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“DESALINATED SEAWATER FOR ALTERNATIVE AND SUSTAINABLE SOILLESS CROP PRODUCTION”

“REVIEW ON THE IMPACT OF BORON ON SOILS AND PLANTS”

ACTION A1. “Characterization of current and expected desalinated seawater production for crop irrigation in the water-stressed south Eastern Spain”

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Abstract

Boron (B) is an essential trace element for the growth, development and productivity of fruit and vegetable crops. Its availability in soil and irrigation water is an important determinant of agricultural production. However, signs of B toxicity may appear when plants are exposed to high B concentrations and there is usually a small window between deficiency and toxicity. Boron concentrations in surface irrigation waters typically is less than 0,1 mg/L but can exceed 1 mg/L in some water sources such as desalinated seawater. Boron toxicity symptoms usually are the result of the combination of B concentration in the irrigation water above 1 mg/L and the management of sensitive crops, therefore there is an emerging concern about the toxicity risk associated to irrigation with desalinated seawater when managing sensitive crops. This deliverable intends to conduct a comprehensive review of the available literature on a broad range of topics dealing with B agronomy, including the occurrence of B in soils; the factors affecting boron availability in soils; the function of B in plants; the impact of B concentration on crops production; the threshold values of boron concentration in crops; the B concentration in desalinated seawater; the tolerance to B in crops, specifically in citrus as the most sensitive crop; and a review of guidelines that limit B concentration in irrigation water.

Resumen

El boro (B) es un oligoelemento esencial para el crecimiento, desarrollo y productividad de los cultivos hortofrutícolas. Su disponibilidad en el suelo y el agua de riego es un determinante importante de la producción agrícola. Sin embargo, pueden aparecer signos de toxicidad cuando las plantas están expuestas a altas concentraciones de B y, generalmente, hay una pequeña ventana entre la deficiencia y la toxicidad. Las concentraciones de boro en las aguas de riego superficiales generalmente son menores que 0,1 mg/L, pero pueden exceder 1 mg/L en algunos suministros como el agua de marina desalinizada. Los síntomas de toxicidad por boro generalmente son el resultado de la combinación de la concentración de B en el agua de riego por encima de 1 mg/L y el manejo de cultivos sensibles, por lo tanto, existe una preocupación creciente sobre el riesgo de toxicidad asociado al riego con agua de mar desalinizada cuando se manejan cultivos sensibles. Este entregable pretende realizar una revisión exhaustiva de la literatura disponible sobre una amplia gama de temas relacionados con la agronomía del B, incluida la aparición de B en los suelos; los factores que afectan la disponibilidad de boro en los suelos; la función de B en las platas; el impacto de la concentración de B en la producción de cultivos; los valores umbral de concentración de boro en los cultivos; la concentración de B en agua marina desalinizada; la tolerancia a B en los cultivos, específicamente en cítricos como el cultivo más sensible; y una revisión distintas recomendaciones institucionales que limitan la concentración de B en el agua de riego.

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1. Introduction

The growth, development and productivity of fruit and vegetable crops depend on several abiotic (environmental) and biotic factors. Among the various abiotic factors a balance supply of essential nutrients is of utmost importance. There are 17 essential nutrients required for plant growth: carbon (C), hydrogen (H), oxygen (O), nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), sulfur (S), iron (Fe), manganese (Mn), zinc (Zn), copper (Cu), boron (B), molybdenum (Mo), chlorine (Cl) and nickel (Ni). Of these 17, all except carbon, hydrogen, and oxygen are derived from the soil. The concept of essentiality for mineral elements proposed by Arnon and Stout (1939) lies in three criteria: (i) a plant must be unable to complete its life cycle in the absence of the mineral element; (ii) the function of the element must not be replaceable by another mineral element; (iii) the element must be directly involved in plant metabolism.

Depending on the quantity needed by the plant, these are called either primary or trace (micronutrients) nutrients. The primary nutrients (N, P, K, Ca, Mg and S) are measured on a percent (parts per 100) dry weight tissue basis while as the trace elements (Fe, Mn, Zn, Cu, B, Mo, Cl and Ni. are measured on a part per million dry weight bases. Although plants require more primary than trace nutrients, all the essential elements need to be present for a healthy plant.

Boron (B) was established as essential in 1923 (Brown et al., 2002). It is the only nonmetal among the plant micronutrients. Since its discovery as an essential trace element, the importance of boron as an agricultural chemical has grown very rapidly, although its requirement differs markedly within the plant kingdom. It is essential for the normal growth of monocots, dicots, conifers, and ferns, but not for fungi and most algae. Therefore B is an essential nutrient for normal growth of higher plants, and B availability in soil and irrigation water is an important determinant of agricultural production

Many ground waters, recycled municipal wastewaters and desalinated seawater contain elevated concentrations of B and salts, but are nonetheless potential irrigation water sources for agricultural production. Therefore B concentrations in surface irrigation waters typically is less than 0,1 mg/L, but can exceed 1 mg/L in some areas/water sources. Unless the pH of the water is high, the majority of B exists in the water as boric acid ($B(OH)_3$). It is in this undissociated form that most of the B is absorbed by the roots (Grattan et al., 2015).

Boron occurs naturally in soil, usually in low concentrations that present no risk to plants. In fact, as micronutrient, small quantities of boron are necessary for plant growth. However, signs of boron toxicity may appear when plants are exposed to higher concentrations of the mineral. Therefore, there is usually a small window between deficiency and toxicity. For some crops, if 0.2 mg/L of B in water is essential, 1 to 2 mg/L of B may be toxic. Soils with insufficient or toxic levels of B are widespread in agricultural areas throughout the world, limiting crop productivity. Whereas B deficiency can be resolved by application of B-enriched fertilizers, toxicity is a more difficult problem to manage (Reid, 2004). Boron toxicity symptoms usually aren’t the result of B in soil, but its presence in the irrigation water in high concentrations. Therefore B problems originating from the water are much more frequent than those originating in the soil.

Boron toxicity symptoms are different depending on the plant, and instead of damage to the foliage, some plants may ooze a gummy substance from the branches or trunk. Toxicity symptoms normally show first on older leaves as a yellowing, spotting, or drying of leaf tissue at the tips and edges. Drying and chlorosis often progress toward the centre between the veins as more and more boron accumulates with time. On seriously affected trees, such as almonds and other tree crops which do not show typical leaf symptoms, a gum or exudate on limbs or trunk is often noticeable (Ayers and Westcot, 1985).

