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CSBE | SCGAB

Paper No. CSBE13-19

SUSTAINABLE PRODUCTION OF CROPS GROWN IN SALINE ROOT ZONES

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Written for presentation at the
CSBE/SCGAB 2013 Annual Meeting
Saskatoon, Saskatchewan
7 – 10 July 2013

ABSTRACT Agricultural salinity stems from the concentration of salts dissolved in soil waters. It is caused by subsurface hydrologic processes and can seriously affect some 20 million hectares across the Canadian Prairies. Although root-zone salinity reduces crop yield, some crops tolerate saline rooting environments better than others. Growing crops with an inherent tolerance of root-zone salinity offers one method for maximizing plant growth and sustaining agricultural production. The ability of a crop to maintain substantial product yield while subject to root-zone salinity, ranging from negligible to severe, defines a crop's salinity tolerance. Yield response data derived from salinity tests rate crops according to the Salinity Tolerance Index: ST-Index = $C_{50} + s\ C_{50}$. The salinity causing a 50% product loss (C_{50}) and the absolute value (s) of the unit decline in relative crop yield with a unit increase in salinity at or near C_{50} can be approximated by visual inspection or calculated from regression analyses of the response data using a discount function, $Y_r = 1 / [1+(C/C_{50})^{\exp(s\ C50)}]$, where relative crop yield (Y_r) equals the absolute yield scaled by the yield obtainable in the absence of salinity, and a measure of salinity (C) as related to Y_r. A current list of Canadian crops and their Salinity Tolerance Indices are included in this review and assists in selecting crops appropriate for soils of known salinity.

Key Words: salinity, sustainable crop yield, salinization

AGRICULTURAL SALINITY Salinity has plagued agriculture in arid and semiarid climates for thousands of years. Whenever surface waters or near-surface ground waters encounter drainage impediments in soils, subsoils, or near-surface geologic materials, possibilities exist for increases in salt concentrations within soil solutions, especially if the waters contain dissolved salts. In arid lands, salinization stems mostly from the distribution and collection of irrigated waters in amounts incompatible with the water-holding and drainage capacities of the soils. In semiarid regions, the salinity of soil solutions can increase from the accumulations and slow movements of subsurface

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waters originating from natural precipitation in association with saline deposits. The waters dissolve salts enriching subsurface solutions with calcium, magnesium, sodium, potassium, boron, carbonates, chlorides, sulphates, nitrates, and other chemical substances (Figure 1).

Figure 1. Root-zone salinization can be so severe that salts show as white crusts on field surfaces. Fields slight to moderate in salinity infrequently exhibit such white crusting.

PRAIRIE LANDS AND WATERS The subsurface foundations which underpin the Canadian Prairies consist of soil, subsoil, and geologic deposits of both loose and cemented particles. All such subsurface material possess a measure of porosity, open spaces between adjacent clay-, silt-, sand-, and gravel-size particles, through which air and water with its dissolved constituents (solutes) reside and move. The larger, the less cemented, the less torturous, and the more connected the pores, the less the medium resists the transmissions of the solutions.

Three forces act on the solutions at any point within a subsurface volume: (1) gravitational, causing hydraulic (hydrostatic) pressure; (2) adhesion to solid surfaces, causing the attraction of liquids to particle surfaces and pore walls (like paint to a barn wall); and (3) diffusion of solutes along concentration gradients, causing solutes to mix uniformly with the water. These transient forces act at the same time at all points within the volume, but generate responses observed at specific locations. Diffusion, for example, occurs throughout a hydraulically-connected soil solution, but operates to move solutes from high to low concentrations, albeit often rather slowly. Gravitational and adhesive forces act on both the solutes and the water of soil solutions, physically moving them over time or simply transmitting hydraulic pressure almost instantaneously. Particle-surface-energy moves solutions within particle surface films and adjacent pores, a process, which if it operates upward, has been termed “capillary rise.” Particle surface forces may exceed gravitational forces by 1000-fold and can operate in all directions: up, down, oblique, and horizontal. Gravitational forces acting on hydraulically-connected soil solutions generate hydrostatic pressure which can also move water and solutes in any direction. If the hydrostatic pressure operates upwardly, it gives rise to "artesian pressure."

