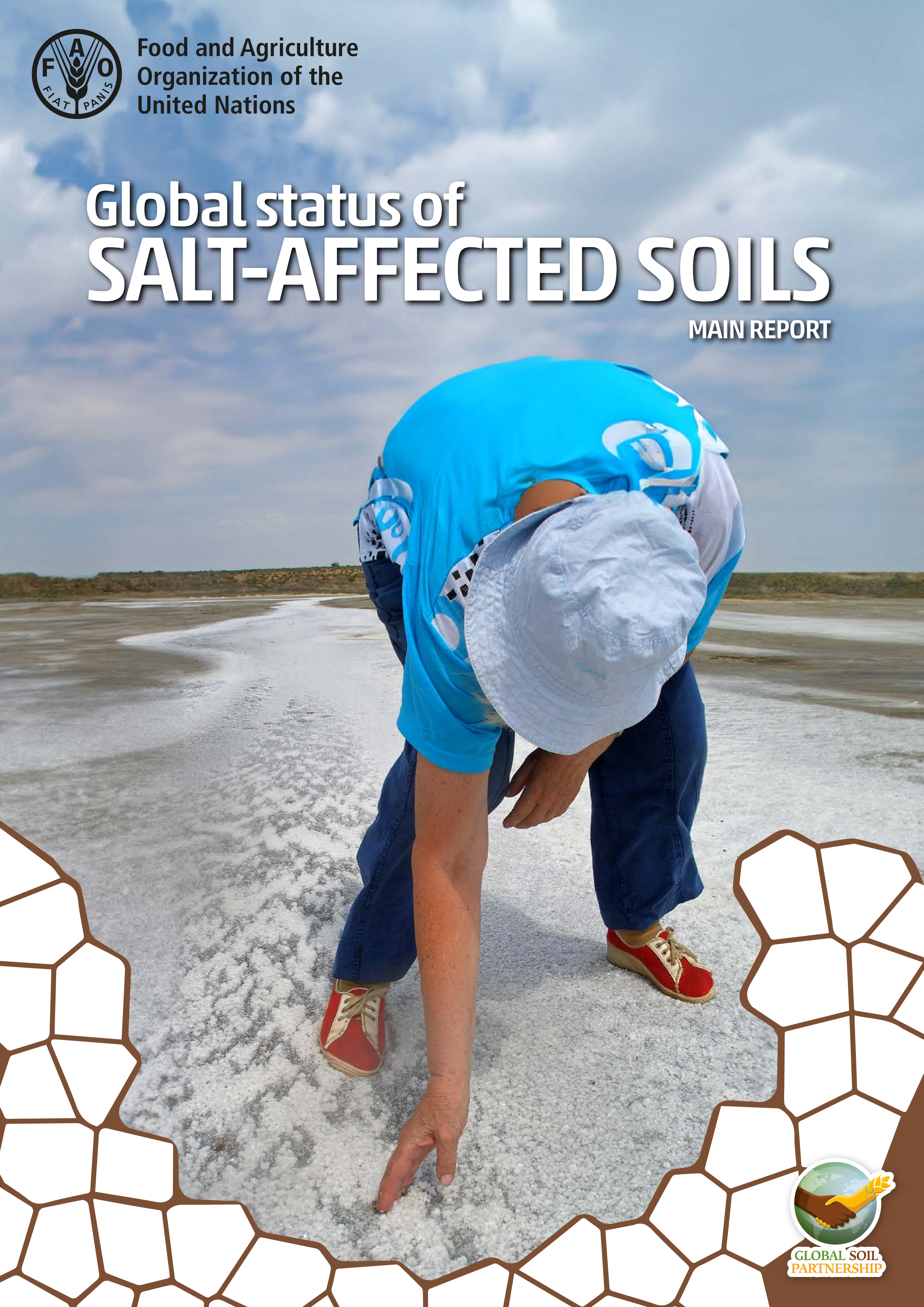
Food and Agriculture
Organization of the
United Nations

Global status of SALT-AFFECTED SOILS

MAIN REPORT



GLOBAL SOIL PARTNERSHIP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GLOBAL STATUS OF SALT-AFFECTED SOILS

MAIN REPORT

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Foreword

Among the diversity of soils on our planet, salt-affected soils are a group that have a distinct specificity. Many are primary or naturallysaline soils, which range from mangroves, marshes and coastal wetlands to inland salt flats and ancient sea beds, all of which are home to unique ecosystems that are adapted to extreme salinity conditions. Their resilience makes a significant contribution to global biodiversity and offers a fascinating insight into life's capacity to adapt. Studying these environments not only enriches our understanding of nature, but also promises to unlock the keys to adapt to future scenarios that are essential for maintaining crops in saline conditions and ensuring food security for the world's growing population.

Yet, as the world's population grows exponentially and living standards improve, the pressure to convert once marginal land into fertile land is intensifying. This phenomenon is particularly pronounced in semiarid and arid regions, which rely heavily on irrigation for agricultural production and are scarce in fresh water resources. As a result, secondary salinization – the gradual and humaninduced accumulation of salts in the soil – is a serious obstacle to agricultural production. The situation is set to worsen with the increasing effects of global warming and climate change, forcing populations to abandon degraded areas and triggering migration.

Against this backdrop, in 2019, the Food and Agriculture Organization of the United Nations (FAO), through its Global Soil Partnership (GSP), established the International Network of Salt-affected Soils (INSAS) during the Global Forum on Innovations for Marginal Environments organized by the International Center for Biosaline Agriculture (ICBA) (ICBA and Food Security Office, 2019). The network now has 743 members from 125 countries, all committed to a shared mission: promoting the sustainable and productive use of salt-affected soils. Their collaborative efforts led to the creation of the first edition of the Global Map of Salt-affected Soils (GSASmap) in 2021 (FAO, 2021), a testament to the power of collective action in addressing pressing environmental challenges.

