Principles and Crop Yield Response To Root-Zone Salinity
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Summary
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. A Salinity-Tolerance-Index specifies the degree of tolerance and yield maintenance for each crop. The salinity causing a 50% product loss ($C_{50}$) and an average decline in relative crop yield with a unit increase in salinity ($s$) at and near $C_{50}$ provides an abridged list of indices for Canadian crops.

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 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](image-url) 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 possesses 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.

Beneath each Prairie farm and ranch, the subsurface geology reveals a history and an influence on the site’s salinity. Approximately, 100 million years ago, oceans covered all of today’s Prairies lasting for eons. 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. During the same era, the Rocky Mountains were born, and the land surface developed a generally decreasing slope toward Hudson’s Bay. Water moving down this slope formed valleys through which the marine salts began moving back to the oceans. Within the last two million years, continental glaciers covered and scraped these landscapes incorporating and depositing ample quantities of marine salts.

The marine deposits consist primarily of loose, cemented, and compressed clays and silts 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.

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. This disruption delays the movement of infiltrated melted snow, rain, or surface waters. Such delays increase the subsurface residence times of these waters and enhance the opportunity for the water 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, adjacent salts are dissolved by the delayed water.

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 especially if the field was fallowed during the previous summer. 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. Unfortunately, problems develop when the concentrations of dissolved salts in root zones exceed those required by the plants growing in the soil. Across the Canadian Prairies, dissolved sulphate salts of calcium, magnesium, and sodium typically dominate within saline soils.

Ayers and Westcot\(^3\), writing for the Food and Agriculture Organization of the United Nations, defined soil salinity as follows: "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\(_{\text{extract}}\) or EC\(_e\)), the strength of the electrical current passed through the collected extract reflects the concentration of its dissolved salts. This is the measurement of salinity conducted and reported by analytical laboratories in determining dissolved concentrations within soil samples submitted by farmers and ranchers. 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\(_{\text{solution}}\)), convey approximately twice the electrical current and contain about twice the dissolved solutes as indicated by the EC\(_e\)-measurements\(^3,\ 38\):

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

Researchers at the U.S. Salinity Laboratory\(^67\) suggested that the electrical conductivity of water-saturated soil paste extracts (EC\(_e\)) provide the most consistent measure of 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."

Agricultural producers have asked if any rules-of-thumb exist relating these electrical conductivity measures of salinity to some observable indications in the field. It happens that, for southeast and south-central Alberta, southwest and south-central Saskatchewan, and likely southwestern Manitoba, one can follow an approximation applicable to the saline soil areas of cultivated fields growing annual crops. This approximation can best be done by the land owner and/or producer observing the field year-after-year. The long-term, visual occurrence of white surface salts tends to reflect the field’s EC\(_e\) rating: rarely if ever seen (0-2 dS/m); infrequently seen (2-5 dS/m); frequently seen (5-8 dS/m); almost always seen (greater than 8 dS/m).
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\(^3\), \(^4\). Advice has also been gleaned from field tests at specific locations on the Prairies\(^3\), \(^7\); 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 \(\text{EC}_e\) have been proven incorrect\(^6\), \(^6\), \(^5\). Tests in Canada's Salinity Testing Laboratory\(^5\) at Swift Current have shown that yield losses for bread wheats (Katepwa and Biggar) begin near 1.0 dS/m and for pastry and pasta wheats (Fielder and Kyle) near 2.0 dS/m (Figure 2)\(^5\). 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.

![Figure 2. Responses in relative grain yield to root-zone salinity for cultivars Katepwa and Biggar (bread), Fielder (pastry), and Kyle (pasta) wheats\(^5\).](image-url)

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**Figure 2.** Responses in relative grain yield to root-zone salinity for cultivars Katepwa and Biggar (bread), Fielder (pastry), and Kyle (pasta) wheats\(^5\).
White crusts on soil surfaces rarely occur in Prairie soils whose average EC₉₀ 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.

Area Affected by Salinity
If 79% of Canada's agricultural lands are located on the Prairies, 36.3 million ha as cultivated fields and tame hayfields and 17.2 million ha as permanent pasture, an estimated 18 million ha of this total are prone to salinization²⁴,²². Steppuhn⁵³ and Wiebe et al.⁶⁹ concluded that some 20 million out of 67 million ha (30%) of the total land across the Canadian Prairies either openly showed salinizat ion (6 million ha) or were at risk of being salinized in 2001 and preceding years (Figure 3).

Based on federal and provincial soil survey data, 2.23 million ha have been estimated as severely saline where non-irrigated crops yields would be lowered by 25% or more²¹. This area reflects those lands where white crusts form on soil surfaces, that is, where EC₉₀ exceeds 5 dS/m. An estimate of the Prairie agricultural land showing slight or moderate salinity was calculated on the basis that 50% of the total land lies in the Black and Gray soil zones, 27% in the Dark Brown, and 23% in the Brown²¹. These percentages coupled with an assessment of the soil samples sent to the Saskatchewan Soil Testing Laboratory during 1992, 1993, and 1994, possessing slight to moderate salinity, indicated an areal extent across the Prairies of about 7 million ha of arable land and 3 million ha of permanent pasture (unpublished study by the Semiarid Prairie Agricultural Research Centre and the Plains Innovative Laboratory staff supervised by Dr. Rigas Karamanos).

