Chapter 13

Soil salinity risk in a climate change scenario and its effect on crop yield

Alexandra Tomaz[1,2], Patrícia Palma[1,3], Paula Alvarenga[4] and Maria Conceição Gonçalves[5]
[1]School of Agriculture, Polytechnic Institute of Beja, Beja, Portugal [2]GeoBioTec, University NOVA of Lisbon, Caparica, Portugal [3]Earth Sciences Institute (ICT), University of Évora, Évora, Portugal [4]Linking Landscape, Environment, Agriculture and Food Research Unit (LEAF), School of Agriculture, University of Lisbon, Portugal [5]National Institute of Agricultural and Veterinary Research (INIAV), Oeiras, Portugal

CHAPTER OUTLINE

Climate Change and Soil Interactions. DOI: https://doi.org/10.1016/B978-0-12-818032-7.00013-8

13.1 OVERVIEW

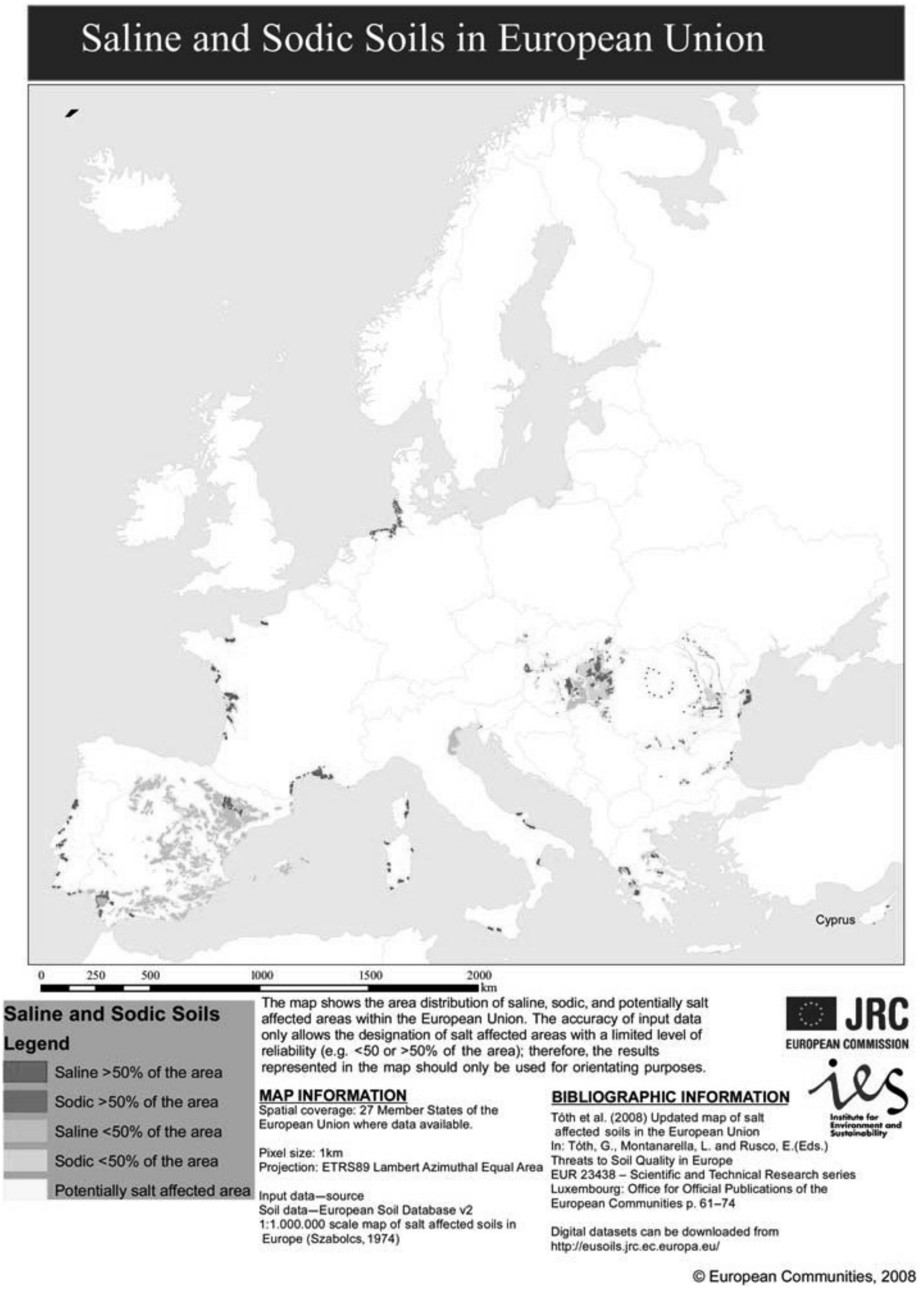
About 20% of the world's agricultural land is irrigated, producing 45% of food supply (Weil and Brady, 2016). Salt-affected soils occupy more than 20% of the global irrigated area; in some countries, salt-affected soils occur in more than half of the irrigated land (Qadir et al., 2014). Examples of past and present important salt-induced land degraded areas include the Aral sea Basin (Central Asia), the Indo-Gangetic Basin (India), the Indus Basin (Pakistan), the Yellow River Basin (China), the Euphrates Basin (Syria and Iraq), the Murray-Darling Basin (Australia), and the San Joaquim Valley (United States) (Qadir et al., 2014). These are all low rainfall regions, where annual potential evapotranspiration is higher than annual precipitation (Weil and Brady, 2016). The presence of salt-affected soils mostly in arid and semiarid regions occurs through a salt *evapo-concentration* process, as pure water evaporates from the soil and is lost by transpiration by vegetal covers, but salts remain in the soil (Aragües and Cerdá, 1998).

The accumulation of salts in the soil is due to the existence of a source of salts and to the insufficiency of precipitation and/or drainage that allows their leaching. Some of the causes are natural and others result from human-induced processes, namely through inadequate irrigation and drainage practices and the use of poor-quality irrigation water (Kibblewhite et al., 2008). Therefore, two types of salinization can be distinguished: primary (natural) salinization and secondary (anthropogenic) salinization. Natural salinization is mainly related to groundwater table from marine origin and/or tidal effects in coastal regions, the deposition of sea salts carried by the wind, seepage, ascending capillary flow from groundwater table as a consequence of evapotranspiration in arid and semiarid climate regions of the world, where annual precipitation is less than 250 mm; secondary (anthropogenic) salinization is caused by the use of improper or poorly adapted soils for the practice of irrigation (with low hydraulic conductivity and without drainage systems), irrigation with water rich in soluble salts, poor irrigation management (inadequate irrigation depths and irregular distribution of water, that can cause the rising of groundwater tables), intensive use of fertilizers or amendments (particularly under conditions of limited leaching), and the use of wastewater or saline products of industrial origin (Ghassemi et al., 1995). Moreover, extensive groundwater withdrawals, especially in coastal aquifers, lead to salt water intrusion and to the degradation of the quality of the irrigation water (Pisinaras et al., 2010). The importance of secondary salinization is likely to increase even further following the future extension of dryland areas and higher frequency of water shortage periods, as a result of climate change, and the consequent increase of irrigation needs (Williams, 1999).

Predicted impacts of climate change on soils include physical (water and wind erosion; loss of structure), biological (loss of biodiversity), biochemical (disruption in biochemical cycles), and chemical degradation (reduction in organic matter, acidification, salinization, and sodification) (Karmakar et al., 2016; Várallyay, 2010). Soil is a nonrenewable resource in that the degradation rates can be rapid, while the processes of formation and regeneration are extremely slow (EC, 2002). In the case of salinization and sodification, negative climate change impacts are likely to occur mainly in dry, drought-prone, and coastal regions, as a consequence of increased evapotranspiration and sea-level rise (Daliakopoulos et al., 2016; Iglesias et al., 2018; Karmakar et al., 2016; Szabolcs, 1990; Várallyay, 2010). Degradation of agricultural land is an ongoing process in the European countries, more pronounced in Eastern Europe and in the Mediterranean region, for climatic reasons (Fig. 13.1; Tóth et al., 2008). Salinization affects around 3.8 million ha in Europe. The most affected areas are Campania in Italy, the Ebro Valley in Spain, and the Great Alföld in Hungary, but also areas in Greece, Portugal, France, Slovakia, and Austria are affected (Commission of the European Communities, 2006).

According to EEA (2012; 2017), water resources are expected to decrease in Europe as a result of an increasing imbalance between water demand and water availability. Trnka et al. (2011), in a study to evaluate agroclimatic conditions in Europe under climate change, reported that the regions that will suffer the most from increases in dryness, will be the Southern and Southwestern Mediterranean regions, with sharp declines in the rainfed crop production potential, leading to the escalation in irrigation requirements.

The intensification of water scarcity due to global change impacts will lead to the increase in irrigation water requirements, and, therefore, to the need for the adoption of water sustainable management measures, like the augmentation of irrigation systems efficiency, the use of deficit irrigation strategies, or the agricultural use of marginal-quality water (Iglesias et al., 2018). However, these management options have the risk of contributing to soil and water salinity. The improvement in irrigation efficiency, identified as a key measure in agricultural management, will reduce salt leaching due to fewer volumes of applied water in the soil profile and, as a result, soil salinity will increase (Aragües and Cerdá, 1998;



The map shows the area distribution of saline, sodic, and potentially salt affected areas within the European Union. The accuracy of input data only allows the designation of salt affected areas with a limited level of reliability (e.g. <50 or >50% of the area); therefore, the results represented in the map should only be used for orientating purposes.

MAP INFORMATION

Spatial coverage: 27 Member States of the European Union where data available.

Pixel size: 1km
Projection: ETRS89 Lambert Azimuthal Equal Area

Input data—source
Soil data—European Soil Database v2
1:1.000.000 scale map of salt affected soils in Europe (Szabolcs, 1974)

BIBLIOGRAPHIC INFORMATION

Tóth et al. (2008) Updated map of salt affected soils in the European Union
In: Tóth, G., Montanarella, L. and Rusco, E.(Eds.)
Threats to Soil Quality in Europe
EUR 23438 – Scientific and Technical Research series
Luxembourg: Office for Official Publications of the European Communities p. 61–74

Digital datasets can be downloaded from
http://eusoils.jrc.ec.europa.eu/

© European Communities, 2008

■ **FIGURE 13.1** Saline, sodic, and potentially salt-affected areas within the European Union. *From Tóth, G., Montanarella, L., Rusco, E., 2008. Threats to Soil Quality in Europe. Joint Research Centre, Institute for Environment and Sustainability. Office for Official Publications of the European Communities, EUR Scientific and Technical Research Series, Luxembourg. Available from: <http://eusoils.jrc.ec.europa.eu/>.*

Aragües et al., 2011; Hoffman et al., 1990). In the case of deficit irrigation strategies, although they can save water, they can also contribute to soil salinization and sodification whenever irrigation is made with poor-quality water (Aragües et al., 2014a; 2014b). The use of wastewater from urban areas, or of saline and sodic water from agricultural drainage or groundwater, requires a vigilant management to avoid harmful impacts on human health and/or soil degradation (Qadir et al., 2007; Rhoades, 1977; Rhoades et al., 1992; Tanji and Kielen, 2002).

Increased demand for irrigation water is leading to the implementation of irrigation plans with subsequent land-use changes and increased risks of soil salinization and sodification, primarily by (1) mobilizing natural salts that accumulate in the subsurface in many semiarid regions; (2) dissolving minerals, such as gypsum; (3) raising water tables, which results in salinization through ET; (4) adding mineral fertilizers, with ammonium, nitrate or phosphate; and (5) transport of applied fertilizers in more humid settings (Chotpantarat and Boonkaewwan, 2018; Jolly et al., 2001; Merchán et al., 2013; Scanlon et al., 2005; 2007; Zalidis et al., 2002).

To select the appropriate sustainable strategies to mitigate soil salinization risks under climate change, it is important to understand soil salinization processes as well as crop responses to salinity, and their interactions with a changing environment.

In this chapter, the following subjects will be addressed: (1) soil salinization processes; (2) crops responses to salinity in a climate change scenario; (3) water quality for irrigation criteria; (4) modeling of soil salinity; (5) salinity management. At the end of the chapter, a case study will be presented with an evaluation of water quality for irrigation, and its potential effects on soil structure and on crop yields in a Mediterranean irrigated area.

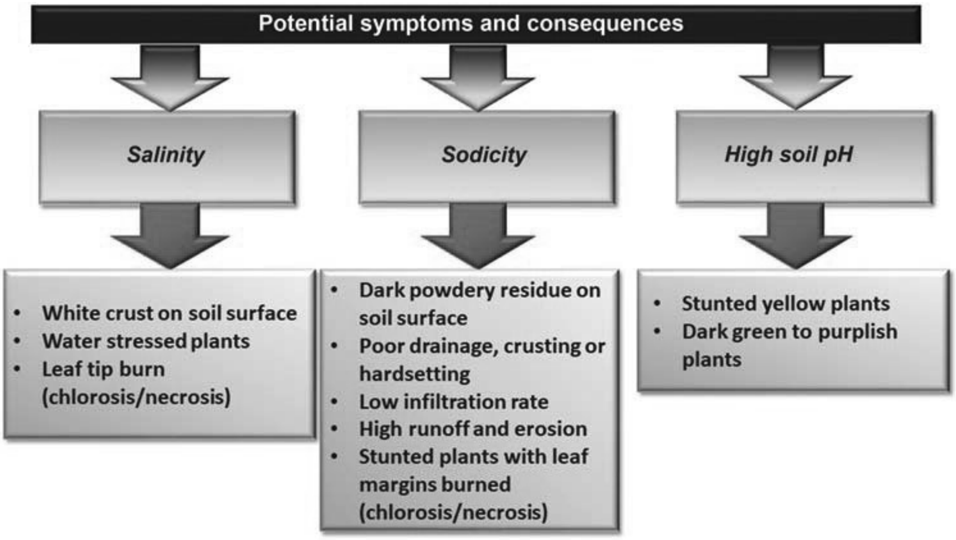
13.2 SOIL SALINIZATION PROCESSES

In a broader sense, soil salinization is the accumulation of free salts in the soil to such a degree that it leads to a soil degradation process, affecting plant productivity and the environment (Pisinaras et al., 2010). The accumulated salts include sodium (Na^+), usually the most common, calcium (Ca^{2+}), magnesium (Mg^{2+}), and potassium (K^+), especially in the form of chlorides (Cl^-), but also sulfates (SO_4^{2-}).

However, soil salinization is a term that can be used comprehensively for different forms of salinity, including not only saline soils, but also, more specifically, sodic and alkaline soils (Bloem et al., 2012; Daliakopoulos et al., 2016), and it is important to clarify the terms and the definitions that are used. Saline soils refer to soils with elevated salt concentrations, irrespective of their type, while the other definitions refer to disturbances attributed to some specific ions. Sodic (also termed alkali) soils refer to soils with a predominance of monovalent ions (Na^+, K^+, especially Na^+ due to its abundance) over divalent cations (Ca^{2+}, Mg^{2+}) (Bloem et al., 2012), while alkaline soils are soils with high soil pH, often due to high carbonate, CO_3^{2-}, and/or bicarbonate, HCO_3^-, concentrations (Bloem et al., 2012; Daliakopoulos et al., 2016). The three forms of soil salinization may be related, but that depends on the case (Bloem et al., 2012), and the processes by which each of these forms of soil salinization affects soil properties are different, and so are the consequences (Fig. 13.2). Although for saline soils the large osmotic potential values on soil solution hinder plant transpiration, diminishing water availability to plant, in sodic soils, the consequences are related to soil structural degradation, caused by a predominance of Na^+ over divalent ions (Bloem et al., 2012). As soil pH affects directly elements availability to plant, the consequences of alkaline soils are usually related to toxicity and deficiency effects, a problem that can appear isolated or may be present in saline or sodic soils (Bloem et al., 2012); however, an alkaline soil is more likely to be saline (Daliakopoulos et al., 2016).

