Salt-affected soils: field-scale strategies for prevention, mitigation, and adaptation to salt accumulation

Ana Marta Paz,[1] Esperanza Amezketa,[2] Loredana Canfora,[3] Nadia Castanheira,[1] Gloria Falsone,[4] Maria C. Gonçalves,[1] Ian Gould,[5] Biser Hristov,[6] Marcello Mastrorilli,[7] Tiago Ramos,[8] Rodney Thompson,[9] Edoardo A.C. Costantini[10]

[1]Instituto Nacional de Investigação Agrária e Veterinária (INIAV), Oeiras, Portugal; [2]Tracasa, Sarriguren, Navarra, Spain; [3]Consiglio per la ricerca in agricoltura e l'analisi dell'economia agraria. Centro di Ricerca Agricoltura e Ambiente, Roma, Italy; [4]Department of Agricultural and Food Sciences, Alma Mater Studiorum - University of Bologna, Italy; [5]Lincoln Institute for Agri-Food Technology, University of Lincoln, UK; [6]University of Forestry, Sofia, Bulgaria; [7]Consiglio per la ricerca in agricoltura e l'analisi dell'economia agraria. Centro di Ricerca Agricoltura e Ambiente, Bari, Italy; [8]Centro de Ciência e Tecnologia do Ambiente e do Mar (MARETEC-LARSyS), Instituto Superior Técnico, University of Lisbon, Portugal; [9]Department of Agronomy, University of Almeria, Spain; [10]CNR-IBE - Department of Biology, Agriculture and Food Sciences, Sesto Fiorentino (FI), Italy

Highlights

- *Salt-affected soils require a specific choice of management strategy: prevent, mitigate or adapt to the salt imbalance.*
- *Phyto and bioremediation can be effective practices for mitigation of soil sodicity, with improved benefits compared to chemical remediation.*
- *Crop rotation and management of soil organic matter can be used as adaptative measures.*
- *Innovative practices such as microbial management show potential for improving the crop's tolerance to salinity.*
- *Increased demonstration and research can widen the use of strategies to counteract the increased risk of salt-affected areas.*

Abstract

The area of salt-affected soils is increasing globally, mainly due to land use and management malpractices, which can threaten soil health and the sustainability of farms. Climate change is likely to increase the prevalence of salt-affected soils in many agricultural areas due to increased aridity and, in coastal areas, due to the increase in sea water level. The causes and processes that develop salt-affected soils are diverse and can result in soil salinity, sodicity, alkalinity, or a combination of these conditions. There is a need to continuously update strategies to tackle salt-affected soils, finding solutions tailored at different scales. This work presents a review of the current knowledge related to salt-affected soils and identifies specific strategies and related case studies for the prevention, mitigation, and adaptation to salt accumulation in soils at the field scale while addressing their limitations, advantages, research needs, and innovation potential. The presented case studies show that adequate irrigation management and drainage can be used as a preventive measure to counter salt accumulation in soils. Phyto and bioremediation can be effective practices for the mitigation of soil sodicity. Leaching and drainage can be effective measures for mitigation of soil salinity. Crop rotation and management of soil organic matter can be used as adaptative measures that improve plant tolerance to salt-affected soils, while a newer approach, microbial management, shows innovation potential as an adaptative measure.

Correspondence: Marcello Mastrorilli, Consiglio per la ricerca in agricoltura e l'analisi dell'economia agraria. Centro di Ricerca Agricoltura e Ambiente Via Celso Ulpiani, 70125 Bari, Italy.
E-mail: mar56mas@gmail.com

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Introduction

The accumulation of salts in the soil is one of the major threats to soil functions on a global scale. Some lands are naturally affected by salts (primary salinization) and others result from human activities (secondary salinization), which is mainly related to the adoption of improper agricultural practices, such as inadequate irrigation management and overexploitation of groundwater (*Katerji et al., 2003; Stolte et al., 2015; Omuto et al.*, 2020). Figures 1 and 2 show examples of primary and secondary salinization, respectively.

During the last decades, several studies have estimated the global extension of salt-affected soils, reaching values around 1,000 Mha. It is difficult to analyze the evolution of the salt-affected area because there are several uncertainties regarding the source data and consistency of the methods used in the different studies (Omuto *et al.*, 2020). Szabolcs (1989) developed the first world map of salt-affected soils, based on the FAO World Soil Map, estimating 955 Mha. Wicke *et al*. (2011) made an estimation based on the Harmonized World Soil Database, reaching 1,125 Mha. Ivushkin *et al*. (2019) using remote sensing, data from the World Soil Information System, and modeling obtained an estimation of 1,050 Mha. The most recent estimate is the FAO Global Map of Salt-affected Soils which separates the results by 424 Mha of topsoil (0-30 cm) and 833 Mha of subsoil (30-100 cm). This estimate is based on nationally collected data, representing 73% of the world's land area (FAO, 2021a). Salt-affected soils are distributed around the globe, but two-thirds of the salt-affected area is located in arid and semi-arid climates (FAO, 2021a), characterized by low and irregular rainfall and high evaporation, often associated with soils with low hydraulic conductivity, promoting salts accumulation in the soil profile. Salt accumulation in coastal areas is also of significant importance, largely due to seawater intrusion. In the European Union, recent estimates indicate 1.5% of the total area affected by secondary salinization, located mainly in the Mediterranean and Central European countries (Stolte *et al.*, 2015; Veerman *et al.*, 2020). The projections for future climatic conditions and their consequences on soils are alarming. The decrease in rainfall in arid and semi-arid areas, the rise of sea water level, and the rise of the global mean temperature with a consequent increase in evapotranspiration boost the risk of increasing the extent of salt-affected soils (Trnka *et al.*, 2013).

As a whole, the imbalance of salts in agricultural soils has a significant negative effect on food production and production costs, by reducing yields and raising costs of agricultural management. The effects of salt accumulation represent some of the most significant limitations to agricultural production (Shrivastava and Kumar, 2015). The negative impacts range from slight crop loss to complete crop failure, depending on several factors including depth, type, and quantity of accumulated salts, plant species and varieties, soil water regime, and climatic conditions (Daliakopoulos *et al.*, 2016). Besides food production, soil degradation by salt accumulation also has severe negative impacts on soil ecosystem services such as the provision of clean water, the regulation of the water and nutrient cycles, the habitat for terrestrial biodiversity, and the support of recreational areas and culturally valued landscapes (Stolte *et al.*, 2016). Salt imbalances in the soil are often accompanied by other severe soil degradation forms, such as water and wind erosion, compaction, and different kinds of pollution, which may lead to desertification and land abandonment. Due to the severe consequences and extent of salt-affected soils, researchers and practitioners have been devoted to developing solutions to manage salt-affected soils in varying contexts. Tedeschi (2020) stresses the importance of the dissemination of successful case studies to promote the adoption of innovative strategies to counter soil salinization. This article reviews the current knowledge related to salt-affected soils and compiles the most relevant strategies that can be used to prevent, mitigate, and adapt at the field level, identifying case studies, and addressing their sustainability and innovation potential.

Salt-affected soils

Salt-affected soils can exhibit salinity (excess of soluble salts), sodicity (excess of exchangeable sodium), alkalinity (high pH), or a combination of these conditions. Globally, 85% of salt-affected topsoils are saline, 10% are sodic, and 5% are saline-sodic. Considering

Figure 1. Badlands of the Murcia region in Spain, result from multiple erosive phenomena acting on primary saline-sodic soils. In the foreground, an example of tunnel erosion caused by soil sodicity in depth (Photo: Costantini).

Figure 2. Salts accumulate at the soil surface, forming a visible salinity crust in the alluvial soils of the Ebro Delta (Spain). Salinization is caused by the progressive rise of salty groundwater (Photo: Costantini).

the subsoil, 62% of soils are saline, 24% are sodic, and 14% are saline-sodic (FAO, 2021a). The following sections discuss the concepts of soil salinity, sodicity, and alkalinity along with the indicators and methods used to measure these soil conditions, their consequences, and an overview of the classification of salt-affected soils.