Although the considerable agronomic importance of B toxicity, our understanding is rather fragmented and limited. The present document intents to conduct a comprehensive review of the available literature on a broad range of topics, from the occurrence of B in soils, to its function in plats, through to the impact of B on crops production. It is based in different reviews on B toxicity (Gupta et al., 1985; Leyshon and Jame, 1993; Nable et al., 1997; Grattan et al., 2015; …).

2. Sources of boron in the Environment

Boron is usually and universally distributed in soils. It is derived from certain boron-bearing rocks, with sedimentary rocks contain more B than igneous rocks. The highest naturally occurring concentrations of soil B are in soils derived from marine evaporites and marine argillaceous sediment. In addition, there are various anthropogenic sources of B such as irrigation water, wastes from surface mining, fly ash, and industrial chemicals (Nable et al., 1997). However, the B in rock is not very available to plants and most of the plant-available B comes from the decomposition of soil organic matter and from B adsorbed and precipitated onto the surfaces of soil particles (Gupta et al., 1985).

The primary sources of B in most soils are tourmaline and the volatile emanations of volcanoes. Tourmaline from high temperature rocks is very resistant to chemical breakdown in the weathering zone and thus accumulates in the clastic fraction of sediments and sedimentary rocks. In most of the well-drained soils formed from acid rocks and metamorphic sediments, tourmaline is the most common boron-containing mineral identified. The name tourmaline represents a group of minerals that are compositionally complex borosilicates containing approximately 3% B. Tourmalines are highly resistant to weathering and virtually insoluble. Additions of finely ground tourmaline to soil failed to provide sufficient boron to alleviate boron deficiency of crop plants (Gupta, 2008).

In igneous, metamorphic, sedimentary rocks, B occurs as borosilicates, which are resistant to weathering and not readily available to plants. Mobilisation of immobile forms of rock B occurs by weathering in the pedosphere, which includes soil reactions of acid-base, oxidation-reduction, and dissolution precipitation (Nable et al.,1997).

The dominant species in the soil when B from primary silicates goes into solution is $B(OH)_3$. This form of B is mobile and easily lost by leaching. In soils, this form of B can be taken up by vegetation, held by organic matter, or temporarily adsorbed on fine mineral fractions (Goldberg, 1993).

3. Boron in soils

The total boron content of most agricultural soils ranges from 1 to 467 mg/kg^{-1}, with an average content of 9 to 85 mg/kg^{-1}. Such wide variations among soils in the total boron content are mainly ascribed to the parent rock types and soil types falling under divergent geographical and climatic zones. Boron is generally high in soils derived from marine sediments. Available boron in agricultural soils varies from 0.5 to 5 mg/kg^{-1} (Gupta, 2008). Most of the available boron in soil is believed to be derived from sediments and plant material. Hou et al. (1994) proposed a fractionation scheme, which indicated that readily soluble and specifically adsorbed B accounted for < 2% of the total B.

As abovementioned, boron mainly exists in soil solution as undissociated acid (H_3BO_3) or boric acid ($B(OH)_3$). Boron occurs in aqueous solution as $B(OH)_3$, which is a weak monobasic acid that acts as an electron acceptor or as a Lewis acid. $B(OH)_3$ can be easily leached under high rainfall conditions leading to deficiencies in plants that grow there. On the contrary, under low rainfall conditions (as southeastern Spain), B cannot be sufficiently leached and therefore may accumulate to levels that become toxic to plant growth (Reid 2004). This is very often in arid and semiarid regions with high-boron groundwater, where the accumulation of B in topsoil due to the evaporation of groundwater reaches toxic levels that reduce crop yields (Camacho-Cristobal et al., 2008).

Generally, soils that have developed in humid regions have low amounts of plant available B because of leaching. Further, the plant-available B that is present in such soils is located in the top 15 cm in the organic matter fraction. This explains the widespread occurrence of B deficiency in many parts of the world. Compared to B deficiency, areas of toxicity due to high levels of B in virgin soils are very few. In general, both total and plant available B can be very high in arid or semiarid areas where leaching is limited. Boron, like sodium and chloride, is soluble and will accumulate where salts accumulate. In semiarid areas, B in the subsoil often exceeds that in surface soil (Gupta et al., 1985).

Sorption capacity of a given soil is crucial in determining the amount of B in solution. A soil that has high adsorption capacity would be expected to maintain lower soil solution B over a longer period of time than a soil with low adsorption capacity when both soils are irrigated with the same B laden water. Therefore, soil adsorption sites may act as a pool from which B is supplied to solution or where B is adsorbed, depending on the changes in solution B concentrations and the affinity of soil for B. That is, adsorbed B may buffer B concentration in soil solution (Keren and Bingham, 1985).

The complex B sorption characteristics of a soil explain frequent observations that plant injury occurs more quickly on coarse textured soils than on fine textured soils when B laden water is used for irrigation. As the key to the assessment of B toxicity is the plant response to B in soil, it is the B concentration of the soil solution under field conditions that must be evaluated in relating soil B to plant response (Ryan et al., 1977).

Dealing with the extraction of available boron from soils, there are various methods available to determine the levels of B in soils, but soil analysis can provide little more than a general risk assessment for B toxicity (Nable et al.,1997). Most procedures for extracting are similar. The most common extractant is hot water because soil solution boron is most important with regard to plant uptake. Extraction of hot-water-soluble boron is the most effective way to evaluate available boron to plants in most agricultural soils (Gupta, 2008). As reference, generally in the soil solution, less than 0.2 mg/L^{-1} of B is considered deficient for crops, whereas greater than 1 mg/L^{-1} if B is considered toxic (Adriano, 1986). On a soil mass basis, less than 1 mg/L^{-1} is considered marginal for boron-sensitive crops whereas greater than 5 mg B kg1 is considered toxic (Reisenauer et al., 1973).

Saturation extracts of soils generally contain 0.1 to 10 mg/L^{-1} of B. The main advantage of a saturation extract is that it is easier to obtain than hot-water-soluble boron. Since the amount extracted by this method is less than that by hot-water extraction, this procedure has an advantage in determining the boron availability in toxic boron soils but would be less useful in soils containing low quantities of boron (Gupta, 2008).

4. Factors affecting boron availability in soil

There are a number of soil and environmental factors which will affect the B uptake by a plant. Knowledge of how B uptake is affected by these factors will improve our assessment of B deficiency and toxicity under different conditions.

Boron Adsorption by Soil

When B is released from soil minerals, mineralized from organic matter, or added to soils by means of irrigation or fertilization, part of the B remains in soil solution and part is adsorbed ("fixed") by soil particulates. Equilibrium exists between the solution and adsorbed B. Since plants obtain B from the soil solution and the adsorbed pool of B acts as a buffer against sudden changes in solution B, it is important to know how B is distributed between the solid and the liquid phases of the soil (Evans and Sparks, 1983).