13.2.1 Soil salinity

Three major impacts can arise in saline soils, as crops could be affected: (1) by specific ionic toxicity; (2) by the ionic imbalance of the soil solution, reducing nutrient uptake; and (3) by the high osmotic potential of the soil solution, which reduces the soil water extraction capacity of the plants (Ayers and Westcot, 1985; Pisinaras et al., 2010). In fact, the higher the concentration of salts in the soil solution, the higher the osmotic potential, and the higher the effort that the plant must make to take in water without salts, which will directly affect its growth (Pisinaras et al., 2010). The symptoms of plants affected by saline soils are like those of plants submitted to water deficit when, in fact, water availability is not the problem, the problem is the water salt concentration. There are several field symptoms of soil affected by salinity, such as the absence of vegetation and other sensitive bioindicators, the presence of salt-tolerant plant species, the presence of areas that take longer to dry, or the presence of unnatural color soil crusts or stains (white or dark) (Daliakopoulos et al., 2016). However, these visual effects must be further investigated, usually with physical and chemical indicators, which are usually used to assess soil salinity extension.



■ **FIGURE 13.2** Potential symptoms and consequences of soil salinity, sodicity, and high soil pH. *Adapted from Daliakopoulos, I.N., Tsanis, I.K., Koutroulis, A., Kourgialas, N.N., Varouchakis, A.E., Karatzas, G.P., et al., 2016. The threat of soil salinity: a European scale review. Sci. Total Environ. 573, 727—739. Available from: <https://doi.org/10.1016/j.scitotenv.2016.08.177>.*

13.2.2 **Soil salinity indicators**

Several parameters could be used to evaluate soil salinity, as they are surrogate measures of soluble salt content, and can be interconverted, given their good correlation. The most common is the measurement of the electrical conductivity (EC), expressed in deci-Siemens per meter (dS m^{-1}), at 25°C, to avoid the influence of temperature, which determines the concentration of all soluble salts in soil or water (Daliakopoulos et al., 2016). The most reliable soluble salt determinations are carried out in aqueous extracts of the soil, and the ideal extract would be obtained at the soil field capacity (EC_f), as this provides the more realistic salt concentration in the soil. However, the difficulty of obtaining such extracts makes impracticable its use in routine analyzes (Richards, 1954). The most frequently used extract in soil salinity studies, and the standard to which the others are usually compared, is the saturation paste extract (EC_e), obtained from a saturated soil paste (Bresler et al., 1982). It has the advantage of being an easy and reproducible preparation method, and is still relatively close to the range of field moisture content, with which it has some relation, as in many soils the water content of the saturated paste is approximately the double from the field capacity, and the quadruple from the wilting coefficient (Richards, 1954). The same author

(Richards, 1954) proposed EC_e ranges to classify soil in different salinity classes, which can vary from negligible effects on crops, to very strong effects, expecting only reasonable yields using very tolerant crops (Table 13.1). However, sometimes 1:1, 1:2, or 1:5 extracts are used (Weil and Brady, 2016), with the first closer to the saturated paste conditions in certain clayey soils. It should be noted that not only the concentration but also the ionic composition of these extracts is affected by the water/soil ratio. Some authors have derived relations between the EC values obtained using these 1:n extracts and EC_e values, which allow the use of Table 13.1 to classify the salinity hazard of a soil (Daliakopoulos et al., 2016).

In fact, the most direct analytical strategy to evaluate soil salinity would be the measurement of the total dissolved solids (TDSs) in the saturated soil paste extract, which could be done by gravimetry, weighing the salt residue obtained after evaporating the water from the extract, at 180°C to ensure that water of hydration is removed from the salt residue (Weil and Brady, 2016). However, as it is highly time- and energy-consuming measurement, TDSs are rarely obtained by actual evaporation, rather they are obtained from the EC_e measurement. EC_e shows a high positive correlation with the TDS and with the osmotic potential of the aqueous extracts of the soil. The following relations are often used:

$$\mathrm{TDS} = \alpha \cdot \mathrm{EC_e} \tag{13.1}$$

where TDS is the total dissolved solids (g L^{-1}), and α takes on the value of 0.85 to extracts that contain mainly Ca^{2+} and SO_4^{2-}, 0.64 to extracts that contain mainly Ca^{2+}, SO_4^{2-}, Na^+, and Cl^-, and 0.48 to those that contain mainly NaCl (Keren, 2000).

Table 13.1 Soil Salinity Classes Considering the Electrical Conductivity of the Soil Saturated Paste Extract (EC_e), and the Expected Effects on Crop Yield.

EC_e (dS m^{-1})	Class	Effect
0–2	Nonsaline	Negligible
2–4	Slightly saline	Yield reduction of very salt-sensitive crops
4–8	Moderately saline	Yield reduction of many crops
8–16	Strongly saline	Normal yields for salt-tolerant crops only
>16	Very strongly saline	Reasonable crop yield for very salt-tolerant crops only

Adapted from Richards, L.A., 1954. Diagnosis and Improvement of Saline and Alkali Soils. Washington, USDA Handbook 60.

Another salinity risk indicator, which can be predicted from the EC_e measurement, is the soil osmotic potential (Ψ_o; MPa):

$$\Psi_o = -0.036 \cdot EC_e \tag{13.2}$$

From Eq. (13.2) it can be deduced that a soil with an EC_e of about 20 dS m^{-1}, corresponding to a value of about 40 dS m^{-1} at field capacity (Richards, 1954), has practically no water available for the plants, as the osmotic potential of the water in the soil at its field capacity approaches 1.5 MPa, which is the potential considered equivalent to the permanent wilting point.

Besides EC_e, the more common measurement in the saturation paste for soil salinity diagnosis are the soluble cations (Ca^{2+}, Mg^{2+}, K^+, Na^+), and anions ($CO_3{}^{2-}$, $HCO_3{}^-$, $SO_4{}^{2-}$, and Cl^-), which are used to assess specific soil salinization indicators, for instance, sodicity risk.

Nowadays, with the advances in instrumentation, it is possible to measure bulk soil conductivity in the field, with a fast, simple, and practical technique, which lowers the costs, allowing the increase in the number of measurements for the same area. The EC value that is measured is the apparent electrical conductivity (EC_a), which can be correlated with EC_e (Weil and Brady, 2016), as well as with other soil physicochemical properties that influences soil conductivity, namely, soluble salts, clay content and mineralogy, soil water content, bulk density, organic matter, and soil temperature (Corwin and Lesch, 2005). The apparatus is equipped with electrodes, which are inserted in the soil with a certain distance between them, which conditions the depth to which the electrodes sense the EC_a. Based on this technique, there are already commercialized mobile apparatus, with integrated geopositioning system, which generate a continuous readout of EC_a in the field, allowing for the characterization of the spatial variability of the main soil physical variables, for the determination of potential management zones and for the generation of production maps with EC_a values (Moral et al., 2009). These maps can be used for a variety of soil management strategies, as part of the so-called precision agriculture (Corwin and Lesch, 2005; Moral et al., 2009; Weil and Brady, 2016). Another technique that allows for rapid field measurement of EC_a is based on electromagnetic (EM) induction of electrical current in the soil, the level of which is related to EC, that is, with soil salinity (Weil and Brady, 2016; Farsamian et al., 2019). This measurement is performed with an EM instrument (Fig. 13.3) that generates a magnetic field within the soil that induces electric currents whose values are related with the soil EC, allowing for measurements in the soil profile without probing the soil (Corwin and Lesch, 2005; Weil and Brady, 2016).

■ **FIGURE 13.3** Electromagnetic induction instrument for the determination of bulk electrical conductivity (EM38, Geonics Limited).

13.2.3 Soil sodicity

Salt-affected soils adversely affect plants not only because of the total concentration of salts in the soil solution (salinity) but also due to the relative concentration of specific cations, especially Na^+ (sodicity). In fact, each soil type has its own capacity to adsorb cations of dissolved salts (e.g., Na^+, K^+, Ca^{2+}, Mg^{2+}). This process involves an equilibrium between soil colloids, mineral and organic, negatively charged, and the soil solution, which depends mainly on the relative concentrations of each cation in the soil solution and on the exchange complex, as well as on the size and energy level of the cations involved (Daliakopoulos et al., 2016).

Sodification is the process by which the Na^+ ion gains preponderance in the soil exchange complex, compared to Ca^{2+} and Mg^{2+}, which will cause deterioration of soil physical properties through the dispersion of the soil aggregates. If a larger number of monovalent ions, Na^+, are available to be exchanged by divalent ions, Ca^{2+} and Mg^{2+}, the aggregate stability is weakened because the Na^+ radius is larger than the radius of Mg^{2+}, and similar to Ca^{2+} radius, with a lower capacity to compensate the negative charges of the soil colloids. A net negative charge will appear, and dispersion will occur (Daliakopoulos et al., 2016; Pisinaras et al., 2010; Weil and Brady, 2016).

In sodic soils, high levels of exchangeable Na^+ favor the degradation of the soil structure. The accumulation of this dispersive cation promotes clay expansion and/or dispersion, modifying soil pore geometry that affects soil hydraulic conductivity, water retention, and crop productivity (Keren, 2000).

It is commonly accepted that, when more than 15% of the cation exchange capacity sites on clays are occupied by Na^+, and when the total EC in the soil solution is low, dispersion will take place (Pisinaras et al., 2010).

Degradation of the soil structure can also be caused by extremely low Ca^{2+} content. In fact, the application of water with a low content of soluble salts may cause a problem analogous to the previous one, although related to the corrosive effect of very low salinity water, such as rainwater, as it dissolves and leaches most of the soluble salts of the surface soil (Ayers and Westcot, 1985).

13.2.3.1 *Soil sodicity indicators*

The most relevant indicator for the diagnosis of sodic soils is the exchangeable sodium percentage (ESP; %). This indicator identifies the degree to which the exchange complex is saturated with sodium. ESP values greater than 15 are associated with severely deteriorated soil physical properties. It consists of the ratio between exchangeable Na^+ concentration, and the cation exchange capacity (CEC):

$$\mathrm{ESP} = \frac{\mathrm{ES}}{\mathrm{CEC}} \cdot 100 \tag{13.3}$$

where ES is the exchangeable sodium ($\mathrm{cmol_c\ kg^{-1}}$), and CEC is the cation exchange capacity ($\mathrm{cmol_c\ kg^{-1}}$).

The sodium adsorption ratio (SAR) is another indicator, more easily to determine. The SAR gives information on the comparative concentrations of Na^+, Ca^{2+}, and Mg^{2+} in soil solutions, usually in the saturated soil paste extract, or in irrigation water, allowing the measurement of soil sodicity. The SAR of a soil extract takes into consideration that the adverse effect of Na^+ is moderated by the presence of Ca^{2+} and Mg^{2+} (Weil and Brady, 2016). It is calculated from the following expression:

$$\mathrm{SAR} = \frac{[\mathrm{Na^+}]}{\sqrt{\frac{[\mathrm{Ca^{2+}}]+[\mathrm{Mg^{2+}}]}{2}}} \tag{13.4}$$

where $[Na^+]$, $[Ca^{2+}]$, and $[Mg^{2+}]$ are the concentrations of dissolved cations in the saturated soil paste extract in milliequivalents per liter ($\mathrm{meq\ L^{-1}}$).

A SAR value of 13, or >13, for the solution extracted from a saturated soil paste, is approximately equivalent to an ESP value of 15, or >15, and the soil is termed sodic (Daliakopoulos et al., 2016). The relationship between ESP and SAR was first proposed by Richards (1954) and is given by

$$\mathrm{ESP} = \frac{100 \cdot (-0.0126 + 0.01475 \cdot \mathrm{SAR})}{1 + (-0.0126 + 0.01475 \cdot \mathrm{SAR})} \tag{13.5}$$

Despite the possibility of using soil SAR and ESP calculation to evaluate soil sodification risk, this risk evaluation should also take into account several other aspects, such as the texture, the type of clay mineral, the sum of the percentage of the exchangeable Na^+ and Mg^{2+}, and the electrolytic concentration of the solution of the soil, in addition to the parameters necessary to evaluate the quality of irrigation water.

When irrigation water has high carbonate ($\mathrm{CO_3}^{2-}$) and/or bicarbonate ($\mathrm{HCO_3}^{-}$) concentrations, an "adjusted" SAR ($\mathrm{SAR_{Adj}}$) should be calculated to account for the calcium carbonate ($\mathrm{CaCO_3}$) or magnesium carbonate ($\mathrm{MgCO_3}$) that will precipitate in the solid phase (Ayers and Westcot, 1985), removing those ions from soil solution, thus lowering their concentration relatively to their irrigation water concentrations. This is done by calculating a corrected calcium concentration, $[\mathrm{Ca}^{2+}]_x$, which will be used in the $\mathrm{SAR_{Adj}}$ expression, and which is a more realistic approach of the Ca^{2+} concentration that will remain available in solution to the exchange complex. The value of $[\mathrm{Ca}^{2+}]_x$ can be obtained in a table, which was first suggested by Ayers and Westcot (1985), using the $\mathrm{EC_w}$ value and the $[\mathrm{HCO_3}^-]/[\mathrm{Ca}^{2+}]$ ratio (ions concentration expressed in meq L^{-1}).

As stated before, soil pH is an indicator of its acidity or alkalinity, affecting directly nutrients available to plants, a problem that can appear isolated, or maybe present in saline or sodic soils (Bloem et al., 2012). However, soil pH influences soil salinity: for instance, if $\mathrm{pH} > 8.5$ (alkaline soil), the soil is more likely to be saline (Daliakopoulos et al., 2016). Taking this into account, soil pH should also be used in the diagnosis of the soil salinization, and that was earlier proposed by USDA Soil Salinity Laboratory (Richards, 1954), which developed a widely adopted salinity classification system that considers, at the same time, different soil indicators, $\mathrm{EC_e}$ (dS m^{-1}, at 25°C), SAR, ESP (%), and pH, which allow the use of an integrated salinity/alkalinity/sodicity scheme (Bloem et al., 2012; Daliakopoulos et al., 2016; Richards, 1954) (Table 13.2).

Regardless of these well-established indicators to evaluate sodicity problems in soils, some authors have alerted for the fact that, when the soil has elevated concentrations of K^+ and/or Mg^{2+}, by primary or secondary

Table 13.2 Salinity/Alkalinity/Sodicity Classification Scheme Using Different Soil Properties.

Soil Type	Soil Property			
	EC_e (dS m^{-1})	SAR	ESP (%)	pH
Nonsaline, nonalkaline	<4	<13	<15	<8.5
Saline	>4	<13	<15	<8.5
Alkaline	<4	>13	>15	>8.5
Saline—alkaline	>4	>13	>15	>8.5

Adapted from Richards, L.A., 1954. Diagnosis and Improvement of Saline and Alkali Soils. Washington, USDA Handbook 60.

salinization origins, the use of the SAR may not be sufficient to evaluate the potential degradation of the soil structure by means of clay swelling and dispersion (Rengasamy and Marchuk, 2011).

In fact, exchangeable K^+ can also have similar effects to those of Na^+ but is usually neglected as sodium salts tend to dominate in salt-affected soils, while Mg^{2+} can also enhance the clay dispersion in some sodic soils (Rengasamy and Marchuk, 2011). Considering these studies, alternative expressions to SAR have been proposed, which also account for the concentration of K^+ and of its effect on the structural stability of the soil. One of these expressions is the monovalent cations adsorption ratio (MCAR) suggested by Smiles and Smith (2004):

$$\mathrm{MCAR} = \frac{[\mathrm{Na}^+] + [K^+]}{\sqrt{\frac{[\mathrm{Ca}^{2+}] + [\mathrm{Mg}^{2+}]}{2}}} \tag{13.6}$$

Although the MCAR predicts the adsorption of monovalent ions by soil colloids, another ratio, the cations ratio of structural stability (CROSS), weights their concentrations according to their relative dispersive and flocculating power (Rengasamy and Marchuk, 2011):

$$\mathrm{CROSS} = \frac{[\mathrm{Na}^+] + 0.56 \cdot [\mathrm{K}^+]}{\sqrt{[\mathrm{Ca}^{2+}] + 0.60 \cdot [\mathrm{Mg}^{2+}]}} \tag{13.7}$$

13.3 CROPS RESPONSES TO SALINITY

13.3.1 Salinity effects on plants

Salt stress is one of the major constraints to profitable crop production, as it affects >800 million (ha) of land worldwide (FAO, 2008), becoming more significant due to global climate change. Salt stress conditions limit plant growth, reduce seed germination, and induce a poor seedling establishment due to the lower osmotic potential in the seedbed and/or toxic ion effects in germinated seeds (Aydinoğlu et al., 2019; Farooq et al., 2017). These effects are correlated with several toxic pathways, such as osmotic imbalance, ion toxicity, water stress, oxidative stress, nutritional disorders, disorganization of membranes, reduction in division and expansion of cells, and genotoxicity (Deinlein et al., 2014; Zhu, 2007).

