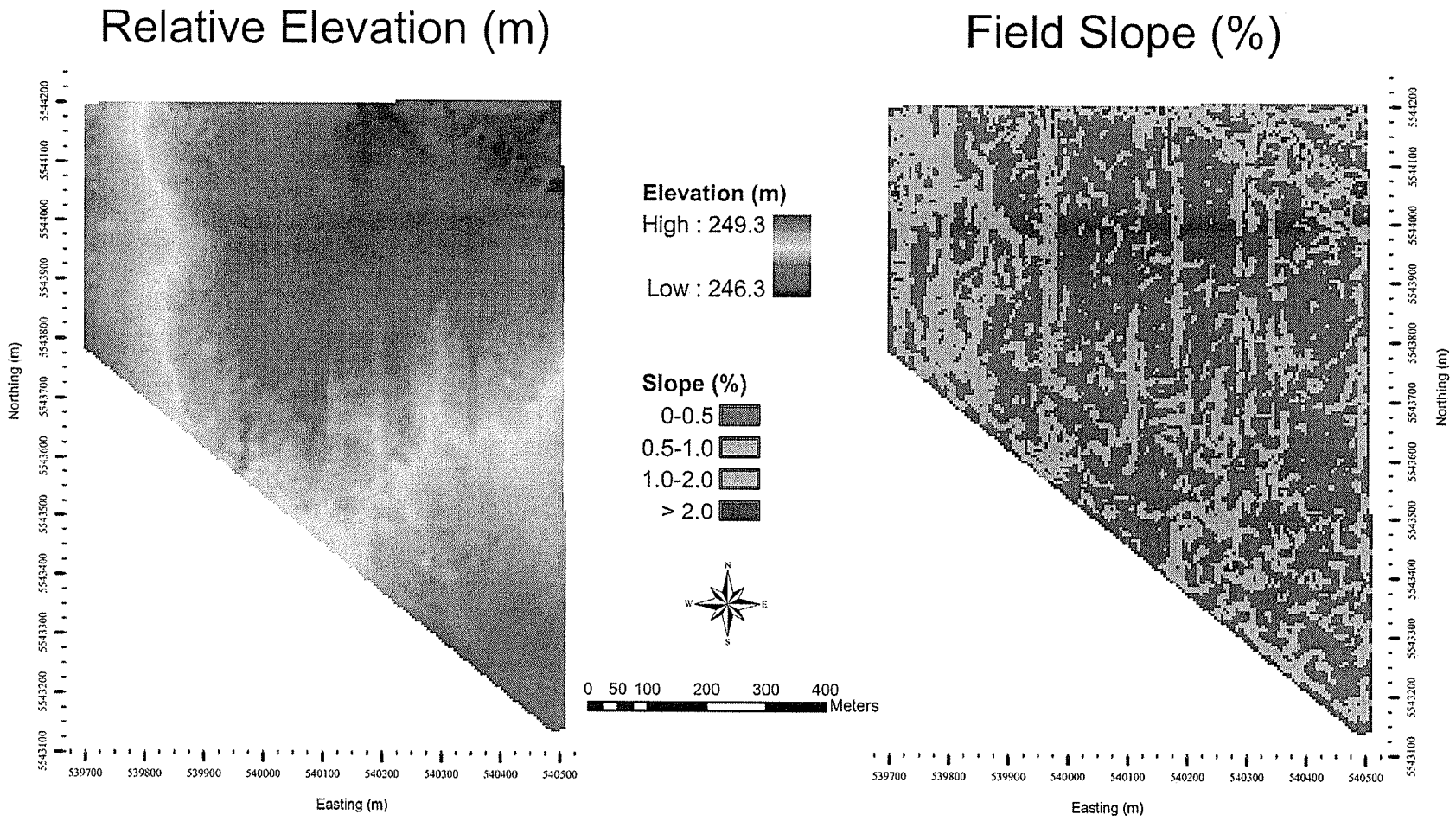

Figure 3.11. Maps of relative elevation and field slope for the Portage 03 site

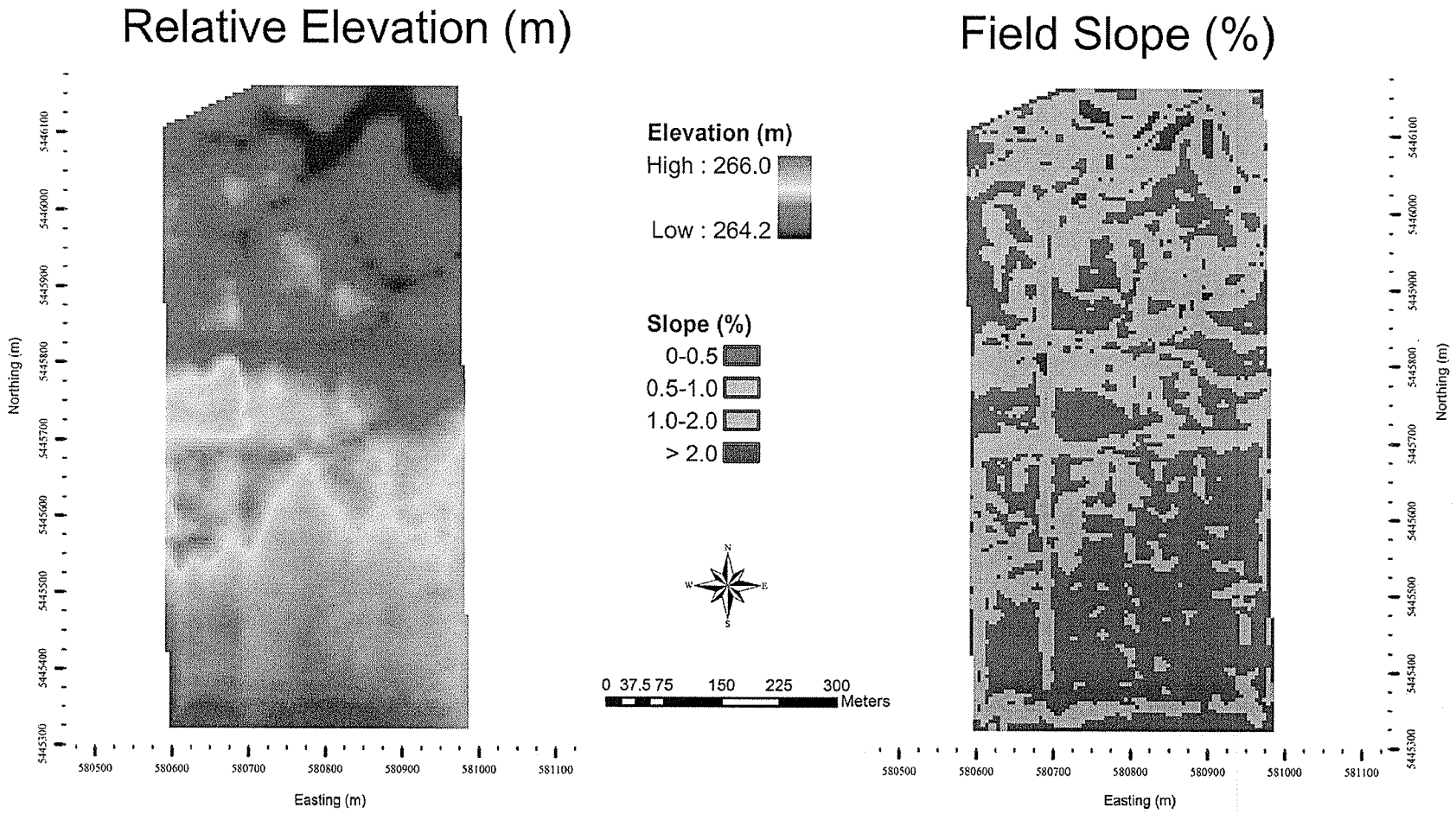

Figure 3.12. Maps of relative elevation and field slope for the Winkler 03 site

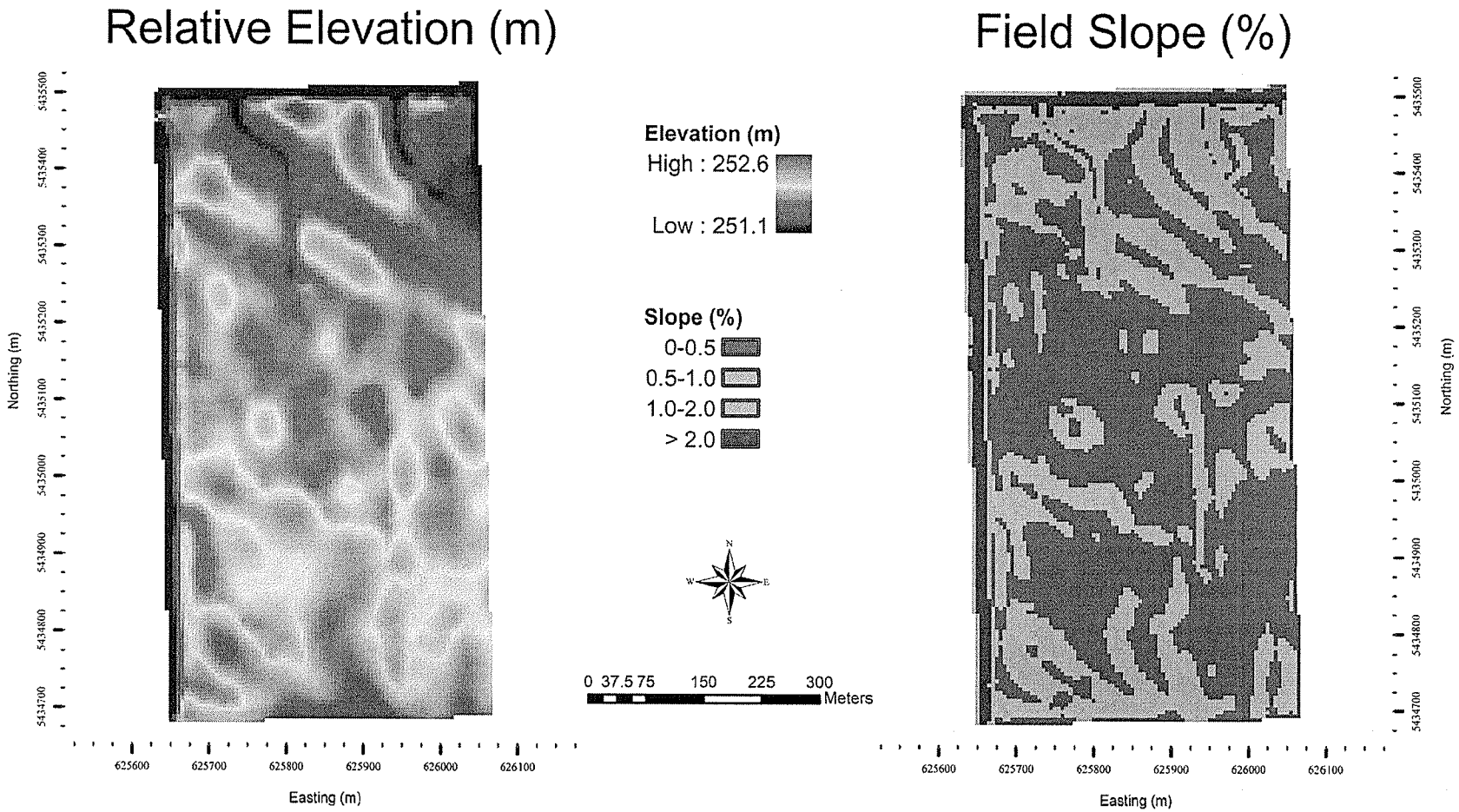

Figure 3.13. Maps of relative elevation and field slope for the Emerson 03 site

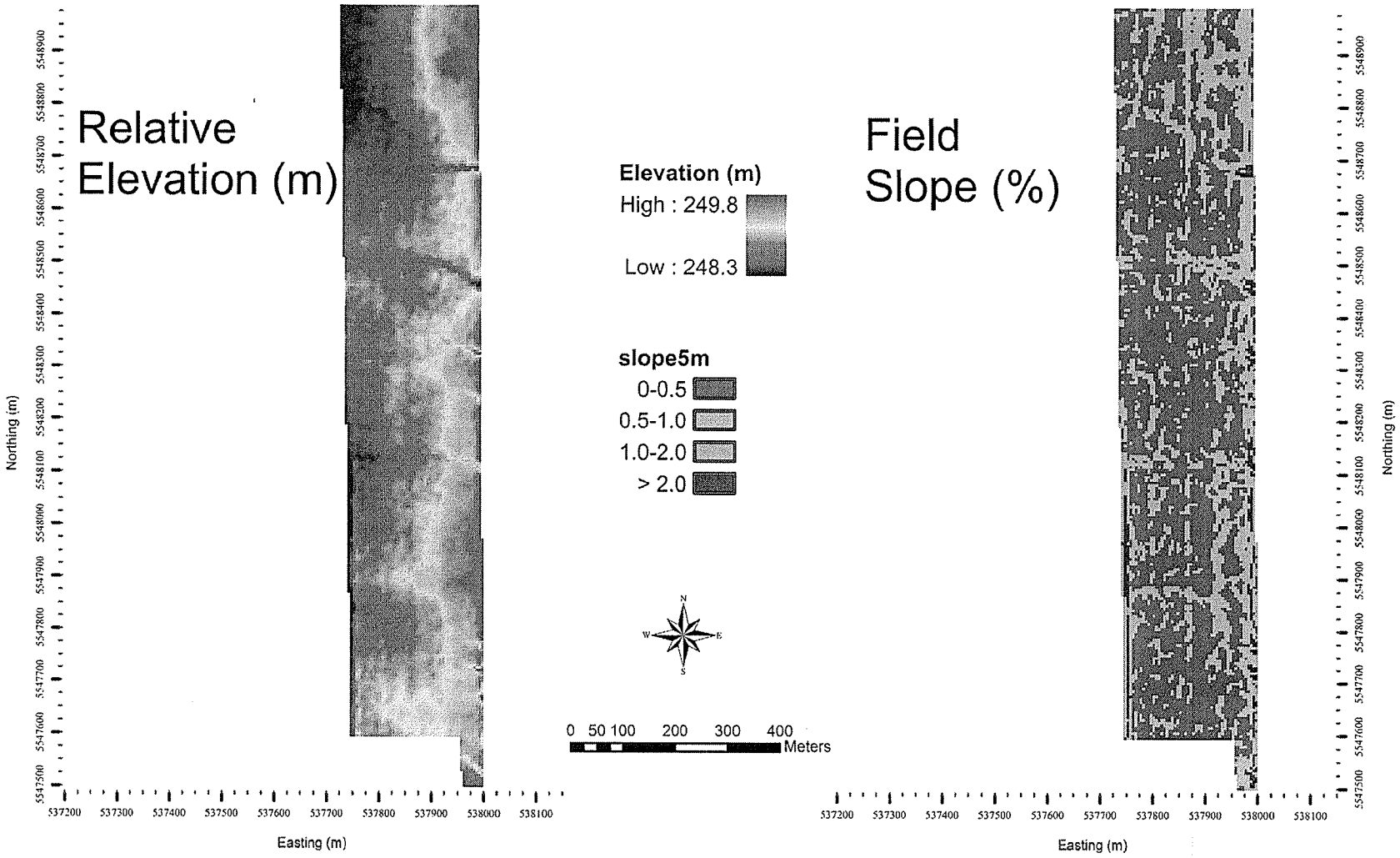

Figure 3.14. Maps of relative elevation and field slope for the Portage 04 site

Table 3.13. Extent and distribution of salinity in study fields

Soil depth	EC_e (dS m^{-1})	Portage 03 Field area (ha)	Portage 03 Percent	Winkler 03 Field area (ha)	Winkler 03 Percent	Emerson 03 Field area (ha)	Emerson 03 Percent	Portage 04 Field area (ha)	Portage 04 Percent
EC_{0-30}	0-2 (non-saline)	7.07	11.67	7.97	24.62	5.36	15.50	12.49	34.23
	2-4 (slightly saline)	37.61	62.09	19.94	61.60	24.23	70.05	13.45	36.86
	4-8 (moderately saline)	14.59	24.09	4.46	13.78	4.81	13.91	7.74	21.21
	8-16 (severely saline)	1.29	2.13	NA	NA	0.19	0.55	2.73	7.48
	> 16 (very severely saline)	0.01	0.02	NA	NA	NA	NA	0.08	0.22
EC_{30-90}	0-2 (non-saline)	6.68	11.03	8.29	25.61	17.25	49.87	9.79	26.83
	2-4 (slightly saline)	22.58	37.28	11.31	34.94	12.27	35.47	13.62	37.33
	4-8 (moderately saline)	28.89	47.70	11.00	33.98	4.89	14.14	11.44	31.35
	8-16 (severely saline)	2.41	3.98	1.78	5.50	0.18	0.52	1.64	4.49
	> 16 (very severely saline)	0.01	0.02	NA	NA	NA	NA	NA	NA

The predicted salinity maps for Portage 03 (Figure 3.7) indicate that the areas of highest salinity occur along the northern edges of the field, decreasing outwardly in southern, eastern, and western directions. As well, differences in EC_{0-30} and EC_{30-90} prediction surfaces indicate that soil salinity increases with increasing soil depth, both in terms of extent and severity. This fact is demonstrated more clearly in Table 3.13, which indicates that about 24% of the field area would be characterized as moderately saline (EC_e from 8-16 dS m^{-1}) for the 0-30 cm depth increment as compared to 48% for the 30-90 cm soil depth. This field, although relatively flat, has a general slope from the south to the north, with both eastern and western edges of the field sloping towards the middle

(see Figure 3.11). The effect of this is a general drainage pattern towards the northern edge of the field, which is bordered by a heavily compacted gravel roadway. This relatively impermeable permanent barrier likely causes subsurface soil water pressure to build up, forcing the ground water table upwards near the surface, causing soil salinization in these areas over time as a greater proportion of water leaves the soil profile through ET than infiltrates through the soil profile.