Usually there is more B adsorbed by soils than is present in solution at any one time and fixation seems to increase with time (Gupta, 1968). Boron adsorption occurs more slowly in soils than does adsorption of other anions such as chlorides, nitrates, sulfates and phosphates. Boron retention in soil depends on B concentration of the solution, soil pH, texture, organic matter, cation exchange capacity, exchangeable ion composition, type of clay, and mineral coatings on the clays. Furthermore, the degree of B fixation is influenced by moisture, wetting and drying, temperature and soil texture (Evans and Sparks 1983).

Generally, soils with low clay content will adsorb less B than those with higher clay content. Fine-textured soils generally require more boron than do the coarse-textured soils to produce similar boron concentrations in plants.

Soil Acidity, Calcium, and Magnesium

Soil reaction or soil pH is an important factor affecting availability of boron in soils. Generally, boron becomes less available to plants with increasing soil pH. Several authors have observed negative correlations between plant boron accumulation and soil pH. The availability of boron to plants decreases sharply at higher pH levels, but the relationship between soil pH and plant boron at soil pH values below 6.5 does not show a definite trend (Gupta, 2008)

Due to plants vary widely in their nutrient requirements, the uptake of B by plants can be markedly affected by the presence of other plant nutrients in soils. The most well-known of these is the effect of Ca. Eck and Campbell (1962) attributed the decreased B uptake caused by liming soils having high B reserves to a high Ca content. The effect was probably related to the Ca:B ratio in the plant tissue. Reeve and Shive (1944) also showed that Ca accentuated the symptoms of B deficiency.

The degree of potassium saturation of the soil colloids also affects B retention (Evans and Sparks 1983).

Desorption of Boron in Soil

Much of the B fixed by soil can be easily desorbed by leaching with water (Eaton and Wilcox, 1939). Two types of B desorption reactions have been observed. In some soils the desorption isotherm mimicked closely the corresponding adsorption isotherm. In other soils, however, the B desorption characteristic was hysteretic (Elrashidi and O'Connor 1982). Hysteresis tended to be greater at higher B concentrations.

It appears that desorption becomes more difficult with ageing of the fixed B (Rhoades et al. 1970), suggesting that B fixed by the formation of stable compounds is not readily desorbed and might only be available if roots decompose the B-bearing mineral. It should be recognized that B desorption may not be reversible in many soils. Ignoring irreversibility of solute adsorption will result in overestimates of B concentration in soil solution (Gupta et al., 1985)

Boron in Soil Minerals and in Organic Matter

The bulk of B in soil comes originally from soil minerals. The B content of soil is primarily related to the B content of the parent material from which the soil was derived. B is also contained in the organic fraction of soil. The B in the soil organic matter is largely restricted to the surface horizon of the soil. Although B in soil minerals and in organic matter are not immediately available to plants, they are the main source of available B when released through mineralization and weathering processes. Okazaki and Chao (1968) reported that organic matter is one of the main sources of B in acid soils since relatively little B adsorption on the soil occurs at low pH levels. The influence of organic matter on the availability of boron in soils is amplified by increases in pH and clay content of the soil (Gupta, 2008).

Boron Interaction with macronutrients

Among the macronutrients, nitrogen is of utmost importance in affecting boron accumulation by plants. Under conditions of high boron, application of nitrogen depresses the level of boron in citrus leaves (Jones et al., 1993). Lysimeter experiments showed that tripled fertilization (NPK) rates and irrigation increased boron accumulation by plants on tested soils (Ruszkowska et al, 1994). The effects of phosphorus, potassium, and sulfur are less clear than those of nitrogen on the availability of boron to plants.

Soil Salinity

An antagonistic relationship existed between soil boron application levels and sodium adsorption ratio (SAR) of irrigation waters (Mehrotra et al., 1989).

Effect of Environment

The availability of B to plants is affected by climatic factors such as precipitation and temperature. Since B is easily leached, its availability is often low in areas of high rainfall. Temperature has a profound effect on B uptake, partly by affecting the B uptake per unit root weight and partly by affecting the relative size of the root system.

Another environmental factor affecting the response of plants to the availability of nutrients is the intensity of light. The faster the plant grows, for example, under high light conditions, the faster it will develop B deficiency symptoms in a particular growth period.

Soil water appears to affect the availability of boron more than that of some other elements. Boron deficiencies are generally found in dry soils where summer or winter drought is severe; when adequate moisture is maintained throughout the summer, deficiency symptoms may not be common (Gupta et al., 1985).

5. Functions of boron in plants

As abovementioned, B availability in soil and irrigation water is an important determinant of agricultural production (Tanaka and Fujiwara 2007). To date, a primordial function of B is undoubtedly its structural role in the cell wall; however, there is increasing evidence for a possible role of B in other processes such as the synthesis of proteins, the translocation of sugars, the maintenance of plasma membrane function and several metabolic pathways (Berger, 1949; Tanaka and Fujiwara, 2007; Gupta, 2007; Camacho-Cristobal et al., 2008). Here we provide a review of recent findings related to the role of B in plants, since in the last years, the knowledge of the molecular basis of B deficiency and toxicity responses in plants has advanced greatly.

Root Elongation and Nucleic Acid Metabolism

Boron deficiency rapidly inhibits the elongation and growth of roots. Root elongation is the result of cell elongation and cell division, and evidence suggests that B is required for both processes (Shelp et al., 1995). When boron is withheld for several days, nucleic acid content decreases. Krueger et al. (1987) demonstrated that the decline and eventual cessation of root elongation in squash seedlings was correlated temporally with a decrease in DNA synthesis, but preceded changes in protein synthesis and respiration.

Protein, Amino Acid, and Nitrate Metabolism

Protein and soluble nitrogenous compounds are decreased in boron-deficient plants. However, the influence of organ age, i.e., whether the organ was actively involved in the biosynthesis of amino acids and protein or remobilization of amino acids from protein reserves, has often been ignored. By contrast, protein concentrations in the actively growing regions could be reduced by lower rates of synthesis caused by boron deficiency (Shelp, 1990).

Sugar and Starch Metabolism

Boron is thought to have a direct effect on sugar synthesis. Under boron deficiency, the pentose phosphate shunt comes into operation to produce phenolic substances (Lee and Arnoff, 1967). Evidence on the impact of boron deficiency on starch concentration is conflicting. It is difficult to explain whether the differences are due to a variation in crop species.

Auxin and Phenol Metabolism

Boron regulates auxin supply in plants by protecting the indole acetic acid (IAA) oxidase system through complexation of o-diphenol inhibitors of IAA oxidase. Excessive auxin activity causes excessive proliferation of cambial cells, rapid and disproportionate enlargement of cells, and collapse of nearby cells. There are many reports in the literature of phenol accumulation under long-term boron deficiency (Lewis, 1980).