Although Na^+ is the dominant ion causing toxicity under salt stress, some plant species, such as strawberry and maize, are also sensitive to Cl^-, the major anion in salt-affected soils. In fact, high concentrations of salts disturb the osmotic balance resulting in "physiological/secondary drought," which restricts plant water uptake (Farooq et al., 2015; Ferreira et al., 2019).

The extent by which one mechanism affects the plant over the others depends upon various factors, such as species, genotype, age, ionic strength, and composition of the solution (Läuchli and Grattan, 2007). The osmotic effect is related to the reduction in the leaves osmotic potential to adjust to the rise in salt content in the soil solution; the specific ionic effect is mainly due to an excessive uptake of certain ions, such as sodium, chloride, or boron; the nutritional effect is caused by synergic or antagonist interactions between the dissolved salts and plant nutrients (Aragües and Cerdá, 1998; Grattan and Grieve, 1992).

Munns (2002) presented the concept of "two-phase growth response to salinity" (biphasic model), consisting in: (1) an initial phase of growth reduction due to an osmotic effect, similar to the initial response to water stress and showing little genotypic differences; (2) a second phase, with a slower effect, as a result of salt toxicity in leaves. In the second phase, a salt-sensitive plant or genotype differs from a more salt-tolerant plant by its inability to prevent salt accumulation in leaves to toxic levels (Läuchli and Grattan, 2007).

Plant responses to salt and water stress have much in common as salinity reduces the ability of plants to take up water, and the early plant response is a reduction in growth rate, along with a suite of metabolic changes identical to those caused by water stress (Munns, 2002). Salinity stress in the early stages of salt exposure promotes a reduction in cell growth and division and a reduction in leaf growth. In more advanced stages, a decline in shoot growth and overall plant size takes place. Visual symptoms of salt injury in plants appear gradually. Wilting, yellowed leaves, and stunted growth are the first signs of salt stress. In the second stage, plants will exhibit chlorosis of green parts, leaf tip burning, and necrosis of leaves. Symptoms appear first in the oldest leaves (Machado and Serralheiro, 2017).

Further, plant response to salt stress varies greatly between species and among cultivars within the same species. In addition, the sensitivity of the same crop changes at different growth stages (Munns, 2002) and under different environmental conditions (Shannon and Grieve, 1998). Salt-tolerant plants have the ability to exclude Na^+ and Cl^- from leaves and/or to compartmentalize them in vacuoles to prevent their build-up in the cytoplasm or cell walls, and thus avoiding salt toxicity (Munns, 2002; Munns and Tester, 2008). Concerning sensitive species, strawberry plants developed typical necrosis of older leaves due to the accumulation of Cl^-, resulting in nutrient imbalance, and causing progressive necrosis (Ferreira et al., 2019). The photosynthesis process in grain legumes decayed due to a decrease in CO_2 supply and/or to reductions in photosynthetic pigments and disturbance in electron transport activity of photo-system II (Farooq et al., 2017). The reduction in CO_2 supply was caused by limitations in diffusion through stomata, while the effects in the photosynthetic pigments and in the electron transport activity were correlated with toxicity of Na^+ and/or Cl^-, and the increase of oxidative stress processes due to the unbalance of ionic concentrations (Khan et al., 2015). Studies by Gong et al. (2013) and Torre-González et al. (2017) in tomato and Li et al. (2014) in rice reported that the high accumulation of Na^+ induces a decline in K^+ concentrations, due to the channels of entry of the cations being occupied with Na^+. In fact, Munns and Tester (2008) reported that increasing the concentration of K^+, in sensitive plants, is one of the ways to combat saline stress. Studies developed with broccoli (Gioia et al., 2018) and cauliflower (Giuffrida et al., 2017) highlighted the prominent influence of salt stress at the first stage of growth of these vegetables with a reduction of the root dry biomass and, consequently, a reduction of the leaf area, and of the total plant dry weight. These effects were induced by accumulation of Na^+ and Cl^-, with the respective decrease of K^+ and NO_3^- (Giuffrida et al., 2017). Moreover, these vegetables were highly resistant to salinity at the second phase of growth after the inflorescence appearance (Gioia et al., 2018).

13.3.2 **Crops tolerance to salinity**

The prediction of crop yields in response to various levels of salinity in the root zone is needed for adopting soil and water management and adaptation strategies that may prevent the damaging effects of soil salinity on crop production, especially under climatic uncertainty. This prediction requires appropriate estimation models and crop salt tolerance data. The most widespread model for the prediction of crop yield losses induced by soil salinity is the threshold (or breakpoint) model of Maas and Hoffman (1977) given by

$$Y = \begin{cases} Y_{\max}, \text{ if } \mathrm{EC_e} \le a \\ Y_{\max} + b \cdot (\mathrm{EC_e} - a), \text{ if } a < \mathrm{EC_e} < c \\ 0, \text{ if } \mathrm{EC_e} \ge c \end{cases} \tag{13.8}$$

where

Y is the crop yield, expressed in appropriate yield units,
$Y_{\max}$ is maximum yield under nonsaline conditions,
a is the threshold (breakpoint) salinity, beyond which yield reduction will occur (dS $\mathrm{m^{-1}}$),
b is the slope of the function, that is, the yield loss per unit increase in $\mathrm{EC_e}$ beyond the threshold, and
c is the level of soil salinity above which the yield is zero (dS $\mathrm{m^{-1}}$).

It is a piecewise linear model with a maximum yield unaffected by soil salinity until a threshold value is reached, and a linear decrease in yield that takes place whenever the root zone salinity is higher than the threshold value for the specific crop.

The Maas–Hoffman threshold model can be presented in terms of percentage of the maximum yield, known as the relative production function, given by

$$\mathrm{Yr} = \begin{cases} 100, \text{ if } \mathrm{EC_e} \le a \\ 100 + b_{\%} \cdot (\mathrm{EC_e} - a), \text{ if } a < \mathrm{EC_e} < c \\ 0, \text{ if } \mathrm{EC_e} \ge c \end{cases} \tag{13.9}$$

where Yr is the crop relative yield (%), given by

$$\mathrm{Yr} = \frac{Y}{Y_{\max}} \cdot 100 \tag{13.10}$$

$b_{\%}$ is the relative slope (% $\mathrm{dS^{-1}\,m}$), that is, the percentage yield loss per unit increase in $\mathrm{EC_e}$ beyond the threshold, given by

$$b_{\%} = \frac{100}{c - a} \tag{13.11}$$

The relative production function can be used once an estimate of the maximum yield ($Y_{\max}$) is unavailable or to predict potential yields at a given set of conditions. In Table 13.3, the values for the a and $b_{\%}$ parameters of the Maas–Hoffman relative production function are presented for different crops.

Table 13.3 Parameters (a and $b_{\%}$) of the Maas–Hoffman Model, in the Relative Production Function, of Some Field, Forage, and Horticultural Crops.

Type	**Crop (*Botanical Name*)**	**Threshold Salinity (a; dS m^{-1})**	**Slope ($b_{\%}$; % per dS m^{-1})**
Field crops	Barley (*Hordeum vulgare* L.)	8.0	5.0
	Maize (*Zea mays* L.)	1.7	12.0
	Soybean (*Glycine max* (L.) Merrill)	5.0	20.0
	Sunflower (*Helianthus annuus* L.)	4.8	5.0
	Wheat (*Triticum aestivum* L.)	6.0	7.1
Grasses and forage crops	Alfalfa (*Medicago sativa* L.)	2.0	7.3
	Red Clover (*Trifolium pratense* L.)	1.5	12.0
	Rye (forage) (*Secale cereale* L.)	7.6	4.9
	Ryegrass (*Lolium perenne* L.)	5.6	7.6
Horticultural crops	Bean (*Phaseolus vulgaris* L.)	1.0	19.0
	Cucumber (*Cucumis sativus* L.)	2.5	13.0
	Melon (*Cucumis melo* L.)	1.0	8.4
	Onion (*Allium cepa* L.)	1.2	16.0
	Pepper (*Capsicum annuum* L.)	1.5	14.0
	Pumpkin (*Cucurbita pepo* L.)	1.2	13
	Tomato (*Lycopersum esculentum* Mill.)	2.5	9.9
Fruit trees	Almond (*Prunus dulcis* (Mill.) D.A. Webb)	1.5	19.0
	Grape (*Vitis vinifera* L.)	1.5	9.6
	Orange (*Citrus sinensis* (L.) Osbeck)	1.3	13.1
	Peach (*Prunus persica* (L.) Batsch)	1.7	21.0
	Plum (*Prunus domestica* L.)	2.6	31.0
	Olive (*Olea europea* L.)[a]	2.5	

Adapted from Maas, E.V., Grattan, S.R., 1999. Crop yields as affected by salinity. In: Skaggs, R.W., van Schilfgaarde, J. (Eds.), Agricultural Drainage Agronomy Monograph No. 38, ASA, Madison, pp. 55–108.

[a] *Values from Chartzoulakis, K.S., 2011. The use of saline water for irrigation of olives: effects on growth, physiology, yield and oil quality. In: Yermiyahu et al. (Eds.). Proc. IS on Olive Irrigation and Oil Quality, Acta Hortic. 888, 97 – 108. <https://doi.org/10.17660/ActaHortic.2011.888.10>.*

Other salinity response functions have been used for the description of crop salt tolerance data, specifically nonlinear models that describe a sigmoidal growth response of plants to salinity. van Genuchten and Hoffman (1984) presented an S-shaped response model, given by

$$Y = Y_{\max} \cdot \frac{1}{1 + \left(\frac{\mathrm{EC_e}}{\mathrm{EC_{e50}}}\right)^p} \tag{13.12}$$

where EC_{e50} is the ECe at which the yield has dropped to 50% ($dS\ m^{-1}$) of the maximum value, Y_{max}, and p is a dimensionless steepness parameter, found to be approximately 3 for several crops (van Genuchten and Hoffman, 1984).

To analyze the salt tolerance of a group of crops using different classification methods, Katerji et al. (2003) compared the classification of Maas and Hoffman (1977) with the water stress day index (WSDI; $MPa\ d^{-1}$). The concept of WSDI, based on leaf water potential (Ψ), is a quantitative method to predict crop water stress based on the hypothesis that crop salt tolerance is experimentally determined as the fractional yield reduction resulting from water deficit imposed on a crop during its growing season (Hiler and Clark, 1971). To calculate WSDI, the following equation was used by Katerji et al. (2003):

$$\mathrm{WSDI} = \sum_{1}^{n} \frac{\Psi_c - \Psi_s}{n} \tag{13.13}$$

where Ψ_c is the daily value of the predawn leaf water potential of the control treatment (MPa), irrigated with fresh water, from the start of leaf growth until the start of senescence, Ψ_s is the equivalent of the saline treatment (MPa), and n is the number of days from the start of leaf growth until the start of senescence.

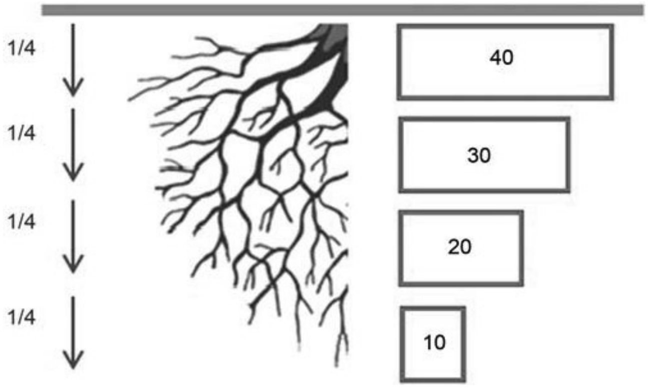
Based on the WDSI, the following relative production (Yr) function was established:

$$\mathrm{Yr} = d + e \cdot \mathrm{WSDI} \tag{13.14}$$

where d is the ordinate, ideally near 100%, and e is the loss of relative yield per unit increase of WSDI ($\%\ MPa^{-1}\ d$).

For irrigated crops, the average soil water salinity (EC_e) in the root zone considered in the Maas–Hoffman and van Genuchten–Hoffman models can be obtained by multiplying the irrigation water salinity, expressed as electrical conductivity (EC_w), and a salt concentration factor (CF) based on the overall leaching fraction (LF) of the root zone. The leaching fraction can be defined as the fraction of applied irrigation water (V_I; $m^3\ ha^{-1}$) that passes through the entire rooting depth and percolates below (V_D; $m^3\ ha^{-1}$), or the quotient between the irrigation water salinity (EC_w) and the drainage water salinity (EC_d; $dS\ m^{-1}$) (Ayers and Westcot, 1985),

$$\mathrm{LF} = \frac{V_D}{V_I} = \frac{EC_w}{EC_d} \tag{13.15}$$



■ **FIGURE 13.4** Schematic representation of the 40—30—20—10 (%) pattern of water extraction by the roots.

As the concentration of the soil water percolating below the root zone (EC_s) is equivalent to the concentration of the drainage water (EC_d) accumulating below the root, for a given EC_w, EC_s at any depth in the root zone is a function of the inverse of the LF that reaches that depth, or directly proportional to CF. The value of EC_s is difficult to measure, so, as described in Section 13.2.3.1, salinity determination is normally done on a saturation extract of the soil (EC_e) and called as the soil salinity, and it is approximately equal to one-half of ECs (Ayers and Westcot, 1985), and the following relation is used:

$$EC_e = EC_w \cdot \frac{1}{LF} = EC_w \cdot CF \qquad (13.16)$$

In the method proposed by Ayers and Westcot (1985) to calculate EC_e, the root zone is divided into quarters with a water extraction pattern of 40%, 30%, 20%, and 10% each, from the surface to the bottom of the root zone, respectively (Fig. 13.4). The salinity at the bottom of each quarter is calculated from the irrigation water EC, the percentage of water leached at the bottom of each quarter, and a concentration factor based on this leaching fraction.

The average root zone salinity is then calculated as the average of the estimated salinity in the four quarters. The method assumes that plants respond to the average root zone salinity, as a high concentration of salt in the lower portion of the root zone can be tolerated with minimal effects on yield, provided the upper portion is maintained at a relatively low salt content. Plants compensate for reduced water uptake from the

Table 13.4 Concentration Factors (CF) for Predicting Soil Salinity (EC_e) From Leaching Fractions (LF).

LF	CF
0.05	3.2
0.15	1.6
0.25	1.2
0.50	0.8
0.80	0.6

Adapted from Ayers, R.S., Westcot, D.W., 1985. Water Quality of Agriculture. FAO Irrigation and Drainage Paper No. 29, Revision 1, Food and Agriculture Organization of the United Nations, Rome.

high salinity zone by increasing water uptake from the low salinity zone (Hoffman et al., 1990; Rhoades et al., 1992). Some values of CF in relation to different values of LF can be found in Table 13.4.

Leaching fraction and irrigation efficiency (IE) are intrinsically related, as IE is the quotient between the volume of water used by the plant, or crop evapotranspiration (ET_c) and the volume of irrigation water applied (V_I), so that the higher the IE, the lower the LF, and the higher is the salt concentration in the soil solution and in the drainage water (Aragües and Cerdá, 1998), which calls into question a probable increase in salt concentration in irrigated soils as irrigation systems become more efficient and more conservative irrigation strategies are adopted, in face of the need to adapt to conditions of increased water scarcity for agriculture.

The concentration factor of the irrigation water reflects the *evapo-concentration* effect due to ET, and the weathering effect due to mineral dissolution, that is, the leaching of salts arising from weathered minerals occurring in the soil profile. Salt loads in irrigation return flows to aquifers or surface water streams are a function of both the salinity and the volume of the drainage waters, and this volume depends to a large extent on the irrigation efficiency (Aragües et al., 2011).