The *Global status of salt-affected soils* report, presented here, is a product of the invaluable contributions from INSAS members and the Intergovernmental Technical Panel on Soils (ITPS), under the coordination of the GSP Secretariat. The report is a synthesis of national and regional reports, meticulously prepared by many experts across the world which examines the threat of salinization and sodification of soils, looking at salt-affected soils in both natural environments and those induced by human activities.

Highlighting the critical link between sustainable soil management, water quality, and food production, the report introduces many innovative ideas and sustainable approaches. It emphasizes the need to conserve natural saline ecosystems and promote compatible uses, recognizing the delicate balance necessary for their preservation. Furthermore, the report outlines strategies for the recovery of agricultural salt-affected soils, including emerging fields like saline agriculture and salinity bioremediation.

Crucially, the report calls for a legal framework at both a national and international level, inspired by agreements like the Ramsar Convention, (RAMSAR, 2023) that aims to safeguard natural saline ecosystems and ensure the sustainable management of agricultural soils under irrigation, particularly in areas at risk of salinization. The main goal is to protect productivity, quality, and overall soil health, thereby ensuring food quality and quantity for future generations.

The rich history of global efforts in this area, led by FAO, is an integral part of this narrative. Since the 1970s, FAO has been at the forefront of the fight against salt-affected soils through publications such as the FAO bulletins and irrigation and drainage papers. The creation of INSAS in 2019 is another milestone in this journey, uniting FAO Members in a common cause.

As we present this global report, we owe a debt of gratitude to the exemplary support and generosity of the INSAS members who devoted their time and expertise to its development. This report, with its wealth of data, practical recommendations, and holistic synthesis, aims to be a comprehensive resource for scientists, engineers, decision-makers, and environmental advocates engaged in the restoration and sustainable management of salt-affected soils.

Finally, we recognize that responsibility for the wellbeing of future generations lies with the choices we make today. This report is not just a collection of conclusions: it is a call to action. We hope that the ideas and recommendations it contains will guide informed decisionmaking and foster a collective commitment to preserving the delicate balance of our planet's soils, for the benefit of all and leaving no one behind.

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Abbreviations

AMF	arbuscular mycorrhizal fungi
ASR	ammonia-soda residue
BD	bulk density
CAP	Common Agricultural Policy
CEC	cation exchange capacity
CWR	crop wild relatives
DCR	diversified crop rotation
EC	electrical conductivity
ECe	electrical conductivity of saturated paste
ESP	exchangeable sodium percentage
F2F	Farm to Fork
FYM	farmyard manure
GHGs	greenhouse gases
GR	gypsum requirement
GSP	Global Soil Partnership
HOM	humidified organic matter
HS	humic substances
ICBA	International Center for Biosaline Agriculture
IPCC	Intergovernmental Panel on Climate Change
INSAS	International Network of Salt-affected Soils
ITPS	Intergovernmental Technical Panel on Soils
LRC	lowrank coal
NENA	Near East and North Africa
OM	organic matter
PAHs	polycyclic aromatic hydrocarbons
PCBs	polychlorinated biphenyls
PCDD/Fs	polychlorinated dioxins and furans
ppt	parts per thousand
QTL	quantitative trait loci
SAR	sodium adsorption ratio
SICS	soil-improving cropping systems
SIDS	Small Island Developing States
SPUSH	Network on Sustainable Productive Use of Salt-affected Habitats
TDS	total dissolved solids
TSS	total soluble salts
TWW	treated wastewater
WHC	water holding capacity
WRB	World Reference Base

Executive summary

1. Salt-affected soils are a specific group of soils that have elevated amounts of soluble salts (saline soils) or of exchangeable sodium (sodic soils) that adversely affect growth of most plants. The technical criteria used to distinguish saline soil from other soils is the relatively high electrical conductivity of saturated paste extract (ECe >4 dS/m at 25 °C or ECe >2 dS/m, depending on classification used), or relatively high content of soluble salts (TSS >0.1–0.2%). However, the threshold of salinity above which a plant will suffer deleterious effects varies according to plant type, salt type, soil health and fertility. The technical criteria to distinguish sodic soils from other soils is the relatively higher sodium adsorption ratio (SAR) of >13 or an exchangeable sodium percentage (ESP) of >15.

2. The drivers of salinisation and sodification are both natural and human-induced factors. Among the drivers of primary (natural) soil salinization and sodification are climate change and related phenomena (increasing aridity and freshwater scarcity, growing salinization of surface and groundwater, or permafrost thawing); increasing sea level rise; and tsunamis. Secondary (human-induced) soil salinization and sodification may result from irrigation with poor quality water, inadequate drainage or irrigation methods, deforestation and removal of deep-rooted vegetation (dryland salinization), excessive water pumping in coastal and inland areas, overuse of fertilizers, use of de-icing agents, and mining activity.

3. Salt-affected soils occur across all continents although they vary in severity. Natural saline and sodic soils often occur in arid, semi-arid and coastal regions, where they can host valuable, adapted ecosystems, harboring species that survive only in such soils. However, in agriculture, human-induced salt-affected soils are a challenging medium for growing conventional crops and if not properly managed, can cause substantial crop damage and decrease in productivity.

4. The *Global status of salt-affected soils* report provides a new estimate on the areas of salt-affected soils in the world. According to this estimate, the total area of salt-affected soils of the world amounts to 1 381 million ha (Mha), or 10.7 percent of the total global land area. The largest areas are found in Australia (357 Mha), Argentina (153 Mha), Kazakhstan (94 Mha), the Russian Federation (77 Mha), the United States (73.4 Mha), the Islamic Republic of Iran (55.6 Mha), the Sudan (43.6 Mha), Uzbekistan (40.9 Mha), Afghanistan (38.2 Mha), and China (36 Mha). These ten countries account for 70 percent of the total area of salt-affected soils of the world. The countries most affected by salinity and sodicity are Oman (93.5 percent of the country land area), Uzbekistan (92.9 percent), Jordan (90.6 percent), Kuwait (88.8 percent), Iraq (70.5 percent), United Arab Emirates (60.5 percent), Afghanistan (58.6 percent), Argentina (56 percent), Australia (46.4 percent) and Eritrea (40.1 percent).