The predicted salinity maps for Winkler 03 (Figure 3.8), the areas of highest salinity occur along the northern edges of the field, decreasing outwardly primarily towards the south. As in the Portage 03 site, differences in EC_{0-30} and EC_{30-90} prediction surfaces indicate that soil salinity increases with increasing soil depth, both in terms of extent and severity. This fact is demonstrated more clearly in Table 3.13, which indicates that approximately 14% of the field area would be characterized as moderately saline (EC_e from 8-16 dS m^{-1}) for the 0-30 cm depth increment as compared to 34% for the 30-90 cm soil depth. This field, although relatively flat (see Figure 3.12), has a general slope from the south to the north, resulting in a general drainage pattern towards the northern edge of the field, which is bordered by a heavily compacted dike, which itself separates the field from a small stream. In this case, it is possible that this relatively impermeable permanent barrier causes subsurface soil water pressure to build up, a salinization process as suggested for the Portage 03 site. However, it also is possible that hydraulic pressure from stream water levels higher than the soil surface level on the opposite side of the dike force soil water under/through the dike, elevating the groundwater table causing salinization over time.

The predicted salinity maps for Emerson 03 (Figure 3.9) indicate that the areas of highest salinity are not as well defined in this field as for the Portage 03 and Winkler 03 study sites. The highest levels of salinity occur in the north-west corner of the field. This particular field is bordered by deep, permanent drainage ditches along the western and northern borders, likely causing development of ditch salinity (see Figure 3.13). However, this would not explain the occurrence of salinity some distance away from either of these ditches. This region of the province experiences a high water table across the whole field, a result of high artesian pressure from subsurface water movement down the Manitoba escarpment towards the Red River. This field also differs from the Portage 03 and Winkler 03 study sites in that the highest levels of salinity occur in the 0-30 cm depth as compared to the 30-90 cm depth. This fact is demonstrated more clearly in Table 3.13, which indicates that approximately 70% of the field area would be characterized as slightly saline (EC_e from 2-4 dS m^{-1}) for the 0-30 cm depth increment as compared to 35% slightly saline for the 30-90 cm soil depth, with similar proportions of higher salinity values in each case.

The predicted salinity maps for the Portage 04 site (Figure 3.10), illustrate that areas of highest salinity occur along the eastern edge of the field, decreasing outwardly towards the west. In this case, the general slope of the field is actually towards the west (see Figure 3.14), in the opposite direction of increasing salinity. The eastern and south-eastern edges of this field are bordered by a deep permanent drainage ditch that is frequently filled with water, a situation that produces a text book example of conditions required for ditch salinity development. In this field, the areas of highest salinity do not

occur directly next to the ditch edge, but some distance away, a relationship demonstrated by Skarie et al. (1987).

3.5 Conclusions

The results of this study show that spatial measurements of EC_a collected using the Veris 3100 can be used to create depth weighted salinity maps on the standard salinity measurement basis of EC_e. In this study, the effect of salinity on measurements of EC_a was the only contributing factor considered. In addition, although there are numerous factors affecting EC_a for a given soil other than salinity (e.g., soil texture and moisture content), in cases of saline soils in fields with minimal textural and topographical variability, the effect of dissolved salts on EC_a will likely dominate, as demonstrated by the very strong MLR results evaluated in terms of r^2.

Simple MLR techniques and innovative methods of directed soil sampling were found to be effective methods of modelling the relationship between EC_a (employing both $EC_{a\text{-}sh}$ and $EC_{a\text{-}dp}$ measurements) and EC_e. In this author's opinion, the more reliable of the two Veris 3100 measurements would be $EC_{a\text{-}dp}$, particularly in fields with deep plough layers. If the Veris 3100 is to be used for soil salinity assessment, the survey should be conducted in the spring, or at a time when a field is close to field capacity in terms of soil moisture content.

The methods proposed in this study are relatively simple and can be adapted directly by agronomists and researchers to effectively and inexpensively characterize the soil salinity status of a given field of interest. This information can directly aid producers by providing an assessment of the current salinity situation in their fields, upon which

informed recommendations to manage specific cases of soil salinity can be formulated. Multiple evaluations of soil salinity in a given field over time using the methods proposed in this study will also enable researchers to evaluate the effectiveness of imposed salinity management techniques.

4 DRY BEAN SALT TOLERANCE

4.1 Abstract

The successful expansion of edible bean (*Phaseolus vulgaris* L.) production in Manitoba has led to an increased concern over the sustainability of growing these crops because of their interaction with soil salinity. In response to these growing concerns, a study examining soil salinity and its impact on edible beans was established. The objective of this study was to evaluate the impact of soil salinity on dry bean crop productivity in Manitoba, including the development of a salt tolerance model for field dry bean crops employing methods proposed by Steppuhn et al. (2005a). Three edible bean fields with a range of soil salinity conditions were selected in each of the 2003 growing season and one in the 2004 growing season. Apparent soil electrical conductivity (EC_a) surveys were collected. Subsequently, a 10-ha evaluation zone was selected out of each field, from which five treatments of salinity were delineated and established. The EC_a surveys in all cases displayed high levels of spatial pattern, with high values of EC_a being associated with high levels of soil saturation extract electrical conductivity (EC_e), and vise versa. Across all site years, average root-zone salinity (EC_e) values ranged from a low of 0.78 dS m^{-1} within the low salinity treatments to a high of 11.16 dS m^{-1} within the very high salinity treatments. The lowest salinity treatments resulted in significantly greater crop biomass, grain yield, and harvested seed size than the highest salinity treatments. Salinity treatment did not have a marked impact on crop emergence or grain protein content. The level of root-zone salinity that caused of 50% decrease in relative crop yield ranged between 4.88 and 8.35 dS m^{-1}.

4.2 Introduction

The expansion in the late 1990s of Manitoba's dry bean (*Phaseolus vulgaris* L.) production in particular, and pulse crops in general, has provided sound economic returns for many Manitoba producers, rendering it one of the great success stories of the agricultural industry in this province. In recent years, Manitoba has been the largest dry bean producing Province in Canada, with approximately 50% of national production at approximately 200,000 MT annually (Manitoba Agriculture, Food and Rural Initiatives 2003). However, this expansion has resulted in an increased concern over the sustainability of growing this crop because of its interaction with soil salinity. Dry beans are among the most salt-sensitive crops (Maas, 1990; Steppuhn et al., 2001; Steppuhn et al., 2005b), with significantly reduced yield and quality when grown in saline conditions. The wheat-fallow cropping system, commonly used in the northern Great Plains has been responsible for increasing the incidence of saline seeps (Black et al., 1981). Given these facts, production of shallow-rooted (Merrill et al., 2002), lower water-use (Halterlein, 1982; Hattendorf et al., 1988) dry bean crops in ever-tightening rotations has the potential to exacerbate the salinity status of a soil. Greater diversity of crop species grown in rotation in terms of rooting pattern and water use are effective methods to manage the potential of increasing soil salinity (Merrill et al., 2004).

The response of crops to environmental influences such as salinity stress or soil fertility is rarely linear in nature, but more often non-linear or sigmoidal. Maas and Hoffman (1977) proposed a two-piece linear response model to characterize the curved crop yield response to salinity. That paper (which was also a review of crop salt tolerance testing results between 1950 and 1975), with updates by Maas (1990) and Maas

and Grattan (1999), is of particular importance as, from that point on (and perhaps until recently) it has been the standard reference for evaluating and classifying the relative salt tolerance of crops grown around the globe. Recent work by Steppuhn et al. (2005a) suggests that a sigmoidal shaped, nonlinear modified compound discount function, would better represent a given crop's growth or yield response to increasing root-zone salinity than a two-piece linear response model. Other researchers (van Genuchten, 1983; van Genuchten and Hoffman, 1984; van Genuchten and Gupta, 1993; Steppuhn et al., 1996) have made this suggestion of non-linear sigmoidal shaped salt tolerance response functions. The case in favour of using the modified discount function is strengthened by Steppuhn (2005, personal communication) who states that: "in over 15 years of testing in Canada's Salt Tolerance Testing Laboratory except in one test crop, we have never found that the linear model (proposed by Maas and Hoffman, 1977) fits better then the non-linear, modified discount model."

Qualitatively, crops have most commonly been classified as either tolerant (T), moderately tolerant (MT), moderately sensitive (MS), or sensitive (S), in terms of their response to increasing levels of salinity (Francois and Maas, 1999). Recent work by Steppuhn et al. (2005a) suggests that a salinity tolerance index (STI) based on a non-linear response function of crop growth to increasing salinity would most closely reflect agricultural crop response to root-zone salinity and be more useful in making comparisons between crops in terms of their relative salt tolerance.

The purpose of the study described in this thesis is to examine soil salinity and its impact on dry bean crops in southern Manitoba. There were two objectives. Firstly, to assess the extent and severity of soil salinity in selected dry bean fields in southern

Manitoba (Ch. 3), and secondly, to evaluate the impact of soil salinity on dry bean crop productivity, including the development of a salt tolerance model for field dry bean crops employing methods proposed by Steppuhn et al. (2005a).

4.3 Materials and Methods

4.3.1 Study Fields

A description of the study sites is found in section 3.3.1. Crops were planted and produced in a similar fashion between sites (i.e., producers had similar management pratices). All fields were planted with a 76.2 cm crop row spacing. Three different market classes of dry beans were utilized in this study. Portage 03 and Winkler 03 sites were planted to Black (cv. AC Hardblack) and Pink (cv. ROG312) bean crops respectively, while both Emerson 03 and Portage 04 sites were planted to Pinto (cv. Maverick) dry beans.

4.3.2 Establishment of Treatment Groups

Apparent soil electrical conductivity (EC_a) surveys were collected utilizing the Veris 3100 and maps of $EC_{a\text{-}sh}$ and $EC_{a\text{-}dp}$ were created using ordinary kriging, methods detailed in section 3.3.2. All GIS (geographic information systems) applications were conducted using ArcView 3.2 and ArcGIS Desktop (versions 8.3 and 9.0). A 10-ha evaluation zone was selected out of each field that contained a wide gradient of EC_a conditions. Within each zone, five ranges of salinity were identified and delineated in terms of both $EC_{a\text{-}sh}$ and $EC_{a\text{-}dp}$ values. The same range of values was used for each field in the 2003 (0-50, 50-75, 75-125, 125-200, and greater than 200 mS m^{-1}), however the

Portage 04 site had a distribution of generally higher EC_a values such that the range of values used to delineate each group was higher (0-75, 75-125, 125-175, 125-225, and greater than 225 mS m^{-1}). The kriged map values of EC_a were used as a direct indication of a given map areas relative salinity level, such that these five ranges were designated as salinity treatments: S1, S2, S3, S4, and S5, in order of increasing EC_a (combinations of both $EC_{a\text{-}sh}$ and $EC_{a\text{-}dp}$). Three separate sampling and evaluation plots were established in each treatment. Plots were approximately 100 m^2 in area, and the center of the three plots within each treatment for a given site were placed approximately 10 to 20 meters from the center of the nearest adjacent plot of the same treatment.

Following the establishment of plot locations for each field site and following crop planting, the center of each plot was located with a Trimble AgGPS 114 GPS system (see section 3.2.2) used in conjunction with ArcPad 6.0 (ESRI), a mobile GIS application installed on either a laptop or a Pocket PC device. Aluminium neutron access tubes were then inserted to a depth of approximately 1.8 m at the center of each plot within a crop row.

4.3.3 Soil and Crop Production Measurements and Analysis

Soil samples were collected twice during the growing season, approximately two weeks after planting and again at crop harvest. See section 3.3.4 for a detailed description of soil sample collection and salinity analysis methods. Salinity analysis results from these two sample dates were averaged over time and depth, such that for each plot, a 0 to 91 cm value of EC_e (dS m^{-1}) was calculated, termed the growing season root-zone salinity.

Plant stand was evaluated approximately four weeks after bean seedlings had emerged (about six weeks after planting). Plants were counted within six 1-m lengths of crop row (4.6 m^2), randomly selected in each plot.

Crop dry matter (DM) samples were collected approximately one month after planting, and approximately every two weeks subsequently. When the crop began to senesce and drop leaves, DM collection was terminated. Samples were collected by cutting two 1-m lengths of crop row (1.5 m^2) randomly within each plot. DM samples were oven-dried at temperature of 65 $^{\circ}C$ for a period not less than 72 hours. Samples were then weighed using an electronic scale. Crop growth rate (CGR) was calculated using the following equation:

$$CGR = (DM_j - DM_i) / (T_j - T_i) \quad [1]$$

where the numerator represents the difference in DM (kg ha^{-1}) between measurement *i* and subsequent DM measurement *j*, and the denominator represents the time interval between measurements *i* and j (days, d). CGR is expressed in units of kg ha^{-1} d^{-1}.

Crop yield samples were collected the day before the producer had planned to cut and windrow their dry bean crops, which occurs approximately when at least some of the pods were dry and the whole plant was yellow. Samples were collected by cutting six 1-m lengths of crop row (4.6 m^2) randomly within each plot. DM samples were placed in cloth bags and left to dry in an aerated room for at least two weeks until they were threshed manually and cleaned with a stationary seed cleaning machine. Two sub-samples of grain yield from each plot were collected and ground in a commercial coffee grinder. Samples were then oven-dried for at least 24 hours at 65$^{\circ}C$ so that, subsequently, seed moisture content could be determined. The moisture content was then averaged

from the two ground seed samples of each plot and then subtracted from the overall grain yield to produce grain yields for each plot on a zero percent moisture basis. The ground seed samples were then analysed for nitrogen (N) content by combustion (LECO Corporation, St. Joseph, MI). Seed protein content was calculated by multiplying N content (%) by 6.25.

Seed size was calculated by depositing seed samples of between 500-1000 seeds (some plots yielded less than 1000 seeds) through an electronic seed counter. Samples were then weighed and values converted to a thousand seed weight basis depending on the number of seeds counted.

4.3.4 Crop Water Use

Volumetric soil water content between soil depths of 0.1 and 1.5 m was determined using a field-calibrated neutron moisture gauge (Troxler Model 4330, Research Triangle Park, NC) with measurement increments of 0.2 m. Measurements were recorded every 2-3 weeks from approximately 30 days after planting until crop harvest. Earlier measurements were intended but were not conducted due to extenuating circumstances. In the 2003 crop year, the neutron moisture gauge was damaged before the first measurement, delaying subsequent measurements, and in 2004, a calculation of measurement depth error negated it's inclusion within the results.

Depth of soil water extraction was evaluated using paired t-tests (Proc ttest, SAS 8.2) and was assumed to have occurred at a given depth where at least one measurement of soil water content during the growing season was significantly ($P \leq 0.1$) different from the initial measurement (Entz et al., 1992; Angadi and Entz, 2002). This method assumes

negligible loss of water due to runoff, deep percolation, and upward soil moisture flux (Angadi and Entz, 2002).

Evapotranspiration (ET) or crop water use was calculated using the following equation (depth of the soil profile included in this calculation was dependant on the results and assessment of the depth of soil water extraction by the dry bean crops):

$$ET = (W_i - W_h) + P \quad [2]$$

where ET is expressed in units of mm, W_i is the initial soil profile water (mm), W_h is the harvest soil profile water (mm), and P is the precipitation during the time interval between initial and harvest soil water measurements. Tipping bucket rain gauges were installed at each study site prior to initial soil moisture measurements to record precipitation events during the growing season. Water use efficiency (WUE) was calculated using the following equation:

$$WUE = \frac{\text{Crop Yield}}{ET} \quad [3]$$

where WUE is expressed in units of kg ha^{-1} d^{-1} mm^{-1}.

4.3.5 Crop Salt Tolerance

Dry bean salt tolerance was assessed according to methods proposed by Steppuhn et al. (2005a), who suggest the following non-linear model:

$$Y_r = 1/[1 + (C/C_{50})^{\exp(sC_{50})}] \quad [4]$$

where Y_r is the relative yield, C is the average root-zone salinity, C_{50} defines C at Y_r = 0.5, and s represents the response curve steepness. Y_r was calculated for the crop yield of each plot using the following equation:

$$Y_r = Y/Y_m \quad [5]$$

where Y represents the actual yield (kg ha^{-1}) and Y_m represents the yield of the crop when grown in a root-zone free of salinity (Maas and Hoffman, 1977; Maas, 1990). To estimate the value of Y_m for each study site, Y/Y_m was substituted for Y_r in Eq. [4], and using non-linear regression Y_m was estimated along with C_{50} and s. After estimating Y_m, the yield data for each plot was converted to a relative ratio value of crop yield (using Eq. [5]), such that data from all four sites could be combined and analysed together.