Either gravitational or particle surface forces may dominate depending on the amount of water filling the pores. The effects of gravitational forces prevail when the pores are fully saturated, but diminish as the water in the pores empties; particle surface forces dominate as the medium dries. Aqueous solutions move from one point to another in the subsurface depending on the difference in the total forces acting on the water at the two hydraulically-connected points and the degree of resistance to flow encountered within the medium between the points. The resistance decreases with increasing pore saturation and increases with decreasing saturation until the solution becomes hydraulically-disconnected. This creates a feed-back process, whereby, as the medium dries, the resistance to water and solute flow increases at the same time as the strength of the particle surface forces also increase.

Approximately 100 million years ago and lasting for eons, oceans covered all of today's Prairies. These ancient seas left saline marine deposits which provide the salts causing today's root-zone salinity. A series of non-marine sedimentary deposits followed and, wherever not subsequently eroded, now cover the marine deposits. Within the last two million years, continental glaciers covered and scraped these landscapes incorporating and re-depositing ample quantities of the marine salts. The marine deposits consist primarily of clays, shales, and mudstones through which water passes very, very slowly. The subsequent non-marine deposits include coarser particles and generally transmit water and dissolved salts much more readily. The glacial deposits (mostly till) feature a mix of the marine and non-marine material representative of the deposits across which the glacial ice travelled. Consequently, water transmission rates through glacial till vary from place to place and from layer to layer.

ROOT-ZONE SALINIZATIION Depending on location, either the generally finer-textured marine or the coarser-textured non-marine sediments underlie the rather mixed glacial drift. The mixing and layering of water-transmitting and water-confining material in the bedrock and in the glacial deposits also exist in the soils developed from these strata and can disrupt the flow rates of the subsurface waters moving through these media in response to subsurface forces. These disruptions delay the movements of these waters and increase their subsurface residence times enhancing opportunities for them to solubilize available salts. If the delay is sufficiently long and widespread, water fills the pores of the glacial deposits beneath soil profiles, creating short-term, perched water-tables. At the same time, matrix salts are dissolved by the delayed water. In time, especially as seasonal precipitation decreases, the accumulated waters drain in response to gravitational and particle surface forces.

During spring on the Canadian Prairies (March-June), day length increases, temperature rises, snow melts and, on average, precipitation peaks. At this time, more water tends to enter the subsurface than drains from it, and internal water accumulations occur. A wet subsurface environment, frequently-recharged with rain or snowmelt, and occurring intermittently between dry periods during the spring encourages soil salinization. As the Prairies enter a new cropping season, atmospheric evaporative demand increases. That is, the increasing temperatures, day-lengths, dry winds, and snow-free fields combine to dry the soil by evaporation and transpiration. Drying the soil reduces the degree of water saturation in the pores near the surface, which generates upward energy (hydraulic) gradients driven by particle surface forces. This process can bring the accumulated waters and their dissolved salts from well below the root zone to near-surface evaporation fronts. Near the surface, the water evaporates or transpires through plants leaving the salts behind as solids or as solutes which increase the salt concentrations of the remaining waters. These processes result in soil salinization. With continual drying, the processes proceed until flow resistance in the upper soil layers becomes too restrictive to convey measurable quantities of subsurface solutions. Not until irrigation or precipitation hydraulically re-wets the upper soil can the salinization processes be revived. If the wetting is sufficient to at least partially fill the upper soil pores, evaporative demand will renew the upward movement of soil solutions and the salinization process re-establishes. If the wetting completely fills the pores, some water will move downwardly driven primarily by gravitational forces and carry dissolved salts with it. Obviously, spring rains, their timing, their frequency, their duration, and their magnitude, affect the salinization processes. Heavy rains will solubilize some upper-layer salts and move them back downward. Frequent, light rains, which keep the subsurface pores wet but below saturation, can maintain conditions just wet enough to keep salts moving upward.