5. Estimates dating back to the 1980s and early 1990s stated that 45 Mha (19.5 percent) of irrigated land and 32 Mha (2.1 percent) of the world's rainfed croplands, totalling 77 Mha, were affected by salinity or sodicity (Oldeman, Hakkeling and Sombroek, 1991)[1]. The new estimates carried out on the basis of FAO's Global Map of Salt-affected Soils (GSASmap)[2] (FAO, 2021) indicate that 10 percent of irrigated cropland and 10 percent of rainfed cropland are affected by salinity or sodicity, although uncertainty remains high due to the scarcity of available data[3].

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1 **Oldeman, L.R., Hakkeling, R.T.A. & Sombroek, W.G.** 1991. *World Map of the status of human- induced soil degradation: An explanatory note.* Wageningen, Kingdom of the Netherlands, International Food Policy Research Institute (IFPRI) & Nairobi, United Nations Environment Programme (UNEP).

2 The GSASmap is a country-driven global data product that covers 75 percent of the world´s land area. FAO. 2021. Global map of salt-affected soils. GSASmap v1.0. Rome, Italy. https://www.fao.org/documents/card/en/c/cb7247en

3 It is worth noting that many countries lack recent information on soil salinity and sodicity. In some cases, the coverage of ground truth (directly measured) data on soil salinity and sodicity are sparse which increases the uncertainty of predictions on the geographic distribution of salt-affected soils. The figures provided in the report are subject to further changes upon the updated information provided by the Members.

6. The models of the global aridity trend in the twenty-first century predict that it may increase to between 24 and 32 percent of the total land surface under the existing trend of temperature increase (Park *et al*., 2018[4]). As much as 80 percent of this aridification will occur in developing countries (Huang *et al*., 2016)[5]. Aridification will negatively affect topsoil moisture in most parts of the world as well as surface runoff in Europe, West Asia, the Near East, North America, the south of South America and Africa (Greve *et al*., 2019)[6].

7. The global predictions on the effect of climate change on soil salinization show that, by the end of the twenty-first century, secondary salinization will affect vast areas in South America, Mexico, the southwest of the United States, southern and western Australia, and South Africa. The opposite trend, or desalination, is predicted for the northwest of the United States, the Horn of Africa, Eastern Europe, Turkmenistan, and west Kazakhstan due to the expected changes in precipitation and evapotranspiration (Hassani, Azapagic and Shokri, 2021)[7].

8. In saline soils, crops that are not adapted to salinity show signs of wilting even if the soil is moist. This causes drought-like effects, with slower and weaker growth, early leaf drop, and reduced yield. Some plants are better adapted to salinity and hence referred to as salt-tolerant crops (domesticated) and halophytes (wild species). There are around 625 species of halophytes, making up 0.2 percent of all plant species (Flowers and Al Azzawi, 2022)[8]. These plants can tolerate very high-amount of salts and offer the genetic basis for a salt response in nature that can be exploited in agriculture. Moreover, there are almost 1 500 salt-tolerant species globally which have nutritional potential but are underused in agriculture in salt-affected areas (Qureshi and Barrett Lennard, 1998)[9].

9. Global water use has increased by a factor of six during the last century. Estimates by UN-Water show that 2.4 billion people – or 30 percent of the global population – already live in water-stressed countries (UN-Water, 2023)[10]. In 2050, this number will increase and hence affect 2.7 to 3.2 billion people. The affected regions are mostly located in the Near East and North Africa region (NENA), and South Asia, Peru, Spain, northeast China, and western United States (WWAP/UN-Water, 2018)[11].

10. The growing trend of water demand is accompanied by the growing deterioration of water quality. Around 40 percent of water bodies globally are of poor quality, according to available data, and at least 16 percent of groundwater worldwide is saline and brackish (UN-Water, 2021; van Weert, van der Gun and Reckman, 2009)[12 13]. However, this number is most probably underestimated as surface and ground water quality data are not monitored in

4 **Park, C.-E., Jeong, S.-J., Joshi, M., Osborn, T.J., Ho, C.-H., Piao, S., Chen, D.** *et al*. 2018. Keeping global warming within 1.5 °C constrains emergence of aridification. *Nature Climate Change*, 8(1): 70–74. https://doi.org/10.1038/s41558-017-0034-4

5 **Huang, J., Yu, H., Guan, X., Wang, G. & Guo, R.** 2016. Accelerated dryland expansion under climate change. *Nature Climate Change*, 6(2): 166–171. https://doi.org/10.1038/nclimate2837

6 **Greve, P., Roderick, M.L., Ukkola, A.M. & Wada, Y.** 2019. The aridity Index under global warming. Environmental Research Letters, 14(12): 124006. https://doi.org/10.1088/1748-9326/ab5046

7 **Hassani, A., Azapagic, A. & Shokri, N.** 2021. Global predictions of primary soil salinization under changing climate in the 21st century. *Nature Communications*, 12(1): 6663. https://doi.org/10.1038/s41467-021-26907-3

8 **Flowers, T.J. & Al-Azzawi, M.** 2022. eHALOPH. In: *Halt Soil Salinization, Boost Soil Productivity – Proceedings of the Global Symposium on Salt-affected Soils*. Rome, FAO. https://www.fao.org/documents/card/en/c/cb9565en

9 **Qureshi, R. & Barrett-Lennard, E.G.** 1998. *Saline agriculture for irrigated land in Pakistan: A handbook*. Canberra, ACIAR.

10 UN-Water. 2023. Blueprint for Acceleration: Sustainable Development Goal 6 Synthesis Report on Water and Sanitation 2023. New York, UN-Water. https://www.unwater.org/sites/default/files/2023-08/UN-Water_SDG6_SynthesisReport_2023.pdf

11 **WWAP (United Nations World Water Assessment Programme)/UN-Water.** 2018. *The United Nations World Water Development Report 2018: Nature-Based Solutions for Water*. Paris, UNESCO.