4.3.6 Statistical Analysis

Analyses of variance (ANOVA) and comparison of means test (Fisher's protected least significant difference) were performed for a completely randomized experimental design using the Proc GLM procedure of SAS 8.2 (SAS institute, Cary, NC) at an alpha significance level of $P = 0.1$. Levene's test for heterogeneity of variance was included in the ANOVA procedures, which in all cases confirmed homogeneity of variances. ANOVA was used for the results of root-zone salinity, plant stand, crop DM accumulation, CGR, yield, seed size, seed protein content, soil water comparisons between treatments, water consumption, and WUE.

Crop salt tolerance non-linear regression analysis was conducted using the Proc Nlin procedure of SAS 8.2. Coefficient of determination (r^2, a.k.a. pseudo r^2 when referring to non-linear regression) was calculated as follows:

$$r^2 = 1 - SS_{res}/SS_{ct} \qquad [6]$$

where SS_{res} is equal to the sum of squares of the residuals and SS_{ct} is the corrected total sum of squares (Kvalseth, 1985; Schabenberger, 1998).

4.4 Results and Discussion

4.4.1 Environmental Conditions

Table 4.1 includes climatic data (1971-2000) for all four study sites, sourced from permanent Environment Canada weather stations that are located within 15 km of a given associated study site. Figure 4.1 contains growing season daily precipitation data collected from tipping bucket rain gauges installed at all four study sites.

The 2003 growing season was, in terms of temperature, a relatively normal crop year at all three study sites of this year. August of 2003 was slightly above average (~ 110% of normals) in terms of average daily mean, minimum, and maximum temperatures, as well as accumulations of growing degree days (GDD). Precipitation levels for the months of May and June at all three sites of 2003 were well above normal, ranging from 113 to 288% above long-term averages. However, the months of July and August experienced quite the opposite conditions, particularly at Portage 03 and Winkler 03 sites where precipitation levels during these months in comparison to long-term averages ranged from 32 to 36% for July and 59 to 70% for August, respectively. The 2003 growing season was ideal in terms of dry bean production; however, the Emerson 03 site experienced more frequent high intensity precipitation events, particularly near the beginning of the growing season (Figure 4.1). With the heavier clay soil texture of the Emerson 03 site, this resulted in longer periods of standing water than at either the Portage 03 or Winkler 03 sites, which contributed to decreased overall dry bean productivity in this field.

Table 4.1. Study site regional climate normals (Environment Canada, 2005)

Month	Temperature			Growing Degree Days		Precipitation (mm)
	Avg. Daily (°C)	Avg. Daily Min. (°C)	Avg. Daily Max. (°C)	Above 5 °C	Above 10 °C	
			Portage la Prairie, 1971-2000			
May	11.9	5.0	18.8	232.9	111.3	47.8
June	17.1	10.9	23.2	361.5	212.6	75.8
July	19.3	13.2	25.4	444.5	289.5	75.2
August	18.0	11.5	24.6	405.7	250.9	70.3
			Portage la Prairie, 2003, % of 1971-2000			
May	106	112	104	102	89	145
June	98	102	97	97	96	183
July	101	104	100	101	102	36
August	116	124	112	122	135	70
			Portage la Prairie, 2004, % of 1971-2000			
May	62	40	68	44	23	242
June	82	83	83	76	60	72
July	96	98	94	94	91	54
August	79	82	78	71	53	60
			Winkler, 1971-2000			
May	12.9	6.2	19.4	248.8	123.0	63.3
June	17.7	11.8	23.6	381.2	232.5	84.4
July	20.1	14.2	25.9	467.1	312.1	71.2
August	19.1	12.9	25.3	439.6	284.7	69.9
			Winkler, 2003, % of 1971-2000			
May	100	102	100	98	83	120
June	98	100	97	97	94	114
July	101	104	100	102	103	32
August	113	116	111	116	125	59
			Emerson, 1971-2000			
May	13.5	6.3	20.6	266.1	134.6	57.3
June	17.8	11.3	24.2	384.4	235.2	87.4
July	19.8	13.5	26.1	466.0	311.0	84.8
August	18.9	12.2	25.5	431.3	276.6	72.9
			Emerson, 2003, % of 1971-2000			
May	96	94	98	93	80	288
June	98	100	98	97	95	113
July	99	99	100	98	97	74
August	111	117	109	115	123	86

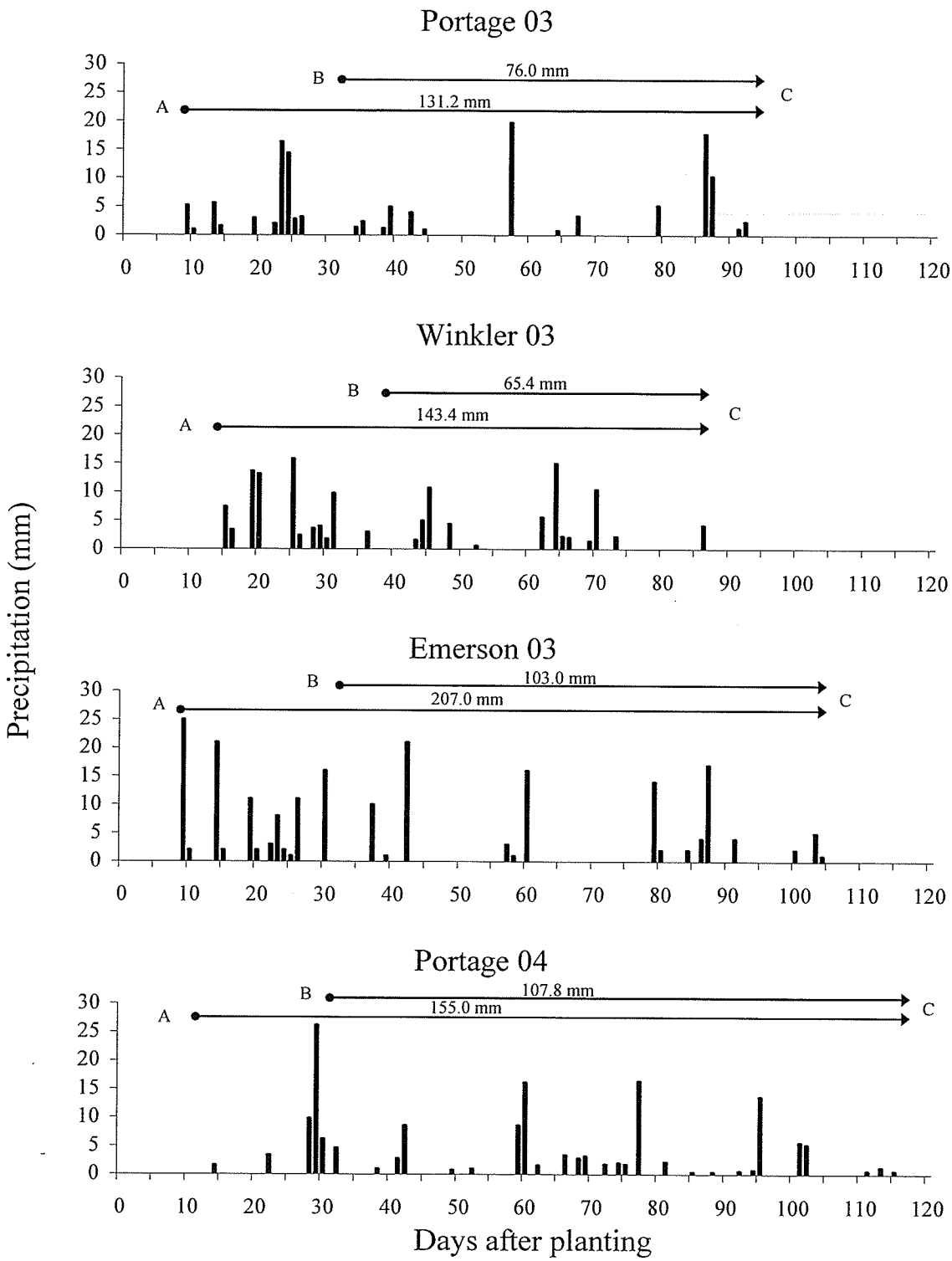

Figure 4.1. Growing season precipitation. Precipitation between initial rain gauge set-up (A) and first soil moisture sampling (B), and between A and final crop harvest soil moisture sampling (C), are included along the endpoints denoting the time of sampling (days after planting)

The Portage 04 growing season was far removed from normal climatic conditions for this region. Accumulations of GDD were well below normal, particularly in the months of May and June, which experienced 44 and 76% of normal GDD with a base temperature of 5°C, respectively. Precipitation levels in the month of May were well above normal at 242%, with the rest of the season below normal. However, cool conditions hampered field drying during June, July, and August, contributing to a lengthened growing season, delaying crop maturity until late in the fall. As well, a severe frost 68 DAP likely resulted in significant damage to the Portage 04 dry bean crop.

4.4.2 Experimental Design and Establishment of Treatment Groups

Table 4.2 includes a schedule of experimental observations conducted over the course of this study.

Figures 4.2, 4.3, 4.4, and 4.5 include both $EC_{a\text{-}sh}$ and $EC_{a\text{-}dp}$ kriged maps, overlain with the 10-ha evaluation zone borders and the placement of the five salinity treatments (S1, S2, S3, S4, and S5) and their corresponding three plots, for the Portage 03, Winkler 03, Emerson 03, and the Portage 04 study sites, respectively. Two plots from the 2003 growing season were omitted from analysis within the entire analysis of results. One plot from the S1 treatment at the Portage 03 site was trampled by a cultivating tractor early in the growing season and did not seem to recover sufficiently to be included in this group. A plot from the S3 treatment of the Winkler 03 site was placed too close to a surface drainage ditch, which resulted in much of the plot being drowned out, and as such was not included in the analysis of results.

Table 4.2. Schedule of field activities and measurements. Numbers in brackets following calendar dates indicate time in days after planting.

Location	Bean market class and cultivar	Planting date	Soil samples	Soil water	Plant stand	Plant DM	Harvest
Portage 03	Black cv. AC Hardblack	June 2	June 19 (17) September 5 (95)	July 4 (32) July 21 (49) August 2 (61) August 16 (75) August 31 (90)	July 21 (49)	July 3 (31) July 21 (49) August 6 (65)	September 5 (95)
Winkler 03	Pink cv. ROG132	May 27	June 20 (24) August 22 (87)	July 5 (39) July 21 (55) August 3 (68) August 17 (82)	July 22 (56)	July 9 (43) July 22 (56) August 7 (72)	August 22 (87)
Emerson 03	Pinto cv. Maverick	June 2	June 22 (20) September 15 (105)	July 5 (33) July 21 (49) August 3 (62) August 17 (76) September 7 (97)	July 22 (50)	July 9 (37) July 22 (50) August 8 (67) August 19 (78)	September 15 (105)
Portage 04	Pinto cv. Maverick	June 10	June 22 (12) October 6 (118)	July 11 (31) July 19 (39) August 6 (57) August 30 (81) September 27 (109) October 6 (118)	July 19 (39)	July 6 (26) July 19 (39) August 6 (57) August 25 (76)	October 6 (118)

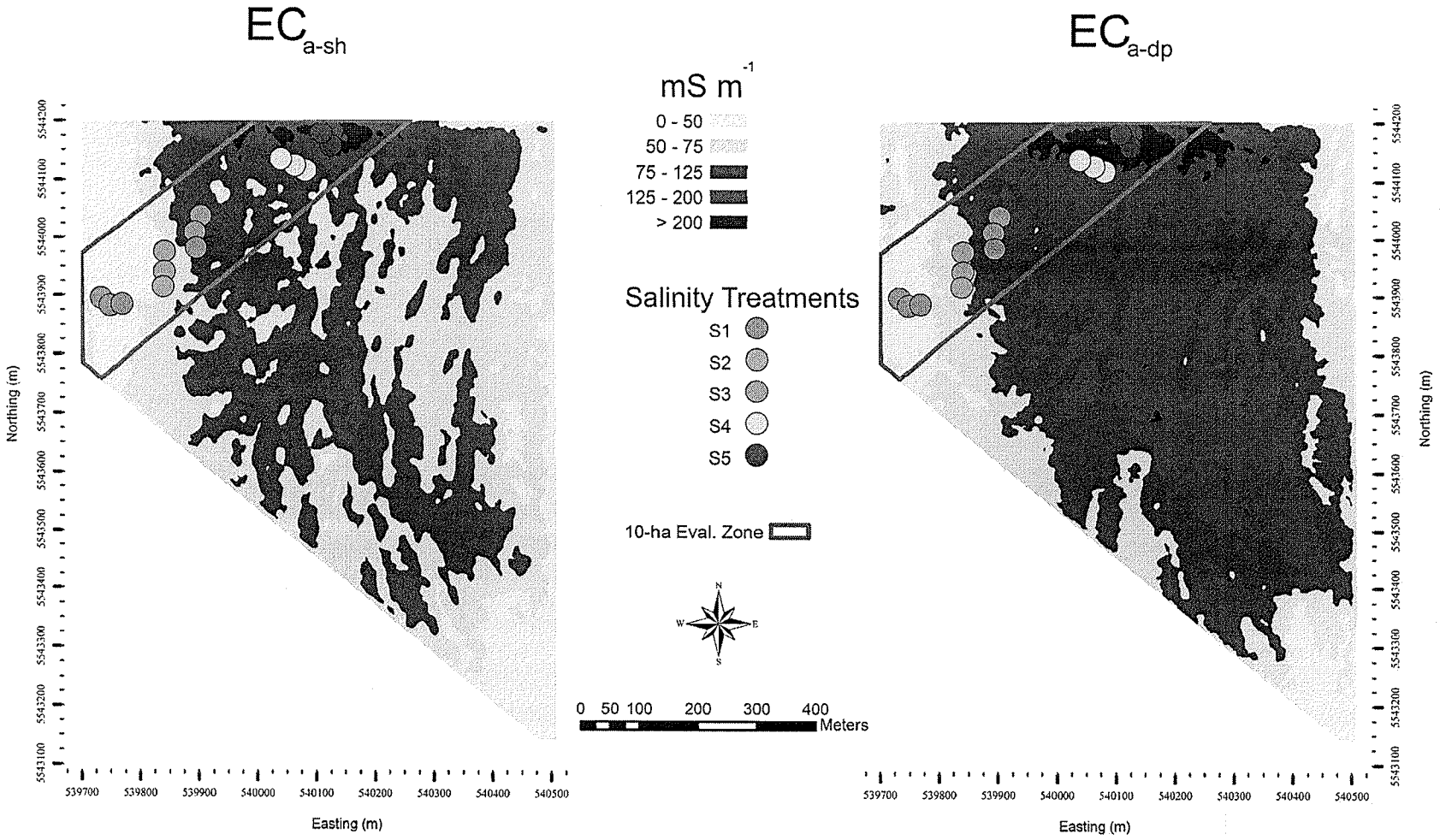

Figure 4.2. Maps of $EC_{a\text{-}sh}$ and $EC_{a\text{-}dp}$ surveys from the Portage 03 study site