SALINITY PROBLEMS Salinity is that property of water which indicates the total concentration of its dissolved constituents. All natural waters, including those occurring in the pores of soil and subsoil, contain soluble solids and gases, and therefore possess a degree of salinity. In fact, the growth of most plant crops depends on soil solutions containing dissolved nutrients. However, as salinity increases, it can generate problems as described by Ayers and Westcot (1985): "A salinity problem exists if the salts in a soil accumulate to concentrations that cause reductions in plant growth and crop yield for plants rooted in the soil." Thus, plants define soil salinity. Furthermore, the severity of the plant damage, or crop loss, defines the magnitude of the salinity problem. The degree to which soil salinity affects crop yield defines the salinity tolerance of the crop plants.

MEASURING SALINITY If a soil consists of 55% solid matrix and 45% pores by volume and is completely filled with water (little or no air), the soil is said to be “saturated.” If the saturated soil water is allowed to drain under subsurface forces, say over 24 hours, the soil reaches a point referred to as being at “field capacity” wherein the volume of the soil solution has reduced to, say 30%, and the air volume increased to 15%. If the drained water were collected and measured for electrical conductivity (designated $EC_{extract}$ or EC_e), the strength of the electrical current passed through the collected extract reflects the concentration of its dissolved salts. This is the measure of salinity received from analytical laboratories which analyze soil samples from farmer’s and rancher’s fields. However, crops tend to use less of this gravitational water and more of the remaining pore water until plants can no longer extract soil solutions. On average, these remaining pore solutions, when measured for electrical conductivity ($EC_{solution}$), convey approximately twice the electrical current and contain about twice the dissolved solutes as indicated by the EC_e-measurements (Ayers and Westcot 1985; Janzen and Chang 1988):

$$EC_{solution} \approx 2\ (EC_e) \qquad [1].$$

Researchers at the U.S. Salinity Lab. (1954) suggested that the electrical conductivity of water-saturated soil paste extracts (EC_e) provide the most consistent measure of soil salinity. They arbitrarily classified soils with EC_e-conductivity between 0-2 deci-Siemens per metre (dS/m) as "non-saline", between 2-4 dS/m as "slightly saline", 4-8 dS/m as "moderately saline", and above 8 dS/m as "severely saline."

SALINITY EFFECTS ON CROP PRODUCTION When a producer asks which crop or variety to seed on saline soil, we have repeatedly sought published tables listing the salinity tolerance data from tests conducted in other countries with foreign varieties (Ayers and Westcot 1985; Maas 1990). Advice has also been gleaned from field tests at specific locations on the Prairies (Holm 1983; McKenzie 1988); unfortunately, because of the large temporal and spatial variability associated with salinity in the field, this information is rarely precise enough to determine salinity tolerance. For example, suggestions that Canadian wheat yields do not decline for crops grown in soils up to 6 dS/m EC_e have been proven incorrect (Taylor et al. 1991; van Genuchten and Gupta 1993; Steppuhn and Wall 1997). Tests in Canada's Salinity Testing Laboratory (Steppuhn and Wall 1999) at Swift Current have shown that yield losses for bread wheats (Katepwa and Biggar) begin near 1 dS/m and for pastry and pasta wheats (Fielder and Kyle) near 2 dS/m (Figure 2). At 4 dS/m, grain production dropped to 90% of that from the control plants for Fielder and Kyle and 45% for Katepwa and Biggar.

White crusts on soil surfaces rarely occur in Prairie soils whose average EC_e salinity remains less than 4 or 5 dS/m. However, we often define soil salinity based mainly on the occurrence of telltale white surface crusting. Land owners and managers are not well served if the specific crop that he or she sows on non-white land suffers a 15% production loss, because we arbitrarily drew the problem line beyond the salinity of his or her soil.