Flower Formation and Seed Production

The role of boron in seed production is so important that under moderate to severe boron deficiency, plants fail to produce functional flowers and may produce no seeds. Plants subjected to boron deficiency have been observed to result in sterility or low germination. Even under moderate boron deficiency, plants may grow normally and the yield of the foliage may not be affected severely, but the seed yield may be suppressed drastically (Gupta, 2007).

Membrane Function

Impairment of membrane function could affect the transport of all metabolites required for normal growth and development, as well as the activities of membrane-bound enzymes. Dugger (1983) summarized early reports that illustrate changes in membrane structure and organization in response to boron deficiency. The involvement of boron in inorganic ion flux by root tissue and in the incorporation of phosphate into organic phosphate was evident from earlier research. In general, the absorption of phosphate, rubidium, sulfate, and chloride was suppressed in boron-deficient root tissues.

6. Boron deficiency and toxicity in plants

Understanding the mechanisms that are involved in B uptake and distribution in plants can be critical to improve agricultural production.

Boron can be absorbed by roots in form of boric acid, transported to the scion and concentrated in leaves to point where toxicity can occur (Grattan et al., 2015). Although originally assumed that B uptake by plant roots was an exclusively passive process, new research has shown that B uptake by plants occurs by (1) passive diffusion across the cell membrane; (2) facilitated transport through major intrinsic proteins in the membrane and (3) energy-dependent transport through a high affinity uptake system (Dannel et al., 2002; Tanaka and Fujiwara, 2007). It also appears that genetic variation accounts for the differences in plants for absorbing and transporting B (Nable et al., 1997).

Once B has been absorbed by root cells this micronutrient must be loaded into xylem. In well B supplied plants this process is mediated by a passive mechanism that involves both B diffusion across lipid bilayer and facilitated permeation of boric acid via MIPs channel (MIPs). After being loaded into xylem, B is transported through this vascular system to shoot in a process mediated by transpiration stream. However, B can be also transported via phloem to both reproductive and vegetative tissues (Shelp et al., 1995)

There is a certain minimum requirement of B for a plant, below which a deficiency symptom will develop. As well, there is a certain maximum level of tolerance, above which toxicity symptoms appear. Therefore, B requires special attention because although the need for B by plants is relatively small, the range between deficiency and excess is narrow (Figure 1). This makes management of crop B nutrition a demanding and complex practice.

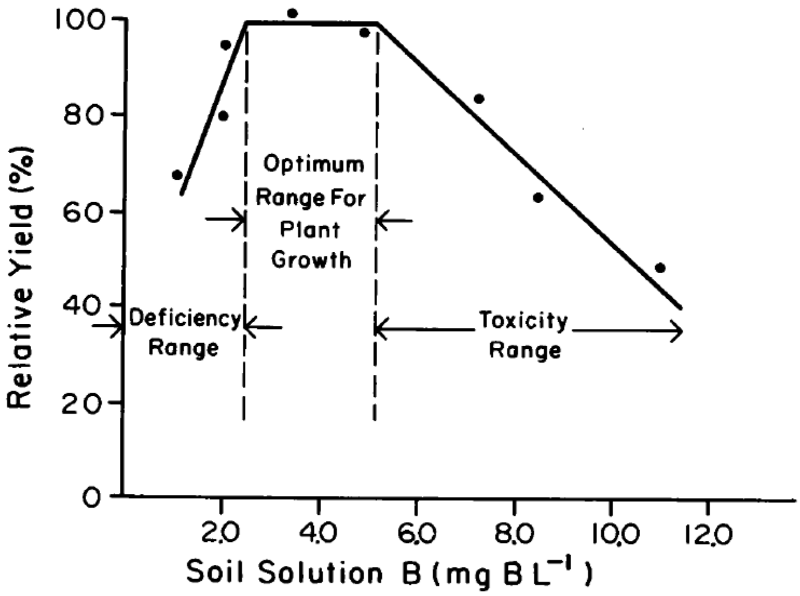

Figure 1. Theoretical Relative yield as influenced by soil solution boron.
Source: Gupta et al., 1985.

6.1. Boron deficiency and fertilizer application.

Boron deficiency in crops is more widespread than deficiency of any other micronutrient. It is well known that B deficiency causes different effects on very diverse processes in vascular plants such as root elongation, IAA oxidase activity, sugar translocation, carbohydrate metabolism, nucleic acid synthesis, and pollen tube growth, the formation of abnormal cell wall with altered physical properties, etc. (Camacho-Cristobal et al., 2008; Bassil et al., 2004; Brown et al., 2002).

Therefore, when the soil cannot supply the level of nutrient required for adequate growth, plants show symptoms of serious disorders in terms of alterations in general appearance as well as color known as hunger signs, and as a result not only the yield but also quality of fruits (Fig. 2) and vegetables are adversely affected (Gupta, 2007). However, except for the most severe cases, yield response to B deficiency is generally not as dramatic as with other micronutrients (Gupta et al, 1985).

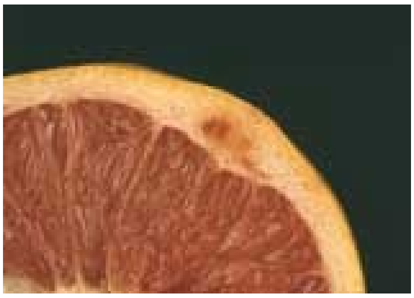

Figure 2. Boron deficiency symptoms in red grapefruit.
Source: http://www.haifa-group.com

Visual nutrient deficiency symptoms can be a very powerful diagnostic tool for evaluating the nutrient status of plants. One should keep in mind, however, that a given individual visual symptom is seldom sufficient to make a definitive diagnosis of a plant’s nutrient status. Many of the classic deficiency symptoms such as tip burn, chlorosis and necrosis are characteristically associated with more than one mineral deficiency and also with other stresses that by themselves are not diagnostic for any specific nutrient stress (Figs. 2 y 3). However, their detection is extremely useful in making an evaluation of nutrient status. General boron deficiency signs for some fruit and vegetable crops are as follows:

- Leaves frequently misshapen and crinkled, thick and brittle, white, irregular spots between veins.
- Growing tips of buds die, with bushy growth near tips, extension growth inhibited with shortened internodes.
- Water-soaked, necrotic spots or cavities in beet and other root crops and in the pith of stems.

- Fruit small and poorly formed, often with corky nodules and lesions.
- Low seed production due to incomplete fertilization.