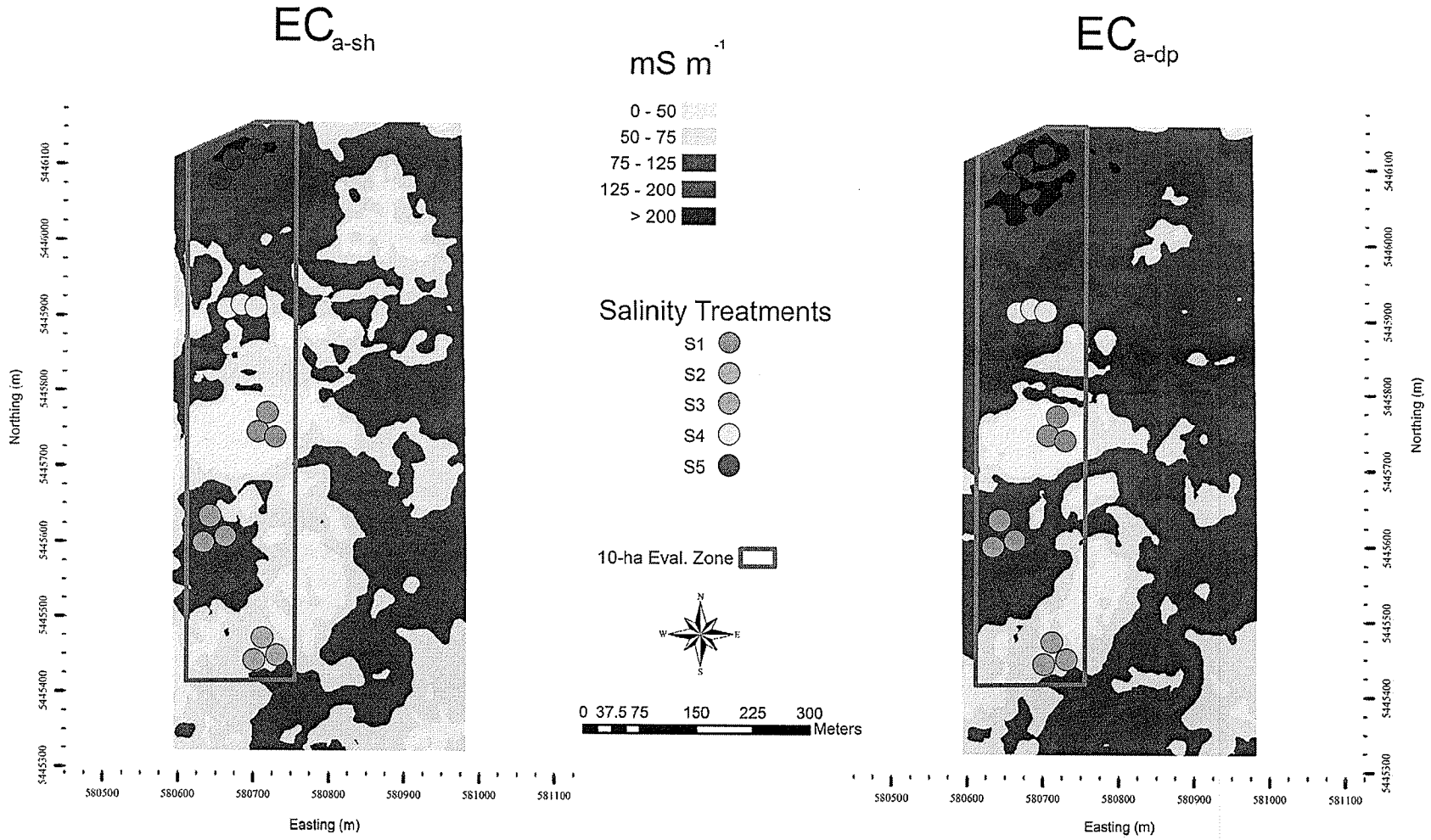

Figure 4.3. Maps of $EC_{a\text{-}sh}$ and $EC_{a\text{-}dp}$ surveys from the Winkler 03 study site

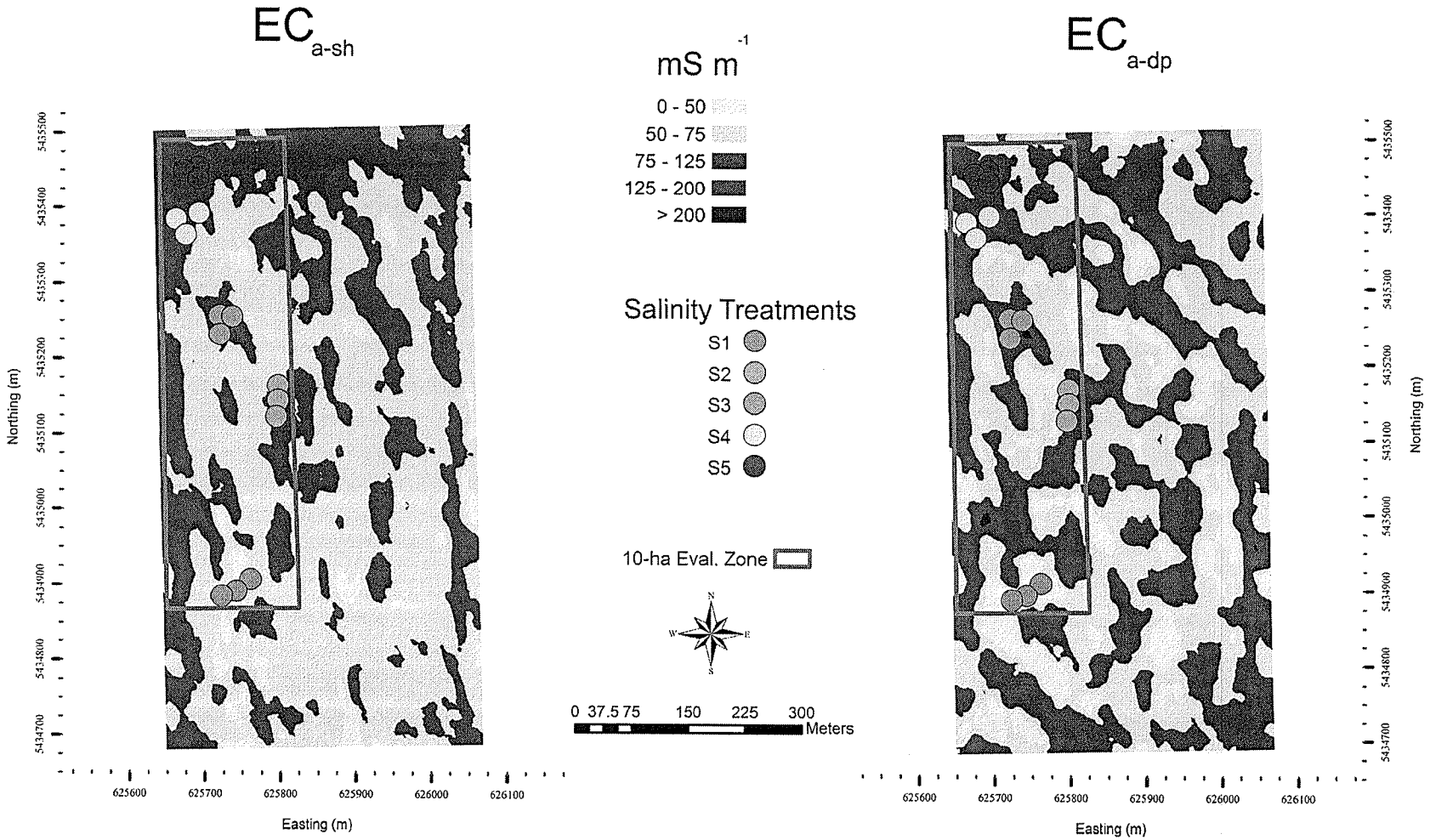

Figure 4.4. Maps of $EC_{a\text{-}sh}$ and $EC_{a\text{-}dp}$ surveys from the Emerson 03 study site

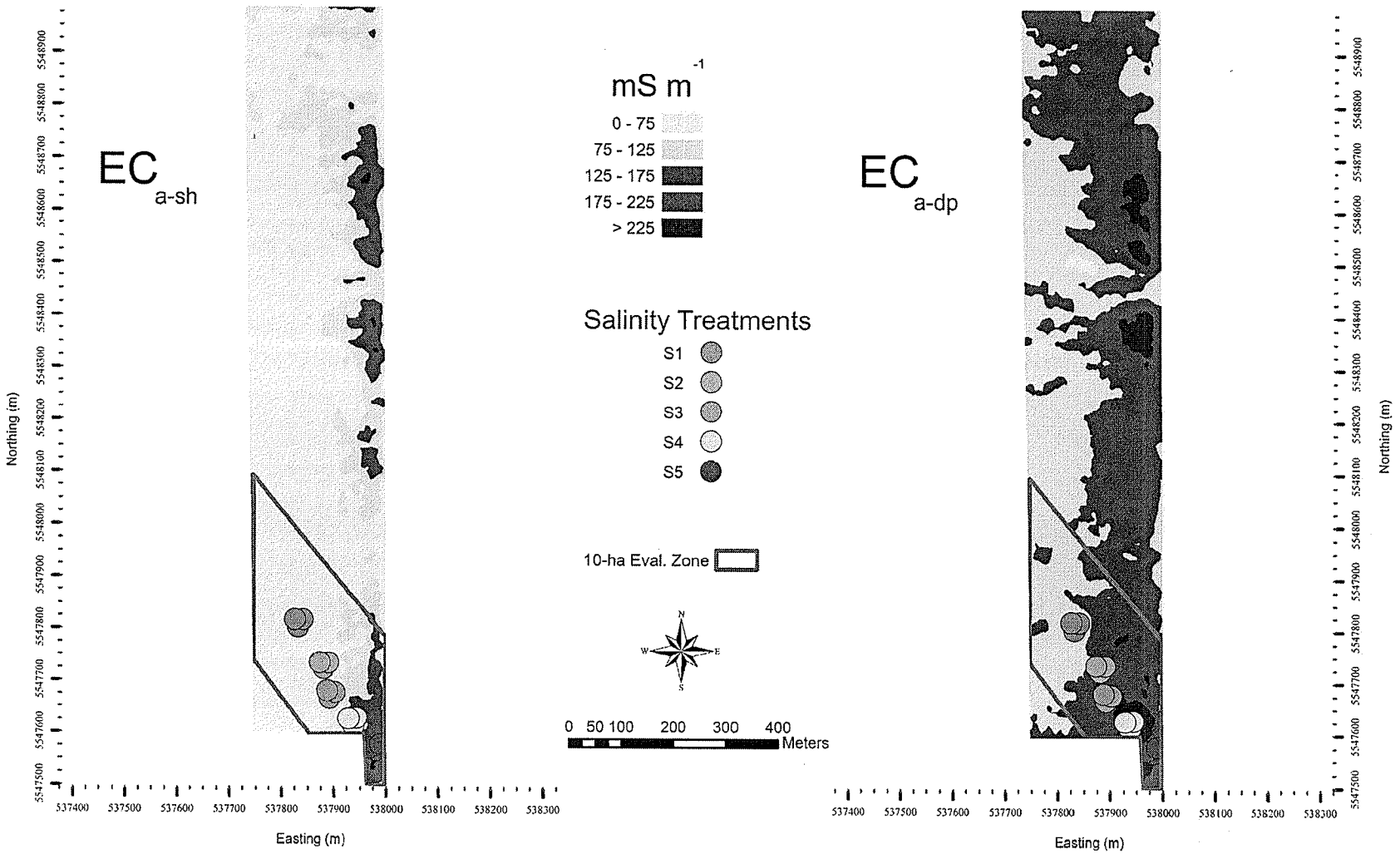

Figure 4.5. Maps of $EC_{a\text{-}sh}$ and $EC_{a\text{-}dp}$ surveys from the Portage 04 study site

The EC_a maps for the Portage 03 (Figure 4.2), Winkler 03 (Figure 4.3), and Portage 04 (Figure 4.5) sites displayed similar spatial patterns in terms of a steady decrease in EC_a away from the highest areas (i.e., areas of high EC_a), as well, differences between $EC_{a\text{-}sh}$ and $EC_{a\text{-}dp}$ prediction surfaces indicate that soil salinity increases with increasing soil depth, both in terms of extent and severity (a condition also true of the Emerson 03 site). Therefore, salinity treatments were arranged outwardly from the areas of highest EC_a along a reasonably steadily decreasing EC_a gradient. The Emerson 03 site (Figure 4.4), on the other hand, displayed a pattern of EC_a distribution where areas of high EC_a were spatially distributed in a seemingly random pattern.

Following the analysis of the average root-zone salinity levels between initial and harvest soil samples (Table 4.3), in all site-years, high values of EC_a (i.e., S5, S4, and S3 treatments) were associated with high levels of EC_e, and vise versa. S1 to S5 treatments ranged from approximately 1 dS m^{-1} to between 9 and 11 dS m^{-1}, respectively, for all sites. There were between three to four significantly different treatment groupings for each site, however, in all cases, the average root-zone salinity increased in order of increasing salinity treatments (i.e., EC_e in dS m^{-1}, S1 < S2 < S3 < S4 < S5). The Winkler 03 site had the lowest salinity levels for all treatments compared to the other site years. Portage 04, on the other hand expressed the highest salinity levels. Treatment levels, although similar between sites, were significantly different in some cases, as well, treatments themselves (for a given site) were not equally spaced in terms of EC_e, and in some cases were not significantly different from each other (e.g., S3 and S4 treatments for Portage 03 and Emerson 03). This is important to keep in mind when interpreting dry bean production results from this study in terms of treatment effects.

Table 4.3. Average growing season root-zone salinity (EC_e, dS m^{-1})

Study site	Treatment				
	S1	S2	S3	S4	S5
	dS m^{-1}				
Portage 03	1.28c†z††	1.88cy	7.16bz	7.44by	10.11az
SE	0.41	0.34	0.34	0.34	0.34
Winkler 03	0.78dx	0.77dx	3.15cy	7.31by	9.30az
SE	0.22	0.22	0.28	0.22	0.22
Emerson 03	1.02cy	1.70cxy	6.29bz	7.69by	10.06az
SE	0.64	0.78	0.64	0.64	0.64
Portage 04	1.37cz	2.91cz	7.18bz	10.3az	11.16az
SE	0.67	0.67	0.67	0.67	0.67

† Means within a row (a,b,c,d) followed by a different letter are significantly different at $P = 0.1$

†† Means within a column (z,y,x) followed by a different letter are significantly different at $P = 0.1$

4.4.3 Crop Production

4.4.3.1 Plant Stand

Dry bean plant stand was generally unaffected by salinity treatments S1, S2, S3, and S4 for all study sites, and S5 for Portage 03 and Portage 04 sites, averaging 75% or higher plant stand in comparison to the plot with the most established plants (Table 4.4). The S5 treatment for the Winkler 03 and Emerson 03 site expressed more significant decreases, with only 51% and 32% plant stand, respectively. Prisco and O'Leary (1970), Bayuelo-Jimenez et al. (2002a), and Steppuhn et al. (2001) found similar results in that they observed less than 20% reductions in bean emergence and or survival below 10 to 12 dS m^{-1}. Both 2003 and 2004 growing seasons had excellent soil moisture conditions at planting, such that one would expect bean seedlings to be less susceptible to salinity stress during this period.

Table 4.4. Evaluation of plant stand and seedling establishment

Study site	Treatment				
	S1	S2	S3	S4	S5
	plants m^{-2}				
Portage 03	11.4c† (78)††	11.3c (77)	14.6a (100)	13.5ab (92)	12.0bc (82)
SE	0.8	0.7	0.7	0.7	0.7
Winkler 03	9.7a (99)	9.8a (100)	9.7a (99)	9.1a (93)	5.0b (51)
SE	0.6	0.6	0.8	0.6	0.6
Emerson 03	6.9a (95)	7.3a (100)	6.6a (90)	5.5b (75)	2.3c (32)
SE	0.4	0.4	0.4	0.4	0.4
Portage 04	8.2ab (95)	7.9abc (92)	8.6a (100)	7.6bc (88)	7.0c (81)
SE	0.4	0.4	0.4	0.4	0.4

† Means within a row followed by a different letter are significantly different at $P = 0.1$
†† Values in brackets are percent plant stand, and was calculated as the mean density of plants for a given treatment relative to the maximum plant density under all salinity treatments for a given site

4.4.3.2 Dry Matter Accumulation and Crop Growth Rate

Figures 4.6, 4.7, 4.8, and 4.9 include above ground DM accumulation for the Portage 03, Winkler 03, Emerson 03, and Portage 04 sites, respectively. In all cases the S5 treatment resulted in the lowest significant accumulations of DM. The DM measurements for the Portage 03 and Emerson 03 sites displayed an ever increasing gap between higher and lower salinity treatments, with DM levels for treatments showing the following relationship throughout the growing season: S1 > S2 > S3 > S4 > S5. At 67 DAP, the Portage 03 site had mean DM levels of 6009 and 1359 kg ha^{-1} for the S1 and S5 treatments, respectively, whereas the Emerson 03 site at 78 DAP had only 1602 and 153 kg ha^{-1} for the S1 and S5 treatments, respectively. By 72 DAP, the S1, S2, S3, and S4

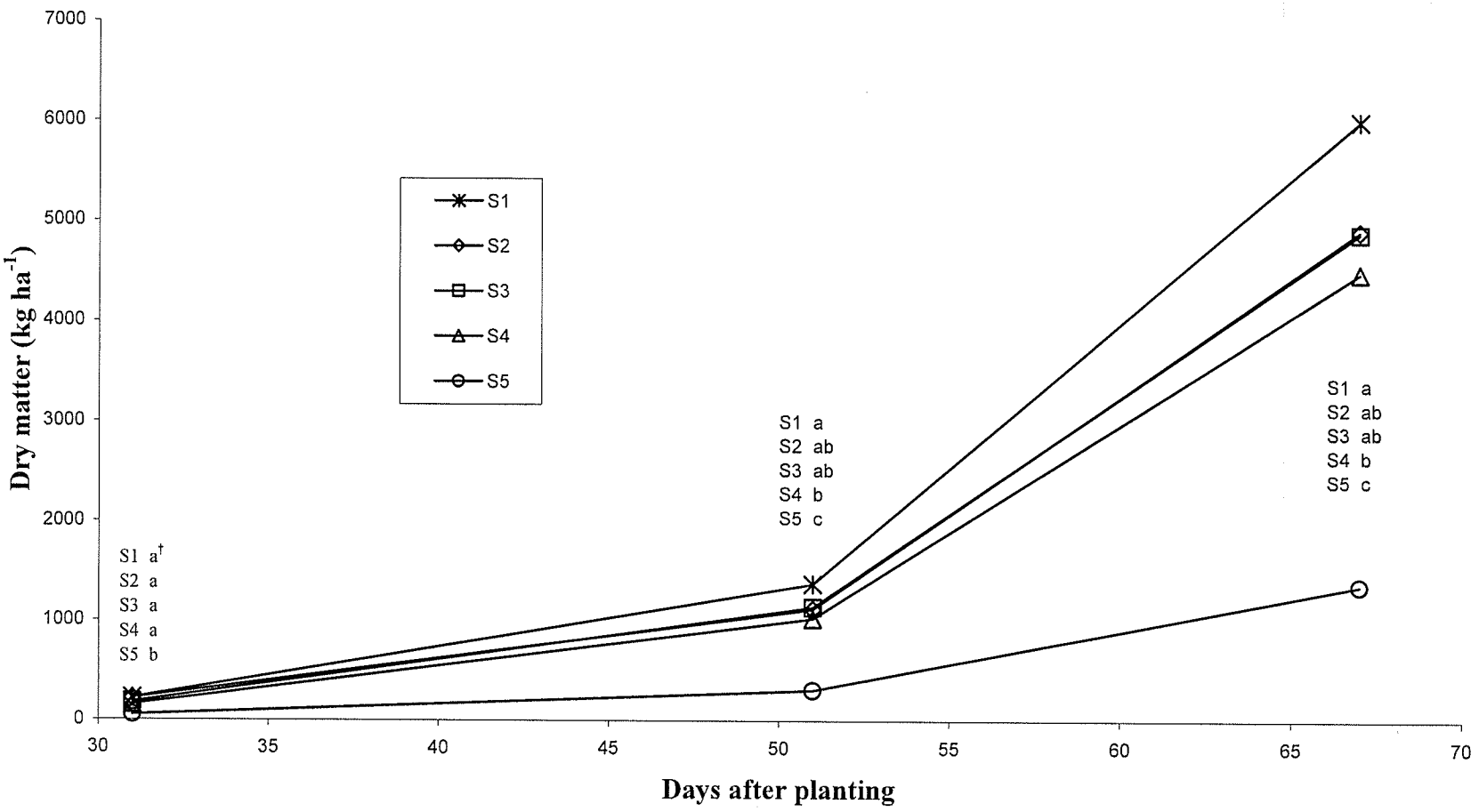

Figure 4.6. Portage 03 growing season dry matter (DM) accumulation. †Treatments within a column followed by different letters have significantly different ($P = 0.1$) mean DM values for that measurement date.