CROP YIELD IN RESPONSE TO ROOT-ZONE SALINITY Salinity slows crop growth (Shannon et al. 1994). This reduces crop yield, especially for crops growing within the short growing seasons common to the Canadian Prairies (McKenzie 1988). To standardize the product yields obtained from crops grown in saline root zones, crop yields are expressed on a relative basis. The usual procedure for converting absolute yield (Y) to relative yield (Y_r) employs a scaling divisor (Y_m) equal to the production where salinity has very little or no influence on the yield (Maas 1990):

$$Y_r = \frac{Y}{Y_m} \qquad [2].$$

The Y_m divisor normalizes the data-set and for non-halophyte crops, usually equals the maximum yield measured in the test, trial, or field study.

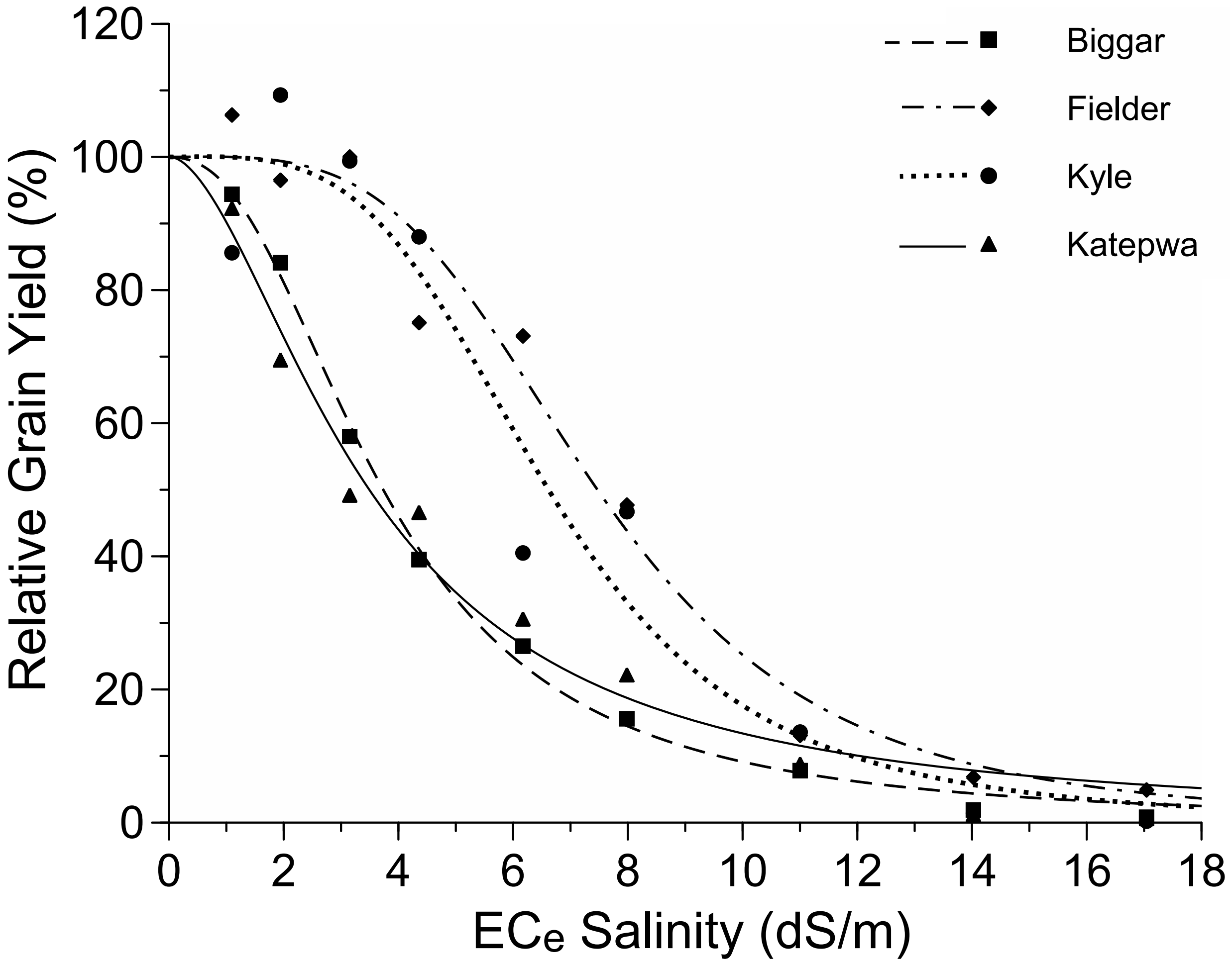

Figure 2. Responses in relative grain yield to root-zone salinity for wheat cultivars, Katepwa and Biggar (bread), Fielder (pastry), and Kyle (pasta) (taken from Steppuhn and Wall 1997).

The most precise relationship for determining relative product yield (Y_r) in response to increasing root zone salinity is the modified discount equation (Steppuhn et al. 2005):

$$Y_r = \frac{1}{1+(C/C_{50})^{\exp(s\ C50)}} \qquad [3],$$

where C equals the salt concentration measured by the electrical conductivity of the test solution ($EC_{solution}$) in dS/m, C_{50} defines C at $Y_r = 50\%$, and s represents the response curve steepness. The steepness indicates the absolute value (slope) of the average yield per unit salinity near C_{50}. The indicator “s” describes the average unit decrease in relative product yield with unit increase in root-zone salinity at and near C_{50}. From Equ. 1, EC_e can substitute for 0.5 $EC_{solution}$ in Equ. 3.

Indices of crop tolerance to root-zone salinity facilitate comparisons among agricultural crops (Steppuhn et al. 2005). If C_{50} were enhanced by a term which indicates the shape of the yield-response curve for crops grown in saline soils at and approaching C_{50}, such as the argument of the exponent ($s\ C_{50}$) in Equ. 3, a comprehensive Salinity Tolerance Index (ST-Index) results:

$$\text{ST-Index} = C_{50}\,(1+s) \qquad [4],$$

where C_{50} and s can be computed as regression constants or approximated by visual inspection of the response data. Since 1988, Canada's Salinity Testing Laboratory has intermittently served in determining the ST-Indices of Canadian crops and varieties (Figure 3).

Figure 3. Canada's "SaltLab" houses a field-simulating, environmentally-controlled testing facility to measure the response of Canadian crops to root-zone salinity.

Determination of the crop yield response to EC_e salinity in the lowest range from 0 to 2 dS/m has proven difficult, because the influence of the salinity relative to other production factors, such as water deficits and so forth, cannot easily be uniquely isolated which leads to wide variability. Most crops will suffer only minimal yield reductions because of salinity at these low salinities; wheat crops and camelina are exceptions.

The literature contains a large number of papers reporting on the yield responses of various crops grown while subjected to root-zone salinity; copies of these papers are maintained at the U.S. Salinity Laboratory in Riverside, California. In 2002, Canadian and U.S. scientists reviewed these papers and re-worked these data to calculate and list the Salinity-Tolerance-Indices for most of the crops reported (Steppuhn et al. 2005). This list is continually being updated for Canadian crops; Table 1 represents the 2013 version.

SELECTING CROPS FROM TABLE 1 Table 1 serves as a guide for agricultural producers wishing to select salinity-tolerant crops for a semiarid climate with or without irrigation but targeted for fields containing saline soils. Once, the EC_e salinity values from soil samples taken from the target field and submitted to an analytical laboratory are known and the extent of the saline soils mapped, the Salinity Tolerance Indices for listed crops can be consulted. The indices reflect tolerances of root-zone salinity ranging from slight through severe. For example, spring wheat with a 3.27 index may not produce satisfactory yields in 2.50 dS/m soils, but tall fescue with a 6.56 index likely will.