Saline soils

Soil salinity refers to the concentration of dissolved salts in the soil solution. The main soluble salts present in soils are Na^+, Ca^{2+}, Mg^{2+}, K^+, Cl^-, SO_4^{2-}, HCO_3^-, CO_3^{2-}, and NO^{3-}. The osmotic pressure of the soil solution increases with the concentration of dissolved salts, hindering water absorption by plants. Salinity can also lead to nutritional imbalances or toxicity caused by specific ions (Sparks, 2003). Soil salinity can be expressed in terms of the total dissolved salts [mg L^{-1}], but the most common measure of salinity is the electrical conductivity (EC) [dS m^{-1}] because it can be easily measured, as detailed in section "Measurement and monitoring" EC can be measured in the soil solution (EC_{sw}), in aqueous extracts obtained from soil-water mixtures, such as 1:1, 1:2, and 1:5 ($EC_{1:1}$, $EC_{1:2}$, and $EC_{1:5}$), or in a saturated soil paste (EC_e). EC_{sw} is related to the actual salinity encountered by crop roots; however, the plant's ability to extract the soil solution varies with specific soil properties, and its value is affected by the existing soil water content. As a result, reference values to interpret EC_{sw} are rarely available. The measurement of EC in the extracts of soil-water mixtures and the soil-saturated paste has the advantage of allowing comparison among samples, independent of the water content under field conditions. The saturated soil paste is obtained by saturating a soil sample with distilled water until reaching a paste that glistens and flows (FAO 2021b). Because EC_e is closely related to EC_{sw}, it is commonly used as a reference for evaluating soil salinity and the crops' sensitivity and response. The laboratory procedure for obtaining EC_e is more laborious than for the fixed soil-water mixtures and simple regression models for estimating EC_e from $EC_{1:1}$, $EC_{1:2}$ or $EC_{1:5}$ can be developed. These models are of difficult generalization, due to specific soil factors such as texture, although some attempts to develop models for general application, including a conversion factor related to texture, have been developed (Seo *et al.*, 2022).

Richards (1954) considered an EC_e above 4 dS m^{-1} for classifying saline soils, a threshold that has been widely used. However, studies show that several crops can start having growth limitations at lower EC_e values. Sensitive crops can have thresholds of 1.5 dS m^{-1}, while highly tolerant plants grow well until EC_e of about 12 dS m^{-1} (Tanji and Kielen, 2002; Weil and Bradley, 2017). The Global Map of Salt-affected Soils defines saline soils as those with $EC_e>2$ dS m^{-1} (FAO, 2021a). Soils Katerji *et al*. (2003) reclassified salt tolerance ranges of Mediterranean crops and they proposed a new methodology to analyse the salt species sensitivity. Such methodology combined soil, physiological and agronomic issues.

Sodic and saline-sodic soils

Sodicity refers to an excess of Na (sodium) in the soil's exchange complex. Sodic soils have a high concentration of exchangeable Na and a low concentration of soluble salts. This combination of factors can lead to severe soil degradation by causing the collapse of the soil structure, as the clay particles swell and/or disperse in the soil solution, resulting in negative effects such as the development of impermeable soil layers, restriction of root growth, and high susceptibility to erosion (Stolte *et al.*, 2015). Even if sodicity occurs only in-depth, as in several sodic profiles, the deep impermeable layers may hinder both root growth and drainage. This can lead to water logging at the surface or lateral drainage, increasing erosion and geomorphologic instability, which may create tunnels and cavities that eventually collapse to form gullies. These landscapes are affected by a great variety of erosive phenomena, in some cases producing unique ecological environments, like those with different kinds of badlands ("biancane" and "calanchi", Calzolari and Ungaro, 1998) as shown in Figure 1. The effect of clay dispersion caused by sodicity can be prevented if the soil has a relatively high concentration of soluble salts. The minimum salt concentration in the soil solution to prevent the dispersion of clays is the flocculation value, which depends on the soil type and increases with the concentration of exchangeable Na in the soil (Weil and Bradley, 2017). Sodicity favors the dispersion of organic matter and its dissolution in the water runoff, which enhances the losses of organic matter.

Sodicity can be assessed by the Exchangeable Sodium Percentage (ESP) [%], which is the relative concentration of exchangeable Na in the soil's exchange complex, expressed as a percentage. The soil sodicity can also be assessed using the Sodium Adsorption Ratio (SAR) [$(\mathrm{mmol_c\ L^{-1}})^{0.5}$] which refers to the concentration of soluble Na relative to the concentrations of soluble Ca and Mg. It is expressed in relation to the volume of the solution, according to the equation (Richards, 1954):

$$SAR = \frac{[Na^+]}{\sqrt{\frac{[Ca^{2+}]+[Mg^{2+}]}{2}}} \qquad [(\mathrm{mmol_c\ L^{-1}})^{0.5}] \tag{1}$$

where $[Na^{2+}]$, $[Ca^{2+}]$, and $[Mg^{2+}]$ are the concentrations of soluble cations measured in the soil saturation paste extract. Because SAR is based on the concentration of soluble cations it is also used to assess the sodicity of water and other solutions. Even if ESP is directly related to the concept of soil sodicity, because it is based on the exchangeable Na, soils with high ESP will have high SAR values. SAR is faster to determine in the laboratory than ESP because it does not demand the extraction of exchangeable cations from the soil. Richards (1954) presented the relation between ESP and SAR and defined tentative thresholds for the classification of sodicity as ESP higher than 15% and SAR higher than 13 $(\mathrm{mmol_c\ L^{-1}})^{0.5}$. The Cation Ratio of Structural Stability (CROSS) has been proposed, to express the influence of both Na and K in clay dispersion and to weigh the flocculating powers of Mg and Ca, as shown in equation (2), where the constants a and b were originally set to be the ratio of the cations flocculation powers (Rengasamy and Marchuk, 2011). Subsequent studies argued that these constants should rather be determined by the ratio of the dispersion powers (Smith *et al.*, 2015), and proposed that these are actually soil-specific (Zhu *et al.*, 2019), suggesting generalizing its definition by replacing these coefficients with adjustable parameters.

$$CROSS = \frac{[Na^+ + aK^+]}{\sqrt{\frac{[Ca^{2+}]+b\,[Mg^{2+}]}{2}}} \; [(\mathrm{mmol_c\ L^{-1}})^{0.5}] \tag{2}$$

Rengasamy and Marchuk (2011) related CROSS and SAR with the dispersion of clays in soil samples with varying proportions of Na, K, Ca, and Mg, showing that CROSS can be a better predictor of clay dispersion than SAR. CROSS has also been proposed as a base for estimating the sodicity hazard of irrigation waters (Qadir *et al.*, 2021), as described in section "Irrigation managment and drainage".

Alkaline soils

According to Weil and Bradley (2017), alkaline soils are those with a pH above 7. Soil alkalinity is mainly dependent on the concentration of dissolved carbonate minerals, which react with water to form OH^- that accumulate in the soil solution. Alkalinity is also influenced by the concentration of carbon dioxide, which increases with roots and microbiome respiration, and can partly counteract the formation of OH^-. If Ca is abundant in the soil solution, the carbonates precipitate forming calcite, which has limited solubility. In such cases, the soil pH remains typically below 8. However, if there is a large relative concentration of Na in the soil solution, the solubility of sodium carbonates can make pH increase to values well above 8. In this manner, the alkalinity of the soil also provides informs regarding its sodicity. The Global Map of Salt-affected Soils defines soil as salt-affected when the pH is above 8.2 (FAO, 2021a). Alkalinity affects the solubility of nutrients and other elements needed by plants and can lead to both deficiency and toxicity. Remediation measures for sodicity can also typically result in a lowering of the soil pH.

Classification of salt-affected soils

The World Reference Base for Soil Resources (WRB) is an international classification system that encompasses all the world's soils (IUSS Working Group WRB, 2022). It defines two main types of salt-affected soils, taking into consideration the entire soil profile: the Solonchaks (saline soils) and the Solonetz (soils with a high content of exchangeable Na). Other kinds of soils with salt accumulation are Gyspisols and Calcisols, which imply specific management problems that are not covered in this review.