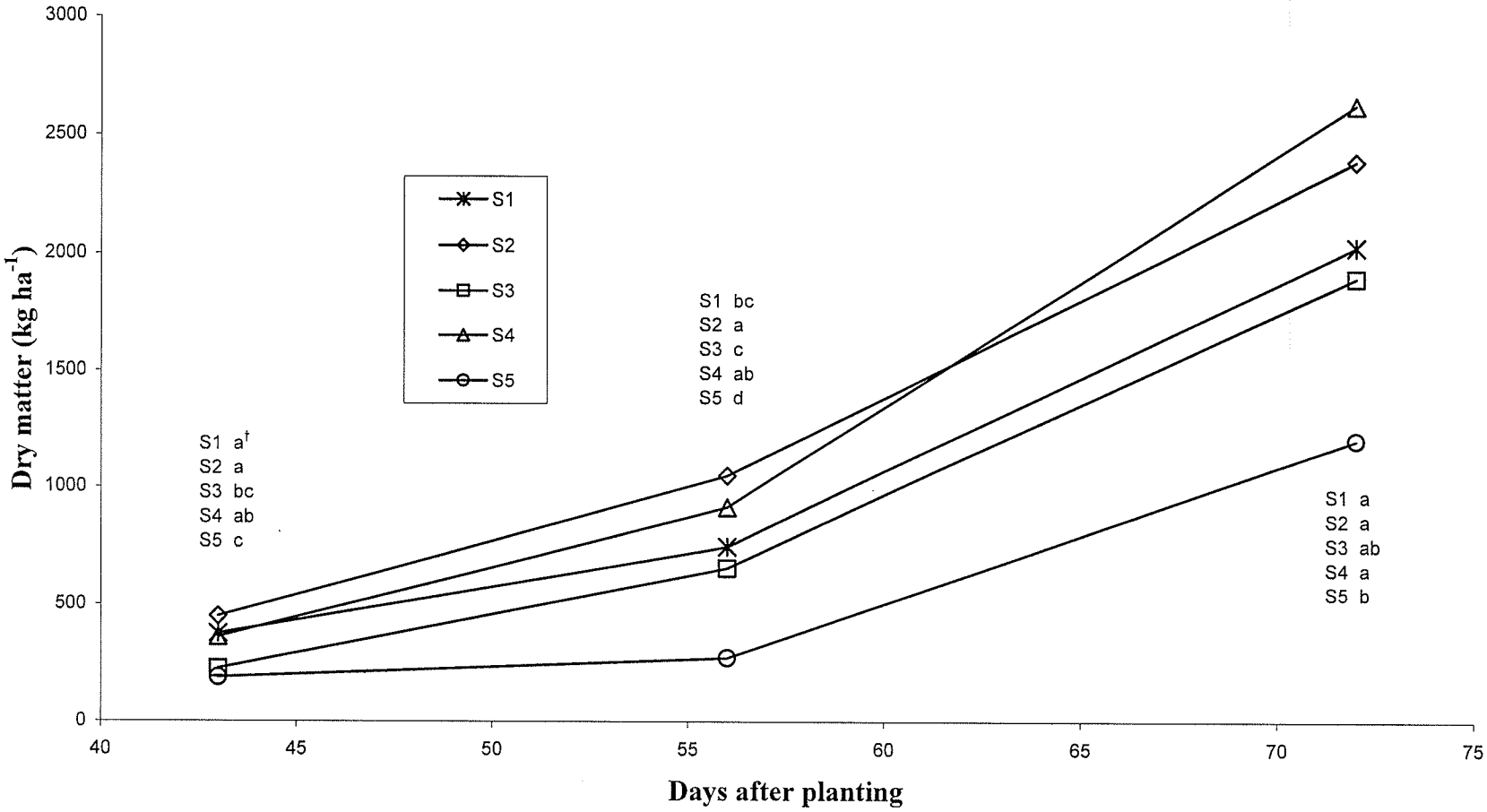

Figure 4.7. Winkler 03 growing season dry matter (DM) accumulation. †Treatments within a column followed by different letters have significantly different ($P = 0.1$) mean DM values for that measurement date.

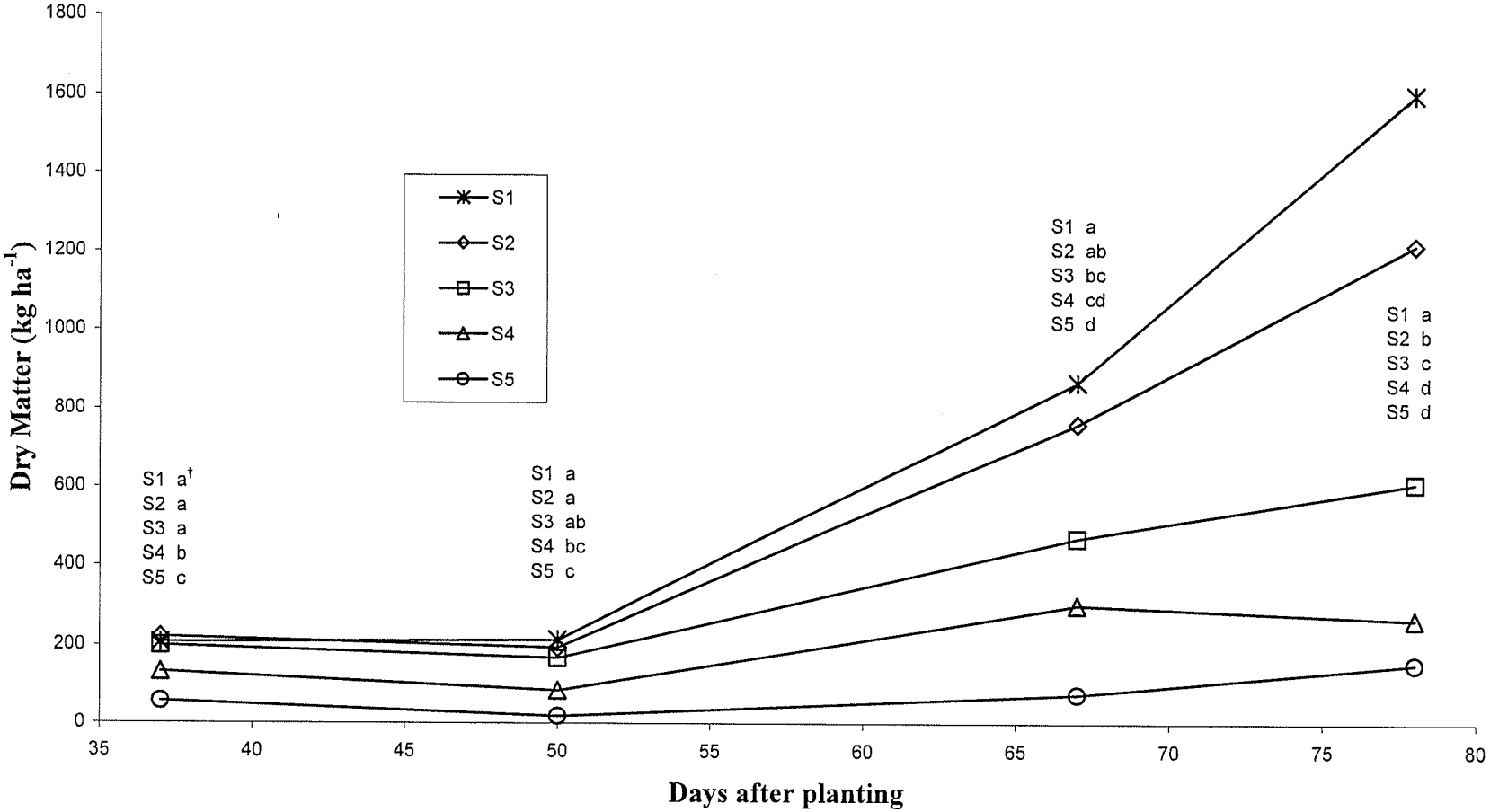

Figure 4.8. Emerson 03 growing season dry matter (DM) accumulation. †Treatments within a column followed by different letters have significantly different ($P = 0.1$) mean DM values for that measurement date.

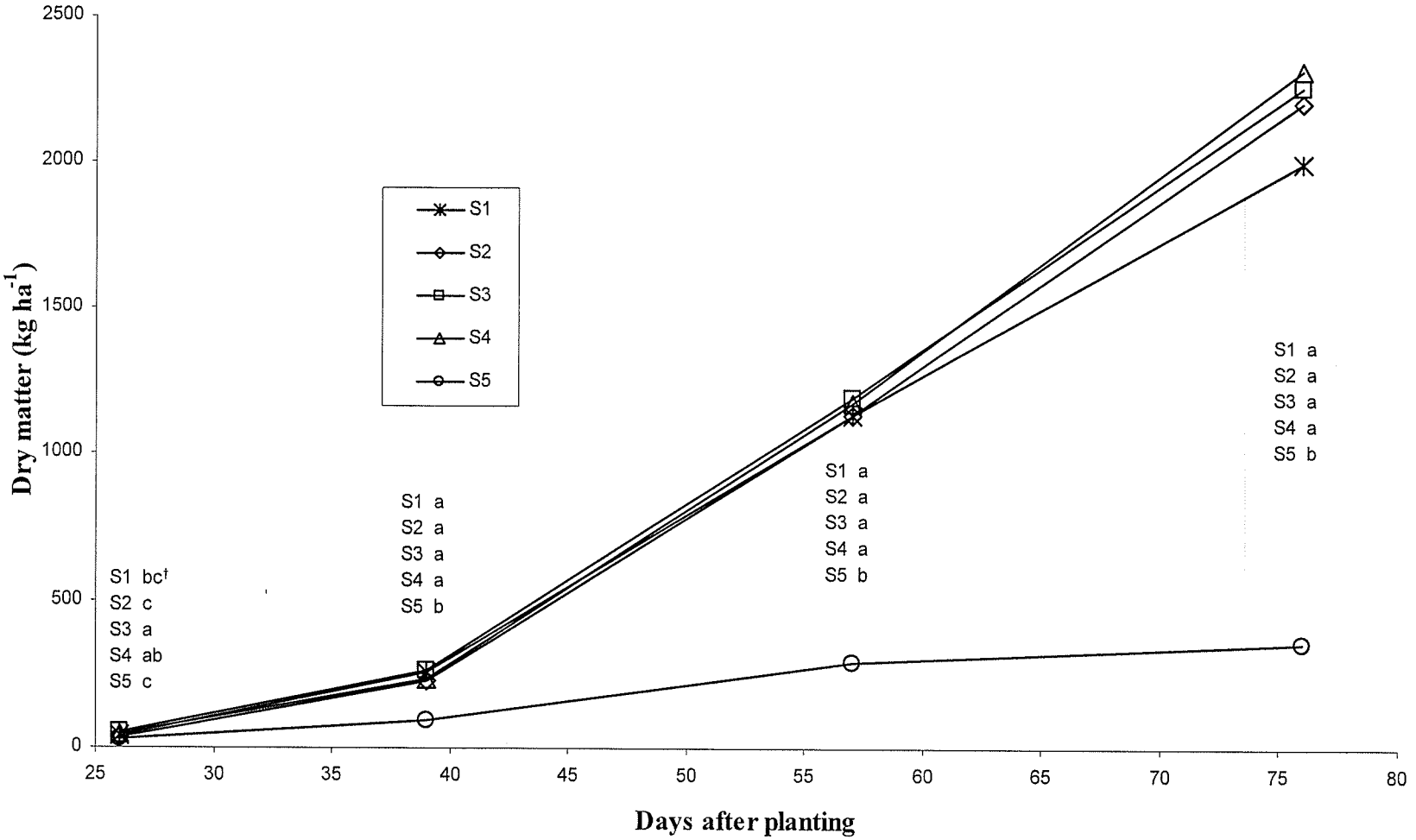

Figure 4.9. Portage 04 growing season dry matter (DM) accumulation. †Treatments within a column followed by different letters have significantly different ($P = 0.1$) mean DM values for that measurement date.

treatments were not significantly different from each other for the Winkler 03 site, and only the S1, S2, and S4 treatments were significantly greater than the S5 treatment, in terms of DM accumulation. The highest and lowest accumulation of DM at the Winkler 03 site occurred in the S4 (2628 kg ha^{-1}) and S5 (1204.4 kg ha^{-1}) treatments, respectively. The S1, S2, S3, and S4 treatments at this site were not significantly different from each other, but were all significantly greater than the S5 treatment. The lower DM accumulation by the S1 treatment in comparison to S2, S3, and S4 treatments could be partially explained by the presence of a well developed wild oat (*Avena fatua* L.) patch in this region of the field, which was not effectively controlled by herbicide applications or cultivation. The highest and lowest accumulation of DM at the Portage 04 site occurred in the S4 (2319 kg ha^{-1}) and S5 (357 kg ha^{-1}) treatments, respectively.

Table 4.5 contains the results of crop growth rate analysis. During early vegetative growth (i.e., the first period of CGR calculation for each site) CGR values were relatively low for all sites, however for treatments S1, S2, S3, and S4, CGR was higher than S5 at all four sites during this period (though not significantly higher in all cases). By the second period of CGR calculation, CGR had increased substantially (with the exception of Emerson 03) for the S1, S2, S3, and S4 treatments, and to a lesser degree, CGR increased for the S5 treatments as well. All treatments of Emerson 03 expressed essentially zero growth during this period, likely a function of excess precipitation (see Figure 4.1). By the end of CGR analysis, the Portage 03 site had mean CGR levels of 290 and 66 kg ha^{-1} d^{-1} for the S1 and S5 treatments, respectively, whereas the Emerson 03 site at had only 67 and 7 kg ha^{-1} for the S1 and S5 treatments, respectively. For these two sites there was a generally steady decrease in CGR from S1

to S5 treatments throughout the period of CGR analysis, a gap increasing over time. The CGR's observed for the Portage 03 site in the S1 to S4 treatments from 51 to 67 DAP is much higher than the same treatment levels of the other three study sites. There are few literature sources that have calculated CGR for dry bean crops. Yusuf et al. (1999) observed maximum CGR for soybeans of approximately 170 kg ha^{-1} d^{-1}, which would seem to indicate that the CGR values observed for the Portage 03 dry bean crop are within reason. The Portage 04 site had significantly greater CGR levels for the S1, S2, S3, and S4 treatments in comparison to S5, a condition also true for the Winkler 03 site, however no significant differences were observed between treatments.