Figure 3. Boron deficiency symptoms on leaves.
Source: http://www.haifa-group.com

Figure 3. Necrosis at the tips and chlorosis beginning between the veins of Valencia orange leaves due to excessive boron.
Source: http://www.haifa-group.com

Types of fertilizers

As aforementioned, Studies on B fertilization have shown that the limits between deficiency and toxicity are very narrow and that applications of B can be extremely toxic to some plants at concentrations only slightly above optimum for others (Gupta 1983).

Boron deficiency has been recognized as one of the most common micronutrient problems in agriculture. Where soil levels are inadequate to maintain plant B requirements, application of B fertilizers will enhance crop yield and quality. Some of the inorganic sources of B fertilizer used commercially include borax, boric acid, borate-65 and solubor. Organic sources include composts, raw sewage and effluent. A list of common fertilizers is shown in Table 1.

Table 1. Boron Compounds Commonly Used as Fertilizers. Source: Gupta et al., 1985.

Name	Chemical Formula	Solubility in Water	% B
Borax	$Na_2B_4O_7.10H_2O$	Soluble	11.3
Fertilizer borate	$Na_2B_4O_7.5H_2O$	Soluble	14.3–14.9
Anhydrous borax	$Na_2B_4O_7$	Soluble	21.5
Solubor	$Na_2B_8O_{13}.4H_2O$	Very soluble	20.5
Boric acid	H_3BO_3	Soluble	17.5
Colemanite	$Ca_2B_6O_{11}.5H_2O$	Slightly soluble	15.8
Ulexite	$NaCaB_5O_9.8H_2O$	Slightly soluble	13.3
Boron frits	Boric oxide glass	Very slightly soluble	2.0–11.0

Recommended rates of boron application generally range from 0.25 to 3 kg ha^{-1}, depending on crop requirements and methods of application.

Boron is generally applied directly to the soil or by foliar spraying. Generally, soil and foliar applications of B are effective for crops. Soil applications are generally used for applying boron to field crops, but foliar sprays are more common on perennial crops such as fruit trees. Soil applications of B made alone or with mixed fertilizers are common and most data on B uptake have been obtained with B-containing fertilizers applied broadcast or in bands. Foliar application rates are usually about 50% lower than soil application rates.

Foliar applications, besides resulting in higher B uptake, could be used to advantage if a farmer omitted the addition of B in the N-P-K bulk fertilizer or if B-deficiency is suspected. Foliar applications during early growth result in greater absorption of B than applications made at later growth stages.

Recommended boron rates and methods of application for some commonly fertilized crops were summarized by Mortvedt and Woodruff (1993).

6.2. Boron toxicity and irrigation management.

Boron toxicity is a worldwide problem that limits significantly crop yield in agricultural areas of Australia, North Africa, and West Asia characterized by alkaline and saline soils together with a low rainfall and very scarce leaching. In addition, B-rich soils also occur as a consequence of over-fertilization and/or irrigation with water containing high levels of B (Nable et al. 1997). Therefore, B toxicity can be an important disorder in arid and semi-arid environments throughout the world.

Boron does not accumulate uniformly in leaves, but typically concentrates in leaf tips of monocotyledons and leaf margins of dicotyledons, where boron toxicity symptoms first appear. The results of Shelp et al. (1995) have also shown that younger leaves contain less boron than mature leaves; the authors assumed that the boron supply for mature leaves is delivered principally via the xylem. Boron accumulation usually follows a pattern from leaf base to tip in many plants and this leads to typical toxicity symptoms on older leaves which appear as marginal or tip chlorosis or both and necrosis. Therefore, the fact that boron deficiency exhibits in the younger leaves and not in the older leaves can be explained by the fact that the boron concentration is higher in the older leaves than in the younger leaves (Gupta, 2008)

Although the physiological basis for B toxicity is not clear enough, three main causes have been proposed taking into account our knowledge on B chemistry, that is, the ability of B to bind compounds with two hydroxyl groups in the cis-configuration: (1) alteration of cell wall structure, (2) metabolic disruption by binding to the ribose moieties of molecules such as ATP, NADH or NADPH, and (3) disruption of cell division and development by binding to ribose, either as the free sugar or within RNA (Camacho-Cristobal et al., 2008; Nable et. al. 1997). Accordingly a reduced growth of shoots and roots is typical of plants exposed to high B levels.

Moreover, the characteristics of B injury are crop specific and are related to plant’s ability to mobilize this element (Grattan et al., 2015). Although in most plant species B is thought to be immobile, accumulating in the margins and tips of the oldest leaves (marginal and tip chlorosis that is quickly followed by necrosis), B can be remobilized by some species like almond, apple, and most stone fruits by complexing with polyols (sugar alcohols). For these crops, B concentrations are higher in younger tissue than in older tissue and injury is expressed in the young developing tissue. This likely explains symptoms such as reduced bud formation and twig dieback. Boron-immobile plants such as Citrus spp., pistachio, and walnut do not have high concentrations of polyols and the B concentrates in older leaves. It is here where injury first develops.

Recent physiological and genetic studies have provided some understanding of genetic variation in the response of plants to high concentrations of B. Moreover, these studies have facilitated the breeding of tolerant genotypes for cultivation on high B soils. Considerable genetic variation in response to high B has been identified in a wide range of plant species, most of which share a similar tolerance mechanism – reduced uptake of B in both shoots and roots. The tolerance mechanism appears to be under the control of several major additive genes, and specific chromosomal locations have been identified for the genes in some species. Considerable success has been achieved in breeding for tolerance to B toxicity, a process that is greatly aided by the ease with which genotypic variation for this characteristic can be assessed and the range of methods available to screen breeding populations. (Nable et al., 1997).

In nature, B toxicity is not as widespread as B deficiency (Gupta et al., 1985). It occurs chiefly under three conditions: owing to its presence in soils inherently high in B or in which B has naturally accumulated; owing to its presence in irrigation water; or owing to accidental applications of too much boron in treating boron deficiency. Large additions of materials high in boron, for example, compost, can also result in boron toxicity in crops. Boron toxicity in arid and semiarid regions is frequently associated with saline soils, but most often it results from the use of high-boron irrigation waters (Gupta, 2008).

Dealing with B presence in irrigation water, few waters have enough B to injure plants directly. It is the concentration of B in the soil due to continued use and evapotranspiration that leads to the eventual toxicity problems. Because B tends to accumulate by adsorption in soil even when its concentration in the irrigation waters is low, it is important to know the eventual B concentration of the soil solution resulting from irrigation water with various B concentrations under differing management practices. The continued use of irrigation and concentration of boron in the soil due to evapotranspiration are the reasons for the eventual toxicity problems (Gupta et al., 1985).