12 **UN-Water**. 2021. *Summary Progress Update 2021 – SDG 6 – water and sanitation for all*. Version: July 2021. Geneva, Switzerland, UN-Water. https://www.unwater.org/sites/default/files/app/uploads/2021/12/SDG-6-Summary-Progress-Update-2021_Version-July-2021a.pdf

13 **van Weert, F., van der Gun, J. & Reckman, J.** 2009. Global Overview of Saline Groundwater Occurrence and Genesis (Report number: GP 2009-1). International Groundwater Resources Assessment Center (IGRAC), Utrecht, Kingdom of the Netherlands. https://www.un-igrac.org/sites/default/files/resources/files/Global%2520Overview%2520of%2520Saline%2520Groundwater%2520Occurences%2520and%2520Genesis.pdf

most countries. The use of unconventional water sources such as municipal wastewater and desalinated water is continuously growing.

11. Groundwater is often used to supply water for irrigation. Globally, 33 percent of water for irrigation comes from groundwater. Global groundwater withdrawals for irrigated agriculture have been continuously increasing in the twentieth and twenty-first century and have increased by 19 percent between 2010 and 2018, reaching 820 km^3/yr (FAO, 2022)[14]. The salinization of groundwater due to overexploitation of the aquifers has been reported for both coastal areas as well as arid and semi-arid inland areas.

12. Insufficient drainage and saline and sodic water are the main causes of human-induced soil salinization in agricultural areas. Around 100 million ha, or one-third of all irrigated areas suffer from inadequate drainage (Tyagi, 2014)[15]. Fresh water is particularly scarce in dry regions, so brackish groundwater and treated wastewater are increasingly used for irrigation in water-stressed countries.

13. Over one billion people inhabiting coastal zones are under threat of progressive flooding and salinization by the end of the twenty-first century due to sea level rise. Low-lying areas will become submerged, shorelines deteriorate, floods worsen, and estuaries and aquifers will become more saline. Many developing countries are especially vulnerable to sea level rise because of their low-lying terrain and lack of resources to make necessary adjustments. The most vulnerable nations are Bangladesh, China, Egypt, and Viet Nam, all of which have substantial populations in deltaic coastal regions (Kulp and Strauss, 2019)[16].

14. In the countries most affected by cropland salinity, potential crop losses due to salinity stress are up to 72 percent for rice, 68 percent for bean, 45 percent for sugarcane, 40 percent for potato, 38 percent for sweet potato, 37 percent for maize, 15 percent for wheat, 14 percent for barley, 12 percent for sorghum, 11 percent for cowpea, and 4 percent for cotton and sunflower, according to GSASmap estimates covering 644 Mha of global cropland.

15. Many countries still lack specific regulations to protect natural salt-affected soils that support valuable ecosystems and rare species. Some of those ecosystems can be protected by the Ramsar Convention on wetlands (RAMSAR, 2023)[17], however, many cannot, leaving them unprotected and at risk of biodiversity loss and even extinction of unique species. It is therefore of paramount importance to raise awareness of the value of these ecosystems, both within and outside wetlands, among respective governmental bodies.

16. In cultivated areas affected by salinity or at risk of salinization, most surveyed countries (76 percent out of 50 countries) lack regulations on the sustainable use and management and reclamation of salt-affected soils. In half of the surveyed countries, there is no governmental body monitoring or supervising the management of salt-affected soils (and soil salinization or sodification).

17. Given that salt affected soils represent at least 10 percent of arable land, the sustainable management of these soils is crucial to meet food demand, which FAO has identified as a critical strategy to increase agricultural productivity. Both mitigation and adaptation strategies can be applied to sustainably manage salt-affected soils for agricultural

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14 **FAO**. 2022. The State of the World's Land and Water Resources for Food and Agriculture – Systems at breaking point. Main report. Rome. https://doi.org/10.4060/cb9910en

15 **Tyagi, A.C.** 2014. Drainage on waterlogged agricultural areas. Irrigation and Drainage, 63(4): 558–559. https://doi.org/10.1002/ird.1888

16 **Kulp, S.A. & Strauss, B.H.** 2019. New elevation data triple estimates of global vulnerability to sea level rise and coastal flooding. *Nature Communications*, 10(1): 4844. https://doi.org/10.1038/s41467-019-12808-z

17 **Ramsar**. 2023. The Convention on Wetlands. In: *Ramsar*. Gland, Switzerland, Convention on Wetlands Secretariat. [Cited July 2023]. https://www.ramsar.org/

production. Mitigation strategies are aimed at the reduction of salinity levels in the root zone and include physical, such as mulch, interlayers of loose material, installation of drainage, land levelling and others, and chemical and biological measures, including calcium-containing amendments, improved crop rotations and diversification, agroforestry and bioremediation. Adaptation strategies are aimed at coping with existing salinity levels through breeding of salt-tolerant plants, domestication of halophytes, halopriming and use of bioinoculants. The traditional approach to manage saline soils is to fight salinity and rehabilitate soils by adding water to leach salts. The recovery of sodic soils is different, usually involving Ca-rich amendments like gypsum, together with organic amendments like farmyard manure. However, the full range of practices that can help manage salt-affected soils is diverse and there is no one-size-fits-all solution; integration of all those locally-adapted practices that allow for productivity improvement should be sought.

18. To respond to this major threat to food security and global soil health, the Food and Agriculture Organization of the United Nations through its Global Soil Partnership established in 2021 the International Network of Salt-affected Soils (INSAS)[18] that brings together more than 830 experts, practitioners and policymakers from around the world.

19. The status of the measurement, monitoring and management of salt-affected soils was evaluated by the INSAS survey. The survey highlighted several key challenges in managing salt-affected soils globally. Many countries lack official, updated data on the extent of these soils, with outdated mapping methods and limited monitoring. Soil salinity is measured variably, often using EC in saturated paste extract, though data harmonization is essential. Electromagnetic methods, which provide efficient salinity mapping, are underutilized, suggesting a need for broader training. Although sustainable soil management practices exist, data on their adoption and effectiveness are sparse, and there is limited assessment of yield impacts from salinity. Agrohydrological models, useful for managing salinity issues, are not widely implemented, and many countries lack policies specifically addressing salt-affected soils. Furthermore, while brackish water is commonly used, irrigation water monitoring is infrequent, despite consensus among experts on its importance.