Table 4.5. Crop growth rate

Time period (days after planting, DAP)	Treatment				
	S1	S2	S3	S4	S5
	kg ha^{-1} d^{-1}				
			Portage 03		
0-31 DAP	7.28a†	7.13a	5.98a	5.16a	1.75b
31-51 DAP	57.39a	45.03a	47.85a	43.27a	12.81b
51-67 DAP	289.70a	236.55ab	235.35ab	216.25b	65.51c
			Winkler 03		
0-43 DAP	8.71a	10.45a	5.25bc	8.37ab	4.36c
43-56 DAP	28.91b	46.22a	33.33ab	42.70a	6.57c
56-72 DAP	80.10	83.74	77.61	107.10	58.22
			Emerson 03		
0-37 DAP	5.62ab	5.98a	5.42a	3.59b	1.57c
37-50 DAP	0.49	-2.09	-2.52	-3.63	-3.02
50-67 DAP	38.54a	33.46ab	17.80abc	12.76bc	3.35c
67-78 DAP	66.58a	41.42ab	12.81bc	-3.29c	7.04bc
			Portage 04		
0-26 DAP	1.57bc	1.43c	2.04a	1.89ab	1.22c
26-39 DAP	17.0a	14.62a	16.53a	14.34a	4.60b
39/-57 DAP	48.46a	50.25a	51.27a	52.06a	11.31b
57-76 DAP	45.44a	56.60a	56.06a	60.31a	3.28b

† Means within a row followed by a different letter are significantly different at $P = 0.1$

The large differences in DM accumulation between dry bean crops of different study sites are largely the result of variation in crop growth between the different dry bean cultivars (only Emerson 03 and Portage 04 grow the same market class of dry beans), as well as differences in environmental conditions. Bayuelo-Jimenez et al. (2002b) demonstrated significant variation in salinity tolerance and DM accumulation within numerous accessions of both wild and cultivated *P. vulgaris* during early vegetative growth. The implications of this are such that direct comparisons between the same treatments of different sites are not practically possible (a statement also true based on significant differences in salinity treatments themselves between sites, see Table 4.3). However, it is apparent that salinity treatment had a significant affect on DM accumulation and CGR. As the growing season progressed, non-salt stressed plants accumulated DM to a higher degree, and were more productive in using existing plant material to further accumulate DM, as reflected by greater increases in CGR.

4.4.3.3 Grain Yield, Seed Size, and Protein Content

Three main components of dry bean grain production were analysed in this study: yield (Table 4.6), seed size (Table 4.7), and seed protein content (Table 4.8). Grain yield data analysis for the 2003 growing season resulted in three to four different significance groupings (i.e., a, b, c, and d), depending on the site. In all three cases, these groupings closely followed the salinity treatments in that yield decreases followed increasing salinity. In other words, there was a significant inverse relationship between crop yield and salinity treatment. The highest yield was observed at the Portage 03 site (2647 kg ha^{-1}, S1), followed by Winkler 03 (2007 kg ha^{-1}, S2), and Emerson 03 (1707 kg ha^{-1}, S1).

According to data provided by the Manitoba Crop Insurance Corporation (2003) for the 2003 growing season: average black bean (cv. AC Hardblack) yields for the Portage la Prairie area were 2212 kg ha^{-1}, average pink bean (cv. ROG312) yields for the Winkler area were 2158 kg ha^{-1}, and average pinto bean (cv. Maverick) yields for the Emerson area were 2141 kg ha^{-1}. Based on this data, it would appear that as a whole field, Portage 03 yield performance was near average for the area, Winkler 03 slightly below average, and Emerson 03 below average. Besides long periods of standing water at the Emerson 03 site that would have contributed to reduced crop yield, there were also large populations of kochia (*Kochia scoparia* L.) distributed throughout the field that were not effectively controlled with either tillage operations or herbicide applications.

Table 4.6. Dry bean grain yield for all site-years

Study site	Treatment				
	S1	S2	S3	S4	S5
	kg ha^{-1}				
Portage 03	2647.2a†	2283.2ab	1966.9b	1553.2c	465.1d
SE	174.1	142.2	174.1	174.1	174.1
Winkler 03	1728.2a	2007.3a	1288.6b	1338.2b	404.7c
SE	117.5	117.5	143.9	117.5	117.5
Emerson 03	1707.6a	1513.9a	600.4b	198.5c	0.0c
SE	117.4	117.4	117.4	117.4	117.4
Portage 04	694.2c	797.8c	1037.7b	1262.5a	104.5d
SE	61.2	61.2	61.2	61.2	61.2

† Means within a row followed by a different letter are significantly different at $P = 0.1$

Grain yield data analysis for the Portage 04 site resulted in four different significance groupings (i.e., a, b, c, and d), however the relationship was opposite that of the 2003 growing season with yield increasing as salinity increased. The exception to this pattern was the S5 treatment which resulted in the lowest yield at 105 kg ha^{-1}. The

highest yielding treatment was S4 (1263 kg ha^{-1}), followed by S3 (1038 kg ha^{-1}), S2 (798 kg ha^{-1}), and S1 (694 kg ha^{-1}). This direct relationship between these four salinity treatments and crop yield is perplexing given their non-significantly different DM accumulations at 76 DAP (Figure 4.9). There was an unseasonal hard frost that occured in southern Manitoba on August 20, 2004 (71 DAP) that significantly damaged the Portage 04 bean crop, and perhaps unevenly. According to data provided by the Manitoba Crop Insurance Corporation (Doug Wilcox, personal communication, 2005) for the 2004 growing season, average pinto bean yields for the Portage la Prairie area were 474.1 kg ha^{-1}, in comparison to 2003 in which they were 1948 kg ha^{-1} (Manitoba Crop Insurance Corporation, 2003). A possible reason behind the uneven impact of the frost damage could be attributed to the dry bean crops of different salinity treatments being at different stages of crop development at the time of the frost. In 2003, it was observed that higher levels of salinity caused crops to mature more quickly than lower salinity treatments. The implications of this for the Portage 04 site are that, for example, S1 and S2 treatments may have still been in the late stages of flowering and/or pod filling, in which case they would be very susceptible to frost damage, whereas S3 and S4 treatments may have been much closer to physiological maturity and thus less impacted by frost damage. Another plausible explanation is that the declining elevation from the S5 to S1 treatments (Figures 3.3 and 3.11) may have caused the more shallowly located S1 and S2 treatments to have experienced lower temperatures (i.e., more severe frost) than S3 and S4 treatments.

There is little information in the scientific literature in regards to the effects of salinity or even drought stress on harvested seed size of dry bean crops. In this study, the

highest yielding treatments (Table 4.6) were accompanied with seeds of larger size (Table 4.7), such that there was an inverse relationship between increasing salinity treatment and seed size. With the exception of the Portage 04 site, increased seed size accompanied increased yield. For the Portage 04 site, the highest yielding treatments (S4 and S3) also had the highest seed sizes, 248 and 232 g 1000 seeds^{-1}, respectively. Wagenet et al. (1983) observed that with a salinity (EC_e) increase from 0 to 8 dS m^{-1}, the number of pods and seeds per dry bean plant decreased by approximately 70 and 92%, respectively. Even though the number of seeds per pod, and the number of pods per plant were not evaluated in this study, it would appear that at least some of the yield loss of dry beans associated with increasing salinity treatment is a result of decreasing seed size.

Table 4.7. Dry bean seed size for all site-years

	Treatment				
Study site	S1	S2	S3	S4	S5
	g 1000 seeds^{-1}				
Portage 03	154.3a† (100)††	144.3b (94)	138.5b (90)	138.4b (90)	120.3c (78)
SE	3.7	3.0	3.0	3.0	3.7
Winkler 03	267.0a (97)	274.6a (100)	260.3a (95)	223.7b (81)	194.0c (71)
SE	6.7	6.7	8.2	6.7	6.7
Emerson 03	317.8a (100)	296.5a (93)	252.2b (79)	221.8b (70)	-
SE	15.1	15.1	15.1	18.5	-
Portage 04	172.5d (69)	199.4c (80)	232.4b (94)	248.3a (100)	206.0c (83)
SE	3.0	3.0	3.0	3.0	5.2

† Means within a row followed by a different letter are significantly different at $P = 0.1$
†† Values in brackets are percent seed size, and was calculated as the mean seed size for a given treatment relative to the maximum mean seed size under all salinity treatments for a given site

Crude protein content of dry bean seeds was not discernibly affected by salinity treatment, even though there were significant differences between treatments (Table 4.8). The smaller seed size (black bean) Portage 03 crop had protein content values ranging

from 26.3% (S3) to 31.4% (S5), whereas the larger seed size (pink and pinto bean) Winkler 03, Emerson 03, and Portage 04 dry bean crops ranged from 20.3 to 25.9%. There is little data in the literature relating seed protein content of dry beans to increasing levels of salinity, however it has been shown that salinity reduces protein synthesis in salt-stressed bean plants (Frota and Tucker, 1978) as well as shoot nitrogen (i.e. crude protein) content (Cordovilla et al., 1995). Dry bean seed protein content is a complex function (particularly if measured on a proportional basis) of numerous factors including cultivar, agronomic and environmental growing conditions, and even location within the plant, and not necessarily one factor having more effect than the others (Adsule and Kadam, 1989).

Table 4.8. Dry bean seed protein content for all site-years

	Treatment				
Study site	S1	S2	S3	S4	S5
	%				
Portage 03	27.5bc†	28.8b	26.3c	27.7bc	31.4a
SE	0.8	0.6	0.6	0.6	0.8
Winkler 03	24.9	24.0	24.7	24.2	24.9
SE	0.34	0.34	0.41	0.34	0.34
Emerson 03	25.9a	25.6ab	24.3c	24.5bc	-
SE	0.36	0.36	0.36	0.45	-
Portage 04	24.4a	23.2b	20.7cd	20.3d	21.4c
SE	0.4	0.4	0.4	0.4	0.4

† Means within a row followed by a different letter are significantly different at $P = 0.1$

4.4.4 Crop Water

4.4.4.1 Depth of Soil Water Extraction

Soil volumetric water content results for the Portage 03, Winkler 03, Emerson 03, and Portage 04 study sites can be found in Figures 4.10, 4.11, 4.12, and 4.13, respectively.

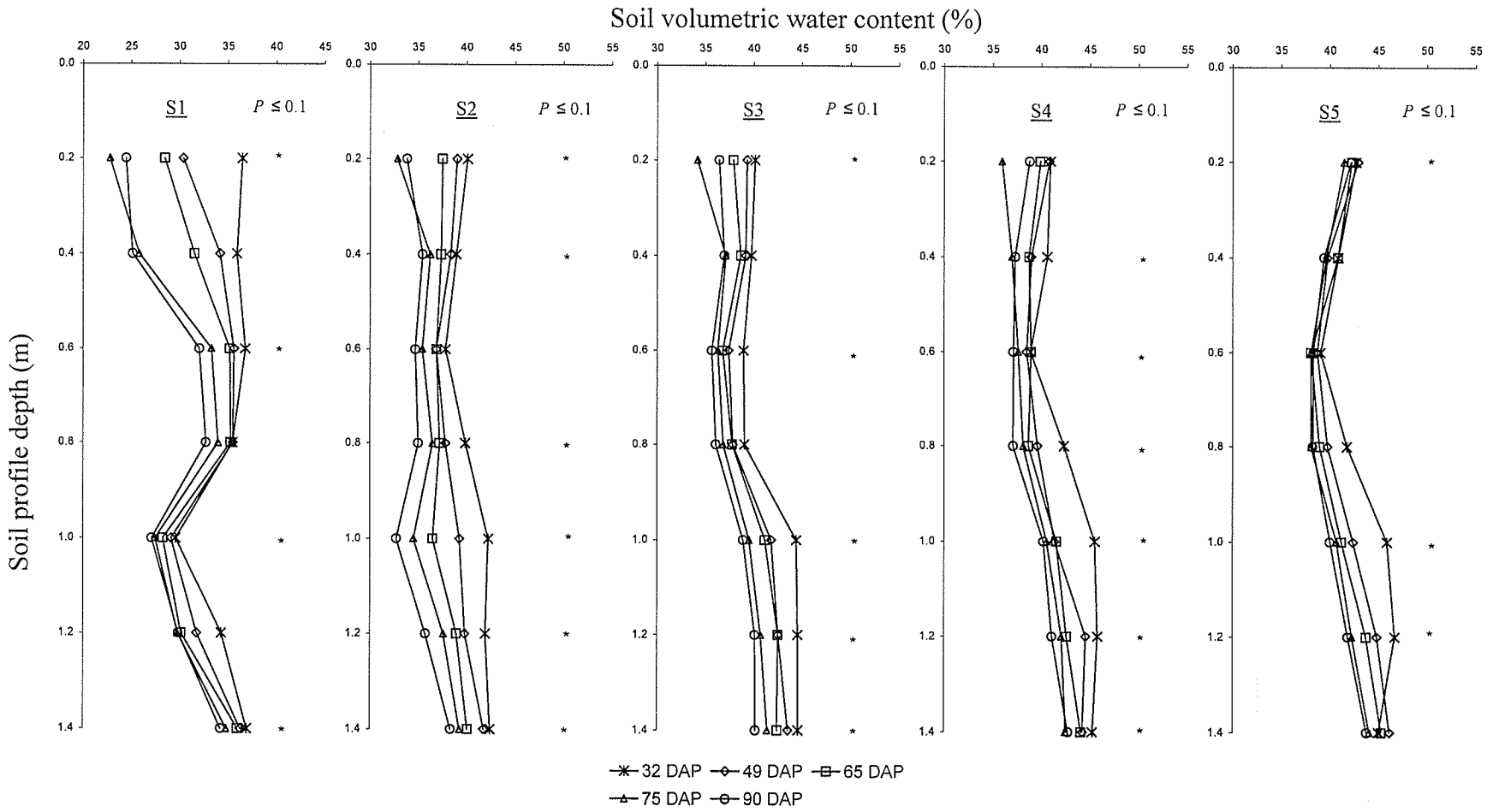

Figure 4.10. Soil profile volumetric water content (%) of S1, S2, S3, S4, and S5 salinity treatments of the Portage 03 study site, measured 32, 49, 65, 75, and 90 days after planting (DAP). Treatments followed by (*) at a given depth had significant differences ($P \leq 0.1$) for soil moisture depletion between planting and at least one subsequent measurement.

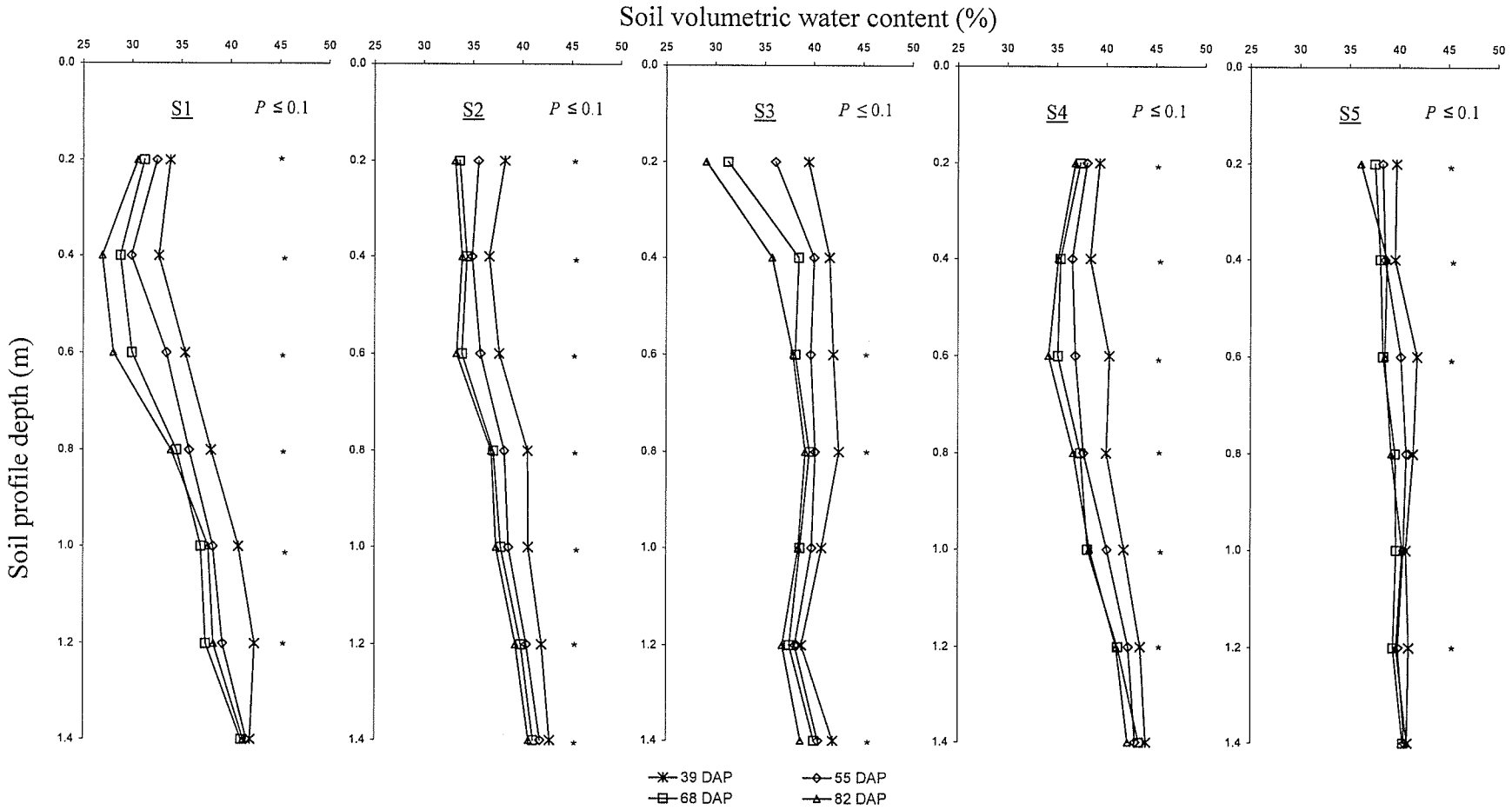

Figure 4.11. Soil profile volumetric water content (%) of S1, S2, S3, S4, and S5 salinity treatments of the Winkler 03 study site, measured 39, 55, 68, and 82 days after planting (DAP). Treatments followed by (*) at a given depth had significant differences ($P \leq 0.1$) for soil moisture depletion between planting and at least one subsequent measurement.