When the plant uptake of B is small compared to the amounts applied in the water, the B concentration in the soil solution will increase with time. Eventually, however, an equilibrium will be reached when the amount of B added to the root zone by irrigation is equal to the amount removed from the root zone by the crop and by leaching. Thus, to prevent the continuous buildup of B in the root zone, a leaching fraction (LF) is essential. For efficient and continued crop production, the LF must be high enough to prevent the buildup of B in the root zone to a toxic level; but it must be low enough to prevent excessive waste of water.

Prior to reaching the equilibrium condition, the B levels that the plants are exposed to will be less than the equilibrium levels. Thus, for a long-term irrigation project, it is the equilibrium condition that will be of most concern. It is more difficult to predict the B concentration of the soil solution within the root zone during the transition period compared to at equilibrium. This difficulty stems from the complex B adsorption characteristics of soils.

Soil type is important since it influences the soil-B adsorption processes, which affect the soil solution B concentration. And the soil type can influence the extent by which leaching can occur. The climate is important since it dictates the amount of water the trees transpire and the amount of rainfall that leaches salts and B below the root zone. Irrigation management is critical since applying too much water is not economical or ecologically sound and applying too little can lead to accumulation of salts and B over the long term regardless of the concentration in the irrigation water. Therefore all these factors need to be considered when analyzing B toxicity problem related to irrigation water quality and management (Grattan et al, 2015).

The relationship between B concentration in the irrigation water (B_w) and that in the soil solution (B_{ss}) is crucial when applying guideline with B concentration limits, which usually refers to B_{ss}. The relationship describe by Jame et al. (1982) [B_{ss} = (1.4–1.9) B_w, when LF equal 25%] is a fairly good practical recommendation (Grattan et al., 2015).

The potentially toxic boron can be reduced by leaching in a manner similar to that for salinity, but the depth of water required varies with the toxic ion and may in some cases become excessive. If leaching becomes excessive, many growers change to a more tolerant crop. Increasing the leaching or changing crops in an attempt to live with the higher levels of toxic ions may require extensive changes in the farming system. In cases where the toxicity problem is not too severe, relatively minor changes in farm cultural practices can minimize the impact. Alternatives for management of toxicity and to maintain production are leaching, crop selection, cultural practices, blending water supplies (if an alternative water supply is available, but not fully adequate in quantity or quality, a blend of waters may offer an overall improvement in quality and reduce the potential toxicity problem).

7. Boron Concentration in Crops

Dealing with boron level in crops, there is a range in values rather than one definite number that could be considered as critical. The *critical level* of a nutrient has been defined as the concentration occurring in a specific plant part at 90% of the maximum yield. The concept is equally valid where crop quality is the main concern rather than yield. The ratio of toxic level to adequate level of boron is smaller than that for most other nutrient elements.

Thus, excessive or deficient levels could be encountered in a crop during a single season. This occurrence emphasizes the fact that a critical value used to indicate the status of boron in crops would be unsuitable. In many cases the values referred to in this section overlap the deficiency and sufficiency ranges. The deficient, sufficient, and toxic boron levels for specific crops as reported by Gupta (2008) are given in Table 2.

Table 2. Deficiency, Sufficiency, and Toxicity Levels of Boron in Horticultural Crops. Adapted from Gupta (2008).

Crop	**Plant Part Sampled**	**mg B kg^{-1} in Dry Matter**		
		Deficiency	**Sufficiency**	**Toxicity**
Beans	43-d-old plants		12	>160
Kidney beans	Plants cut 50 mm above the soil		44	132
Faba bean	Whole plants		25-100	
Snap beans	Pods		28	43
	Recently matured leaves a prebloom			109
	Plant tops at prebloom	<12	42	>125
Broccoli	Leaves		70	
	Leaf tissue when 5% heads formed	2-9	10-71	
Brussels sprouts	Leaf tissue when sprouts begin to form	6-10	13-101	
	Leaf tissue when sprouts begin to form			161
Cabbage	Mature leaf blade prior to head formation			132
Carrots	Mature leaf lamina	<16	32-103	175-307
	Leaves	18		
	Whole plants at swelling of roots	<28	54	
Cauliflower	Whole tops before the appearance of curd	3	12-23	
	Leaves	23	36	
	Leaf tissue when 5% heads formed	4-9	11-97	
Cucumber	Mature leaves 2 weeks after first picking	<20	40-120	>300
Potatoes	32-d-old plants		12	>180
	Fully developed first leaf 75 d after planting	<15	21-50	>50
Radish	Whole plant when roots began to swell	<9	96-217	
Strawberries	Old and young leaves at active growth stage			123
Tomatoes	Mature young leaves from top of the plant	<10	30-75	>200
	63-d-old plants			>125
	Whole plants when 15 cm tall	>12	51-88	<172
	Whole plant			10-20

An examination of tolerance to B toxicity among diverse plants species reveals that the B concentration in leaves and shoots are usually not closely related to B tolerance (Eaton, 1944; Francois and Clark, 1979).

Most crop toxicity symptoms occur after boron concentrations in leaf blades exceed 250–300 mg kg^{-1} (dry weight) but not all sensitive crops accumulate boron in leaf blades. For example, stone fruits (peaches, plums, almonds, etc.), and pome fruits (apples, pears and others) are easily damaged by boron but they do not accumulate sufficient boron in the leaf tissue for leaf analysis to be a reliable diagnostic test. With these crops, boron excess must be confirmed from soil and water analyses, tree symptoms and growth characteristics.

8. Boron in desalinated seawater

The use of recycled wastewaters and desalinated seawater has considerable potential as a sustained future-supply of supplemental irrigation water, increasing dramatically in many arid and semi-arid climates all over the world including China, the Middle East, Mediterranean countries, Australia, North and South America and Africa. Therefore, there is an increasing Interest in B levels in these irrigation waters, which could content concentration of B toxic for sensitive crops.

Desalinated Seawater (DSW) usually presents a high B content due to (1) the high boron concentration in seawater (4.5 to 6 mg L^{-1}) in relation to natural waters (0 to 1.5 mg L^{-1}); and (2) the high boron membrane passage in the reverse osmosis processes (Martínez Alvarez et al., 2017) . As a result, DSW boron content is higher than in natural waters, so that irrigation with DSW can increase soil boron content substantially, triggering toxicity problems and leading to yields reductions in sensitive crops. This effect has already been found in Israel with B^{3+} concentrations of 0.6, 1.2 and 2.0 mg L^{-1} (Martínez Alvarez et al., 2017).