Selecting a crop from Table 1 for saline agricultural fields involves a series of steps:

1. Select a tolerable yield reduction for the target field based on fields without the salinity. Let's say that the field's salinity, averaging 2.5 dS/m, should not impose more than a minus 10% (0.10 ratio) yield penalty across the field.
2. Select a tentative crop and find it in the table, for example, a dryland durum wheat crop with average 4.26 dS/m C_{50} and 0.212 s values. The C_{50}-value tells us that saline soils with an EC_e of 4.26 dS/m reduce dryland durum wheat yields by 50% (equal to a 0.50 fraction) or approximately 40% (0.40) less than the 10% (0.10 ratio) reduction which we identified in Step #1 as tolerable. Thus, we must estimate the EC_e which will reduce yield by 10%, a C_{10}-value, from the tabulated information.
3. The steepness (s) in the table tells us the approximate number of units of crop yield maintenance in relative terms with each unit of root-zone salinity averted. Moving from C_{50} to C_{10} preserves 0.4 relative yield units.
4. To estimate C_{10}, solve Equ. 3 for $C = C_{10}$ and $Y_r = 0.9$:

   $$C_{10} = e^{\{[\ln((Yr/1)-1) / (\exp(s\ C50))] + [\ln C50]\}} \qquad [5].$$

   Using $C_{50} = 4.26$ dS/m and $s = 0.212$ for durum wheat, C_{10} equals 1.75 dS/m. That is, C_{10} for durum wheat equals 1.75 dS/m, an approximate EC_e value which, on average, results in a saline soil yield reduction of 10%.
5. A C_{10}-value of 1.75 for the durum wheat falls within the 2.50 dS/m average for the saline soils in this field example by 0.75 dS/m and more often than not will result in a salinity-imposed yield reduction greater than the 10% tolerable.
6. Returning to Table 1, one can estimate the C_{10}-values for other candidate crops: 1.12 dS/m for Prairie Spring wheat, 0.74 dS/m for Hard Red Spring wheat, 2.75 dS/m for barley, 2.89 dS/m for canola, 0.63 dS/m for camelina, 1.45 dS/m for common bean, 1.83 dS/m for common alfalfa, 2.35 dS/m for common slender wheatgrass, 2.80 dS/m for intermediate wheatgrass, 5.60 dS/m for green wheatgrass, and 4.84 dS/m for tall wheatgrass. Within these C_{10}-calculated values, only barley or canola, or one of the intermediate, green, or tall wheatgrasses meets the 10% tolerable yield criterion.

Table 1. Salinity Tolerance Indices^z of selected Canadian agricultural crops grown under dryland (I) or irrigated (II) conditions.