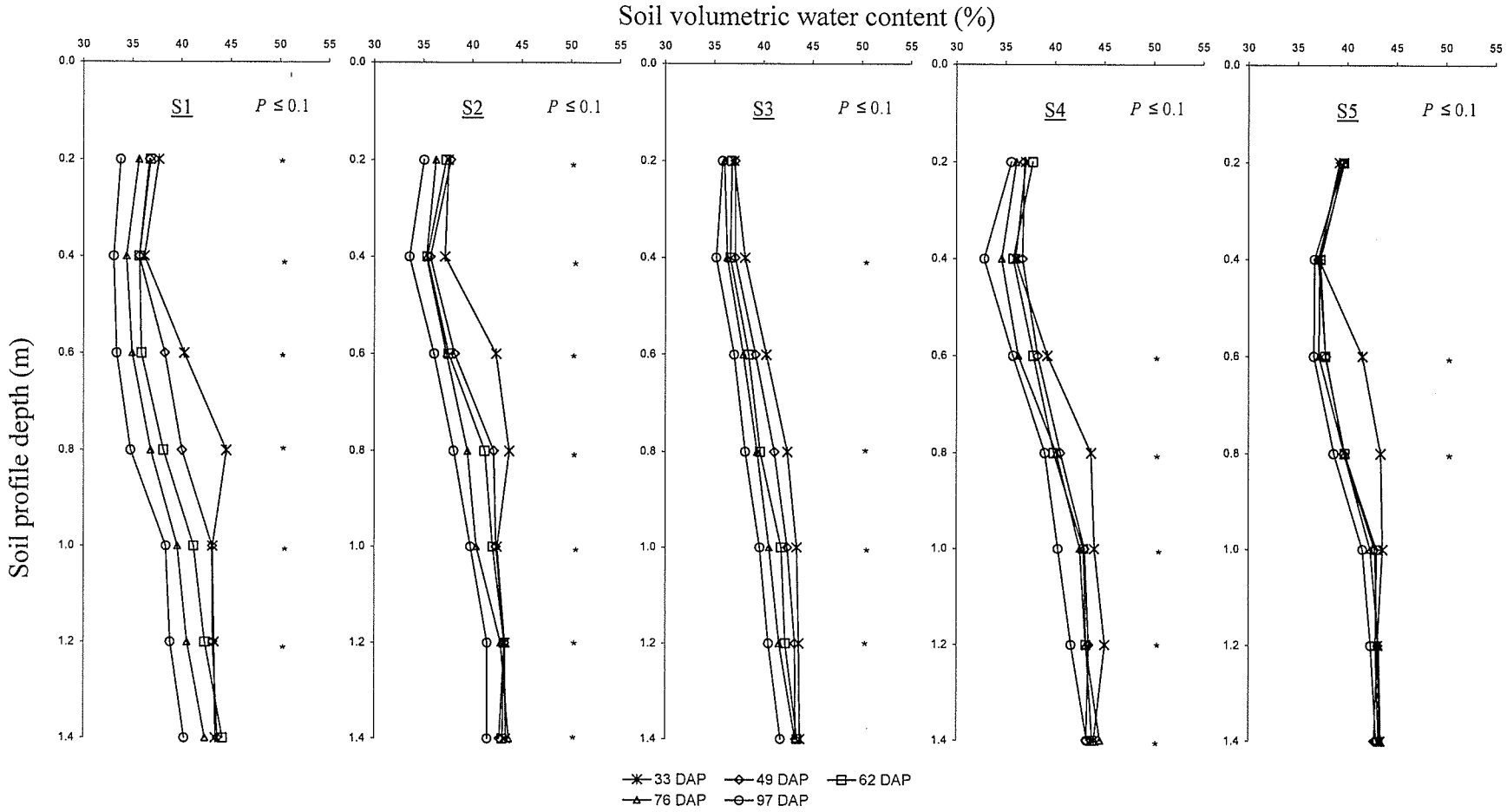

Figure 4.12. Soil profile volumetric water content (%) of S1, S2, S3, S4, and S5 salinity treatments of the Emerson 03 study site, measured 33, 49, 62, 76, and 97 days after planting (DAP). Treatments followed by (*) at a given depth had significant differences ($P \leq 0.1$) for soil moisture depletion between planting and at least one subsequent measurement.

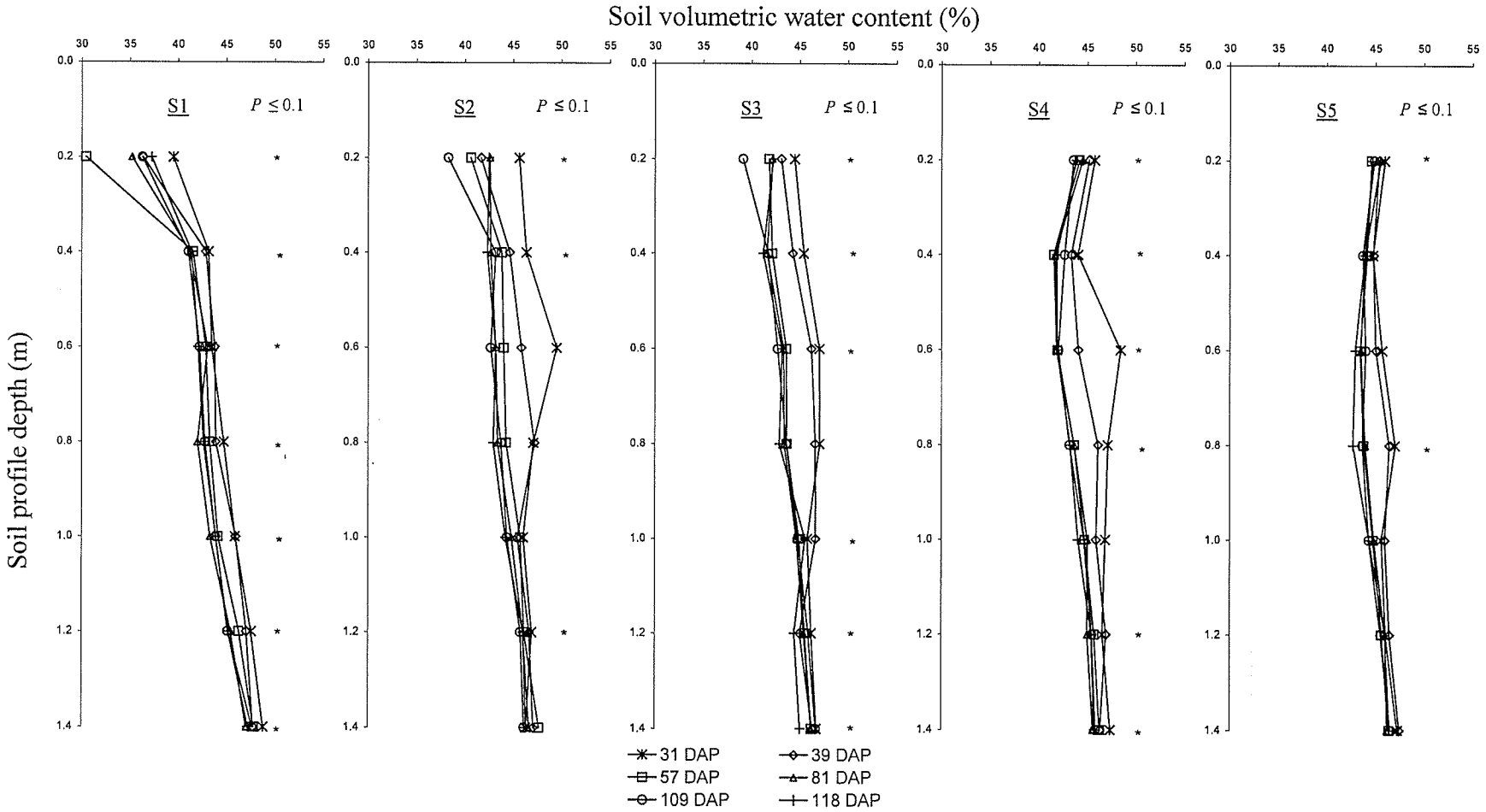

Figure 4.13. Soil profile volumetric water content (%) of S1, S2, S3, S4, and S5 salinity treatments of the Portage 04 study site, measured 31, 39, 57, 81, 109, and 118 days after planting (DAP). Treatments followed by (*) at a given depth had significant differences ($P \leq 0.1$) for soil moisture depletion between planting and at least one subsequent measurement.

Entz et al. (1992) and Angadi and Entz (2002) have previously demonstrated for wheat (*Triticum aestivum* L.) and sunflowers (*Helianthus annuus* L.), respectively, that depth of soil water extraction and rooting depth can be estimated as the deepest soil profile depth where at least one measurement of soil water content during the growing season is significantly different from the initial measurement. In this study, this method proved to be ineffective.

The maximum depth of statistically significant difference in soil water content between sampling dates was either 1.2 or 1.4 m in all cases, except for the S5 treatment of both the Emerson 03 and Portage 04 sites. Stegman and Olson (1976) and Merrill et al. (2002) observed the mean maximum rooting depth of dry beans to be approximately 1.0 m. Halterlein (1982, citing Halterlein, Teare, and Clayberg, unpublished data) also observed the maximum rooting depth of dry beans to approach 1.0 m, however less than 10% of roots ever extended beyond a depth of 0.5 m.

In this study, analysis of net change of soil water content between initial and harvest soil moisture samplings (Figure 4.14) reveal a number of observations that may be more useful in estimating depth of water extraction of dry bean crops under salinity stress. The S1 treatment of the Portage 04 site extracted significantly more water from the soil profile than all other treatments up to a depth of 0.4 m. For this site, the order of net soil water extraction mimics that of yield decrease in response to increasing salinity treatment at the 0.2 m depth. There were less discernable differences at the other three sites, although, in general, the more productive treatments used more water.

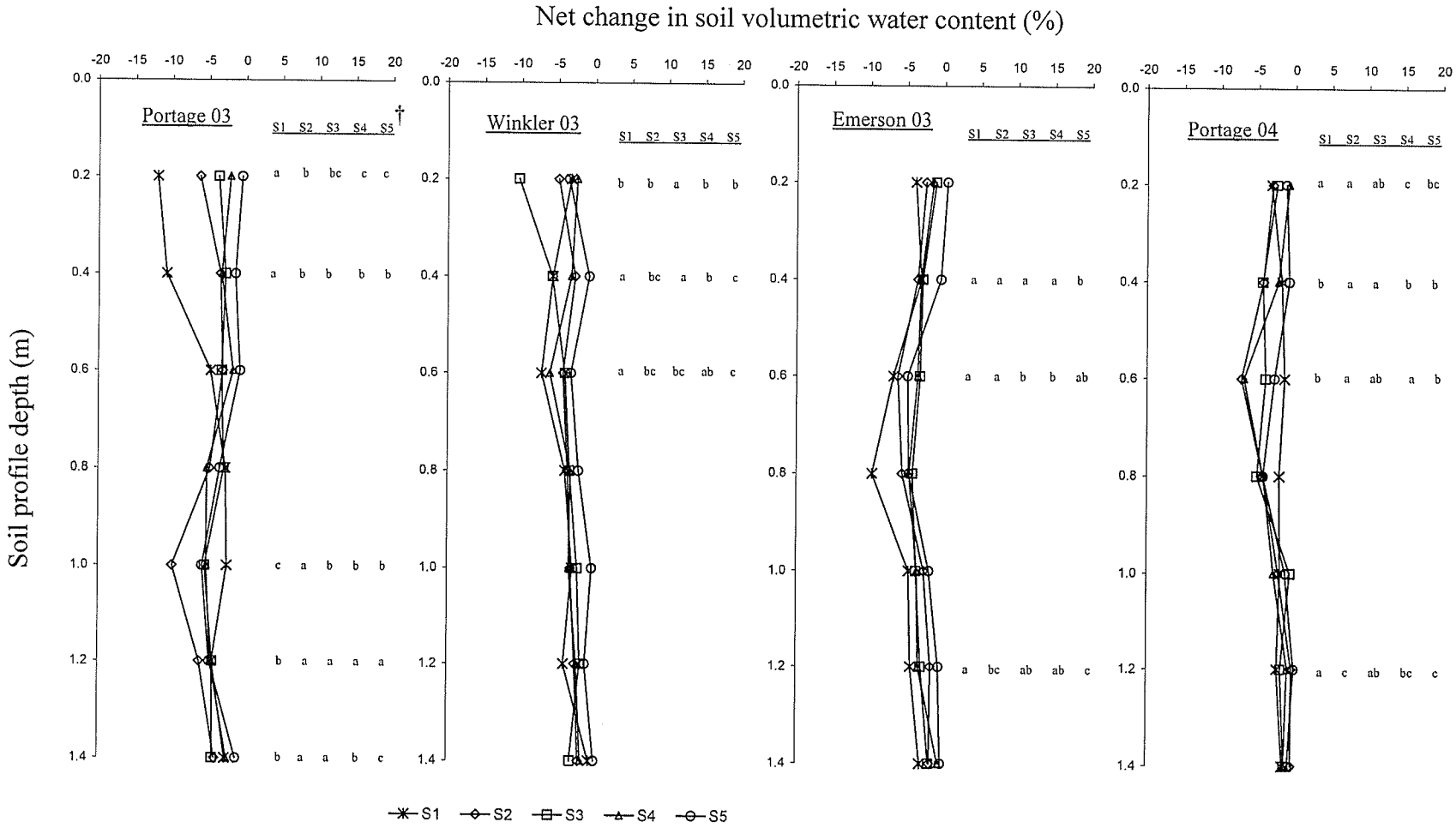

Figure 4.14. Net change in soil profile volumetric water content (%) between initial and harvest soil moisture samplings for S1, S2, S3, S4, and S5 salinity treatments of the Portage 03, Winkler 03, Emerson 03, and Portage 04 study sites.
† Treatments (in columns under associated treatment, S1, S2, S3, S4, or S5) followed by different letters at a given depth and site had significant differences ($P \leq 0.1$) for net changes in soil moisture between initial and harvest moisture samplings.

The results in Figure 4.13 suggest that, for all practical purposes, the maximum depth of soil water extraction would be between 0.6 and 0.8 m, even though there are significant differences beyond this depth. In this particular study, it would appear that our assumptions of negligible loss of soil water below the rooting zone are incorrect, indicating that deep percolation of soil water below the rooting is significant, and perhaps more so in lower than higher salinity treatments. Little if any deep percolation of soil water observed in high salinity treatments could be attributed to the presence of a high water table associated with the development of these saline soils, preventing soil water from draining through the profile, even though there was little crop water use (i.e., interception of percolating water) as there was little crop production in these treatments.

4.4.4.2 Evapotranspiration and Water Use Efficiency

Precipitation between initial and harvest soil moisture samplings were 76.0, 65.4, 103.0, and 107.8 mm, for Portage 03, Winkler 03, Emerson 03, and Portage 04 (Figure 4.1), respectively. ET was calculated between soil depths of 0.1 and 0.9 m (one measurement depth below estimation of maximum depth of soil water extraction). Salinity treatment was found to have a significant effect on ET at all sites (Table 4.9). Mean maximum ET for Portage 03, Emerson 03, Winkler 03, and Portage 04 sites was 136.6 (S1), 112.9 (S3), 150.3 (S1), and 145.6 mm (S2), respectively. Similarly, mean maximum soil water depletion for Portage 03, Emerson 03, Winkler 03, and Portage 04 sites was 60.6 (S1), 47.5 (S3), 47.3 (S1), and 37.8 mm (S2), respectively. Chescu (2002) observed approximately 32 mm of soil water depletion between soil depths of 0 – 0.9 m for an unstressed dry bean crop at Carman, MB, although ET was estimated to be

approximately 335 mm (i.e., ~ 303 mm of precipitation). Stegman and Olson (1976), in North Dakota, estimated ET for dry beans as approximately 232 mm. Calvache et al. (1997) observed similar ET results in Ecuador, at 172 mm. Merril et al. (2004) measured soil water depletion to a depth 1.8 m for dry beans and observed it to be between 39 mm (wet year, ~ 450 mm of precipitation between planting and harvest) and 110 mm (normal year, ~ 260 mm of precipitation between planting and harvest). The values of ET and WUE for the higher salinity treatments are likely more a function of run-off than crop water use (transpiration), again discounting our assumptions of negligible loss of soil water.