Therefore specific technologies for B^{3+} reduction must be considered in SWDPs supplying agricultural use, such as a second reverse osmosis pass or the use of B^{3+} selective resins for ion exchange processes, although this entails increased investment and operational costs per cubic metre.

The guideline value for B content in potable water issued by the World Health Organisation was 0.5 mg L^{-1}, so the regulations with relation to B content in DSW followed this standard in most countries. Current guideline value for B content in potable water issued by the World Health Organisation was 2.4 mg L^{-1}. 0.5 mg L^{-1} is an acceptable threshold value for DSW agricultural use, since only extremely sensitive crops would be affected. Whereas the Israeli recommendation (0.3 mg L^{-1}) would protect even the most sensitive crops, the requirement for DSW in Spain was 1 mg L^{-1} (the potable water standard in Spain).

Boron content in Israeli SWDPs (Ashkelon = 0.2-0.3 mg L^{-1} and Hedera = 0.2-0.4 mg L^{-1}) is considerably lower than in Spanish ones, in agreement with their more stringent regulations. Values in Spain (Escombreras = 0.8-1.0 mg L^{-1} and Águilas = 1 mg L^{-1}) which could be excessive for sensitive crops.

It should be noted that higher water temperature produces a higher boron membrane passage, so B phytotoxicity should be assessed with annual mean and variation range values of boron concentration, rather than punctual measurements.

The majority of surface waters have B concentrations of 0. 1-0.3 mg L^{-1}; well waters are more variable in their B content and often have excessive amounts.

9. Tolerance to boron in crops

Determining the tolerance limits for B in the irrigation water for crops is a complex process. There are a number of factors based on crop variety, soil type, water chemistry, climatic conditions, and management practices that all play an important role (Grattan et al., 2015). Regardless, the ultimate goal is to establish appropriate irrigation water quality limits for B that protect long-term use for irrigation of crops.

Much of the existing B tolerance data for crops were obtained from experiments conducted during the 1920s and 1930s by Haas (1929) and Eaton (1935, 1944). These data provided threshold tolerance limits for more than 40 different crops. While very useful, Eaton's experimental data cannot be fitted to any reliable growth–response function for most crops like those for salinity. The thresholds indicate maximum permissible concentrations in the soil water where foliar injury occurs and is not related to fruit yield or quality.

One of the criteria was proposed by Wilcox (1960) and adopted by Ayers and Westcot (1976, 1985, 1994) (Table 3).

Table 3. Relative Boron Tolerance of agricultural crops. Source: Ayers and Westcot (1994). The authors indicate that values refer to maximum concentration tolerated in soil-water or saturation extract without yield or vegetative growth reductions.

Very Sensitive (<0.5 mg/l)	
Lemon	*Citrus limon*
Blackberry	*Rubus spp.*
Sensitive (0.5 – 0.75 mg/l)	
Avocado	*Persea americana*
Grapefruit	*Citrus X paradisi*
Orange	*Citrus sinensis*
Apricot	*Prunus armeniaca*
Peach	*Prunus persica*
Cherry	*Prunus avium*
Plum	*Prunus domestica*
Persimmon	*Diospyros kaki*
Fig, kadota	*Ficus carica*
Grape	*Vitis vinifera*
Walnut	*Juglans regia*
Pecan	*Carya illinoiensis*
Cowpea	*Vigna unguiculata*
Onion	*Allium cepa*
Sensitive (0.75 – 1.0 mg/l)	
Garlic	*Allium sativum*
Sweet potato	*Ipomoea batatas*
Wheat	*Triticum eastivum*
Barley	*Hordeum vulgare*
Sunflower	*Helianthus annuus*
Bean, mung	*Vigna radiata*
Sesame	*Sesamum indicum*
Lupine	*Lupinus hartwegii*
Strawberry	*Fragaria spp.*

Artichoke, Jerusalem	*Helianthus tuberosus*
Bean, kidney	*Phaseolus vulgaris*
Bean, lima	*Phaseolus lunatus*
Groundnut/Peanut	*Arachis hypogaea*
Moderately Sensitive (1.0 – 2.0 mg/l)	
Pepper, red	*Capsicum annuum*
Pea	*Pisum sativa*
Carrot	*Daucus carota*
Radish	*Raphanus sativus*
Potato	*Solanum tuberosum*
Cucumber	*Cucumis sativus*
Moderately Tolerant (2.0 – 4.0 mg/l)	
Lettuce	*Lactuca sativa*
Cabbage	*Brassica oleracea capitata*
Celery	*Apium graveolens*
Turnip	*Brassica rapa*
Bluegrass, Kentucky	*Poa pratensis*
Oats	*Avena sativa*
Maize	*Zea mays*
Artichoke	*Cynara scolymus*
Tobacco	*Nicotiana tabacum*
Mustard	*Brassica juncea*
Clover, sweet	*Melilotus indica*
Squash	*Cucurbita pepo*
Muskmelon	*Cucumis melo*
Tolerant (4.0 – 6.0 mg/l)	
Sorghum	*Sorghum bicolor*
Tomato	*Lycopersicon lycopersicum*
Alfalfa	*Medicago sativa*
Vetch, purple	*Vicia benghalensis*
Parsley	*Petroselinum crispum*
Beet, red	*Beta vulgaris*
Sugarbeet	*Beta vulgaris*
Very Tolerant (6.0 – 15.0 mg/l)	
Cotton	*Gossypium hirsutum*
Asparagus	*Asparagus officinalis*

It seems clear that the concentrations cited in Eaton's reports are the concentrations of the culture solution he used to irrigate his crops; therefore, they should represent irrigation water concentrations (B_w). However, since the sand cultures used in his experiments were leached every day with more than one pore volume of water, it would be expected that the soil solution concentrations were identical with irrigation water concentrations. Therefore, to transpose B concentrations established by Eaton from his sand culture studies to the field, Eaton's values should be interpreted as B concentration in the soil solution (B_{ss}) (Gupta et al., 1985).

Ayers and Westcot (1985) equated the upper limits for B in the soil water (B_{ss}) to that of the irrigation water (B_w). These authors state that the “maximum concentrations (of boron) in the irrigation water are approximately equal to these values (the maximum soil water concentration) or slightly less”. While the authors recognized the difference between B_w and soil water B_{ss}, and the complex relationship between them, they decided to equate one with the other. However, as aforementioned, the relationship describe by Jame et al. (1982) [B_{ss} = (1.4–1.9) B_w, when LF equal 25%] is a fairly good practical recommendation (Grattan et al., 2015).