The WRB foresees qualifiers to indicate the depth of occurrence or the degree of expression of certain soil features. There are qualifiers related to soil salinity that are used in conjunction with other soil types than Solonchaks and Solonetz to characterize soils that are salt-affected in specific layers, such as:

Salic – refers to soils with a salic horizon starting within 100 cm of the soil surface. A salic horizon is defined by:

1. at some time of the year,
    a. if the water of the saturation extract has $pH \geq 8.5$, $EC_e \geq 8$ dS m^{-1} and a product of thickness and $EC_e \geq 240$ cm dS m^{-1}; or
    b. $EC_e \geq 15$ dS m^{-1} and a product of thickness and $EC_e \geq 450$ cm dS m^{-1};
2. a thickness of ≥15 cm (combined thickness if there are superimposed sub horizons meeting criteria 1.a and 1.b)

Sodic – refers to soils with having a layer ≥20 cm and starting ≤100 cm from the mineral soil surface, that has ≥15% Na plus Mg, and ≥6% Na on the exchange complex; and not having a natric horizon starting ≤100 cm from the soil surface, as in the Solonetz.

According to the WRB classification, the qualifiers can be further specified according to a depth range, layer, or percentages, forming sub qualifiers, such as Hypersalic or Protosodic.

Measurement and monitoring

Appropriate management of salt-affected soils demands accurate measurement and monitoring of the salts' accumulation and comprehension of its leading processes. Salinity values, especially in topsoil, may change according to the amount of seasonal rainfall, soil site characteristics, and quantity and management of irrigation water. Then, farmers may not fully appreciate the effects of salt accumulation in the short term, especially when these effects are incipient, seasonal, or periodic (De Pascale *et al.*, 2012).

The electrical conductivity can be measured using a conductivity electrode in different aqueous solutions obtained from the soil, as described in section "Saline soils", either in the laboratory under controlled conditions or in the field. The methods for manual determination of EC are detailed by Rhoades *et al*. (1999). In the last decades, many proximal sensors have been used for direct *in-situ* measurement of the soil's apparent electrical conductivity (EC_a), a complex property resulting from the conjunction of several soil properties such as salinity, water content, and the soil's particle size distribution (Allred *et al.*, 2008). The presence of dissolved salts in the soil is likely to dominate EC_a and, as a result, EC_a can be correlated to EC_e or EC_{sw} by establishing local-specific calibrations. Proximal sensors that are currently used for crop and land management applications are dielectric sensors, resistivity sensors, and electromagnetic induction (EMI) sensors. Dielectric sensors can use Time Domain Reflectometry, Amplitude Domain Reflectometry, or Frequency Domain Reflectometry and consist of hand-held or fixed probes that are inserted in the soil. Dielectric sensors are commonly used to measure the volumetric soil water content directly in the field, while some models can also measure EC_a (Visconti and de Paz, 2016). Resistivity sensors consist of an array of electrodes that are inserted in the soil and measure the difference in current flow potential. The depth of penetration of the electrical current and the volume of measurement increase as the inter-electrode spacing increases. Resistivity sensors can give reliable EC_a measurements for a large volume of soil but are an invasive method, which makes them less practical for measurements of large areas. EMI sensors are non-invasive as they do not require contact with the soil and can be held at different heights over the soil, allowing the determination of soil salinity at different soil depths. EMI sensors can be hand-held or pulled by a vehicle, covering large areas of soil in a short time, as shown in Figure 3. It is important to have in mind that EC_a represents a depth-weighted average of the soil EC and it does not reflect the real variation of EC with depth. This is a limitation when aiming to study the EC profile of the soil. If EC_a is collected at multiple soil depths by placing the sensor at different heights from the soil surface, this set of measurements can be numerically inverted to find the EC of the soil at each depth. In this manner, it is possible to obtain 3D maps of the soil properties related to EC_a. EMI and inversion methods have been used in several studies to obtain 3D maps of EC_e (Farzamian *et al.*, 2019) and SAR (Paz *et al.*, 2020). The maps of salt-affected soils have different levels of detail, according to the scale of use that they are aimed at. At the field level, very detailed maps with points at less than 100 m of spatial resolution, are needed to allow farmers to apply site-specific management decisions. For grazing and extensive farming, less detailed maps might be suitable. Maps with more than 1 km resolution provide information that is key to identifying and understanding major trends and status and to guiding policies related to agriculture, landscape planning, and the environment. Examples of the latter are the Map of Salt-affected Soils in the European Union (Tóth *et al.*, 2008) and the more recent Global Map of Salt-affected Soils (FAO, 2021a). At a scale larger than the field, methods using remotely sensed data have also been tested for mapping soil salinity. Remote sensing includes air-borne sensors (such as those installed in helicopters, light aircraft, drones, *etc.*) and space-borne sensors installed in satellites. These applications can facilitate regional mapping by reducing time-consuming and costly field surveys and can be combined with proximal sensors for calibration of the remotely sensed data. Soil salinity can be estimated by measuring the spectral reflectance of the bare soil surface or indirectly, by inferring the presence of salt in the soil through the reflectance of the plant canopy (Corwin and Scudiero, 2019).

Strategies to deal with salt-affected soils at the field level

Salt imbalances may be a future risk, or may already be a real problem. In at-risk areas, it is necessary to take preventive measures; remediation strategies can be put into place in areas where the salt equilibrium must be restored. Adaptation strategies can be used in areas where salt accumulation is recurrent, remediation is not possible, or as a complement to remediation. The boundaries between these three approaches are not always rigid as illustrated in the reviewed case studies.

Prevention

The risks of the development of salt-affected soils can have different origins. We differentiate these as risks related to irrigation and drainage practices, seawater intrusion, and finally the origin of the soil parent material or the groundwater. Conjugation of these aspects may be needed to prevent the development of salt-affected soils.

Irrigation management and drainage

Appropriate irrigation and drainage management at the field scale for the prevention of salt-affected soils include evaluating the quality of the irrigation water, the selection of irrigation method, adjusting the irrigation scheduling, meeting the leaching requirements, and in some cases, managing irrigation with saline water.

Quality of the irrigation water

The effects of the salinity and sodicity of the irrigation water are highly dependent on the characteristics of the soil and the conditions for leaching and drainage. Therefore, it is a rather complex task to establish general guidelines for the usage of irrigation water according to its quality. Based on several long-term studies, Ayers and Westcot (1985) proposed guidelines for evaluating the risk of salinity- and sodicity-derived soil problems, according to SAR and EC of the irrigation water (EC_w). These guidelines, summarized in Table 1, indicate that:

- No salinity-derived cropping problems are expected when using water with EC_w<0.7 dS m^{-1}.
- Salinity-derived cropping problems when using water with

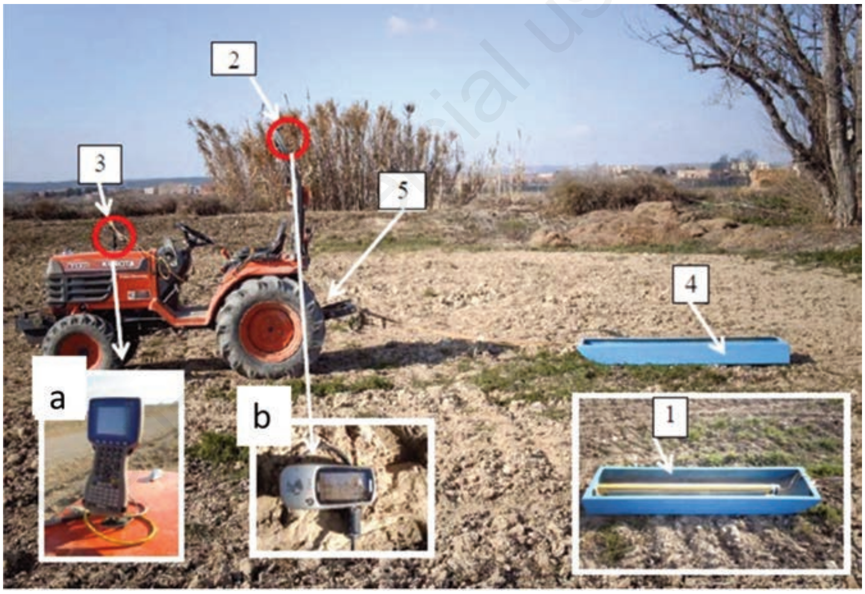

Figure 3. Example of a mobile and georeferenced electromagnetic induction sensor with five basic components: 1) electromagnetic sensor [Dualem-1S in (a) and EM38-RT in (b)]; 2) GPS unit; 3) data acquisition system; 4) non-metallic sledge; 5) vehicle. Adapted from Urdanoz *et al.* (2008).