The large range in ET observed in the previous studies and other literature sources, is similarly accompanied by wide ranges in estimates of WUE, even though grain yield is quite similar. For example, WUE of dry beans has been observed by Hattendorf et al. (1988), Miller et al. (2002), and Chescu (2002) at 4.9, 2.9, and 8.4 kg ha^{-1} mm^{-1}, respectively. In this study, mean maximum WUE for Portage 03, Emerson 03, Winkler 03, and Portage 04 sites was 20.5 (S2), 20.9 (S2), 11.4 (S1), and 9.3 kg ha^{-1} mm^{-1} (S4), respectively. Trends in WUE and the effect of soil salinity on this growth parameter were difficult to evaluate in this study. ET was not reliably estimated, as loss of water due to run-off and/or deep percolation were likely in this study, contributing to much higher estimates of WUE for dry beans than previous studies have observed.

Table 4.9. Growing season soil water depletion ($W_i - W_h$), evapotranspiration (ET), and water use efficiency (WUE)

Treatment		W_i-W_j (mm)	ET (mm)	WUE (kg ha^{-1} mm^{-1})
		Portage 03		
S1		60.6a†	136.6a	19.5a
	SE	8.4	8.4	1.6
S2		35.5b	111.5b	20.5a
	SE	6.9	6.9	1.3
S3		25.4bc	101.4bc	19.5a
	SE	6.9	6.9	1.3
S4		24.8bc	100.8bc	15.5b
	SE	6.9	6.9	1.3
S5		12.5c	88.5c	7.8c
	SE	6.9	6.9	1.6
		Winkler 03		
S1		40.7ab	106.1ab	16.4b
	SE	5.7	5.7	1.6
S2		31.6abc	97.0abc	20.9a
	SE	5.7	5.7	1.6
S3		47.5a	112.9a	11.6c
	SE	7.0	7.0	2.0
S4		30.4bc	95.8bc	14.0bc
	SE	5.7	5.7	1.6
S5		19.8c	85.2c	4.9d
	SE	5.7	5.7	1.6
		Emerson 03		
S1		47.3a	150.3a	11.4a
	SE	3.8	3.8	0.9
S2		36.1b	139.1b	10.9a
	SE	3.8	3.8	0.9
S3		23.4c	126.4c	4.7b
	SE	3.8	3.8	0.9
S4		25.9c	128.9c	2.2b
	SE	3.8	3.8	1.1
S5		19.6c	122.6c	-
	SE	3.8	3.8	-

† Means within a column followed by a different letter are significantly different at $P = 0.1$

Table 4.9. Cont'd

Treatment		W_i-W_j (mm)	ET (mm)	WUE (kg ha^{-1} mm^{-1})
		Portage 04		
S1		15.1b†	122.9b	5.7b
	SE	4.5	4.5	0.6
S2		37.8a	145.6a	5.8b
	SE	5.5	5.5	0.7
S3		32.1a	139.9a	6.9b
	SE	5.5	5.5	0.7
S4		28.6ab	136.4ab	9.3a
	SE	5.5	5.5	0.7
S5		18.3b	126.1b	0.8c
	SE	4.5	4.5	0.6

† Means within a column followed by a different letter are significantly different at P = 0.1

4.4.5 Salinity Tolerance

Frost damage to the Portage 04 bean crop and resulting increase in crop yield in response to increasing salinity, resulted in the exclusion of this site from salinity tolerance analysis. The decline in crop yield for dry beans in response to increasing root-zone salinity was modelled strongly by the modified discount function for all sites analysed (Table 4.10). Coefficient of determination (r^2) values were: 0.925, 0.808, 0.922, and 0.704 for Portage 03, Winkler 03, Emerson 03, and for all sites combined, respectively. Portage 03 and Winkler 03 bean crops were very similar in terms of salt tolerance results, with C_{50} values of 8.35 and 8.27 dS m^{-1}, respectively. These two sites displayed higher levels of salt tolerance than the Emerson 03 bean crop (C_{50} of 4.88 dS m^{-1}). When modelled graphically (Figure 4.15), the differences in salt tolerance between sites is more evident. Results of this study would seem to indicate that the value of C_{50} for bean crops in southern Manitoba lies between 4.88 and 8.35 dS m^{-1}. However, the relatively poor performance of the Emerson 03 bean crop and relatively average

performance of the Portage 03 and Winkler 03 bean crops would suggest that the results of these two sites merits more weight in terms of reliability and reproducibility (That is, root-zone salinity was a greater factor of production in comparison to other factors for the Portage 03 and Winkler 03 sites than Emerson 03), at least under the growing conditions experienced in 2003.

Table 4.10. Parameters and statistical results of non-linear regression analysis using the modified discount function relating bean relative yield to root-zone salinity

Location	Y_m (kg ha^{-1})	C_{50} (dS m^{-1})	s	r^2	RMSE	STI
Portage 03	2415.1	8.35	0.245	0.925	0.093	10.4
Winkler 03	1721.9	8.27	0.283	0.808	0.161	10.6
Emerson 03	1627.3	4.88	0.285	0.922	0.131	6.3
All sites	-	7.21	0.189	0.704	0.218	8.6

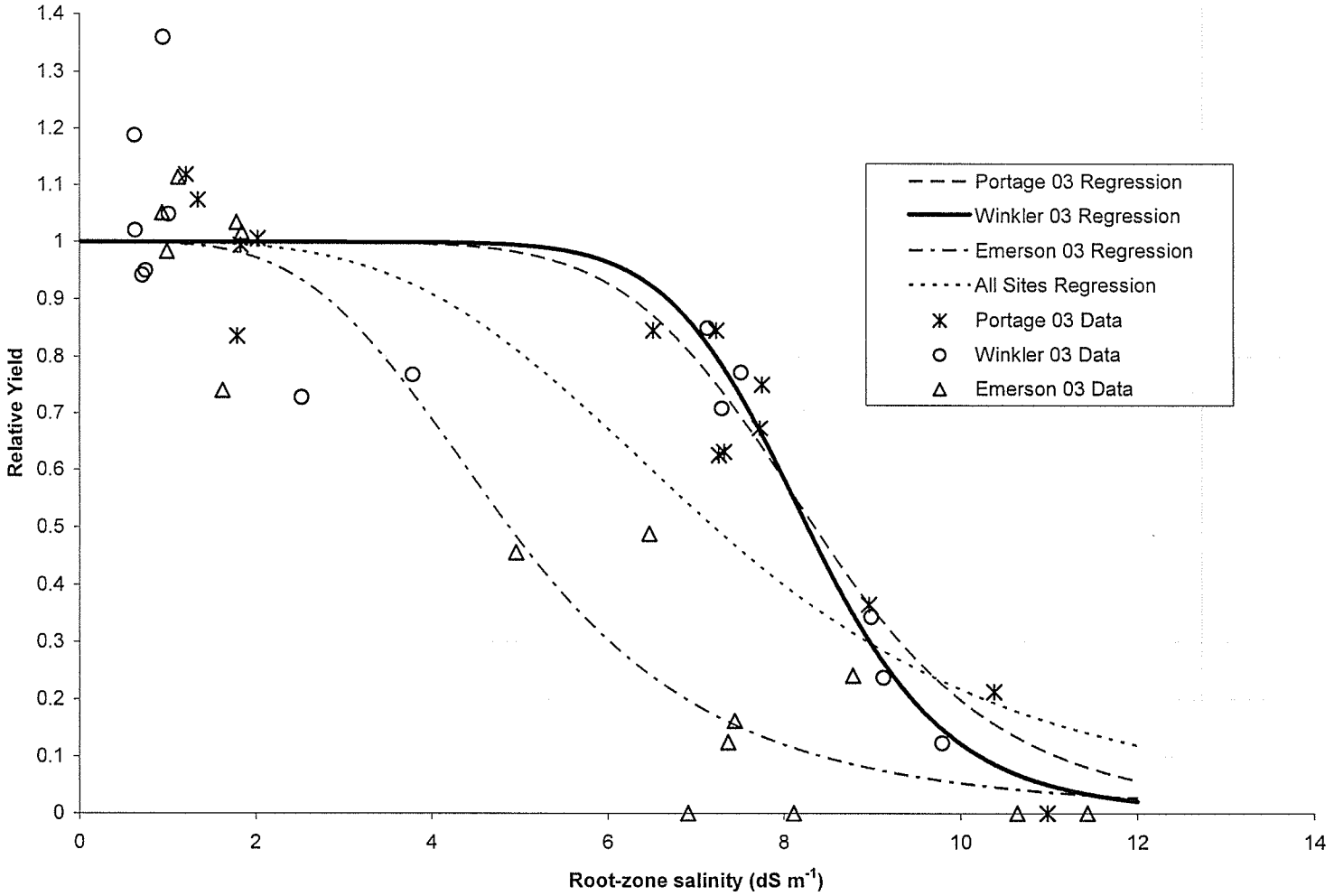

Figure 4.15. Dry bean relative yield response to increasing levels of root-zone salinity, described by the modified discount function

Steppuhn et al. (2005b) developed methods to convert salinity tolerance parameters for numerous agricultural crops estimated by Maas and Hoffman (1977), who used the two-piece linear function to model crop salt tolerance (see Section 2.2.3.2.1). For beans, the original sources of data used by Maas and Hoffman (1977) were: Magistad et al. (1943), Bernstein and Ayers (1951), Nieman and Bernstein (1953), Osawa (1965), and Hoffman and Rawlins (1970). Salt tolerance results of this study differ from results reported by Steppuhn et al. (2005b) for beans. They reported values of 3.34 dS m^{-1}, 0.289, and 4.30 for C_{50}, s, and STI, respectively. Results of this study likely differ from those reported by Steppuhn et al. (2005b) for a number of reasons:

1. The studies included in the salinity tolerance results reported by Steppuhn et al. (2005b) for beans were conducted in greenhouse or controlled environment studies and employed varieties of beans different than those employed in this study, where products were either dry beans or green beans (intra-specific variation in salt tolerance of beans has been well demonstrated by Bayuelo-Jimenez et al. (2002b)).
2. The distribution of salt within the soil rooting-zone was likely uneven in this experiment in terms of depth (see Ch. 3) and time, as opposed to previous studies where it would have been more even.
3. Growing conditions in the 2003 crop year were ideal for dry bean production: excellent soil moisture conditions and well timed precipitation events. These conditions would have decreased the impact of soil salinity on dry bean crop growth in this growing season.

4.5 Conclusions

The results of this study indicate that salinity has a significantly adverse impact on the production of dry bean crops in the province of Manitoba. However, it was shown that this relationship is perhaps less severe than the published literature would suggest, as in this study the value of C_{50} was estimated to lie between 4.88 and 8.35 dS m^{-1}, in comparison to a value of 3.34 dS m^{-1} observed by Steppuhn et al. (2005b). That is, producers may be able to grow acceptable dry bean crops under conditions of higher salinity than previously thought possible. However, the rapidly changing and highly variable soil salinity conditions observed in study fields indicate that a single composite soil sample from a given field would likely incorrectly estimate the true soil salinity conditions.

Analysis of dry bean water use revealed an important observation in terms of the effect growing dry beans in short rotations might have on the soil salinity status of a given field. For example, results in this study suggest that deep percolation of water through the soil rooting zone of the non-salt stressed crop plants did occur, and that even the high yielding dry bean crops utilized relatively small amounts of spring soil moisture reserves. Given these conditions of inefficient soil water use, it is possible that the level of ground water tables could be closer to the surface for longer periods of time as compared to other more water efficient crop rotations, perhaps aiding in the development of soil salinization in these fields.

This study is the first of its kind to measure the effect of increasing salinity on crop growth in producers' fields. The biggest drawback from the methods employed in this study was perhaps the inability to impose salinity treatments directly and evenly. At

the same time, the methods used to establish salinity treatments were highly innovative and reasonable simple, whilst still effective. It would appear that crop salt tolerance testing is possible in a field environment. With a number of replications over time, under varying growing conditions, it may be possible to model factors of salinity and growing conditions and measure their impact on dry beans, as well as other crops of interest.

5 GENERAL DISCUSSION AND CONCLUSIONS

In this thesis, two main experiments were described. The goal of the first study was to develop methods of mapping soil salinity employing the Veris 3100, and use this information to assess the extent and severity of selected dry bean fields of southern Manitoba (Ch. 3). The second study evaluated the impact of increasing levels of root-zone salinity on dry bean crop production, with salinity treatments established utilizing apparent electrical conductivity (EC_a) surveys employing the Veris 3100 (a direct contact method of measuring soil EC_a, Ch. 4).

In the past, soil salinity has been assessed through electromagnetic induction measurements of EC_a. This study is the first to utilize the Veris 3100 to spatially evaluate soil salinity in agricultural fields (Ch. 3). Simple multivariate regression techniques and innovative methods of directed soil sampling were found to be effective means of modelling the relationship between EC_a and EC_e (electrical conductivity of the saturated-soil-paste extract). The EC_a to EC_e calibration models developed in this study may be applied to fields similar to the ones employed in this study (i.e., comparable soil characteristics and topography) and surveyed with the Veris 3100. The calibration model selected for a particular field should be the model used for the field in this study (Portage, Winkler, or Emerson) which most closely matches the field in question (i.e., regionally closest in proximity, similar soil types and crop production practices). The further removed a field of interest is from a study field, the less reliable the results. In any case, a limited number of soil samples should be collected to confirm calibration of EC_a to EC_e results.

There have been numerous studies evaluating soil salinity in the field, as well as crop salt tolerance under controlled environmental conditions. However, until this project, there had not been a study that attempted to evaluate crop salt tolerance in the field using spatial field evaluations of soil salinity. Since the relationship between EC_a (collected with the Veris 3100) and EC_e was estimated at the time the treatment groups were located within study fields (i.e., before soil sample analysis could confirm the salinity status of the established plots) direct comparisons between study sites in terms of the effect of soil salinity on dry matter accumulation, crop growth rate, and yield were not possible. However, conversion of absolute crop yield data to a relative field basis and the development of dry bean salt tolerance models allowed for direct comparisons between sites in these two regards.

The results of this study indicate that the salt tolerance of dry bean crops observed in southern Manitoba fields is greater than the published literature would suggest (studies conducted in controlled environment conditions), with values of C_{50} (salinity concentration at which there is a 50% decrease in relative yield) observed in this study ranged between 4.9 and 8.4 dS m^{-1}, as compared to 3.3 dS m^{-1} (Steppuhn et al., 2005b). This suggests that producers may be able to grow acceptable dry bean crops under conditions of higher salinity than previously thought possible. However, the reliability of a salt tolerance model established from the data of one growing season must be regarded with some reservation. Harold Steppuhn (personal communication) makes the following point in referring to field crop salt tolerance trials:

> "With care, one can assess relatively fairly the responses to salinity for crops grown side-by-side under the conditions imposed by that season for that season, but that

these relative responses cannot be validly extrapolated to all seasons or all conditions. The degree that the inherent salinity tolerance of a crop is manifested in each field trial varies with the growing condition. Typically, the effects of severe salinity result in very measurable crop responses. That is, the salinity effects dominate. But, as the root-zone salinity decreases, the crop responses from such environments diminish and become more and more variable until at low levels of soil salinity the effects cannot be detected amongst the many other factors affecting crop production. This is when response data tend to show a horizontal response segment which gave rise to the incorrect threshold concept. Field trials typically project these types of results."

This author thoroughly agrees with Dr. Steppuhn's statement, however that is not to say that field salt tolerance trials such as this one are not just as valid and important and those conducted in controlled environment situations, a point alluded to in the previous statement. The difference depends on a given researcher's goal: Is one interested in comparing the effects of salt treatment on crop growth in comparison to other crops (or other cultivars of the same species) with everything else being equal, or is one interested in predicting or modeling the crop yield of a given crop grown under normal growing conditions for a given area in response to soil salinity? It is common knowledge that beans are among the most salt sensitive agricultural crops grown worldwide, with dry bean salinity yield response models evaluated by Maas and Hoffman (1977) and Steppuhn et al. (2005b). However, does that knowledge (i.e., yield salinity response models developed from controlled environment studies) allow prediction of crop yield response to soil salinity in the field (as agronomists and producers commonly do with the

effect of soil fertility on, for example, crop yield)? Is that relationship feasible to evaluate without field experiments? Perhaps it is not feasible.

Results of this thesis demonstrate that soil salinity can be successfully assessed using measurements of EC_a collected with the Veris 3100, and that this soil salinity assessment can be used to establish soil salinity treatments in field crop salt tolerance evaluation studies. The applications of this thesis are numerous. If one were interested in the effect of salinity on crop yield, one could use grain yield monitors installed in commercial harvesting equipment (currently a common situation among western Canadian producers) coupled with GPS (global positioning system) equipment to collect very large datasets which could be related to the similarly sized datasets of soil salinity assessment, developed from EC_a surveys. Given this information, it would be possible to collect immense amounts of field crop salt tolerance data over time, with hundreds of possible collaborating researchers, including field agronomists and producers, with the aim of predicting crop yield in the field, given the mapped soil salinity for the same field. Another application, using the methods employed in this study over a longer period of time, is the evaluation of different soil salinity management strategies (for example, including deep rooted perennial crops in rotation, such as alfalfa (*Medicago sativa* L.) or tile drainage, to lower the ground water table in saline areas) and how well they may mitigate the impact of soil salinity and risk of increasing soil salinity.

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