In addition to the osmotic and toxic effects of salts, described in Section 13.3.1, crops can be subjected to additional salt damage when the foliage is wetted by saline water, as is the case of sprinkler irrigated crops. Therefore a cumulative effect occurs as plants are subjected to injury from both soil salinity and salt spray. According to Maas and Grattan (1999), any genetically controlled mechanisms that may have evolved in salt-tolerant plants to restrict Na^+ and Cl^- effects may

Table 13.5 Relative Susceptibility of Some Field and Horticultural Crops to Saline Sprinkling Waters, Expressed as Na^+ or Cl^- Concentration Causing Foliar Injury.

Crops	Na^+ Concentration (mg L^{-1})[a]	Cl^- Concentration (mg L^{-1})
Pepper, potato, tomato	46–230	175–350
Alfalfa, barley, corn, cucumber, sesame, sorghum	231–460	351–700
Cauliflower, cotton, sugar beet; sunflower	>460	>700

Adapted from Bauder, T.A., Waskom, R.M., Sutherland, P.L., Davis, J.G., 2011. Irrigation Water Quality Criteria. Fact Sheet No. 0.506. Crop Series, Irrigation. Colorado State University Extension. and Maas, E.V., Grattan, S.R., 1999. Crop yields as affected by salinity. In: Skaggs, R.W., van Schilfgaarde, J. (Eds.), Agricultural Drainage Agronomy Monograph No. 38, ASA, Madison, pp. 55–108.

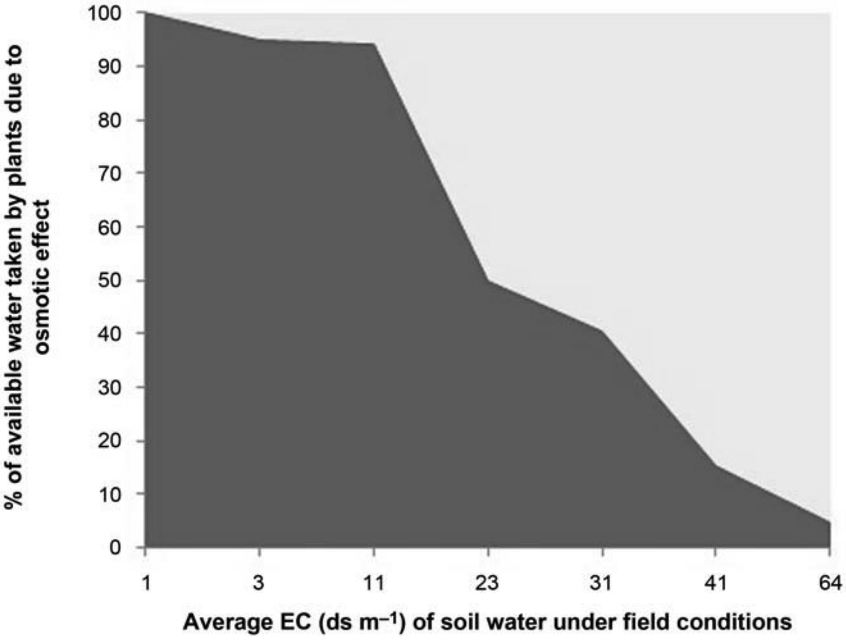
[a] *General guidelines for daytime sprinkling.*

become irrelevant under sprinkler irrigation. Furthermore, the degree of injury is related to the salt concentration in the leaves but high temperatures and aridity conditions, leading to water stress, can influence the onset of injury (Bauder et al., 2011; Maas and Grattan, 1999). Relative susceptibility of some field and horticultural crops to foliar injury from saline sprinkling waters is presented in Table 13.5.

13.3.3 Combined effects of salinity and environmental conditions on crop responses

Climate is a major factor affecting crop tolerance to salinity (Rhoades et al., 1992). According to Maas and Grattan (1999), the combined effects of salinity and high evaporative demand conditions are more stressful than the effects of salinity alone, and, most likely, climatic conditions influence the response of plants to salinity more than any other factor.

When potential water requirements of a crop are not met by readily available water, a stress condition develops (Allen et al., 1998), and soil water depletion becomes more difficult due to the development of lower matric potential in the soil. Therefore in addition to soil water content, soil salinity also influences the soil available water range, and subsequently the water use of plants. Salinity, via reduction of soil water potential and ionic toxicity, reduces the photosynthetic rate, the transpiration rate, stomatal conductance, and root hydraulic conductance (Khataar et al., 2018). Rengasamy (2010) states that "*Concomitant changes in matric and osmotic potentials determine plant water uptake in the field*." That is, the effects of decreases in osmotic and matric soil potential appear to be additive, and soil salinity influences the range of available water for plants (Fig. 13.5), thus influencing their water uptake and productivity.



■ **FIGURE 13.5** Percentage of available water not taken up by plants in soils affected by salinity, based on average values of several observations from seven locations in southern Australia. *Based on Rengasamy, P., 2010. Soil processes affecting crop production in salt-affected soils. Funct. Plant Biol. 37, 613–620. Available from: <https://doi.org/10.1071/FP09249>.*

The majority of crops tolerate salinity stress better in cooler, humid climates (Rhoades et al., 1992). Interactions between salinity and air humidity, between salinity and temperature, and between salinity and radiation were reported by Gale (1975). Crops such as beans, onion, beet, or radish showed increased tolerance to saline stress in cool and humid environments when compared to dryer conditions and higher levels of radiation (Gale et al., 1967; Gale, 1975; Hoffman and Rawlins, 1970, 1971). As stomata partial closure is one of the plant responses to salinity, photosynthesis and overall growth are likely to be more affected if radiation levels are higher (Gale, 1975).

13.4 ASSESSMENT OF WATER QUALITY FOR IRRIGATION

The characteristics of the irrigation water can have a major role in the appearance or augmentation of soil secondary salinization problems. Because of that, it is very important to evaluate its quality. Some of the parameters, which are used to evaluate soil salinization problems, are the same that are used to evaluate the irrigation water quality, namely, electrical conductivity, in this case, water electrical conductivity (EC_w), TDS, SAR, and some specific ions that might cause toxicity to the crop. Although the suitability of saline water for irrigation depends on different conditions of use, like crop, climate, soil, irrigation method, and management practices, only very tolerant crops can have satisfactory yields if irrigated with waters that exceed about 10 dS m^{-1} in EC. In fact, a few normally used irrigation waters exceed electrical conductivities of about 2 dS m^{-1} (Rhoades et al., 1992).

It is consensual the use of the FAO water quality guidelines for irrigation, reported by Ayers and Westcot (1985), which considers three levels of restriction to the use of irrigation water: none, slight to moderate, and severe (Table 13.6). The potential irrigation problems addressed are as follows: (1) salinity, assessed from EC_w; (2) infiltration rate of water in the soil, assessed using EC_w and SAR together; (3) specific ion toxicity by sodium, chloride, or boron (B), when sensitive crops are being irrigated; (4) miscellaneous effects on sensitive crops, regarding NO_3^- and bicarbonate (HCO_3^-) concentrations, and pH. These water quality guidelines for irrigation, proposed by Ayers and Westcot (1985), systematized and updated work previously developed by U.S. Salinity Laboratory Staff (1954), Wilcox (1955), Maas and Hoffman (1977), Rhoades (1977), or Oster and Schroer (1979).

These guidelines emphasize the long-term influence of water quality on crop production, soil conditions, and farm management, considering, not only the water salt content, evaluated by EC_w, but also the combined effect of EC_w and SAR. In fact, the higher the irrigating water salt content (high EC_w values), the worse is its quality, leading to high input of salts, and to restriction of water availability to the plant. However, for the same SAR, the water that poses a higher restriction to their use would be the one with the lower EC_w, once a higher salt content in the irrigation water compensates, to some extent, the increase in sodium hazard. So in fact, water with a low salt content may worsen soil physical problems (Weil and Brady, 2016).

13.5 **MODELING SOIL SALINIZATION**

The assessment of the quality of the natural resources, soil and irrigation water, is very important, however, modeling is usually required for an adequate risk assessment, which is also dependent on the management (Bloem et al., 2012). In fact, the impacts of climate change on crop

Table 13.6 FAO Guidelines for Interpretation of Water Quality for Irrigation.

		Degree of Restriction on Use		
Potential Irrigation Problem	**Units**	**None**[a]	**Slight to Moderate**[b]	**Severe**[c]
Salinity[d]				
EC_w	$dS\ m^{-1}$	<0.7	0.7–3.0	>3.0
Infiltration[e,f]				
SAR 0–3 and EC_w	$dS\ m^{-1}$	>0.7	0.7–0.2	<0.2
SAR 3–6 and EC_w		>1.2	1.2–0.3	<0.3
SAR 6–12 and EC_w		>1.9	1.9–0.5	<0.5
SAR 12 – 20 and EC_w		>2.9	2.9–1.3	<1.3
SAR 20–40 and EC_w		>5.0	5.0–2.9	<2.9
Specific ion toxicity[g]				
Sodium (Na)	SAR	<3	3–9	>9
Surface irrigation	$meq\ L^{-1}$	<3	>3	–
Sprinkler irrigation				
Chloride (Cl)				
Surface irrigation	$meq\ L^{-1}$	<4	4–10	>10
Sprinkler irrigation	$meq\ L^{-1}$	<3	>3	
Miscellaneous effects[h]				
Nitrate (NO_3)	$mg\ L^{-1}$	<5	5–30	>30
pH	–	Normal range: 6.5–8.4		

Adapted from Ayers, R.S., Westcot, D.W., 1985. Water Quality of Agriculture. FAO Irrigation and Drainage Paper No. 29, Revision 1, Food and Agriculture Organization of the United Nations, Rome.

[a] *None—no soil or cropping problems are experienced.*

[b] *Slight to moderate—gradually increasing care in selection of crop and management alternatives is required if full yield potential is to be achieved.*

[c] *Severe—there will be soil and cropping problems or reduced yields, but even with cropping management designed especially to cope with poor-quality water, a high level of management skill is essential for acceptable production.*

[d] *Affects crop water availability.*

[e] *Affects infiltration rate of water into the soil.*

[f] *Evaluated using EC_w and SAR together.*

[g] *Affects sensitive crops.*

[h] *Affects susceptible crops.*

productivity can be projected by evaluating the outputs of crop simulation models when running with climate change scenarios (Ruiz-Ramos and Mínguez, 2010).

The models that describe and quantify the physical, chemical, and biological processes of the soil, by being able to integrate several processes, are very useful tools to calculate water and salt balances in the soil and the leaching requirements. They could also be used to optimize agricultural practices, such as irrigation and fertilization, and to define environmental sustainability policies. Models work as integrative tools, for the processes involved and the data, allowing the study of scenarios (e.g., climatic change scenarios, quality, and quantity of irrigation water and applied fertilization) and supporting the optimization of agricultural practices.

The dynamics of the salts involves the cation exchange between the dissolved phase and the adsorbed phase, precipitation/dissolution, and also ion production or modification reactions (e.g., ammonium, phosphate), sometimes mediated by biological processes. The relatively complex process of adsorption and cation exchange began to be represented by empirical adsorption isotherms and degradation reactions by first order, or even zero-order decays, but, gradually, several models emerged capable of simulating the interdependence between solutes as well as precipitation/dissolution processes and competition for the adsorption sites (Daliakopoulos et al., 2016; Šimůnek and Valocchi, 2002). The models LEACHM (Wagenet and Hutson, 1987) and UNSATCHEM (Šimůnek et al., 2005) are the precursors of this type of simulation, the latter having been added as a geochemical module to the HYDRUS − 1D model (Šimůnek et al., 2005), making it one of the most used for predicting soil ion concentrations, the irrigation water quality effects on the soil and on the aquifers, and for quantifying the volume of water required to recover sodium and saline soils to lower levels of salinity and of percentage of exchangeable sodium. An example of the application of the HYDRUS − 1D model is the study of Ramos et al. (2011). These authors used the major ion chemistry module of HYDRUS − 1D model to predict, in the medium−long term, the soil water content, the overall salinity given by the EC of the soil solution, the concentration of soluble cations (Na^+, Ca^{2+}, Mg^{2+}), and the SAR, in the different plots in a soil irrigated with waters of different qualities. The experiments involved irrigating maize with synthetic saline irrigation waters blended with fresh irrigation waters and waters with different nitrogen concentrations. The standard HYDRUS − 1D solute transport module was further used to model $N{-}NH_4{}^+$ and $N{-}NO_3{}^-$ concentrations in the soil solution while either including or neglecting the effects of the osmotic stress on nutrient uptake. The model was able to successfully simulate the soil water content, exchange cations, and root water and nutrient uptake reductions due to osmotic stress. The reduction of water and nutrient uptake by the roots due to osmotic stress increased, consequently, the leached $N{-}NH_4{}^+$ and $N{-}NO_3$. The modeling and control of the risks of salinization and/or sodification is fundamental for the preservation of soil functions, and it is all the more important the more intensive the irrigation, the worse the water quality applied, and the less the annual precipitation available for the leaching of the accumulated salts, therefore constituting a key tool in the evaluation of salinity risk under climate change. A summary of the most relevant models, their main characteristics, and the respective reference are reported by Daliakopoulos et al. (2016).

13.6 SALINITY MANAGEMENT

Crop yield losses induced by soil salinity can often be prevented through the implementation of management practices adapted to the soil, crop, and environmental conditions. The aim of these strategies is to primarily ensure a favorable salt balance within the root zone, and in a lesser extent, to maintain soil structure. From a simple point of view, to achieve the salt balance in the soil, the amount of salt coming in must be counterbalanced by the amount of salt being removed (Weil and Brady, 2016). When this equilibrium is achieved, the long-term sustainability of an irrigated agriculture area is guaranteed.

Leaching is the basic management tool for salinity control, and it refers to water that is purposely applied in excess to keep the salts in solution and transport them below the root zone. In this case, the amount of water needed is called the leaching requirement (LR) (Ayers and Westcot, 1985; Rhoades et al, 1992; U.S. Salinity Laboratory Staff, 1954). Frequently, the terms LF and LR are used interchangeably, as they both correspond to the portion of irrigation that passes through the root zone to control salts at a specific level, as defined in Eq. (13.15). An estimate of drainage water salinity (EC_d) was introduced by Rhoades (1974), given by:

$$EC_d = 5 \cdot a - EC_w \tag{13.17}$$

where a is the crop threshold salinity that can be obtained from Table 13.3.

This way, Eq. (13.15), for the calculation of leaching requirement, can be written using the following expression, known as the Rhoades Model (Ayars et al., 2012; Rhoades, 1974):

$$LR = \frac{EC_w}{5 \cdot a - EC_w} \tag{13.18}$$

The success of control strategies based on the application of leaching fractions with irrigation depends on the irrigation uniformity and on the rate at which water infiltrates the soil profile. Irrigation uniformity refers to the evenness of the applied water. The less uniformly the water is applied, the greater the differences in the infiltrated amount of water, and the higher the average leaching fraction needed to control salinity in the poor-irrigated areas of the field (Hanson, 2006a).

The effective leaching of salts through percolating water also depends on soil drainage and a long-term salt balance in soils can only be achieved at a farm, or regional scale, if there is adequate drainage. In some conditions, meeting the leaching requirement is difficult and large amounts of water are needed, which can possibly add to waterlogging and drainage problems (Ayers and Westcot, 1985). Whenever soils are poorly drained or shallow water tables are present, the use of subsurface drainage systems is required to provide a desirable root zone environment, by lessening the root zone waterlogging and improving salinity control (Hanson, 2006b; Tanji and Kielen, 2002).

Irrigation timing and other several irrigation management options can be used for salinity control. Irrigations in the early growing season are very important due to the higher salt sensitivity of seeds and seedlings. More frequent irrigations can help maintain more favorable moisture content in the soil, aiding the leaching process and avoiding ascending capillary flow from saline water tables (Ayers and Westcot, 1985; Hillel, 2000).

Other management practices can have a positive effect on salinity control, like (Ayers and Westcot, 1985; Machado and Serralheiro, 2017; Weil and Brady, 2016): (1) the use of residues on soil surface to decrease evaporation; (2) the fertilization management to avoid inadequate application of fertilizers (which are a source of many soluble salts); (3) suitable seed or plant placement in furrow irrigated crops avoiding the planting in the center of the raised bed where salts are expected to concentrate; (4) use of more salt-tolerant crops (5) changing or blending water supplies; (6) use of precision agriculture technologies, like variable rate irrigation (VRI) with salt-sensing devices, to increase irrigation uniformity and efficiency.