Crop^y			Nonlinear tolerance Indicator			
Common Name	Botanical Name	Tolerance^x based on	C$_{50}$ (EC$_e$) dS/m	s Steepness	Salinity tolerance index	References
I. Under Dryland Agriculture (where seed are sown immediately and directly in contact with saline seedbeds and root zones)						
Alfalfa	Medicago sativa L.	Shoot DW	6.20	0.095	6.79	Steppuhn et al. 1999
Barley	Hordeum vulgare L.	Grain yield	7.51	0.104	8.29	Steppuhn 1993
Bean, common	Phaseolus vulgaris L.	Seed yield	3.34	0.289	4.30	Bernstein & Ayers 1951; Hoffman & Rawlins 1970; Magistad et al. 1943; Nieman & Bernstein 1959;Osawa 1965
Bean, pinto	Phaseolus vulgaris L.	Seed yield^w	5.30			Stepphun et al. 2001
Camelina	Crantz.	Seed yield	3.37	0.087	4.30	Steppuhn et al. 2010
Canola	Brassica napus L.	Seed yield	7.10	0.126	8.00	Steppuhn et al. 2001; Steppuhn et al. 2002; Steppuhn & Raney 2005
Corn	Zea mays L.	Ear FW	5.54	0.183	6.56	Kaddah & Ghowail 1964
Corn, sweet	Zea mays L.	Ear FW	5.54	0.183	6.56	Bernstein & Ayers 1949b (p.41-42)
Fescue, tall	Festuca arundinacea Schreber	Shoot DW	7.97	0.083	8.63	Steppuhn 1997
Flax	Linum usitatissimum L	Seed yield	6.00	0.183	7.10	Hayward & Spurr 1944
Kochia	Kochia scoparia (L.)					
Saskatchewan seed	Schrad.	Shoot DW	10.71	0.055	11.31	Stepphun 1990
New Mexico seed		Shoot DW	10.82	0.055	11.41	Stepphun 1990
Lettuce	Lactuca sativa L.	Top FW	4.83	0.198	5.79	Ayers et al. 1951; Bernstein et al. 1974; Osawa 1965
Onion (bulb)	Allium cepa L.	Bulb yield	4.02	0.244	5.00	Bernstein & Ayers 1953b; Bernstein et al. 1974; Hoffman & Rawlins 1971; Osawa 1965
Pea, field						
Green seeded	Pisum sativum L.	Seed DW^w	6.44			Stepphun et al. 2001
Yellow seeded		Seed DW^w	5.51			Stepphun et al. 2001
Turnip	Brassica rapa L. (Rapifera group)	Storage root	6.13	0.137	6.97	Francois 1984
Wheat, spring (Leavened bread)	Triticum aestivum L.	Grain yield	2.76	0.186	3.27	Steppuhn et al. 1996; Steppuhn & Wall 1997
Wheat, flat bread	Triticum aestivum L.	Grain yield	2.97	0.273	3.78	Steppuhn & Wall 1997
Wheat, durum	Triticum turgidum L. Desf.	Grain yield	4.26	0.212	5.20	Steppuhn et al. 1996; Steppuhn & Wall 1997; Steppuhn et al. 2001
Wheat, pastry	Triticum aestivum L.	Grain yield	6.06	0.214	7.35	Steppuhn & Wall 1997
Wheatgrass,green	Elymus hoffmanni					
(AC Saltlander)	Jensen & Asay	Shoot DW^v	11.80	0.095	12.92	Steppuhn & Asay 2005
		Shoot DW^u	11.77	0.029	12.51	Steppuhn & Asay 2005
Wheatgrass, Hoffmann (NewHy)	Elymus hoffmanni Jensen & Asay	Shoot DW	10.27	0.086	11.15	Steppuhn & Asay 2005
Wheatgrass, intermediate	Thinopyrum intermedium (Host) Bark. & Dewey	Shoot DW	7.72	0.100	8.49	Steppuhn 1997
Wheatgrass, slender	Thinopyrum trachycaulus (Link) Bark. & Dewey	Shoot DW	7.16	0.095	7.84	Steppuhn 1997
Wheatgrass, tall	Thinopyrum ponticum	Shoot DW^v	11.41	0.029	11.73	Steppuhn 1997; Steppuhn & Asay
(Orbit)	(Podp.) Bark. & Dewey	Shoot DW^u	10.07	0.109	11.17	2005

Table 1. Continued.