![Figure 3. View of the Canadian Prairies with the 1996 soil salinity risk evaluation based on five physical and biological factors which include the existence of root-zone salts.](image-url)
Crop Yield in Response to Root-Zone Salinity

Salinity slows crop growth and this reduces crop yield, especially for crops growing within the short growing seasons common to the Canadian Prairies. 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) expressed as a ratio from zero to one) employs a scaling divisor (Y_m) equal to the production where salinity has very little or no influence on the yield:

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

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

As shown in Figure 2, the product yield in percent of a crop varies with the severity of the root-zone salinity (EC_e). This relationship between salinity and crop yield differs among crops but more-or-less follows an inverted S-shape curve. The midpoint of the curve defines an EC_e salinity value (C_50) at which crop yield is reduced by 50% of that produced in root zones with negligible salinity. In addition, the shape of the specific curve for each crop can be identified by a steepness value (s). The steepness value approximates the average unit decrease in relative product yield with each unit increase in root-zone salinity at and near the C_50 point. If these two values, C_50 and s, are combined, they provide an index of salinity tolerance unique to each crop:

\[
\text{Salinity-Tolerance-Index} = C_{50} + s C_{50}
\] [3],

where C_50 and s can be computed mathematically or approximated by visual inspection of the response data. Since 1988, Canada’s Salinity Testing Laboratory has served intermittently in determining these indices for Canadian crops and varieties (Figure 4).

Figure 4. Canada’s “SaltLab” houses a field-simulating, environmentally-controlled testing facility to measure the response of Canadian crops to root-zone salinity.
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 Salinity-Tolerance-Indices for all the crops reported. These researchers also presented an abridged list of these indices associated with Canadian agricultural crops at the 41st Annual Meeting of the Alberta Soil Science Workshop. This list is continually being updated; 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 are 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, beans with a 4.30 index may not produce satisfactory yields in 3.50 dS/m soils, but tall fescue with a 6.56 index likely will.

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 leading to wide variability. But, most crops will suffer only minimal yield reductions because of salinity at these low salinities; wheat crops and camelina are exceptions.

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 (say, 3.50 dS/m) should not impose more than an overall minus 10% (0.10 ratio) yield penalty across the field, at an EC$_e$ which equals this C$_{10}$-value.

2. Select a tentative crop and find it in the table, for example, a dryland durum wheat crop with an average 4.26 dS/m C$_{50}$-value and a 0.212 s-value. These values tell us that C$_{50}$ 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$_e$ for 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$_{10}$, subtract a value derived from the division of 0.4 over the s-value for the candidate crop (0.4 / 0.212 for the durum wheat) from the C$_{50}$-value (4.26 dS/m). This calculation, [4.26 dS/m – (0.4 / 0.212)], equals 2.37 dS/m. That is, C$_{10}$ for durum wheat equals 2.37 dS/m, an approximate EC$_e$ value which results in a saline soil yield reduction of 10%.

5. A C$_{10}$-value of 2.37 for the durum wheat falls within the 3.50 dS/m average for the saline soils in this field example by 1.13 dS/m and more often than not will result in a salinity-imposed yield reduction greater than the 10% allowable.

6. Returning to Table 1, one can estimate the C$_{10}$-values for other candidate crops: 1.50 dS/m for Prairie Spring wheat, 0.61 dS/m for Hard Red Spring wheat, 3.66 dS/m for barley, 3.92 dS/m for canola, 1.23 dS/m for camelina, 1.96 dS/m for common bean, 1.99 dS/m for common alfalfa, 2.95 dS/m for common slender wheatgrass, 3.72 dS/m for intermediate wheatgrass, 7.59 dS/m for green wheatgrass, and 7.74 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.

Acknowledgement

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

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

\(^a\) Nonlinear tolerance Indicator

\(^b\) Steepness
### Table 1. Continued.