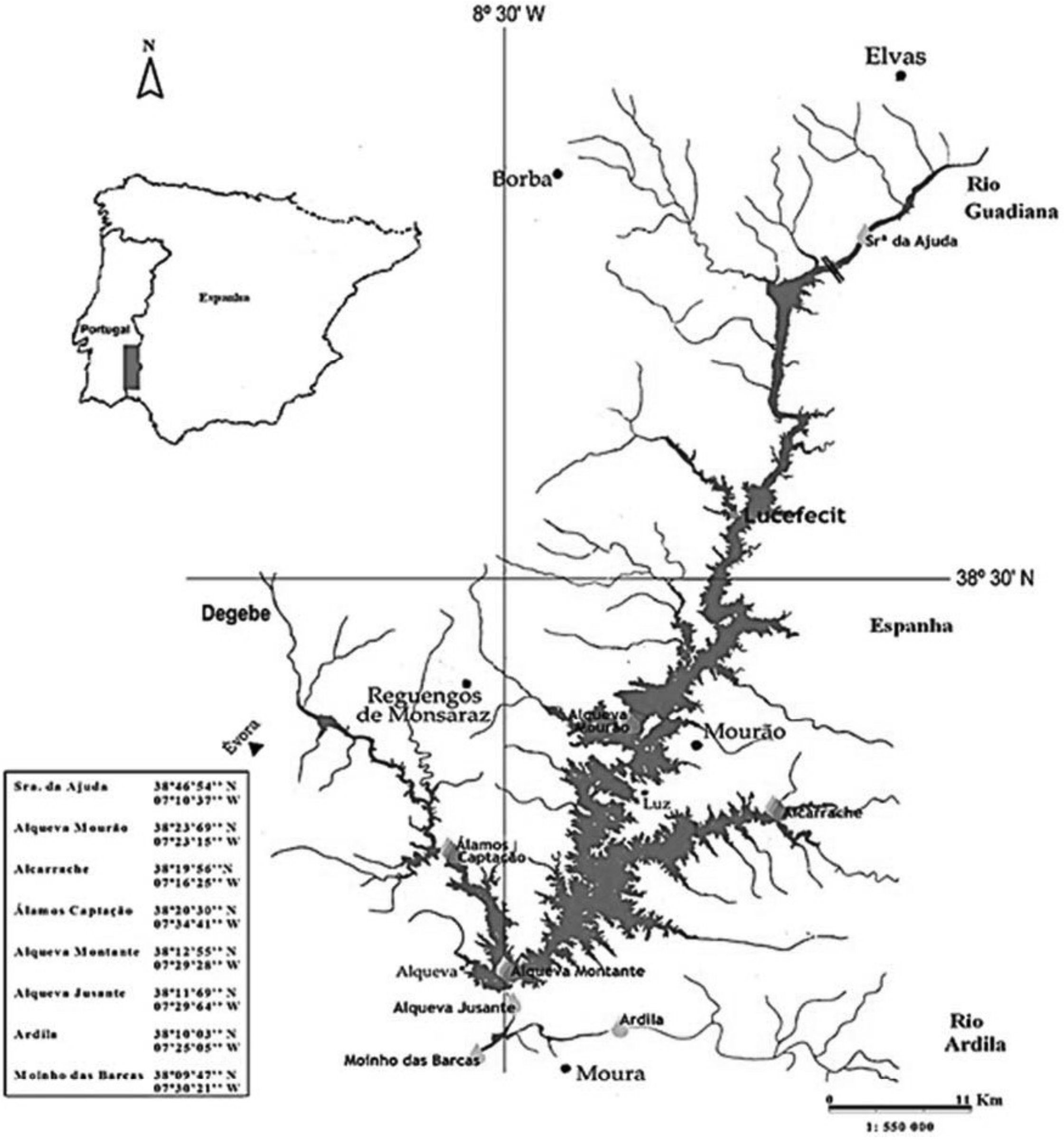
For sodicity control, the classic approach is the use of soil chemical amendments, like the application of gypsum ($CaSO_4 \cdot 2H_2O$), to remove Na^+ ions from the exchange complex, replacing them with Ca^{2+}. Adding gypsum is also beneficial because it increases the salinity of low salt waters, thus improving infiltration. Another possibility is the addition of sulfuric acid (H_2SO_4) which reacts with soil lime ($CaCO_3$) to release Ca^{2+} to the soil solution (Ayers and Westcot, 1985; Weil and Brady, 2016). For these amendments to be effective, water needs to be applied to leach the Na^+ that is pushed off-exchange sites by Ca^{2+}, which means that proper soil drainage must exist (McCauley and Jones, 2005). Establishing a salt-tolerant crop, such as sugar beet, cotton, barley or sorghum, or forage, such as berseem clover or rye, shortly after reclamation can increase the effectiveness of reclamation efforts (McCauley and Jones, 2005; Weil and Brady, 2016). Deep-rooted crops, such as alfalfa, can also be effective in improving the water conductivity of gypsum treated soils (Weil and Brady, 2016).

13.7 CASE STUDY—EVALUATION OF WATER QUALITY FOR IRRIGATION, AND ITS POTENTIAL EFFECTS ON SOIL STRUCTURE AND ON CROP YIELDS IN THE ALQUEVA IRRIGATION AREA (SOUTH PORTUGAL)

In Alentejo (Southern Portugal), one of the driest regions of Portugal, the low precipitation and high temperatures highpoint the importance of water reservoirs, built mainly for water storage (Silva et al., 2011). Presently, in Alentejo, about 69% of the water withdrawals are from surface water (INE, 2010), highlighting the importance of dams in the management plan of water resources in the region.

The Alqueva reservoir, in the Guadiana River Basin, was chosen as a case study because it constitutes the most important water supply source in Alentejo, a region where agriculture is one of the main activities (Palma et al., 2010). The reservoir—the largest artificial lake in the Iberian Peninsula (83 km along the main course of Guadiana)—is the center of the Alqueva Multi-Purpose Development Project (EFMA), and provides water for public supply, irrigation, industrial uses, energy production, and tourism (Fig. 13.6). The irrigation plan of Alqueva started to operate in 2002 and presently covers nearly 120,000 ha (EDIA 2017). As in many other regions, where the construction of dams induced an increment of economic activities (Hering et al., 2010), significant land-use changes have occurred in Alentejo (Southern Portugal) after the implementation of the irrigation area adjoining the Alqueva reservoir, that have led to the intensification of agriculture (Tomaz et al., 2018). For example, vast areas of rainfed cereal dedicated to the production of soft wheat were replaced by high density irrigated olive groves, and more recently, high density irrigated almond groves (Palma et al., 2009, 2014).

In the irrigation area, the predominant soils are Luvisols (orthic, calcic, vertic, and gleyic), Vertisols (chromic and pelic), and Cambisols (calcic and chromic) where main parent materials are intermediate or basic igneous rocks (diorite and gabbro), limestone, and schist (GPAa, 2005; IUSS Working Group WRB, 2014).



Sra. da Ajuda	38°46'54'' N 07°10'37'' W
Alqueva Mourão	38°23'69'' N 07°23'15'' W
Alcarrache	38°19'56''N 07°16'25'' W
Álamos Captação	38°20'30'' N 07°34'41'' W
Alqueva Montante	38°12'55'' N 07°29'28'' W
Alqueva Jusante	38°11'69'' N 07°29'64'' W
Ardila	38°10'03'' N 07°25'05'' W
Moinho das Barcas	38°09'47'' N 07°30'21'' W

■ **FIGURE 13.6** Map showing the location of the water sampling stations on the Alqueva reservoir during the campaigns of 2006—2007 and 2011—2012. *Adapted from Palma, P., Ledo, L., Soares, S., Barbosa, I.R., Alvarenga, P., 2014. Spatial and temporal variability of the water and sediment quality in the alqueva reservoir (Guadiana Basin; Southern Portugal). Sci. Total Environ. 470—471. Available from: <https://doi.org/10.1016/j.scitotenv.2013.10.035>.*

The climate in the region is predominantly Mediterranean, or temperate with hot and dry summer (Csa, in Köppen classification), with a small area of mid-latitude steppe (Bsk). According to the Portuguese Institute for Sea and Atmosphere (IPMA; 2018), the 1981–2010 climatological normal for annual rainfall and average temperature, in Beja, a main town near the Alqueva region, is 558 mm and 16.9°C, respectively. During the years of 2006 and 2007, according to the meteorological station of Quinta da Saúde (Beja), the annual mean temperature was 16.9°C (2006) and 16.4°C (2007). Relatively to the precipitation, the annual values were 646 mm and 359 mm, in 2006 and 2007, respectively (COTR, 2019). The hydrological year 2006–2007, especially the winter period (from December 2006 to February 2007) was characterized by values of precipitation much lower than normal, being classified as very dry (IPMA, 2007). In 2011 and 2012, the annual mean temperature was 16.8°C and 16.0°C, respectively; annual precipitation values were 621 mm and 484 mm, in 2011 and 2012, respectively. During the 2011–2012 hydrological season, annual mean temperature and annual precipitation were 23.8°C and 356 mm, respectively (COTR, 2019), which demonstrates that the hydrological year was drier and warmer than normal. According to IPMA (2013), the year 2012 in Portugal was characterized by a meteorological drought situation, which began at the end of 2011 and remained for most of the year 2012, with almost all of the territory in the severe and extreme drought classes of the PDSI index (Palmer drought severity index, PDSI; Palmer, 1965) in the months of February and March. Drought severity in southern Europe has increased in the past five decades, as a consequence of greater atmospheric evaporative demand resulting from temperature rise (Vicente-Serrano et al., 2014) and climate projections for the 21st century point to dryer conditions and an increase in the area affected by droughts in the Iberian Peninsula (Páscoa et al., 2017).

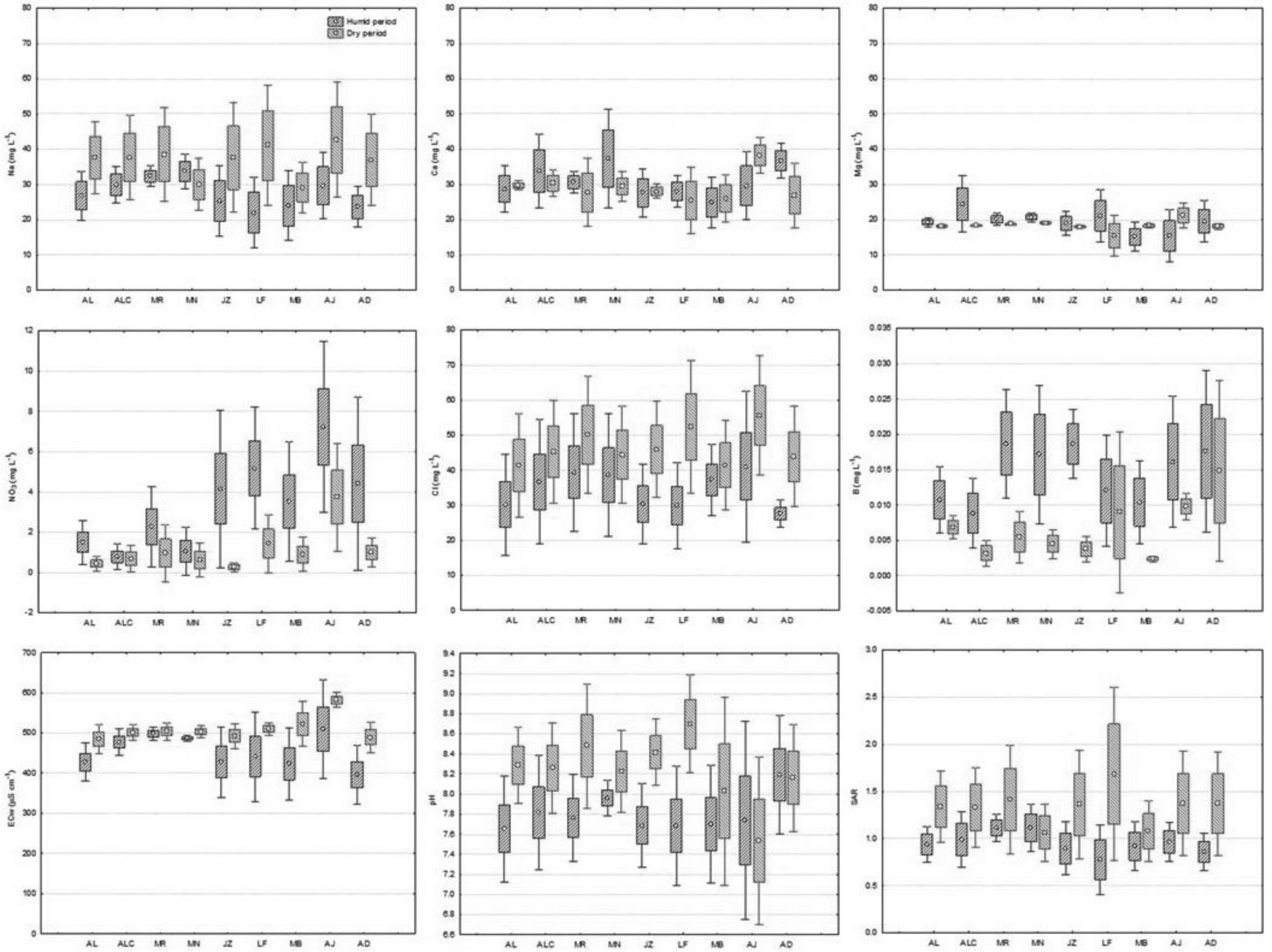
The evolution of water quality for irrigation and its potential effects on soil structure and on crop yields in the Alqueva irrigation area was assessed during the periods of 2006–2007 and 2011–2012. In 2006–2007, the main crops cultivated in the irrigation area were olive, maize, and grapevine (EDIA, 2013). The prominence of these three crops remained through the expansion of the irrigation plan, and during the 2011–2012 season land occupation was the following (EDIA, 2013, 2017): olive, occupied more than half of the irrigated area, specifically, 53%; maize, occupied 13% of the area; grapevine was grown in 8% of the area. The remaining area was mainly occupied by forage crops (8%), cereals other than maize (6%), open field horticultural crops (5%), fruit trees (3%), and oil crops, mostly sunflower (3%). Irrigation systems used in the region are predominantly sprinkler irrigation with center-pivots in field crops and drip irrigation in perennial crops. The use of surface irrigation systems is practically limited to rice cultivation (EDIA, 2017).

During the study established in 2006–2007, nine sampling sites along the Alqueva reservoir were assessed (Fig. 13.6): three upstream sites [Sra. Ajuda (AJ), Alcarrache (ALC), Álamos-Captação (AL)]; three sites at the middle [Lucefécit (LF), Alqueva-Mourão (MR), Alqueva-Montante (MN)]; three sites downstream of the reservoir [Alqueva-Jusante (JZ), Ardila confluência (AD), Moinho das Barcas (MB)]. The study developed during 2011–2012 integrated five sampling sites along Alqueva: AJ, ALC, AL, LF, and MR.