20. The FAO Global Soil Partnership recommends urgent and coordinated global action to manage salt-affected soils to ensure food security and ecosystem conservation. Scaling up sustainable management practices and advancing saline agriculture with salt-tolerant crops and halophytes are key to boosting food production and environmental resilience in affected regions. Building markets for these crops, with targeted policy support, can create economic opportunities for farmers and reinforce food security. Enhanced data collection on salinity and sodicity, along with rigorous water quality monitoring, will ensure sustainable resource management. Quantifying yield impacts, conserving salt-affected ecosystems, and fostering cross-sector collaboration can strengthen governance. Expanding research capabilities, encouraging academia-industry partnerships, and enhancing training for farmers and students will equip stakeholders with the expertise needed to manage these soils effectively. This integrated approach aims to address the challenges of salinity by promoting sustainable agriculture, innovation and cross-sectoral coordination, thereby improving resilience in salt-affected regions and ensuring food production in the midst of climate challenges.

18 https://www.fao.org/global-soil-partnership/insas/en/


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Chapter 1 | Salt-affected soils: the global perspective

1.1 | Description of salt-affected soils

Salt-affected soils include saline, sodic and saline sodic soils. Saline and sodic soils often occur naturally, especially in arid, semi-arid and coastal regions, where they can host valuable, adapted ecosystems. However, in agriculture, secondary (human induced) salt-affected soils are a challenging medium for growing conventional crops (Figure 1.1). Salt-affected soils occur across all continents although they vary in severity. Some of the most affected regions are Central Asia, the Near East and North Africa (NENA), the Pacific, and South America, although many more areas are also affected worldwide.

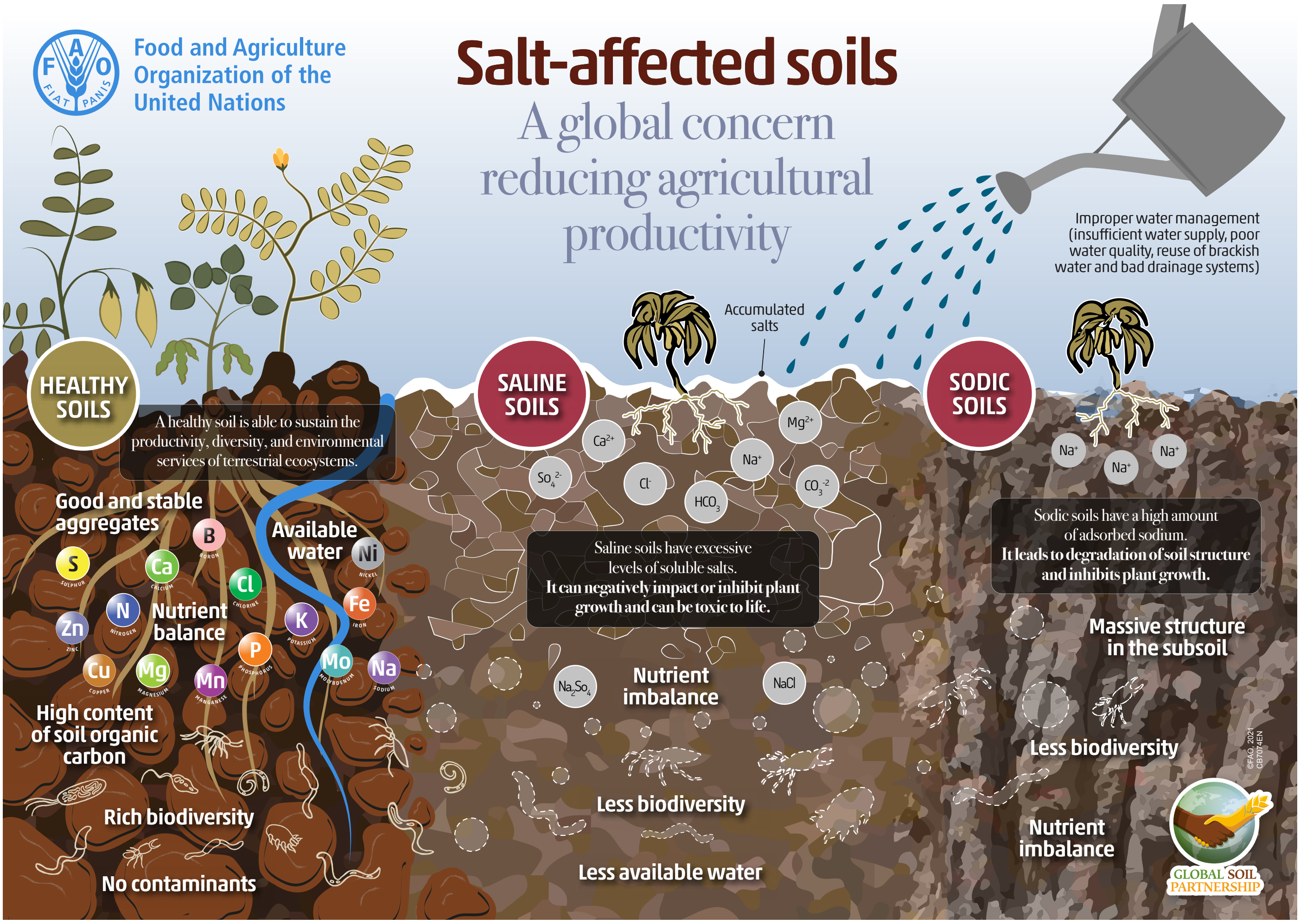

Figure 1.1 | Salt-affected soils: A global concern reducing agricultural productivity

Source: FAO. 2021. Salt-affected soils: A global concern reducing agricultural productivity [poster]. Rome. *https://www.fao.org/3/cb7074en/cb7074en.pdf*

Salts are common components of the Earth. Globally, the total reserves are colossal, with more than 3.5–4.0 × 10^{15} tonnes of salts on land and at least ten times more (35–50 × 10^{15} tonnes) in the oceans (Figure 1.2). The total reserves of salts in the upper metre of global soils can be roughly estimated at a minimum of 2 × 10^{10} tonnes, based on the Food and Agriculture Organization of the United Nations (FAO)'s Global Map of Salt-affected Soils (GSASmap) (FAO, 2021). This means that only 0.0005 percent of salts on land and 0.00005 percent of all salts on Earth are present in soils as they are mainly leached from the surface by fresh water. However, climate change that leads to less rainfall and higher aridity can alter salt circulation from the deeper soil layers to the surface, causing greater accumulations in soils (Schofield and Kirkby, 2003).