<table>
<thead>
<tr>
<th>Crop</th>
<th>Botanical Name</th>
<th>Tolerance(^{\mathrm{b}}) based on</th>
<th>Nonlinear tolerance Indicator</th>
<th>Salinity tolerance index</th>
<th>References</th>
</tr>
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<tr>
<td></td>
<td></td>
<td>C(<em>{50}) (EC(</em>{e}))</td>
<td>s Steepness</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Alfalfa</td>
<td><em>Medicago sativa</em> L.</td>
<td>Shoot DW</td>
<td>8.49</td>
<td>0.111</td>
<td>9.43</td>
</tr>
<tr>
<td>Asparagus</td>
<td><em>Asparagus officinalis</em> L.</td>
<td>Spear yield</td>
<td>28.50</td>
<td>0.030</td>
<td>29.37</td>
</tr>
<tr>
<td>Barley</td>
<td><em>Hordeum vulgare</em> L.</td>
<td>Grain Yield</td>
<td>17.53</td>
<td>0.076</td>
<td>18.87</td>
</tr>
<tr>
<td>Beet, red</td>
<td><em>Beta vulgaris</em> L.</td>
<td>Storage root</td>
<td>9.19</td>
<td>0.137</td>
<td>10.45</td>
</tr>
<tr>
<td>Broccoli</td>
<td><em>Brassica oleracea</em> L. (Botrytis Group)</td>
<td>Shoot FW</td>
<td>7.88</td>
<td>0.140</td>
<td>8.99</td>
</tr>
<tr>
<td>Bromegrass, smooth</td>
<td><em>Bromus inermis</em> Leyss.</td>
<td>Shoot DW</td>
<td>16.10</td>
<td>0.094</td>
<td>17.61</td>
</tr>
<tr>
<td>Canola or rapeseed</td>
<td><em>Brassica campestris</em> L. [syn. <em>B. rapa</em> L.]</td>
<td>Seed yield</td>
<td>12.86</td>
<td>0.213</td>
<td>15.60</td>
</tr>
<tr>
<td>Canola or rapeseed</td>
<td><em>B. Napus</em> L.</td>
<td>Seed yield</td>
<td>14.42</td>
<td>0.198</td>
<td>17.27</td>
</tr>
<tr>
<td>Carrot</td>
<td><em>Daucus carota</em> L.</td>
<td>Storage root</td>
<td>4.26</td>
<td>0.213</td>
<td>5.17</td>
</tr>
<tr>
<td>Celery</td>
<td><em>Apium graveolens</em> L. var dulce (Mill.) Pers.</td>
<td>Petiole FW</td>
<td>9.49</td>
<td>0.094</td>
<td>10.39</td>
</tr>
<tr>
<td>Corn</td>
<td><em>Zea Mays</em> L.</td>
<td>Ear FW</td>
<td>5.54</td>
<td>0.183</td>
<td>6.56</td>
</tr>
<tr>
<td>Corn, sweet</td>
<td><em>Zea Mays</em> L.</td>
<td>Ear FW</td>
<td>5.54</td>
<td>0.183</td>
<td>6.56</td>
</tr>
<tr>
<td>Pea</td>
<td><em>Pisum sativum</em> L.</td>
<td>Seed FW</td>
<td>7.77</td>
<td>0.161</td>
<td>9.02</td>
</tr>
<tr>
<td>Potato</td>
<td><em>Solanum tuberosum</em> L.</td>
<td>Tuber yield</td>
<td>5.54</td>
<td>0.183</td>
<td>6.56</td>
</tr>
<tr>
<td>Radish</td>
<td><em>Raphanus sativus</em> L.</td>
<td>Storage root</td>
<td>4.73</td>
<td>0.198</td>
<td>5.67</td>
</tr>
<tr>
<td>Ryegrass, perennial</td>
<td><em>Lolium perenne</em> L.</td>
<td>Shoot DW</td>
<td>11.78</td>
<td>0.116</td>
<td>13.14</td>
</tr>
<tr>
<td>Sugar beet</td>
<td><em>Beta vulgaris</em> L.</td>
<td>Storage root</td>
<td>15.04</td>
<td>0.090</td>
<td>16.39</td>
</tr>
<tr>
<td>Sunflower</td>
<td><em>Helianthus annuus</em> L.</td>
<td>Seed yield</td>
<td>14.37</td>
<td>0.076</td>
<td>15.46</td>
</tr>
<tr>
<td>Wheat, leavened bread</td>
<td><em>Triticum aestivum</em> L.</td>
<td>Grain yield</td>
<td>5.85</td>
<td>0.242</td>
<td>7.89</td>
</tr>
<tr>
<td>Wheatgrass, tall</td>
<td><em>Thinopyrum ponticum</em> (Podp.) Barkworth, Dewey</td>
<td>Shoot DW</td>
<td>18.92</td>
<td>0.065</td>
<td>20.13</td>
</tr>
<tr>
<td>Wildrye grass, beardless</td>
<td><em>Elymus triticioides</em> Buckl.</td>
<td>Shoot DW</td>
<td>10.65</td>
<td>0.091</td>
<td>11.62</td>
</tr>
</tbody>
</table>

\(^{a}\) 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).

\(^{b}\) Botanical and common names follow the convention of Hortus Third (Liberty Hyde Bailey Hortorium Staff, 1976) where possible.

\(^{c}\) FW = fresh weight; DW = dry weight.

\(^{d}\) Without a measure of steepness resulting in only C\(_{50}\).

\(^{e}\) Sulfate based root-zone test solutions.

\(^{f}\) Chloride based root-zone test solutions.

\(^{g}\) Less tolerant during seedling stage, EC\(_{e}\) at this stage should not exceed 4 or 5 dS/m.

\(^{h}\) Sensitive during germination and emergence, EC\(_{e}\) should not exceed 3 dS/m.

\(^{i}\) Unpublished U.S. Salinity Laboratory data.
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