Crop[y]			Nonlinear tolerance Indicator			
Common Name	Botanical Name	Tolerance[x] based on	C_{50} (EC_e) dS/m	s Steepness	Salinity tolerance index	References
II. Under Irrigated Agriculture (where seed are placed into non-saline seedbeds, grown into seedlings, and the seedlings subjected to salinity only after crop establishment)						
Alfalfa	Medicago sativa L.	Shoot DW	8.49	0.111	9.43	Bernstein & Francois 1973; Bernstein & Ogata 1966; Bower et al. 1969; Brown & Hayward 1956; Gauch & Magistad 1943; Hoffman et al. 1975
Asparagus	Asparagus officinalis L	Spear yield	28.50	0.030	29.37	Francois 1987
Barley[t]	Hordeum vulgare L.	Grain Yield	17.53	0.076	18.87	Ayers et al. 1952; Hassan et al. 1970
Beet, red	Beta vulgaris L.	Storage root	9.19	0.137	10.45	Bernstein et al. 1974; Hoffman & Rawlins 1971; Magistad et al. 1943
Broccoli	Brassica oleracea L. (Botrytis Group)	Shoot FW	7.88	0.140	8.99	Bernstein & Ayers 1949a (p. 39); Bernstein et al. 1974
Bromegrass, smooth	Bromus inermis Leyss.	Shoot DW	16.10	0.094	17.61	McElgunn & Lawrence 1973
Canola or rapeseed	Brassica campestris L. [syn. B. rapa L.]	Seed yield	12.86	0.213	15.60	Francois 1994
Canola or rapeseed	B. Napus L.	Seed yield	14.42	0.198	17.27	Francois 1994
Carrot	Daucus carota L.	Storage root	4.26	0.213	5.17	Bernstein & Ayers 1953a; Bernstein et al. 1974; Lagerwerff & Holland 1960; Magistad et al. 1943; Osawa 1965
Celery	Apium graveolens L. var dulce (Mill.) Pers.	Petiole FW	9.49	0.094	10.39	Francois & West 1982
Corn	Zea Mays L.	Ear FW	5.54	0.183	6.56	Bernstein & Ayers 1949b (p. 41-42); Kaddah & Ghowail 1964
Corn, sweet	Zea Mays L.	Ear FW	5.54	0.183	6.56	Bernstein & Ayers 1949b (p. 41-42)
Pea	Pisum sativum L.	Seed FW	7.77	0.161	9.02	Cerdá et al. 1982
Potato	Solanum tuberosum L.	Tuber yield	5.54	0.183	6.56	Bernstein et al. 1951
Radish	Raphanus sativus L.	Storage root	4.73	0.198	5.67	Hoffman & Rawlins 1971; Osawa1965
Ryegrass, perennial	Lolium perenne L.	Shoot DW	11.78	0.116	13.14	Brown & Bernstein 1953 (p.44-46)
Sugar beet[s]	Beta vulgaris L.	Storage root	15.04	0.090	16.39	Bower et al. 1954
Sunflower	Helianthus annuus L.	Seed yield	14.37	0.076	15.46	Cheng 1983; Francois 1996
Tomato	Lycopersicon lycopersicum (L.) Karst. Ex Farw. [syn. Lycopersicon esculentum Mill.]	Fruit yield	7.21	0.151	8.29	Bierhuizen & Ploegman 1967; Hayward & Long 1943; Lyon 1941; Shalhevet & Yaron 1973
Wheat, bread	Triticum aestivum L.	Grain yield	5.85	0.242	7.89	USSL[r] 1979
Wheatgrass, ttall	Thinopyrum ponticum (Podp.) Barkworth, Dewey	Shoot DW	18.92	0.065	20.13	Bernstein & Ford 1958 (p. 32-36)
Wildrye grass, beardless	Elymus triticoides Buckl.	Shoot DW	10.65	0.091	11.62	Brown & Bernstein 1953

[z] Salinity Tolerance Index = salinity causing 50% product loss times ("1" plus the absolute values of a unit decline in relative crop yield with an average unit increase in salinity at and about 50% yield).

[y] Botanical and common names follow the convention of Hortus Third (Liberty Hyde Bailey Hortorium Staff, 1976) where possible.

[x] FW = fresh weight; DW = dry weight.

[w] Without a measure of steepness resulting in only C_{50}.

[v] Sulfate based root-zone test solutions.

[u] Chloride based root-zone test solutions.

[t] Less tolerant during seedling stage, EC_e at this stage should not exceed 4 or 5 dS/m.

[s] Sensitive during germination and emergence, EC_e should not exceed 3 dS/m.

[r] Unpublished U.S. Salinity Laboratory data.

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