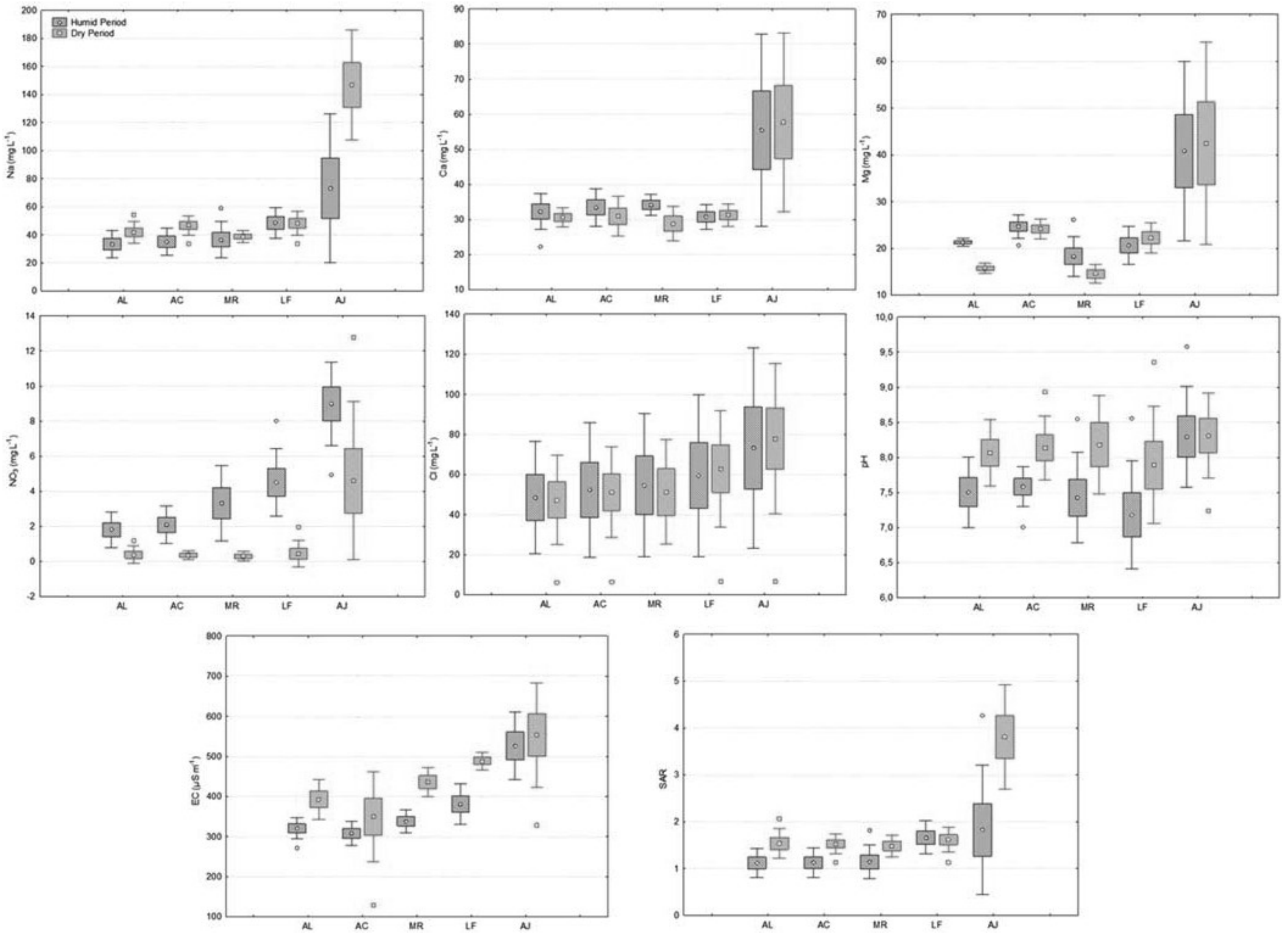
Sampling of 2006–2007 was carried out in February, March, May, July, September, and November 2006, and in February, March, and May 2007; the campaign of 2011–2012 was performed from February 2011 to November 2012 (for both years, in the months of February, April, June, July, September, and November). The humid period included the months of November, February, and March, and the dry period included the months of May, July, and September (ARH Alentejo, 2011). The key inorganic ions for irrigation water quality evaluation were determined using the officially recommended methods of analysis (APHA, 1998): boron, sodium (Na^+), calcium (Ca^{2+}), magnesium (Mg^{2+}), nitrate (NO_3^-), chloride (Cl^-), all in mg L^{-1}. Water pH and EC_w (dS m^{-1}) were measured in situ at a 50-cm depth using a multiparametric probe YSI 6820 MPS ®. SAR was calculated using Eq. (13.4).

In the absence of available soil measurements, soil salinity estimates (EC_e) were obtained from Eq. (13.16), using two concentration factors from Table 13.4: $CF = 1.2$, corresponding to a leaching fraction of 0.25; $CF = 3.2$, corresponding to a leaching fraction of 0.05. The former should be an appropriate value for average-efficiency sprinkler irrigation systems and the later for high-efficiency drip irrigation systems, respectively, with average irrigation efficiencies of 75% and 95% (Brouwer et al., 1989; Irmak et al., 2011). The Maas–Hoffman (MH) model (Eq. 13.9), and the van Genuchten- Hoffman (GH) model (Eq. 13.12) were used to determine relative yield for the main crops grown in the Alqueva irrigation area. In the case of Eq. (13.9), values in Table 13.3 for *a* and *b*% parameters were used. For Eq. (13.12), the $EC_{e50\%}$ values were obtained, whenever available, from Ayers and Westcot (1985).

The results of temporal and spatial variability of the physicochemical parameters are presented in Fig. 13.7 (campaign 2006–2007) and in Fig. 13.8 (campaign 2011–2012). In both campaigns, considering the



■ **FIGURE 13.7** Spatial and temporal variation of chemical parameters in the humid (means ± standard deviation, $n = 5$) and dry periods (means ± standard deviation, $n = 4$), during 2006—2007, at the Alqueva reservoir. AL—Álamos; ALC—Alcarrache; MR—Mourão; MN—Montante; LF—Lucefécit; JZ—Juzante; LF—Lucefécit; MB—Moinho das Barcas; AJ—Ajuda; AD—Ardila.



■ **FIGURE 13.8** Spatial and temporal variation of chemical parameters in the humid and dry periods (means ± standard deviation, $n = 6$), during 2011—2012, at the Alqueva reservoir. AL—Álamos; ALC—Alcarrache; MR—Mourão; LF—Lucefécit; AJ—Ajuda.

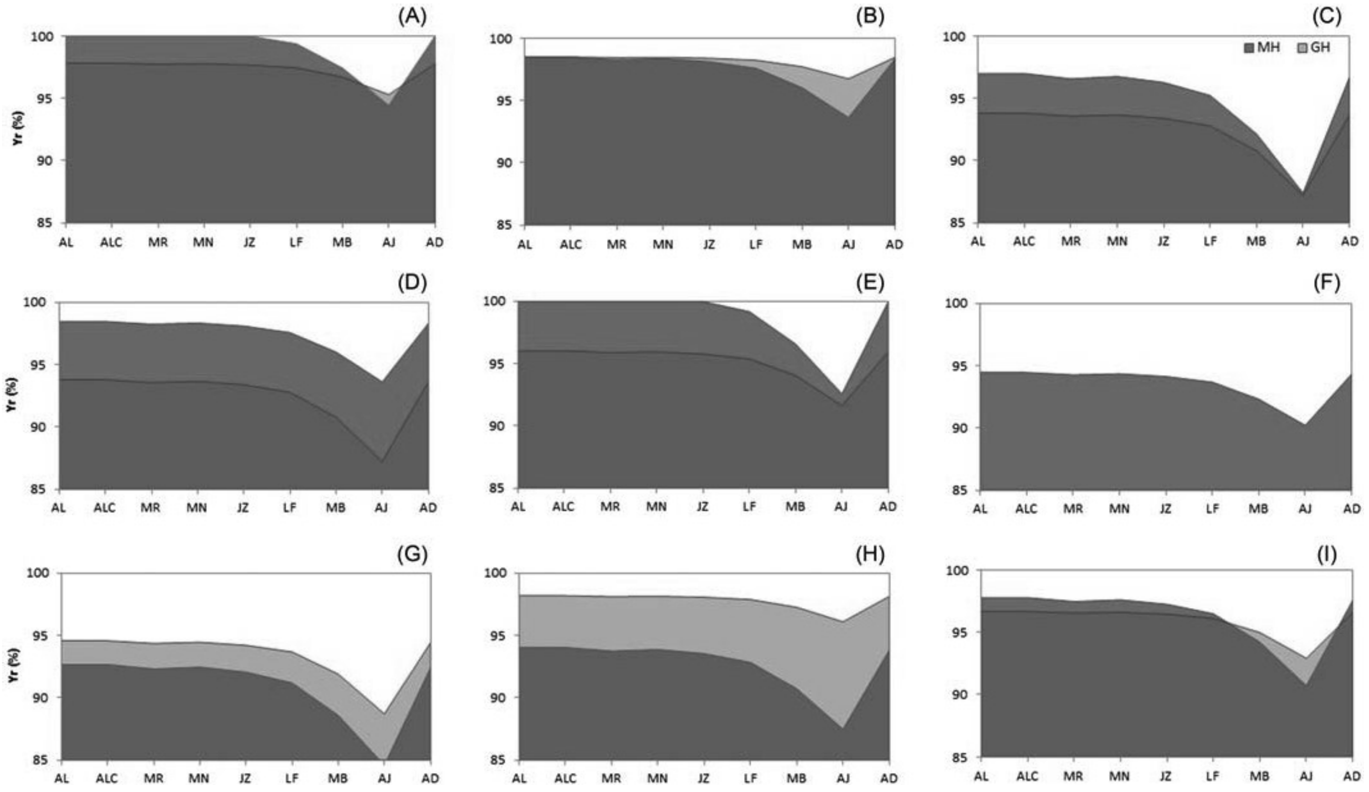
parameters selected, the order of cation abundance was $Na^+ > Ca^{2+} > Mg^{2+}$. Concerning the anion chemistry, the order of anion abundance was $Cl^- > NO_3^- >$ Boron. In 2006−2007, the average water pH for all dates and sites was 8.0. In the case of ECw and SAR, average values were 479 $\mu S\ cm^{-1}$ (about 0.5 $dS\ m^{-1}$) and 1.1, respectively. However, average values of pH, EC_w, and SAR were, in general, higher in the dry months (8.2, 510 $\mu S\ cm^{-1}$, and 1.3, respectively). Concentrations of Na^+ (36.0 $mg\ L^{-1}$) and Cl^- (46.1 $mg\ L^-1$) were also higher in the dry period. Overall, Ca^{2+}, Mg^{2+}, NO_3^-, and boron average concentrations were higher in the humid period. Lucefécit (LF) was the site with the highest values of pH (8.7) and SAR (1.7), in the dry period. Na^+, Cl^-, and EC_w during the dry period in Ajuda (AJ) were the highest (42.7 $mg\ L^{-1}$, 55.6 $mg\ L^{-1}$, and 582 $\mu S\ cm^{-1}$, respectively).

Overall, the results from the campaign of 2011−2012 (Fig. 13.8), indicated an increment of the ionic concentrations at the water body more significant for Na^+ (+55%), Cl^- (+44%), and Mg^{2+} (+30%). Average pH at all sites and dates was about 7.8. The SAR values showed an average increase of 36%. The temporal patterns were similar to those found in 2006−2007, with an increase of ionic concentrations of Na, of pH, EC_w, and SAR in the dry period, and a humid period with higher concentrations of NO_3^-, Cl^-, and Mg^{2+}. Spatial analysis indicated that AJ and LF remained the sites where ion concentrations were higher.

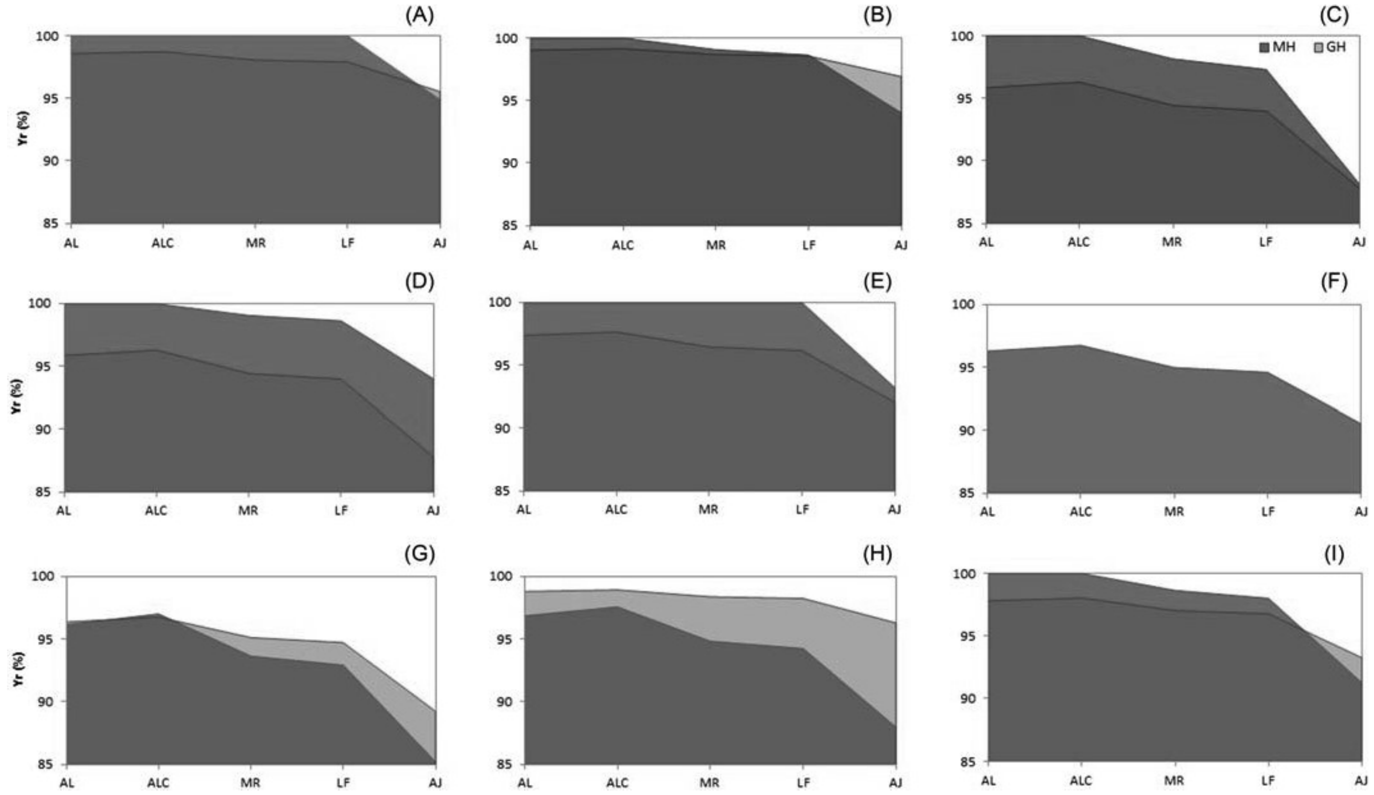
The assessment of water quality for agriculture performed for 2006−2007 using the FAO guidelines (Ayers and Westcot, 1985) showed a slight-to-moderate risk of reduced infiltration rates in every site and date. This means that low salt water can reduce infiltration even for low SAR as the effect of increasing SAR grows as the salinity of the water decreases (Ayers and Westcot, 1985; Rhoades et. al., 1992). This is especially important in fine-textured soils, and whenever sprinkler irrigation systems are used, as the energy of water droplets impacting soil surface adds supplementary energy to the dispersing effect of Na^+ in this type of soil. pH values were outside the normal range (>8.4), especially in the dry months: at all sites, in September 2006; at AL, JZ, LF, MB, and AD, in May 2006; at AD, in March 2007. These last values, however, recorded in a humid month can be due to the dry conditions felt during the previous winter months. In 2011−2012, the assessment showed the same risk of reduction in infiltration rates of water into the soil, at all sites and dates. pH values higher than 8.4 were registered mostly in dry months: at AL and AJ, in June 2011, at AJ, in July 2011; at AL, ALC, and AJ, in September 2006. In addition, the water collected at LF (September and November 2006) and AJ (February and April 2006) had characteristics consistent with a slight-to-moderate risk of Na^+ and Cl^- toxicity when using sprinkler irrigation. Overall, these evaluations performed in campaigns separated by 5 years, point to a degradation in water quality for irrigation that could be attributed, on one hand, to the expansion of the irrigation area with the intensification of agriculture, and, in the other hand, to the increase in drier conditions resulting from climate change.

Regarding the soil salinity in the Alqueva area from 2006–2007 to 2011–2012, the maximum ECe estimates obtained using $CF = 1.2$ and $CF = 3.2$ were 0.8 dS m^{-1} and 2.2 dS m^{-1}, respectively, for both the performed campaigns. Given the values of threshold salinity (a) in Table 13.3, and considering the more relevant crops in Alqueva, only crops with a threshold salinity <2.2 dS m^{-1} could have been affected by the use of irrigation water with the salinity values found in the assessment. Therefore the following crops were considered: maize, wine and table grape, almond, orange, melon, onion, pumpkin, and pepper. There was no $ECe_{50\%}$ datum available for melon, so the GH model was not applied in this crop. The minimum relative yield estimates for 2006–2007 and 2011–2012 are presented in Figs. 13.9 and 13.10, respectively.