Table 1. Irrigation water-quality guidelines, based on electrical conductivity and sodium adsorption ratio of the irrigation water. Adapted from Ayers and Westcot (1985).

Potential hazards		No restriction	Slight to moderate restriction	Severe restriction
Salinity hazard		EC_w<0.7	EC_w=0.7-3	EC_w≥3
Sodicity hazard	SAR=0-3	EC_w>0.7	EC_w=0.7-0.2	EC_w≤0.2
	SAR=3-6	EC_w>1.2	EC_w=1.2-0.3	EC_w≤0.3
	SAR=6-12	EC_w>1.9	EC_w=1.9-0.5	EC_w≤0.5
	SAR=12-20	EC_w>2.9	EC_w=2.9-1.3	EC_w<1.3
	SAR=20-40	EC_w>5.0	EC_w=5.0-2.9	EC_w<2.9

SAR, sodium adsorption ratio; EC_w, electrical conductivity of irrigation water.

EC_w between 0.7-3.0 dS m^{-1} can be prevented in soils with adequate drainage by ensuring sufficient leaching of the excess salts to keep concentration under the crops' salinity tolerance threshold. Specific leaching requirements will need to be estimated and applied (see the section "Estimating the leaching requirements").

- Irrigation water with EC_w >3 dS m^{-1} has several usage restrictions. Even though, in regions with freshwater scarcity, saline water sources are used for irrigation. This is done by combining strategies described in the section "Irrigation with saline waters" with adaptation measures such as the use of high-tolerant crops;
- Sodicity-derived problems can be prevented by keeping EC_w above the corresponding flocculation value, depending on the SAR of the irrigation water. When EC_w is below the flocculation value, some prevention strategies can be adopted, such as reusing the irrigation effluent water, which has higher EC_w, and making use of practices to avoid soil crusting (see section "Chemical remediation of sodicity"). An example of soil structure degradation from using water with low EC_w occurred in areas of the Middle Ebro River basin (Spain), where soils irrigated with low EC_w<0.4 dS m^{-1} water were left bare exposed to rainwater, typically with EC<0.01 dS m^{-1} (Amezketa *et al.*, 2003; Isidoro and Aragüés, 2007).

The guidelines for irrigation water quality presented in Table 1 are the most currently used. Qadir *et al.* (2021) have recently proposed new global irrigation water quality guidelines, based on those by Ayers and Westcot (1985), replacing SAR with CROSS to include the complex effects of K and Mg in the evaluation of the sodicity hazards of the applied water. The new guidelines can be represented graphically, as presented in Figure 4, in which the vertical and horizontal bars represent the combination of EC_w and CROSS ranges that result in a "slight to moderate" sodicity-related hazard, according to the values presented in Table 1. Above the bars, the sodicity hazard is not expected, while below the bars, a severe sodicity hazard is expected. The proposed guidelines apply to whatever combinations of *a* and *b* coefficients are used to calculate CROSS.

The presented guidelines constitute an effort to define a general framework regarding the quality of the irrigation water, but the specific conditions of the agricultural system must be considered to evaluate the real risk. An example is constituted by the results of Gonçalves *et al.* (2006), which evaluated the salinization risks in a medium-textured Eutric Fluvisol under irrigation with waters of varying quality [$0.3<EC_w<3.2$ dS m^{-1} and $1<SAR<6$ (mmol$_c$ L^{-1})$^{0.5}$]. The results showed that the salts added with waters with EC_w up to 1.6 dS m^{-1} were washed from the profile after the rainy season (with a rainfall of about 500 mm in a hot-summer Mediterranean climate, according to the Köppen classification). The ESP of the soil after the irrigation period also decreased with the rainfall, but it showed a gradual annual increase for all irrigation waters, but was most evident for waters with SAR above 3 (mmol$_c$ L^{-1})$^{0.5}$, showing that Na accumulation over sufficient years can result in sodicity. If soluble salts are leached and the salt concentration is below the flocculation value, there will be degradation of the soil structure. This example demonstrates the importance of monitoring the soil salinity and sodicity and continuously adapting the agronomic measures.

Irrigation method

Adequate irrigation methods aim to provide favorable water and salt concentrations in the root zone so that water is readily available to plants, without affecting root water uptake and damaging yields. The selection of an irrigation method should consider the quality of irrigation water and associated potential hazards to soil and plants, as reviewed by Pereira *et al.* (2014) and Minhas *et al.* (2020). Following their guidelines, modern surface irrigation methods, particularly flat basins and borders are appropriate to apply saline waters and for salt leaching. These systems require land to be precisely leveled to ensure uniform distribution of water as shown in studies carried out in Syria and China (Darouich *et al.*, 2014; Miao *et al.*, 2015). As they are usually characterized for delivering large irrigation volumes at long intervals, they are well adapted for leaching. However, they may be less suitable for irrigation of less tolerant crops that require small and frequent applications of water, *e.g.*, vegetable crops. Sprinkler irrigation may promote toxicity problems and cause severe leaf damage, affecting yields, as water and salts are applied at the top of the plant's canopy. The greater the irrigation frequency, the greater the leaf damage. Yet, these systems may be suitable for irrigation with low-quality waters, except when low distribution uniformity occurs resulting, for example, from strong winds. The leaching requirements need to be considered in the system design as well as salinity-induced infiltration problems, including soil crusting, which may promote runoff losses. Drip irrigation is usually considered the most advanced irrigation system, allowing the precise application of water and nutrients, alongside improved efficiency and potential benefits under saline conditions. Yet, proper management needs also to be considered. On one hand, drip irrigation systems allow for the application of small and frequent irrigation depths, maintaining soil moisture at higher levels which help to ameliorate the effect of salts on plants. On the other hand, the risk of salts returning to the wetted bulb and the clogging of emitters needs also to be considered. An example of successful management of salty waters using drip irrigation was given by Dudley *et al.* (2008), who showed a careful adaptation of the system to local soil and plant conditions. The adoption of small volumes and more frequent irrigation events ensured both maximum leaching in the root zone and reduced salt load to the drainage water, as salts were stored in upper soil layers, but beyond the root's zone of active uptake.

Irrigation scheduling

Even low salinity water will add salts to the soil, which may accumulate over time, especially in arid climates. As a result, adequate irrigation and drainage management at the farm scale are necessary to prevent salt-affected soils. The irrigation schedule must meet the crop water requirements and promote salt leaching from the root zone, but there can be further constraints to consider, such as controlling the groundwater level or dealing with limited water availability. The irrigation scheduling is specific to each type of irrigation system, and irrigation frequency is likely the most flexible variable. The adjustment of the water volume applied is of major importance, as water availability is often limited, and the use of excess irrigation can also cause the leaching of nutrients and soluble organic compounds, especially in soils with a low water holding capacity (Vittori Antisari *et al.*, 2020).