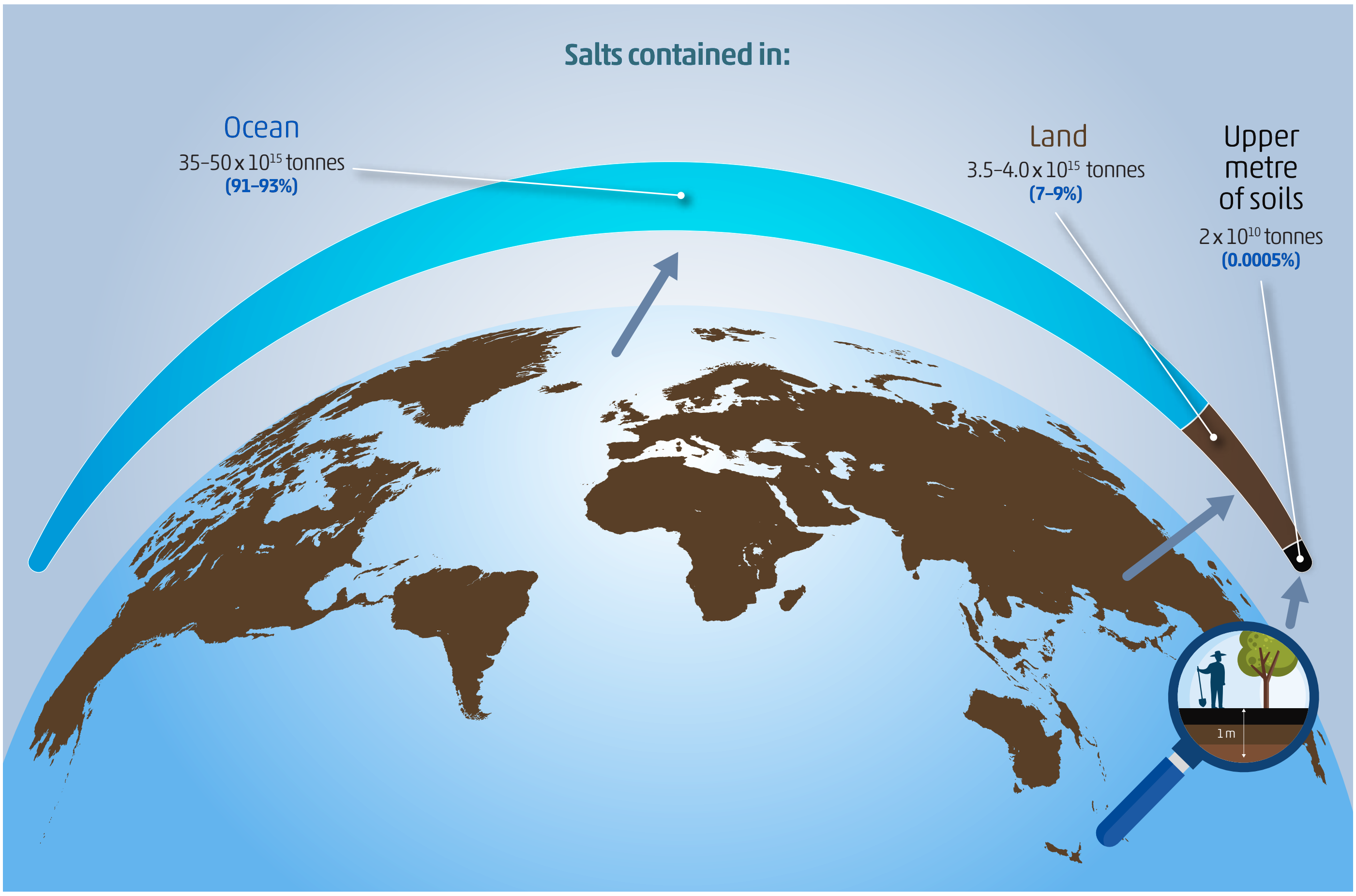

Figure 1.2 | Salt reserves on Earth

Soluble salts such as sodium (Na), magnesium (Mg) and potassium (K) are present in all soils as sulphates and chlorides. They contribute to soil particle aggregation and the formation of soil structure, as well as providing many of the nutrients needed for plant health and growth. However, in excess, soluble salts can drastically inhibit the ability of a plant to germinate and grow successfully, by restricting, disrupting or preventing the plant's ability to take up water and take up the dissolved nutrients it needs.

In **saline soils**, crops that are not adapted to salinity show signs of wilting even if the soil is moist. This is because when the concentration of solutes and salts in the soil becomes too high, the process of osmosis is interrupted and the plant cell is unable to take up water and nutrients from the surroundings. Osmosis either stops, or actually reverses, and removes water from the plant (Figure 1.3). This causes drought-like effects, with slower and weaker growth, early leaf drop and reduced yield.