The minimum Yr estimates were never below 85%. The lower Yr using the MH model occurred for almond, onion, and pumpkin. In the case of the GH model, the lower Yr values were also found for almond and onion, but for table grape as well. When comparing the two models, Yr, especially the lowest estimates, were higher using the GH model in horticultural crops (onion, pumpkin). The contrary occurs with fruit trees (almond, table grape, orange) yield estimates, which are higher when using the MH model. Similar estimates from both models were found in wine grape and pepper. The sites with lower Yr were MB and AJ, in 2006–2007, and AJ in 2011–2012, which is in accordance with the water salinity values found in these locations, particularly in the dry period. These results indicate that attention should be given to sensitive and moderately sensitive crops cultivated in the Alqueva irrigation area, especially in drought years, and at periods with high atmosphere evaporative demands.



■ **FIGURE 13.9** Minimum relative yield for some crops grown in the Alqueva irrigation area in 2006—2007, using the Maas and Hoffman model (1977) (MH) and the van Genuchten and Hoffman model (1984) (GH). (a) Maize, (b) wine grape, (c) almond, (d) table grape, (e) orange, (f) melon, (g) onion, (h) pumpkin; (i) pepper. AL—Álamos; ALC—Alcarrache; MR—Mourão; MN—Montante; JZ—Juzante; LF—Lucefécit; MB—Moinho das Barcas; AJ—Ajuda; AD—Ardila.



■ **FIGURE 13.10** Minimum relative yield for some crops grown in the Alqueva irrigation area in 2011—2012, using the Maas and Hoffman model (1977) (MH) and the van Genuchten and Hoffman model (1984) (GH). (a) Maize, (b) wine grape, (c) almond, (d) table grape, (e) orange, (f) melon, (g) onion, (h) pumpkin, (i) pepper. AL—Álamos; ALC—Alcarrache; MR—Mourão; LF—Lucefécit; AJ—Ajuda.

13.8 ACKNOWLEDGMENTS

This work was cofinanced by the European Union by the European Regional Development Fund, under ALENTEJO 2020 (Alentejo Regional Operational Program) through the project “ALOP: Observation, forecasting, and warning systems in the atmosphere and water reservoirs of the Alentejo” under the reference ALT20-03-0145-FEDER-000004. Further, this work is a contribution to the Projects: UID/GEO/04035/2013, funded by FCT—Fundação para a Ciência e a Tecnologia, Portugal; UID/GEO/04683/2013, funded by European Union through FEDER (Fundo Europeu de Desenvolvimento Regional) with the reference POCI-01-0145-FEDER-007690.

13.9 LIST OF SYMBOLS

$\boldsymbol{a}$	threshold (breakpoint) salinity (dS m^{-1})
α	dimensionless coefficient
$\boldsymbol{b}$	slope of the Maas–Hoffman production function; yield loss per unit increase in ECe beyond the threshold (expressed in appropriate yield units per dS m^{-1})
$\boldsymbol{b\%}$	relative slope; percentage yield loss per unit increase in ECe beyond the threshold (% per dS^{-1} m)
$\boldsymbol{c}$	level of soil salinity above which the yield is zero (dS m^{-1})
CEC	cation exchange capacity (cmol$_c$ kg^{-1})
CF	concentration factor of the irrigation water in the soil at a given depth
CROSS	cations ratio of structural stability
$\boldsymbol{d}$	ordinate of the WDSI relative production function
$\boldsymbol{e}$	loss of relative yield per unit increase of WSDI
EC	electrical conductivity (dS m^{-1})
$\mathbf{EC_a}$	apparent electrical conductivity (dS m^{-1})
$\mathbf{EC_d}$	drainage water electrical conductivity (dS m^{-1})
$\mathbf{EC_e}$	average root zone salinity expressed as the electrical conductivity of the soil saturation extract (dS m^{-1})
$\mathbf{EC_{e50}}$	average root zone salinity, expressed as the electrical conductivity of the soil saturation extract, at which the yield has dropped to 50% of the maximum value (dS m^{-1})
$\mathbf{EC_f}$	electrical conductivity of the soil saturation extract obtained at field capacity (dS m^{-1})
$\mathbf{EC_s}$	average root zone salinity to which the plant is exposed or concentration of the soil water percolating below the root zone (dS m^{-1})
$\mathbf{EC_w}$	irrigation water salinity (dS m^{-1})
ES	exchangeable sodium (cmol$_c$ kg^{-1})
ESP	exchangeable sodium percentage (%).
$\mathbf{ET_c}$	crop evapotranspiration (m^3 ha^{-1})
IE	irrigation efficiency
LF	leaching fraction

LR	leaching requirement
MCAR	monovalent cations adsorption ratio
n	number of days from the start of leaf growth until the start of senescence
p	dimensionless steepness parameter
Ψ**c**	predawn leaf water potential in plants of a control treatment, irrigated with fresh water, from the start of leaf growth until the start of senescence (MPa)
Ψ**o**	soil osmotic potential (MPa)
Ψ**s**	predawn leaf water potential in plants of a saline treatment (MPa)
SAR	sodium adsorption ratio
$\mathbf{SAR_{Adj}}$	sodium adsorption ratio adjusted to account for the calcium carbonate ($CaCO_3$) or magnesium carbonate ($MgCO_3$) that precipitate in the solid phase
TDS	total dissolved solids ($g\ L^{-1}$)
V_I	volume of applied irrigation water ($m^3\ ha^{-1}$)
V_D	volume of water that passes through the entire rooting depth and percolates below ($m^3\ ha^{-1}$)
VRI	variable rate irrigation
WDSI	water day stress index ($MPa\ d^{-1}$)
Y	crop yield (expressed in appropriate yield units)
Y_{max}	maximum crop yield under nonsaline conditions (expressed in appropriate yield units)
Yr	crop relative yield (%)

REFERENCES

Allen, R.G., Pereira, L.S., Raes, M., Smith, M., 1998. Crop Evapotranspiration Guidelines for Computing Water Requirements. FAO Irrigation and Drainage Paper 56, Food and Agriculture Organization of the United Nations, Rome.

APHA, 1998. Standard Methods for the Examination of Water and Wastewater, twentieth ed., American Public Health Association, American Water Works Association and Water Environmental Federation, Washington, DC.

Aragües, R., Cerdá, A.C., 1998. Salinidad de Aguas y Suelos en la Agricultura de Regadio. In: Díaz, R.M., Espinosa, J.L. (Eds.), Agricultura Sostenible, Agrofuturo, Life, Ediciones Mundi-Prensa, Madrid, pp. 249−274 (in Spanish).

Aragües, R., Urdanoz, V., Çetin, M., Kirda, C., Daghari, H., Ltifi, W., et al., 2011. Soil salinity related to physical soil characteristics and irrigation management in four Mediterranean irrigation districts. Agric. Water Manag 98, 959−966. Available from: https://doi.org/10.1016/j.agwat.2011.01.004.

Aragües, R., Medina, E.T., Clavería, I., Martínez-Cob, A., Faci, J., 2014a. Regulated deficit irrigation, soil salinization and soil sodification in atable grape vineyard drip-irrigated with moderately saline waters. Agric. Water Manag 134, 84−93. Available from: https://doi.org/10.1016/j.agwat.2013.11.019.

Aragües, R., Medina, E.T., Martínez-Cob, A., Faci, J., 2014b. Effects of deficit irrigation strategies on soil salinization and sodification in a semiarid drip-irrigated peach orchard. Agric. Water Manag 142, 1−9. Available from: https://doi.org/10.1016/j.agwat.2014.04.004.

ARH Alentejo (Administração da Região Hidrográfica do Alentejo I.P.), 2011. Plano de gestão das bacias hidrográficas integradas nas regiões hidrográficas 6 e 7: Região Hidrográfica 7, Ministério do Ambiente e do Ordenamento do Território, Lisboa (in Portuguese).

Ayars, J.E., Hoffman, G.J., Corwin, D.L., 2012. Leaching and rootzone salinity control. In: Wallender, W.W., Tanji, K.K. (Eds.), Agricultural Salinity Assessment and Management, second ed. ASCE, pp. 371−403. Available from: http://dx.doi.org/10.1061/9780784411698.ch12.

Ayers, R.S., Westcot, D.W., 1985. Water Quality of Agriculture. FAO Irrigation and Drainage Paper No. 29, Revision 1. Food and Agriculture Organization of the United Nations, Rome.

Aydinoğlu, B., Shabani, A., Safavi, S.M., 2019. Impact of priming on seed germination, seedling growth and gene expression in common vetch under salinity stress. Cell Mol Biol (Noisy-le-grand) 65, 18−24.

Bauder, T.A., Waskom, R.M., Sutherland, P.L., Davis, J.G., 2011. Irrigation Water Quality Criteria. Fact Sheet No. 0.506. Crop Series, Irrigation. Colorado State University Extension.

Bloem, E., van der Zee, S., Tóth, T., Hagyó, A., 2012. Soil salinization. In: van Beek, C., Tóth, G. (Eds.), Risk Assessment Methodologies of Soil Threats in Europe: Status and Options for Harmonization for Risks by Erosion, Compaction, Salinization, Organic Matter Decline, and Landslides. European Commission, Joint Research Centre, Institute for Environment and Sustainability, Publications Office, Luxembourg (Chapter 4).

Bresler, E., McNeal, B.L., Carter, D.L., 1982. Saline and Sodic Soils. Principles-Dynamics-Modeling. Advanced Series in Agricultural Sciences, vol. 10. Springer-Verlag, Berlin, Germany.

Brouwer, C., Prins, K., Heibloem, M., 1989. Irrigation Water Management: Irrigation Scheduling. FAO Training manual No. 4. Food and Agriculture Organization of the United Nations, Rome.

Chotpantarat, S., Boonkaewwan, S., 2018. Impacts of land-use changes on watershed discharge and water quality in a large intensive agricultural area in Thailand. Hydrolog. Sci. J 63 (9), 1386−1407. Available from: https://doi.org/10.1080/02626667.2018.1506128.

Commission of the European Communities, 2006. Thematic Strategy for Soil Protection. Impact Assessment of the Thematic Strategy on Soil Protection. SEC(2006)620, Document Accompanying the Communication from the Commission to the Council, the European Parliament, the European Economic, and Social Committee and the Committee of the Regions. <http://ec.europa.eu/environment/archives/soil/pdf/SEC_2006_620.pdf>.

Corwin, D.L., Lesch, S.M., 2005. Apparent soil electrical conductivity measurements in agriculture. Comput. Electron. Agric 46, 11−43. Available from: https://doi.org/10.1016/j.compag.2004.10.005.

COTR, 2019. Centro Operativo e de Tecnologia de Regadio: SAGRA − Sistema Agrometeorológico para a Gestão da Rega no Alentejo. <http://www.cotr.pt/cotr/sagra.asp> (accessed 12.04.19.) (in Portuguese).

Daliakopoulos, I.N., Tsanis, I.K., Koutroulis, A., Kourgialas, N.N., Varouchakis, A.E., Karatzas, G.P., et al., 2016. The threat of soil salinity: a European scale review. Sci. Total Environ 573, 727–739. Available from: https://doi.org/10.1016/j.scitotenv.2016.08.177.

Deinlein, U., Stephan, A.B., Horie, T., Luo, W., Xu, G., Schroeder, J., 2014. Plant salt-tolerance mechanisms. Trends Plant Sci 19, 371–379. Available from: https://doi.org/10.1016/j.tplants.2014.02.001.

EDIA, 2013. Relatório de Sustentabilidade 2012-2013, Empresa de Desenvolvimento e Infraestruturas de Alqueva, S.A. Available from: <http://www.edia.pt/pt/o-que-fazemos/apoio-ao-agricultor/anuario-agricola/225> (in Portuguese).

EDIA, 2017. Anuário Agrícola de Alqueva 2017, Empresa de Desenvolvimento e Infraestruturas de Alqueva, S.A. Available from: <http://www.edia.pt/pt/o-que-fazemos/apoio-ao-agricultor/anuario-agricola/225> (in Portuguese).

EEA, 2012. Water Resources in Europe in the Context of Vulnerability. EEA 2012 State of Water Assessment. EEA Report No̲ 11/2012. European Environmental Agency, Luxembourg.

EEA, 2017. Climate Change, Impacts, and Vulnerability in Europe 2016. An Indicator-Based Report. EEA Report No̲ 1/2017. European Environmental Agency, Luxembourg.

FAO, 2008. Land and Plant Nutrition Management Service. <http://www.fao.org/ag/agl/agll/spush>.

Farooq, M., Hussain, M., Wakeel, A., Siddique, K.H.M., 2015. Salt stress in maize effects resistance mechanisms and management: a review. Agron. Sustain. Dev 35, 461–481. Available from: https://doi.org/10.1007/s13593-015-0287-0.

Farooq, M., Gogoi, N., Hussain, M., Barthakur, S., Paul, S., Bharadwaj, N., et al., 2017. Effects, tolerance mechanisms and management of salt stress in grain legumes. Plant Physiol. Biochem 118, 199–217. Available from: https://doi.org/10.1016/j.plaphy.2017.06.020.

Farsamian, M., Paz, M.C., Paz, A.M., Castanheira, N.L., Gonçalves, M.C., Santos, F. M., et al., 2019. Mapping soil salinity using electromagnetic conductivity imaging – a comparison of regional and location-specific calibrations. Land Degrad. Dev 2019, 1–14. Available from: https://doi.org/10.1002/ldr.3317.

Ferreira, J.F.S., Liu, X., Suarez, D.L., 2019. Fruit yield and survival of five commercial strawberry cultivars under field cultivation and salinity stress. Sci. Hortic 243, 401–410. Available from: https://doi.org/10.1016/j.scienta.2018.07.016.

Gale, J., 1975. The combined effect of environmental factors and salinity on plant growth. In: Poljakoff-Mayber, A., Gale, J. (Eds.), Plants in Saline Environments. Ecological Studies (Analysis and Synthesis), vol. 15. Springer-Verlag, Berlin, Heidelberg, New York, pp. 186–192.

Gale, J., Kohl, H.C., Hagan, R.M., 1967. Changes in the water balance and photosynthesis of onion, bean and cotton plants under saline conditions. Physiol. Plant 20, 408–420.

van Genuchten, M.T., Hoffman, G.J., 1984. Analysis of crop salt tolerance data. In: Shainberg, I., Shalhevet, J. (Eds.), Soil Salinity Under Irrigation, Processes, and Management. Ecological Studies 51. Springer Verlag, New York, pp. 258–271.

Ghassemi, F., Jakeman, A.J., Nix, H.A., 1995. Salinization of Land and Water Resources: Human Causes, Extent, Management and Case Studies. University of New South Wales Press Ltd, Sydney, 526 pp.

Gioia, F., Rosskopf, E.N., Leonardic, C., Giuffrida, F., 2018. Effects of application timing of saline irrigation water on broccoli production and quality. Agric. Water Manag 203, 97−104.

Giuffrida, F., Cassaniti, C., Malvuccio, A., Leonardi, C., 2017. Effects of salt stress imposed during two growth phases on cauliflower production and quality. J. Sci. Food Agric 97, 1552−1560.

Gong, B., Wen, D., VandenLangenberg, K., Wei, M., Yang, F., Shi, Q., et al., 2013. Comparative effects of NaCl and $NaHCO_3$ stress on photosynthetic parameters nutrient metabolism, and the antioxidant system in tomato leaves. Sci. Hortic 157, 1−12.

Grattan, S.M., Grieve, C.M., 1992. Mineral element acquisition and growth response of plants grown in saline environments. Agric. Ecosyst. Environ 38, 275−300.

Hanson, B.R., 2006a. Leaching fractions and irrigation uniformity. In: Hanson, B.R., Grattan, S.R., Fulton, A. (Eds.), Agricultural Salinity and Drainage. Division of Agriculture and Natural Resources Publication 3375, University of California Irrigation Program. University of California, Davis, CA, pp. 131−132.

Hanson, B.R., 2006b. Improving subsurface drainage. In: Hanson, B.R., Grattan, S.R., Fulton, A. (Eds.), Agricultural Salinity and Drainage. Division of Agriculture and Natural Resources Publication 3375, University of California Irrigation Program. University of California, Davis, CA, pp. 119−120.