Irrigation scheduling to prevent salt imbalances is complex and highly dependent on the specific pedo-climatic, crop, and farm conditions. Some counteracting processes can be identified: on one hand, frequent irrigation events help ensure matric and osmotic potentials are optimal for the crop but can increase evaporation losses from the shallower soil layers, increase the salt load to the soil due to the larger overall applied volume, and promote the concentration of roots in the shallower soil layers, which can increase the crops' vulnerability by limiting the access to water in deeper soil layers. On the other hand, larger irrigation intervals promote root growth and water use from larger soil volumes but can enhance salt transport from deeper layers or saline groundwater. According to Minhas *et al*. (2020), this issue demands further experimentation, but modeling can provide indicative solutions, combining adequate water volume and irrigation frequency to obtain optimal results. A recent example can be found in Liu *et al*. (2021), who developed a dual crop coefficient water balance model for improving soil and water resources management in the Hetao region, China. Their modeling approach considered the impact of upward fluxes from shallow saline groundwater tables to the root zone and crop evapotranspiration fluxes, providing a valuable tool for irrigation scheduling in that water-scarce region.

Estimating the leaching requirements

The effects of both insufficient and excessive leaching were referred to in the previous sections. But how can the adequate leaching requirements be estimated? The traditional salinity management approach considers the following equation to calculate the leaching fraction (LR) (Richards, 1954):

$$LR = \frac{\mathrm{EC_w}}{5\ \mathrm{EC_e} - \mathrm{EC_w}} \qquad (3)$$

where EC_e is the crop's salinity tolerance for an acceptable yield of 70-90%. The equation does not take into account specific system characteristics and is valid for a steady state, which often leads to an overestimation of LR (Corwin and Grattan, 2018). An improved approach to estimate LR is to use simulation models that take into account the soil and plant water uptake characteristics and the influence of soil water content and salinity, as reviewed by Minhas *et al.* (2020). However, there are no established guidelines for the determination of the LR taking into consideration these factors.

Irrigation practices with saline waters

As freshwater supplies are not always available to fulfill crop water requirements, saline waters are often seen as a valuable alternative resource. Saline irrigation waters can be applied either separately or, if freshwater is available, in a cyclic way or mixed with fresh water. When cyclic strategies are considered, fresh water is applied to the most sensitive crop growth stages (germination and seedling) while saline water can be given when the crop can tolerate higher salinity levels. When mixing strategies are adopted, two or more water sources are mixed to reach a targeted salinity for a particular crop depending on the crops' salt tolerance, the soil type, climate, and the long-term management plan for irrigation and crop production. Blending also requires additional infrastructures (dilution network, storage reservoirs) to allow the control mixing of two (or more) water sources.

This is exemplified in the case study by Ramos *et al*. (2011, 2012), who applied blends of fresh and salty water in drip irrigation of maize grown under Mediterranean conditions during three cropping seasons followed by sweet sorghum during another three growing seasons (Figure 5). The drip irrigation system was further used for applying nitrogen fertilizer to crops. The HYDRUS model (Simunek *et al.*, 2018) was then used to model soil water contents, overall salinity, the major cations, and the fate of nitrogen species. The results showed a build-up of salts along the cropping season in plots irrigated with the blended waters (plot A), but also with fresh waters only (plot C). However, as summarized in Table 2, the salinity build-up in the root zone layer (0-0.6 m) of plot A was higher than in plot C, where EC_e dropped to values close to the initial conditions after most rainfall seasons and before the following cropping periods. In plot A, leaching from rainfall was never sufficient to return the soil to the initial salinity levels, with EC_e values at the beginning of the next season sometimes being comparable to those at harvest of the previous season, although salts accumulating at lower soil depths but still within the root zone. Figure 5 also shows the simulated EC_{sw} along the soil profile at the beginning and end of the sweet sorghum cropping season. Figure 5 shows that the salts mainly accumulated below the emitters and progressively increased over the years. The effect of irrigation with blended saline waters on maize yields and sorghum total sugar content was also analyzed (Ramos *et al.*, 2009, 2012). This case study shows that the build-up of salts in soil is highly dependent on the annual rainfall, which can be very variable under Mediterranean conditions (see Table 2). To prevent productivity loss and crop failure, irrigation with blends of salty water must be carefully managed and adapted to the evolving pedo-climatic conditions both within and between cropping seasons.

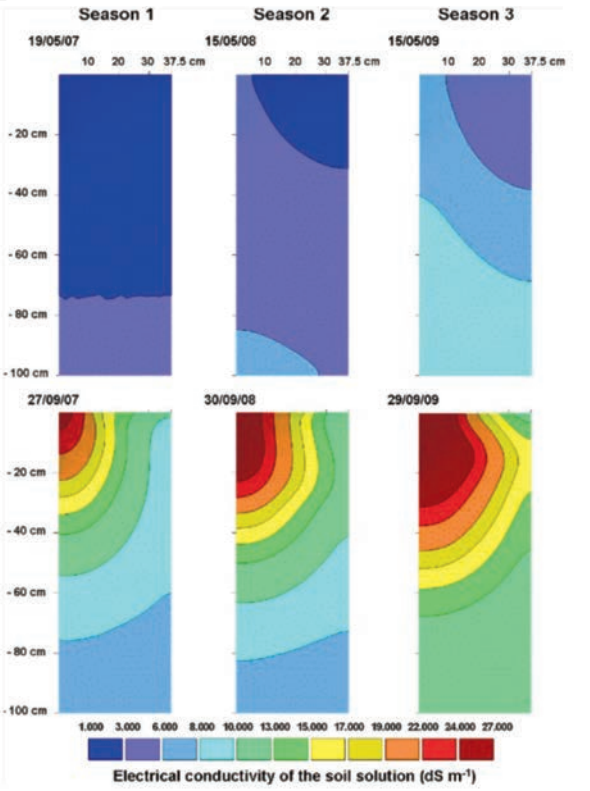

Figure 5. Simulated distributions of soil solution in sweet sorghum irrigated with a blend of salty water during sowing (top) and harvest (bottom) of each crop season. The drip emitter was located in the top left corner of each contour plot. Adapted from Ramos *et al.* (2012).).

Drainage

Drainage conditions must be considered as part of the salt accumulation process because insufficient soil drainage hinders the leaching of salts. Many agricultural systems depend on the soil's ability to transport water along the profile, and some include artificial drainage systems. In irrigated areas, drainage systems can consist of open-air channels or subsoil drainage channels. As an example, Castanheira and Serralheiro (2010) tested the installation of mole drains by sub-soiling at a depth of 0.7 mm and 1.5 m apart, in a Vertisol irrigated with saline-sodic waters, and showed that the mole drains improved leaching of the salts added by the irrigation water by over 20% than without mole drains. The characteristics of the drainage system (such as depth, distance, and type of drains) also have to be carefully planned according to the properties of the soil, groundwater, and rainfall, to ensure sufficient drainage, and avoid cases where excessive removal of irrigation water and rainfall from surface layers may favor the rise of existing deeper saline water, particularly in dry months, when evapotranspiration increases. Models simulating the water and salt transport in the soil are also useful to plan the drainage systems corresponding to the demands of different agricultural systems (Liu *et al.*, 2021).

Seawater intrusion

In coastal and estuarine areas, seawater intrusion can result from storm surges, droughts, sea-level rise, and human activities associated with the overexploitation of groundwater resources, land-use changes, river damming, and dredging of navigation corridors.

Saline inundation from seawater flooding can lead to severe consequences for agricultural soils in many coastal regions of the world. Such low-lying areas often comprise fertile alluvial soils, producing food to sustain large populations, which further compounds the severity of salinity. In some regions, such as Northern Europe, soil salinization from coastal flooding is identified as an emerging threat, predicted to increase under future sea level rise (Gould *et al.*, 2021). Other parts of the world experience frequent storm surges, causing devastating flooding and salinization, such as in Bangladesh (Ashrafuzzaman *et al.*, 2022). Following a seawater flood, salt deposits in soils will reduce productivity and cropping options until soils are fully recovered (Gould *et al.*, 2020). Recovery rates of soils will depend on geographic location and are largely attributed to rainfall and leaching rates, with drier parts of the world taking longer to recover soil salinity to pre-inundation levels (Mainuddin and Kirby, 2021).

Saline intrusion in coastal regions can also impact ground and surface waters. Over-exploitation of groundwater resources, such as increased freshwater abstraction rates, coupled with rising sea levels results in a gradual rise in saline groundwater in coastal regions (Oude Essink *et al.*, 2010). In certain instances, the ascending saline interface can rise to a level where it interacts with crop rootzones or irrigation waters, thus increasing saline pressures on agricultural lands.