Recent studies (Grattan et al., 2015) suggest that the existing B tolerance guidelines, which refer to the B_{ss} concentration in soil water, should be adjusted downwards if they refer to the B_w. Taking into account this reduction in the B tolerance threshold when referring to irrigation water, even the most sensitive seasonal vegetable crops (e.g. onion, garlic, sweet potato, broccoli, red pepper or carrot) could be affected if direct irrigation with desalinated seawater with a B concentration of 1 mg L^{-1} is practised.

Boron’s affinity for the soil is dependent upon many characteristics including, among others, clay content, texture, organic matter, pH, soil water content and temperature. Over the short term, much higher B concentrations can be used for irrigation than the guidelines indicate because the B in the soil water becomes adsorbed onto the soil thereby keeping the solution concentration lower (Gupta et al., 1985). However, over the long term, soils may eventually become saturated with B so additional irrigation can cause B concentrations to increase in the soil solution. Therefore, a lag time exists both in terms of the time it takes B concentrations to increase in the soil water and the time and amount of water it takes to reclaim soils once they become B-affected (Grieve et al., 2012).

10. Citrus tolerance to boron

Studies have shown that Citrus spp. is one of the most sensitive crops to B and that tolerance varies among Citrus species and rootstocks (Grieve et al., 2012). However, many of these research studies upon which current water quality guidelines are based, were conducted over 60 years ago. Although these studies are scientifically sound and continue to be cited regularly in the literature, additional studies have been conducted more recently.

Unlike most agricultural crops, Citrus spp. is among the most sensitive to B and salinity. Grattan et al. (2015) conducted an extensive review of the literature on Citrus spp. tolerance to B. They concluded that, since salinity and B stresses often occur together, the overall suitability may depend on interactive abiotic stresses as well. The combination and potential interaction of these constituents, combined with the soil and climatic conditions, can affect the overall suitability of B in irrigation water over the long-term.

Table3 contains the B tolerance limits for Citrus spp. These limits indicate that orange and grapefruit can only tolerate 0.50–0.75 mg/L of B in the soil water (B_{ss}) before injury occurs. Lemon, on the other hand, can be injured when B_{ss} is less than 0.5 mg/L. It is therefore one of the most sensitive crops to B toxicity. Grattan et al. (2015) also stated that new research does not provide any more information to suggest that the existing B tolerance guidelines for orange (0.50–0.75 mg/L in the soil solution, B_{ss}) should be adjusted upwards or downwards. The challenge comes in determining the maximum B concentration in the irrigation water (B_w) that would result in these B_{ss} tolerance values. Two steady-state approaches that were used suggest that the maximum B_w for the protection of orange falls between 0.3 and 0.5 mg/L over the long term provided good water management, adequate leaching and no additional stresses are affecting the tree. For lemon, maximum B_w concentrations would be less.

11. Guideline limits for boron in irrigation water

A summary of norms and recommendations established for boron concentration in irrigation waters are shown in the following table.

Value, depending on plant sensitivity	Place or institution	Date	Reference
0,5 – 0,6 mg/L	Canadá	1987	CCREM (1987) CCME (1999)
0,75 – 2,0 mg/L	Ontario, Canadá	1984	Ontario Ministry of the Environment (1984)
0,5 – 2,0 mg/L	Manitota, Canadá	1983	Williamson (1983)
0,5 – 6,0 mg/L	Alberta, Canadá	1999	Alberta Environment (1999)
0,3 – 2,0 mg/L	Australia	1974	Hart (1974)
0,5 mg/L	Australia	1999	Australia and New Zealand Environment and Conservation Council (1999)
0,3 – 1,25 mg/L for sensitive crops	USA	1987	Sprague (1972), Papachristou et al (1987), EPA (1975) in Eisler (1990)
0,65 – 2,5 mg/L	USA	1987	Sprague (1972), Papachristou et al (1987), EPA (1975) in Eisler (1990)
0,3 – 1,0 mg/L Sensitive 1 – 2 mg/L Semitolerant 2 – 4 mg/L Tolerent	USA	1935	Eaton (1935) in Butterwick et
0,5 – 1,0 mg/L 1, - 2 mg/L 2 – 10 mg/L	Food and Agriculture Organization (UNESCO)	1976	Gupta (1983) in Butterwick et al (1989)
0,7 mg/L	Israel	Gupta (1983) in Butterwick et al (1989)	0,7 mg/L
< 0,5 mg/L No Risk 0,5 – 2,0 mg/L Medium Risk 2,0 – 10,0 mg/L High risk	Food and Agriculture Organization	1976	Ayers et al (1976 in Butterwick et al (1989)
1,0 mg/L	Arizona, USA	1986	EPA (1988)
0,75 mg/L (promedio en 30 días)	Colorado, USA	1986	EPA (1988)
0,75 mg/L	Florida, USA	1986	EPA (1988)
0,75 mg/L	Kansas, USA	1987	EPA (1988)
0,75 mg/L	Missouri, USA	1988	EPA (1988)
0,5 mg/L	Minnesota, USA	1982	EPA (1988)

The Canadian Council of Resource and Environment Ministers (CCREM) (1987) suggests that the concentration of boron in irrigation waters should not exceed 0.5 mg L^{-1} for sensitive plants, but could be as high as 6 mg L^{-1} for tolerant plants. The CCREM, accepted as the norm for boron that developed in 1987, since the most recent data do not present evidence to make changes. The Ontario Ministry of the Environment (1984) recommended a value of 0.75 mg L^{-1} for irrigation water used continuously on all soils and 2.0 mg L^{-1} for irrigation water used more than 20 years on fine-textured soils of pH 6.0 to 8.5. In Manitoba, recommended a boron concentration not greater than 0.5 mg L^{-1} for irrigation waters used as the sole source of boron on the crop. In crops that receive natural precipitation and supplemental irrigation, the concentration should not be higher than 1.0 mg L^{-1}. For the protection of fine and medium-textured soils over 20 years, the concentration should not be higher than 2.0 mg L^{-1}. Alberta Environment (1999) adopted the values placed by CCREM (1987).

The US Environment Protection Agency developed three specific boron guidelines for irrigation water since the cultures show different sensitivity to this compound. For sensitive crops (citrus trees) the range is between 0.3 and 1.25 mg L^{-1} of B. For semi-tolerant crops, such as cereals and grains, the range is 0.67 to 2.5 mg L^{-1} of B and for tolerant compounds, which include most vegetables; the range is 1.0 to 4.0 mg L^{-1} of B. For large periods of irrigation on sensitive crops, the US EPA recommends a value of 0.75 mg L^{-1} (EPA, 1988).

Numerous US states have boron guide values between 0.75 to 1.0 mg L^{-1} of B. In Australia and New Zealand, it was recommended that the concentration of boron in irrigation waters should not exceed 0.5 mg L^{-1} (ANZECC, 2000).

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