Hering, D., Borja, A., Carstensen, J., Carvalho, L., Elliot, M., Feld, C.K., et al., 2010. The European water framework directive at the age of 10: a critical review of the achievements with recommendations for the future. Sci. Total Environ 408, 4007−4019. Available from: https://doi.org/10.1016/j.scitotenv.2010.05.031.

Hiler, E.A., Clark, N., 1971. Stress day index to characterize effects of water stress on crop yields. Trans. ASAE 14, 757−761.

Hillel, D., 2000. Salinity Management for Sustainable Irrigation. Integrating Science, Environment, and Economics. Environmentally and Socially Sustainable Development. The World Bank, Washington, DC.

Hoffman, G.J., Rawlins, S.L., 1970. Design and performance of sunlit climate chambers. Trans. ASAE 13, 656−660.

Hoffman, G.J., Rawlins, S.L., 1971. Growth and water potential of root crops as influenced by salinity and relative humidity. Agron. J 63, 877−880.

Hoffman, G.J., Rhoades, J.D., Letey, J., Sheng, F., 1990. Salinity management. In: Hoffman, G.J., Howell, T.A., Solomon, K.H. (Eds.), Management of Farm Irrigation Systems. ASAE Monograph. American Society of Agricultural and Biological Engineers, St. Joseph, pp. 667−715.

INE (Instituto Nacional de Estatística), 2010. Statistical Year Book of Alentejo Region. Instituto Nacional de Estatística, p. 55.

IPMA, 2007. Informação Climática Inverno 2006/2007. Instituto Português do Mar e da Atmosfera, IP (in Portuguese).

IPMA, 2013. Boletim Climatológico Anual − 2012. Portugal Continental, Instituto Português do Mar e da Atmosfera, IP (in Portuguese).

IPMA, 2018. Instituto Português do Mar e da Atmosfera: Normais climatológicas 1981−2010 provisórias de Beja. <https://www.ipma.pt/pt/oclima/normais.clima/1981-2010/002/> (accessed 12.05.18.) (in Portuguese).

Iglesias, A., Santillán, D., Garrote, L., 2018. On the barriers to adaption to less water under climate change: policy choices in Mediterranean countries. Water Resour. Manage . Available from: https://doi.org/10.1007/s11269-018-2043-0.

Irmak, S., Odhiambo, L.O., Kranz, W.L., Eisenhauer, D.E., 2011. Irrigation Efficiency and Uniformity, and Crop Water Use Efficiency. Biological Systems Engineering: Papers and Publications 451. Available from: <https://digitalcommons.unl.edu/biosysengfacpub/451>.

Jolly, I.D., Williamson, D., Gilfedder, M., Walker, G., MORTON, R., Robinson, G., et al., 2001. Historical stream salinity trends and catchment salt balances in the Murray-Darling Basin, Australia. Mar. Freshw. Res 52, 53−63.

Karmakar, R., Indranil, D., Dutta, D., Rakshit, A., 2016. Potential effects of climate change on soil properties: a review. Sci. Int 4, 51−73. Available from: https://doi.org/10.17311/sciintl.2016.51.73.

Katerji, N., van Hoorn, J.W., Hamdy, A., Mastrorilli, M., 2003. Salinity effect on crop development and yield, analysis of salt tolerance according to several classification methods. Agric. Water Manag 62, 37−66. Available from: https://doi.org/10.1016/S0378-3774(03)00005-2.

Keren, R., 2000. Salinity. In: Sumner, M.E. (Ed.), Handbook of Soil Science. CRC Press, Boca Raton, FL, pp. G3−G25.

Khan, H.A., Siddique, K.H.M., Munir, R., Colmer, T.D., 2015. Salt sensitivity in chickpea: growth, photosynthesis, seed yield components and tissue ion regulation in contrasting genotypes. J. Plant Physiol 182, 1−12. Available from: https://doi.org/10.1016/j.jplph.2015.05.002.

Kibblewhite, M.G., Jones, R.J.A., Baritz, R., Huber, S., Arrouays, D., Micheli, E., et al., 2008. ENVASSO Final Report Part I: Scientific and Technical Activities. ENVASSO Project (Contract 022713) coordinated by Cranfield University, UK, for Scientific Support to Policy, European Commission 6th Framework Research Programme.

Läuchli, A., Grattan, S.R., 2007. Plant growth and development under salinity stress. In: Jenks, M.A., Hasegawa, P.M., Jain, S.M. (Eds.), Advances in Molecular Breeding Toward Drought and Salt Tolerant Crops. Springer, Dordrecht, pp. 1−32. Available from: https://doi.org/10.1007/978-1-4020-5578-2.

Li, X., Mu, C., Lin, J., Wang, Y., Li, X., 2014. Effect of alkaline potassium and sodium salts on growth photosynthesis, ions absorption and solutes synthesis of wheat seedlings. Exp. Agric 50, 144−157.

Maas, E.V., Grattan, S.R., 1999. Crop yields as affected by salinity. In: Skaggs, R.W., van Schilfgaarde, J. (Eds.), Agricultural Drainage Agronomy Monograph No. 38. ASA, Madison, WI, pp. 55−108.

Maas, E.V., Hoffman, G.J., 1977. Crop salt tolerance - current assessment, ASCE J. Irrig. Drain. Div, 103. pp. 115−134.

Machado, R., Serralheiro, R., 2017. Soil salinity: effect on vegetable crop growth. Management practices to prevent and mitigate soil salinization. Horticulturae 3 (2), 30. Available from: https://doi.org/10.3390/horticulturae3020030.

McCauley, A., Jones, C., 2005. Salinity & Sodicity Management. Montana State University Extension service.

Merchán, D., Causapé, J., Abrahão, R., 2013. Impact of irrigation implementation on hydrology and water quality in a small agricultural basin in Spain. Hydrolog. Sci. J 58 (7), 1400−1413. Available from: https://doi.org/10.1080/02626667.2013.829576.

Moral, F.J., Terrón, J.M., Marques da Silva, J.R., 2009. Delineation of management zones using mobile measurements of soil apparent electrical conductivity and multivariate geostatistical techniques. Soil Tillage Res 106, 335−343. Available from: https://doi.org/10.1016/j.still.2009.12.002.

Munns, R., 2002. Comparative physiology of salt and water stress. Plant Cell Environ 25, 239−250.

Munns, R., Tester, M., 2008. Mechanisms of salinity tolerance. Annu. Rev. Plant Biol 59, 651−681. Available from: https://doi.org/10.1146/annurev.arplant.59.032607.092911.

Oster, J.D., Schroer, F.W., 1979. Infiltration as influenced by irrigation water quality. Soil Sci. Soc. Am. J 43, 444−447.

Palma, P., Kuster, M., Alvarenga, P., Palma, V.L., Fernandes, R.M., Soares, A.M.V.M., et al., 2009. Risk assessment of representative and priority pesticides, in surface water of the Alqueva reservoir (South of Portugal) using on-line solid phase extraction-liquid chromatography-tandem mass spectrometry. Environ. Int 35 (3), 545−551. Available from: https://doi.org/10.1016/j.envint.2008.09.015.

Palma, P., Alvarenga, P., Palma, V.L., Fernandes, R.M., Soares, A.M.V.M., Barbosa, I. R., 2010. Assessment of anthropogenic sources of water pollution using multivariate statistical techniques: a case study of the Alqueva's reservoir, Portugal. Environ. Monit. Assess 165. Available from: https://doi.org/10.1007/s10661-009-0965-y.

Palma, P., Ledo, L., Soares, S., Barbosa, I.R., Alvarenga, P., 2014. Spatial and temporal variability of the water and sediments quality in the alqueva reservoir (Guadiana Basin; Southern Portugal). Sci. Total Environ 470−471. Available from: https://doi.org/10.1016/j.scitotenv.2013.10.035.

Palmer, W.C., 1965. Meteorological Drought. Res. Paper No. 45, Weather Bureau, Washington, DC.

Páscoa, P., Gouveia, C.M., Russo, A., Trigo, R.M., 2017. Drought trends in the Iberian Peninsula over the last 112 years. Adv. Meteorol 2017, 13. Available from: https://doi.org/10.1155/2017/4653126.

Pisinaras, V., Tsihrintzis, V.A., Petalas, C., Ouzounis, K., 2010. Soil salinization in the agricultural lands of Rhodope District, northeastern Greece. Environ. Monit. Asses 166, 79−94. Available from: https://doi.org/10.1007/s10661-009-0986-6.

Qadir, M., Wichelns, D., Raschid-Sally, L., Minhas, P.S., Drechsel, P., Bahri, A., et al., 2007. Agricultural use of marginal-quality water— opportunities and challenges. In: Molden, D. (Ed.), Water for Food, Water for Life. A Comprehensive Assessment of Water Management in Agriculture. IWMI - International Water Management Institute, Earthscan, London and Colombo (Chapter 11). Available from: <http://www.iwmi.cgiar.org/assessment/Publications/books.htm>.

Qadir, M., Quillérou, E., Nangia, V., Murtaza, G., Singh, M., Thomas, R.J., et al., 2014. Economics of salt-induced land degradation and restoration. Nat. Resour. Forum 38, 282−295. Available from: https://doi.org/10.1111/1477-8947.12054.

Ramos, T.B., Šimůnek, J., Gonçalves, M.C., Martins, J.C., Prazeres, A., Castanheira, N. L., et al., 2011. Field evaluation of a multicomponent solute transport model in soils irrigated with saline waters. J. Hydrol 407, 129–144. Available from: https://doi.org/10.1016/j.jhydrol.2011.07.016.

Rengasamy, P., 2010. Soil processes affecting crop production in salt-affected soils. Funct. Plant Biol 37, 613–620. Available from: https://doi.org/10.1071/FP09249.

Rengasamy, P., Marchuk, A., 2011. Cation ratio of soil structural stability (CROSS). Soil Res 49, 280. Available from: https://doi.org/10.1071/SR10105.

Rhoades, J.D., 1974. Drainage for salinity control. In: van Schilfgaarde, J. (Ed.), Drainage for Agriculture. Agronomy Monograph No. 17. SSSA, Madison, WI, pp. 433–461. (Chapter 16).

Rhoades, J.D., 1977. Potential for Using Saline Agricultural Drainage Waters for Irrigation. Free. Proc. Water Management for Irrigation and Drainage. ASCE, Reno, NV, 20–22 July 1977, 85 – 116.

Rhoades, J.D., Kandiah, A., Mashali, A.M., 1992. The Use of Saline Waters for Crop Production, FAO irrigation and Drainage. Food and Agriculture Organization of the United Nations, Rome, Paper 48.

Richards, L.A., 1954. Diagnosis and Improvement of Saline and Alkali Soils. Washington, USDA Handbook 60.

Ruiz-Ramos, M., Mínguez, M., 2010. Evaluating uncertainty in climate change impacts on crop productivity in the Iberian Peninsula. Clim. Res 44, 69–82. Available from: https://doi.org/10.3354/cr00933.

Scanlon, B.R., Reedy, R.C., Stonestrom, D.A., Prudic, D.E., Dennehy, K.F., 2005. Impact of land use and land cover change on groundwater recharge and quality in the southwestern USA. Global Change Biol 11, 1577–1593.

Scanlon, B.R., Jolly, I., Sophocleous, M., Zhang, L., 2007. Global impacts of conversions from natural to agricultural ecosystems on water resources: quantity versus quality. Water Resour. Res 43, 1–18. Available from: https://doi.org/10.1029/2006WR005486.

Shannon, M., Grieve, C., 1998. Tolerance of vegetable crops to salinity. Sci. Hortic 78, 5–38.

Silva, H., Morais, M., Rosado, J., Serafim, A., Pedro, A., Sarmento, P., et al., 2011. South Portugal Reservoirs – Status and Major Concerns. The 12th International Specialized Conference on Watershed & River Basin Management, 2011. International Water Association, Recife, p. 8.

Šimůnek, J., Valocchi, A.J., 2002. Geochemical transport. In: Dane, J.H., Topp, G.C. (Eds.), Methods of Soil Analysis, Part 1, Physical Methods, third ed. Soil Sci. Soc. of Am., Madison, WI, pp. 1511–1536. (Chapter 6.9).

Šimůnek, J., van Genuchten, M. Th, Šejna, M., 2005. The HYDRUS – 1D Software Package for Simulating the One-Dimensional Movement of Water, Heat, and Multiple Solutes in Variably-Saturated media. Version 3.0, HYDRUS Software Series 1. Department of Environmental Sciences, University of California, Riverside, CA, 270 pp.

Smiles, D., Smith, C., 2004. A survey of the cation content of piggery effluents and some consequences of their use to irrigate the soil. Aust. J. Soil Res 42, 231–246. Available from: https://doi.org/10.1071/SR03059.

Szabolcs, I., 1990. Chapter 6 impact of climatic change on soil attributes: influence on salinization and alkalinization. Developments in Soil Science. Elsevier. Available from: http://dx.doi.org/10.1016/S0166-2481(08)70482-3.

Tanji, K.K., Kielen, N.C., 2002. Agricultural drainage water management in arid and semi-arid areas. FAO Irrigation and Drainage. Food and Agriculture Organization of the United Nations, Rome, Paper 61.

Tomaz, A., Patanita, M., Guerreiro, I., Boteta, L., Ferro Palma, J., 2018. Efficient use of water and nutrients in irrigated cropping systems in the Alqueva region. Spanish J. Soil Sci 8 (1), 12−23. Available from: https://doi.org/10.3232/SJSS.2018.V8.N1.02.

Torre-González, A., Albacete, A., Sánchez, E., Blasco, B., Ruiz, J., 2017. Comparative study of the toxic effect of salinity in different genotypes of tomato plants: carboxylates metabolism. Sci. Hortic 217, 173−178.

Tóth, G., Montanarella, L., Rusco, E., 2008. Threats to Soil Quality in Europe. Joint Research Centre, Institute for Environment and Sustainability. Office for Official Publications of the European Communities, EUR Scientific and Technical Research Series, Luxembourg. Available from: <http://eusoils.jrc.ec.europa.eu/>.

Trnka, M., Olesen, J.E., Kersebaum, K.C., Skjelvag, A.O., Eitzinger, J., Seguin, B., et al., 2011. Agroclimatic conditions in Europe under climate change. Global Change Biol 17 (7), 2298−2318. Available from: https://doi.org/10.1111/j.1365-2486.2011.02396.x.

U.S. Salinity Laboratory Staff, 1954. Diagnosis and Improvement of Saline and Alkali Soils. Handbook No. 60. US Department of Agriculture, Washington, DC.

Várallyay, G., 2010. The impact of climate change on soils and on their water management. Agron. Res 8 (Special Issue II), 385−396.

Vicente-Serrano, S.M., Lopez-Moreno, J., Beguería, S., Lorenzo-Lacruz, J., Sanchez-Lorenzo, A., García-Ruiz, J.M., et al., 2014. Evidence of increasing drought severity caused by temperature rise in southern Europe. Environ.Res. Lett 9 (44001), 9. Available from: https://doi.org/10.1088/1748-9326/9/4/044001.

Wagenet, R.J., Hutson, J.L., 1987. LEACHM: Leaching Estimation and Chemistry Model, A Process-based Model of Water and Solute Movement, Transformations, Plant Uptake and Chemical Reactions in the Unsaturated Zone, Continuum 2, Report. Water Resour. Inst., Cornell Univ., Ithaca, NY.

Weil, R.R., Brady, N.C., 2016. The Nature and Properties of Soils, fifteenth ed. Pearson, Columbus, OH (Chapter 10).

Wilcox, L.V., 1955. Classification and Use of Irrigation Waters, Circular No. 969. United States Department of Agriculture, Washington, DC.

Williams, W.D., 1999. Salinisation: a major threat to water resources in the arid and semi-arid regions of the world. Lakes Reserv. Res. Manag 4, 85−91.

Zalidis, G., Stamatiadis, S., Takavakoglou, V., Eskridge, K., Misopolinos, N., 2002. Impacts of agricultural practices on soil and water quality in the Mediterranean region and proposed assessment methodology. Agric. Ecosyst. Environ 88, 137−146.

Zhu, J.K., 2007. Plant Salt Stress. Encyclopedia of Life Sciences. John Wiley & Sons Ltd, Chichester.