The changes associated with global climate uncertainty, such as sea level rise, cause serious risks to coastal agricultural areas and demand strategies at scales larger than the field scale. Most low-lying agricultural areas located close to coasts or estuaries need to be protected from seawater intrusion. Robust sea defenses, such as the dikes and drainage systems of reclaimed land in Northern Europe, can be constructed to protect against seawater inundation, although this may come at high investment costs. However, the high cost of such engineered solutions often means prioritization to protect urban areas rather than agricultural lands (Vousdoukas *et al.*, 2020).

To protect freshwaters, prevention measures often need to include upstream flow regulation to reduce the intrusion of seawater in the estuary and the groundwater. Water abstraction limits can be implemented to maintain freshwater levels in groundwater and help prevent saline rise. Farmers can also reduce reliance on saline water sources in the summer months by increasing on-farm storage of fresh waters supplied in times of high rainfall (wet seasons or winter months) with reservoirs.

Parent material and groundwater

The soil may be naturally rich in soluble salts due to the weathering of parent rock constituents such as carbonate minerals and/or feldspar. Often the salts are transported dissolved in water from higher altitude areas to lower zones or from wetter to drier zones. If the weathering rocks are rich in Na, sodicity can arise. As the water evaporates, the salts are left in the soil and may accumulate under conditions of high evapotranspiration, low rainfall, and low infiltration. Saline and sodic soils may also arise due to earth movements carried out to prepare the fields for the plantation of crops, namely deep ploughing and slope reshaping, which may cause the outcrop of the salt-affected layers, and the reduction of soil functionality, and even the partial or total failure of the culti-

Table 2. Summary of rainfall, irrigation, and electrical conductivity of irrigation water during the three cropping seasons. Adapted from Ramos *et al*. (2011, 2012).

Season	1	2	3	1	2	3
Crop	Maize	Maize	Maize	Sweet sorghum	Sweet sorghum	Sweet sorghum
Rainfall during cropping season [mm]	24	18	74	91	63	35
Rainfall during leaching season [mm]	181	521	511	371	299	667
Irrigation water [mm]	997	1012	1028	425	522	546
EC_w of saline irrigation water $[dSm^{-1}]$	7.8	7.8	14.6	7.6	9.6	10.6
EC_w of fresh irrigation water $[dSm^{-1}]$	1.20	1.20	1.20	0.81	0.81	0.81
Plot A (blended saline waters						
EC_e at the beginning of season $[dSm^{-1}]$	0.53	3.89	5.88	2.78	8.73	5.46
EC_e at the end of season $[dSm^{-1}]$	3.32	7.94	5.71	5.46	5.84	5.38
Plot C (fresh waters)						
EC_e at the beginning of season $[dSm^{-1}]$	0.50	0.87	2.03	2.40	0.99	0.71
EC_e at the end of the season $[dSm^{-1}]$	2.69	1.56	2.28	1.22	1.30	4.03

EC_w, electrical conductivity of irrigation water; EC_e, saturated soil paste.

vation. Appropriate tuning of slope reshaping and earth movements before crop plantation can prevent the outcropping of salty sediments and the risk of soil salinization (Costantini *et al.*, 2018).

Irrigation can also be responsible for mobilizing salts, including Na, from parent materials. Herrero and Castañeda (2018) found different behaviours depending on the soil characteristics in an irrigated area in the Ebro Valley (N.E. of Spain). In soils with good hydraulic conductivity and where gypsum in the profile impeded sodification, irrigation with low EC_w water was able to desalinate the profile and allowed rice cultivation, but in other soils, the characteristics of the parent material (with silt and sodic clay varved structure), the absence of gypsum, and the low EC_w water converged to cause soil particle dispersion leading to land abandonment after some years of irrigation.

Another source of salts to the soil can be the dissolved salts available in groundwater, which can rise to the surface in the low-lying parts of the landscape. Those salts can accumulate in the subsurface or even ascend to the surface. This phenomenon can occur naturally or can be the result of a disturbed water balance arising from land-use changes in semiarid regions. This was the case in vast zones in Australia, where perennial vegetation with deep roots was substituted by annual crops, which lowered the evapotranspiration rate, resulting in the rise of the saline water table and consequent salt accumulation in the soil profile (Weil and Bradley, 2017).

Mitigation

When soil salinization and/or sodification have already occurred, several strategies can be considered to mitigate or reduce them. The possibilities include the use of chemical treatments, phyto- and bioremediation, leaching, and drainage of excess salts, and agronomical practices, including the increase of soil organic matter content.

Chemical remediation of sodicity

Soil sodicity can be reduced by using chemical amendments. The remediation process involves the Ca in the chemical amendments, exchanging with the Na adsorbed in the soil's exchange complex. Once in the soil solution, Na can be leached from the soil profile. The most widely used chemical amendments are gypsum (calcium sulphate) and gypsum-like by-products. Other amendments such as calcium chloride and calcium nitrate, which are highly soluble, are possible, but they are usually more expensive solutions. Other types of amendments that can be useful in soils with calcite are acids or acid-formers. Compounds such as sulphur, sulphuric acid, and calcium polysulfide dissolve the calcite releasing Ca. Chemical amendments also increase the soil salinity level, mitigating or even preventing soil crusting. Amezketa *et al.* (2005) tested four amendments in crusting prevention of two calcareous soils (non-sodic and sodic) and remediation of sodic soils. The four chemical amendments, *i.e.*, mined gypsum, coal gypsum (a by-product obtained from coal power plants), lacto-gypsum (a by-product from the manufacture of lactic acid and lactates), and sulfuric acid, were effective in crusting prevention and sodic soil remediation, but sulfuric acid was the most efficient, leading to a quicker reduction of soluble salts and Na in the soil leachates. The three gypsum materials were equally effective in the sodic remediation process and the crusting prevention of the non-sodic soil, whereas lacto-gypsum was less efficient in the crusting prevention of the sodic soils (Amezketa *et al.*, 2005). Such amendments work best when integrated with other measures, such as increased drainage which aids removal of Na replaced into the soil solution. Most often, the high pH values of sodic soils are decreased by sodicity remediation. As the soil becomes saturated with Ca, this cation precipitates with the carbonate and bicarbonate anions, lowering the soil's pH. This process is enhanced by the biological activity in the soil.

Phyto and bioremediation of sodicity

Phytoremediation can be used for the removal of Na from the soil through a mechanism similar to that of chemical remediation, that is, by making Ca available to replace Na adsorbed in the soil's exchange complex. Other mechanisms, such as the bioaccumulation of salts in the aboveground biomass of halophytes are less effective in reducing soil salinity. Therefore, Na removal by phytoremediation requires a source of Ca, which typically is the calcite existing in soils. The role of the plants in this process is to increase the CO_2 level in the root zone, which enhances the dissolution of calcite. The increase of CO_2 in the root zone can be further helped by the activity of the rhizosphere's microbiome, therefore the mechanism can be termed bioremediation as both plants and the microbiome intervene in the process. Phytoremediation can be used in cases of low to medium sodicity, and can constitute a cheaper and more sustainable method than chemical remediation because it avoids the use of synthetic products and may improve other soil characteristics such as the level of organic matter (Qadir *et al.*, 2007). Qadir *et al.* (2007) reviewed seventeen phytoremediation studies and showed that this approach can have similar or improved results compared to chemical remediation with the application of gypsum, but it requires specific and more complex planning of the amelioration process (crop rotation, crop type, irrigation timings, *etc*). This review also showed an improvement in the overall plant nutrient availability in the soil, as a result of root exudates and calcite dissolution. An advantage is that Na removal occurs more uniformly and in-depth when compared to chemical remediation, as it occurs along with the root depth, for instance, alfalfa roots can reach 1.2 m deep.