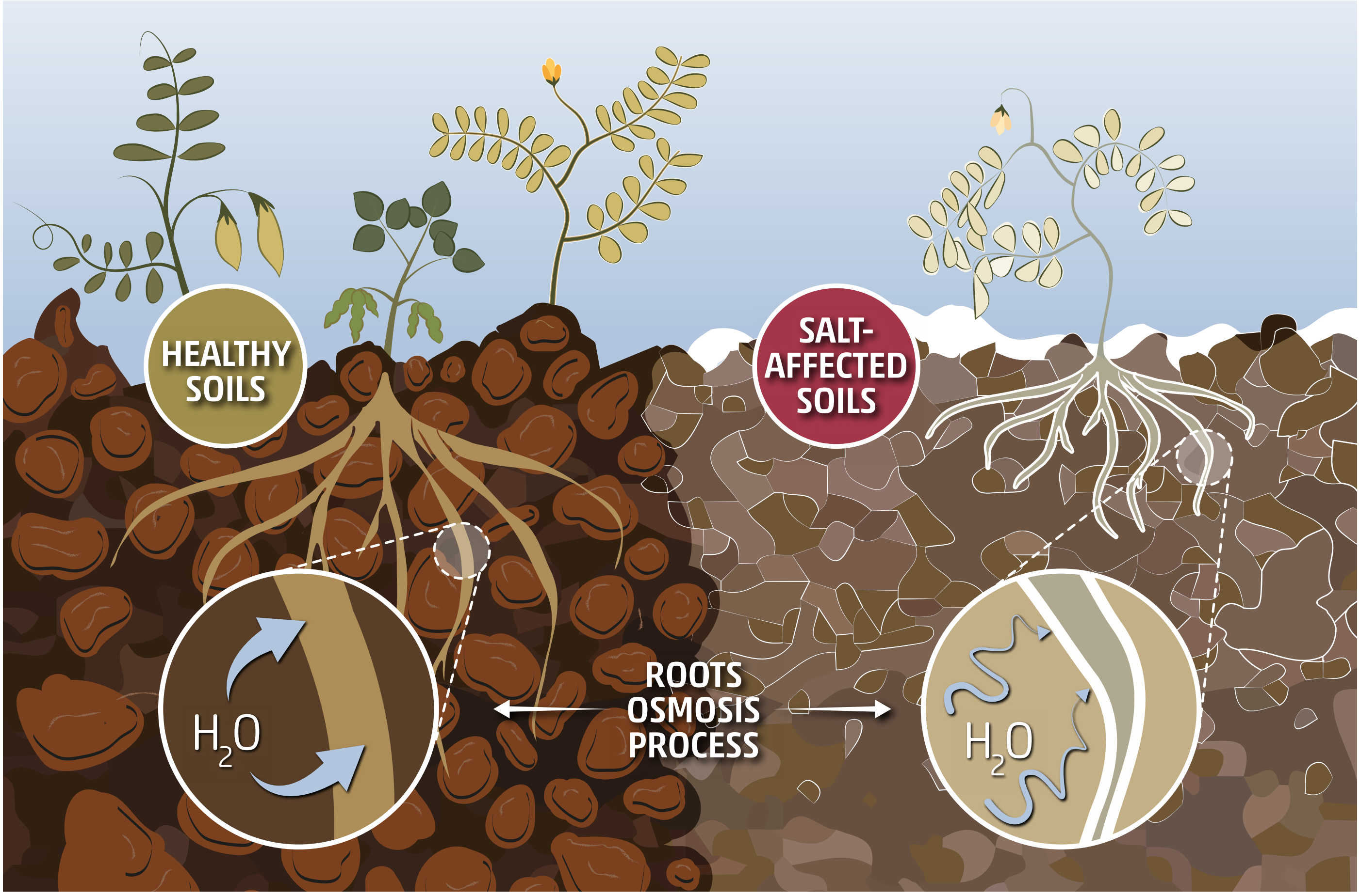

Figure 1.3 | Impact of salts on plant growth

Source: **FAO**. 2021. Global Map of Salt-affected Soils [flyer]. Rome.
https://www.fao.org/3/cb7247en/cb7247en.pdf

However, some plants have adapted to salinity stress and are able to extract water and nutrients from saline soils. These plants are called halophytes (Box 1.1).

Box 1.1 | Halophytes

The Earth has huge reserves of water, made up from mostly seawater and dominated by the presence of sodium ions (Na^+) and chlorine ions (Cl^-) (480 mM and 560 mM, respectively).

Most plants can survive only when fresh water is available. However, some plants have developed morphological features to cope with salinity. Plant tolerance to salts greatly varies across species, from those killed by just 25 mM of salt, such as the most sensitive cultivars of chickpea (Flowers *et al.*, 2010) to plants that are able to tolerate twice the salt concentrations of seawater (around 35 grams of sodium chloride [NaCl] per litre of seawater), such as *Tecticornia* (English and Colmer, 2013). Within this range, arbitrary lines have been drawn that separate plants into the following groups:

- **Glycophytes** (plants that are intolerant of salt).
- **Salt-tolerant** (plants that are able to tolerate salinity in the range from 80 to 200 mM NaCl).
- **Halophytes** (plants that grow in 200–360 mM NaCl) (Flowers and Colmer, 2008).
- **Euhalophytes** (plants that are able to grow in the salt concentration of seawater and beyond).

There are around 625 species of halophytes which makes up 0.2 percent of plant species (Flowers and AlAzzawi, 2022). These plants hold the genetic basis for a salt response in nature that can be used in agriculture (Rozema *et al.*, 2015).