Leaching and drainage

Leaching of soluble salts is necessary to remediate saline soils and sodic soils when Na is dissolved. While in the arid regions leaching requires the use of irrigation, in the semi-arid regions rain could provide the necessary leaching. The leaching of the soluble salts is usually accompanied by nutrients such as nitrates. Therefore, it is necessary to monitor and control the drainage effluent to minimize harmful effects on downstream users and habitats. It can also be necessary to restore soil fertility. A determinant part of a mitigation strategy is to ensure adequate drainage, in which a soil structure that sustains good infiltration levels is fundamental. The role of practices such as the incorporation of organic matter into the soil, leaving harvest residues on the surface, mulching, maximizing cover crops, and adoption of minimum tillage approaches, in improving soil organic matter content and the soil structure, has been widely studied (Bronick and Lal, 2005; Priori *et al.*, 2021). Therefore, these practices should be considered in terms of favoring water movement in the soil and improving leaching within a strategy for the remediation of salt-affected soils.

Synthetic soil conditioners such as water-soluble polymers, generally described as polyacrylamides (PAM) and polysaccharides can be used to increase the soil structural stability. PAM molecules are adsorbed by the clay surface causing a physico-chemical change at the clay surface and acting as a bridge between soil particles. Due to their large size, these compounds do not penetrate soil aggregates but are adsorbed simultaneously by several soil particles and act as cementing agents binding soil particles (Chenu, 1993). The economic cost can limit the use of PAM to very high-added-value crops. Studies, under field conditions, have shown that PAM applied with sprinkler irrigation significantly improved the soil infiltration rate and reduced runoff, which contributes to reducing soil crusting and erosion. Bjorneberg *et al.* (2003) showed, under field conditions, that PAM applied in single or multiple applications, at a rate of 1 kg ha^{-1} (10 mg L^{-1}), with sprinkler irrigation, reduced cumulative runoff for the irrigation season by 38%, 15%, and 22% of the applied irrigation water for the control, single, and multiple treatments, respectively. Also, Santos and Serralheiro (2000) showed that PAM applied through the irrigation water increased cumulative infiltration by 15% to 20% on furrow-irrigated Mediterranean soils.

Adaptation

In this section, we consider strategies that do not attempt to directly reduce salt accumulation, but use the salt-affected soils in their existing conditions.

Agronomical practices

Plant selection and crop rotation

Some crops and varieties have a moderate or high tolerance to salinity, with a productivity reduction of only 10% at EC$_e$ above 4 dS·m^{-1} or higher (Weil and Bradley, 2017). Moderate salinity can even improve the quality of some crops like tomatoes (Pascali *et al.*, 2001) or grapevine (Costantini *et al.*, 2010). New varieties are being developed that can successfully cope with high salinity conditions. Physiological and agronomical traits allowing Mediterranean crops to achieve adequate productivity levels in saline soils have been outlined in studies by Katerji *et al*. (2009, 2011 *i. a.*). In addition, the plantation of halophytes is becoming an agronomical niche in some very high-salinity areas. Grafting can also constitute an approach to growing less tolerant crops in soils susceptible to salinization. Gioia *et al*. (2013) showed that grafting a salt-sensitive tomato variety into a more resistant tomato rootstock can improve the salinity tolerance of the salt-sensitive cultivar and maintain its organoleptic properties. Vine rootstocks have also been produced to cope with salinity and drought conditions (Galletto *et al.*, 2014).

Adapted crop rotation can be an efficient adaptation but also a preventive measure against recurrent salinity. Gabriel *et al.* (2014) incorporated cover crops into a cropping system to study the adaptation to salinity levels. The authors showed that the inclusion of barley and vetch in a cropping system with irrigated maize in a Mediterranean area was able to maintain and reduce the salinity of the topsoil because of the increase in soil organic matter. Crop rotation between barley, vetch, and maize also decreased nitrate leaching in comparison to the option of having a fallow period (Gabriel *et al.*, 2014). A different approach that has been applied in rainfed cropping systems is the use of plants that are less tolerant to salinity during the rainy season, while more tolerant crops can be grown during the dry period. There could be the need for a set-aside period at the beginning of the rainy season, to allow for the leaching of salts by rainfall and bring salinity to levels tolerable for the crops (Cuevas *et al.*, 2019).

Decrease in foliar transpiration

One of the salinity-derived problems for plants is the reduction of water absorption by roots, which decreases plant growth and development due to adverse effects on physiological processes such as photosynthesis (Katerji *et al.*, 2003). A proposed adaptation solution to minimize such an effect is the foliar application of salicylic acid, an important phytohormone, which has been shown to enhance the vegetative growth of several crops under salinity stress. Exogenous sources of salicylic acid can be supplied to plants either through seed soaking, adding to the nutrient solution, irrigating, or spraying and the influence on plant functions happens in a dose-dependent manner (Khan *et al.*, 2012). Improvement or inhibition of plant functions occurs depending on salicylic acid concentrations. Kováčik *et al.* (2008) showed in *Matricaria chamomilla* L., that 50 and 250 µM salicylic acid concentrations were, respectively, promoting and inhibiting plant growth. The role of salicylic acid in strengthening salinity stress-tolerance mechanisms was also evidenced in mustard plants (*Brassica juncea* L.) by Nazar *et al.* (2015) where photosynthesis and plant growth were promoted with the application of 0.5 mM of salicylic acid.

Microbial and organic matter management

It is well known that soil organic matter reduces the negative effects of salinity and that organic amendments can have a beneficial effect on soil microorganisms. In general, all the agronomic practices that favor the production of biomass and its incorporation into the soil, both through mechanical incorporation or root depositions, can improve soil biological activity and contribute to counteracting soil salinization and sodification.

The application of beneficial microorganisms is also widely accepted as a promising and efficient alternative to chemical treatments for more sustainable agriculture and the mitigation of abiotic and biotic stress. Isolation, selection, characterization, and proper testing in several salt-affected soils are widely studied, as shown by Otlewska *et al.* (2020). Different saline-related microorganisms, belonging to several taxa of bacteria, archaea, and fungi, can be used to formulate bioinocula to promote and enhance plant salt tolerance (Saghafi *et al.*, 2019). They can also be used in reclamation or preventing salt-affected soils. Several studies suggested the beneficial effects and the success of the microbial amelioration of salt stress, which included the inoculation with specific bacteria strains of the crop seeds, the soil, and farmyard manure applied to the soil (Kayasth *et al.*, 2014; Arora *et al.*, 2016; Koganti *et al.*, 2018). However, the application of microorganisms promoting plant resistance under stressful salinity conditions still needs further research to be applied as beneficial bioinoculants for crops (Otlewska *et al.*, 2020). There are different issues with the application of microorganisms to salt-affected soil: little or limited knowledge of the microbial properties, little knowledge of their interaction with the native soil microflora, and the complex web of environmental factors. Furthermore, the fermentation and the formulation process are not well developed to guarantee the shelf-life of the microorganisms, bearing in mind that different factors might affect the metabolism, activity, biomass, and spores yield of the other microbial species used (Manfredini *et al.*, 2021; Vassileva *et al.*, 2021). Another possibility for the wider application of microbial-based products is to exploit the beneficial microorganisms naturally present in salt-affected soils, which offer a unique and essential genetic source for future biotechnological applications. From the genetic point of view, these species display an under-or over-expression of peculiar genes and metabolites, which confer them the capability of coping with osmotic stress (Canfora *et al.*, 2014) and an excellent example in the production of metabolites capable of accomplishing the necessary actions for increasing stress tolerance. However, it's not a matter of scouting new beneficial microorganisms, but rather a question of new research for the characterization of existing microorganisms, the exploitation of the metabolic processes, fostering the adaptation and the mitigation of saline stress, and the optimization of the strategies for fermentation and formulation.

Land-use changes

The success of the previously presented adaptation strategies depends on several factors, and in some cases, they may not be able to counter the problem. As an alternative, land-use change as an adaptation measure can be considered. This option is most likely to take place at a scale larger than the field scale, in which case it can offer opportunities to implement soil ecosystem services beyond food production, such as providing and regulating environmental, health, climate, cultural, and recreational functions.

In a land-use change, it is crucial to evaluate the best use for a given soil. Innovative methods include georeferenced soil surveys and fieldwork observations integrated into a Geographic Information System, which allows the identification of the main limiting factors for agricultural production and enables decision-makers to develop an environmentally-sound range of strategies. A recent example of the application of this approach was made by De Feudis *et al.* (2021), in a coastal area of about 3,500 ha in Italy. The land suitability and degradation susceptibility were accessed and results showed that classifying the lands based on the land capability and suitability could help to define the best agricultural practices or other land uses to apply to preserve soil, as shown in Figure 6. In cases where agricultural uses can lead to severe soil degradation, alternative soil uses can be a solution, such as converting them into recreation and ecotourism areas, cultural heritage, or natural protection areas. An example of such an alternative measure is the “Soto de Los Tetones” (Navarre, Spain), a riparian area that exhibited strong soil salinization problems under improper irrigated agricultural management, and underwent a conversion to a natural protection area, as described by Amezketa and Lersundi (2008).

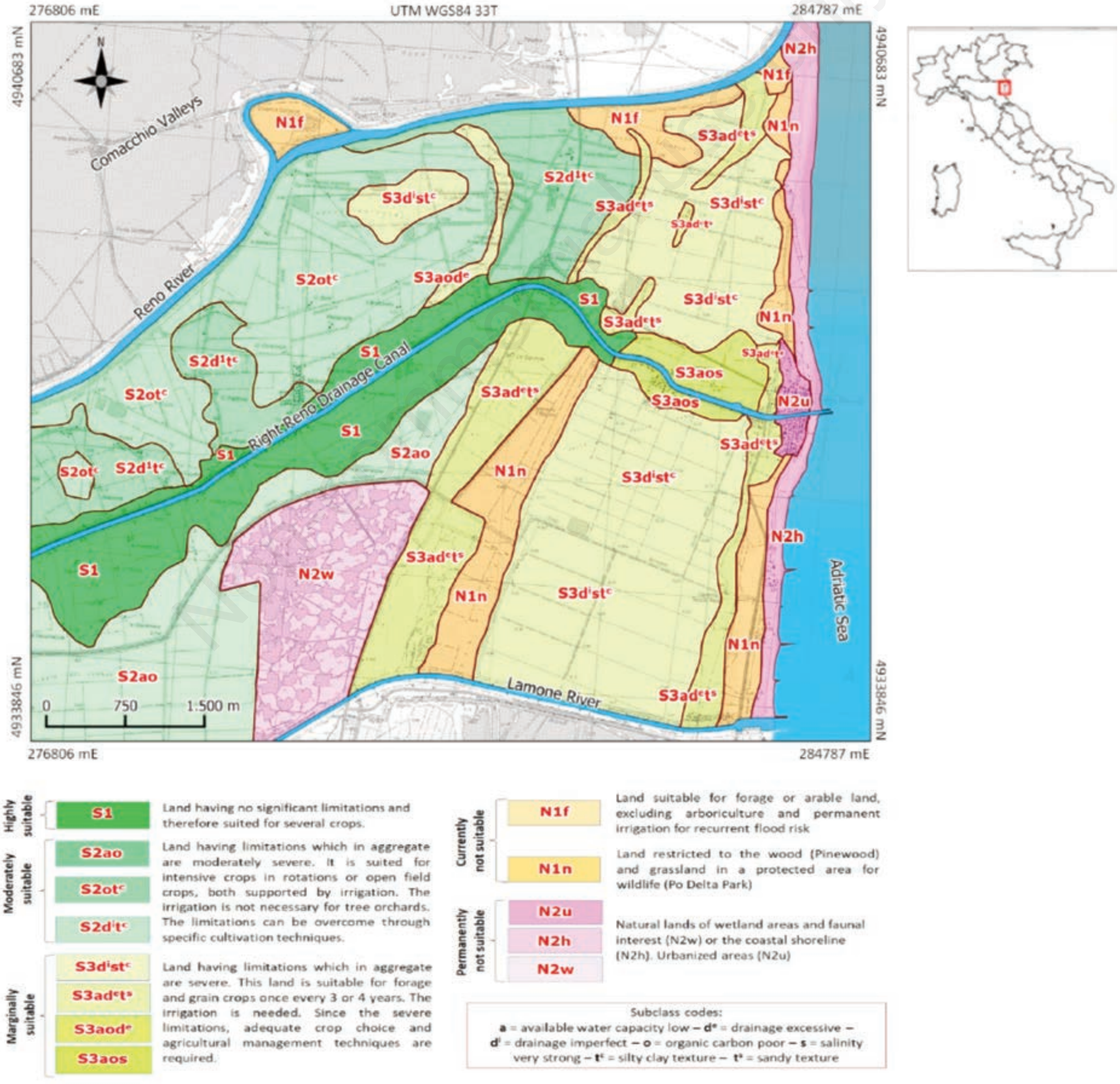

Figure 6. Land suitability map of a coastal area located in northeastern Italy. Adapted from De Feudis *et al.* (2021).

Summary of selected strategies with innovation potential and research needs

This article reviewed a series of strategies and respective case studies considering different approaches (prevention, mitigation, and adaptation) to counter the negative effects of salt-affected soils for agriculture. Table 3 summarizes the strategies, within each of the three approaches, which have, arguably, the highest innovation potential, identifying their limitations, advantages, and research needs.

Conclusions

This review showed how soils can be affected by salts in different ways and extents. As a result, strategies to counter salt-affected soils were divided into three approaches: preventive, mitigating, and adaptative. Even though, the specific practices can be used under more than one of these three approaches, according to the specifics of each system.

The case studies presented in the review show that adequate irrigation management and drainage can be used as a preventive measure to counter salt accumulation in soils. Phyto and bioremediation can be effective practices for the mitigation of soil sodicity, which can result in improved benefits compared to chemical remediation. Leaching and drainage can be effective measures for the mitigation of soil salinity. The case studies also show that crop rotation and management of soil organic matter can be used as adaptative measures that improve the plant's tolerance to salt-affected soils, while a newer approach, microbial management, shows innovation potential as an adaptative measure.

The identified successful case studies can be used as a practical basis for application at the field level and also to identify knowledge gaps and innovation potentials, showing that there is often a need for further research and demonstration to facilitate the wider application of these strategies.

The risk of development of salt-affected soils can be masked in the early stages, as there might be no obvious symptoms of salt accumulation but only a gradual decrease in fertility. Salt accumulation can lead to severe soil degradation and eventually to land abandonment; therefore, it deserves more attention from society. New policy instruments for encouraging the mapping and monitoring of salt-affected soils and promoting adapted management measures should be developed. At the same time, widespread knowledge of successful case studies and of the available strategies to counter salt-affected soils is needed.

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Table 3. Summary of strategies to counter salt-affected soils with innovation potential and research needs.

Approach	Specific strategy	Limitations	Advantages	Research needs	Innovation potential
Prevention	Irrigation practices including leaching requirements.	Specific to pedoclimatic conditions, crops, and water availability.	Potential for use of saline waters. Methodology for application in pedoclimatic regions that could be implemented with current irrigation projects.	Development of adequate water quality guidelines and leaching requirements for specific pedoclimatic regions; Development of guidelines for wider successful use of saline waters.	Achievement of sustainable irrigation projects in water-scarcity contexts.
Mitigation	Phyto and bioremediation.	Only possible in soils with a source of calcium (*e.g.* calcite); Only possible in low to medium sodicity.	No residues are left on the soil. More uniform and in-depth reclamation can be possible. Improvement of soil health and ecosystem services compared to chemical reclamation.	Case studies to understand specific relations between the remediation practices for each pedoclimatic and plants used. Guidelines and case studies of phytoremediation systems.	Improved methods for sustainable remediation of sodic and saline-sodic soils. Improved knowledge of soil-microbiome relationships.
Adaptation	Microbial and organic matter management.	Specific to each soil-plant system.	Potential for the general improvement of soil health.	More knowledge of the *in situ* role of soil biodiversity on plants tolerance; More practical case studies on the environmental impact caused by the use of new microorganisms.	Introduction of inoculates that are beneficial for soils and plants' tolerance.

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