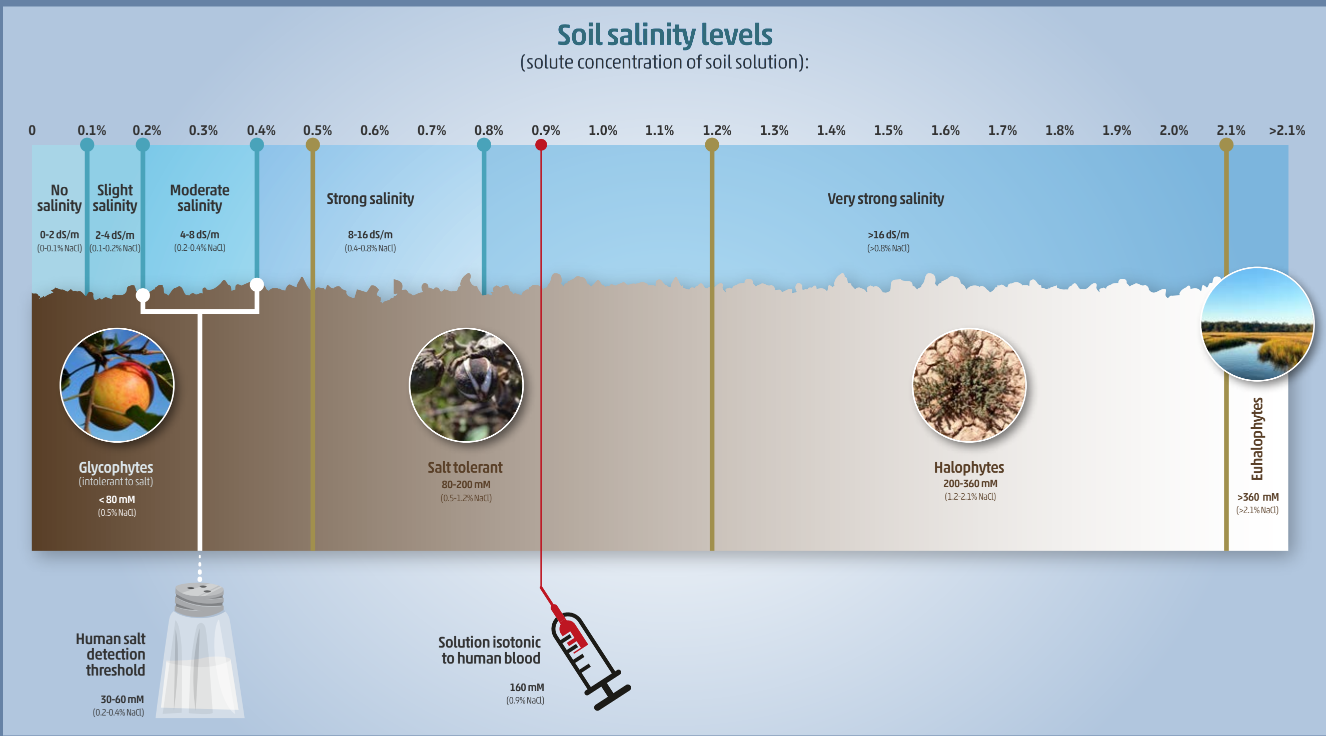

Figure B 1.1 | Levels of plant tolerance and soil salinity

Sources: **Flowers, T.J., Gaur, P.M., Gowda, C.L.L., Krishnamurthy, L., Samineni, S., Siddique, K.H.M., Turner, N.C., Vadez, V., Varshney, R.K. & Colmer, T.D.** 2010. Salt sensitivity in chickpea. *Plant Cell & Environment*, 33(4): 490–509. doi: 10.1111/j.1365-3040.2009.02051.x
English, J.P. & Colmer, T.D. 2013. Tolerance of extreme salinity in two stem-succulent halophytes (Tecticornia species). *Functional Plant Biology*, 40(8-9): 897–912. doi:10.1071/fp12304
Flowers, T.J. & Colmer, T.D. 2008. Salinity tolerance in halophytes. *New Phytologist*, 179(4): 945–963. doi: 10.1111/j.1469-8137.2008.02531.x
Flowers, T.J. & Al-Azzawi, M. 2022. eHALOPH. In: *Halt Soil Salinization, Boost Soil Productivity – Proceedings of the Global Symposium on Salt-affected Soils*. Rome, FAO. https://www.fao.org/documents/card/en/c/cb9565en
Rozema, J., Cornelisse, D., Zhang, Y., Li, H., Bruning, B., Katschnig, D., Broekman, R., Ji, B. & van Bodegom, P. 2015. Comparing salt tolerance of beet cultivars and their halophytic ancestor: consequences of domestication and breeding programmes. *AoB Plants*, 7: 1–12. https://pdfs.semanticscholar.org/2d55/f17e6ba5a24ff2cfc7c1d6dd5d3190422001.pdf

A saline soil often occurs in areas of low rainfall, where more water is lost through evaporation than can be replaced by rain or irrigation. This can lead to salts not being leached out through the soil as would usually happen, and instead are concentrated in the root zone, with all the resultant problems for plants. Saline soils are also widespread in coastal areas where soils become salinized due to the influence of seawater through tides or saline aquifers.

Extremely saline soils often have low biodiversity, a lessened microbial presence, nutrient deficiencies and can become toxic to life.

The salinity of a soil is defined by measuring the conductivity of an electric current passed through a soil water extract (electrical conductivity of saturated paste extract, or ECe) or by the amount of salts containing in soil (total soluble salts [TSS]). The technical criteria used to distinguish **saline soil** from other soils is the relatively high EC of a saturation extract (EC >4 dS/m at 25 °C) and a relatively lower sodium adsorption ratio (SAR) of <13 or an exchangeable sodium percentage (ESP) of <15. The content of soluble salts should be higher than 0.1–0.2 percent. However, the threshold of salinity above which a plant will suffer deleterious effects varies according to plant type, salt type, soil health and fertility.

Sodic soils get their name from sodium ions (Na^+), that can adversely change soil structure when present in excessive amounts within soil particles, leading to clay dispersion. Normally, soil particles are held together by flocculation[1] (Figure 1.4). Because of this phenomenon, sodic soils are also called dispersive soils in Australia (DPIRD, 2021). As opposed to dissolved Na, the adsorbed Na in sodic soils is hardly removed from the soil by natural processes and remains in soils for prolonged periods. Special measures are developed to reclaim such soils (described in Chapter 5.2 of the full report).

Sodic soils are also sometimes known as Solonetz (IUSS Working Group WRB, 2022) and black alkali soils (Qadir, Schubert and Steffens, 2005). A sodic soil is often highly prone to waterlogging and will often be hard and compact when dry, and deeply cracked, with an almost cementlike composition. Such a hard surface reduces and hinders the natural flow of water through the soil – whether via rain or irrigation – which affects a plant's emergence and root growth as well as making the soil highly susceptible to erosion.

[1] Flocculation is a term describing a process by which a chemical coagulant added to the water acts to facilitate bonding between particles, creating larger aggregates which are easier to separate (Bridle, ed., 2013).

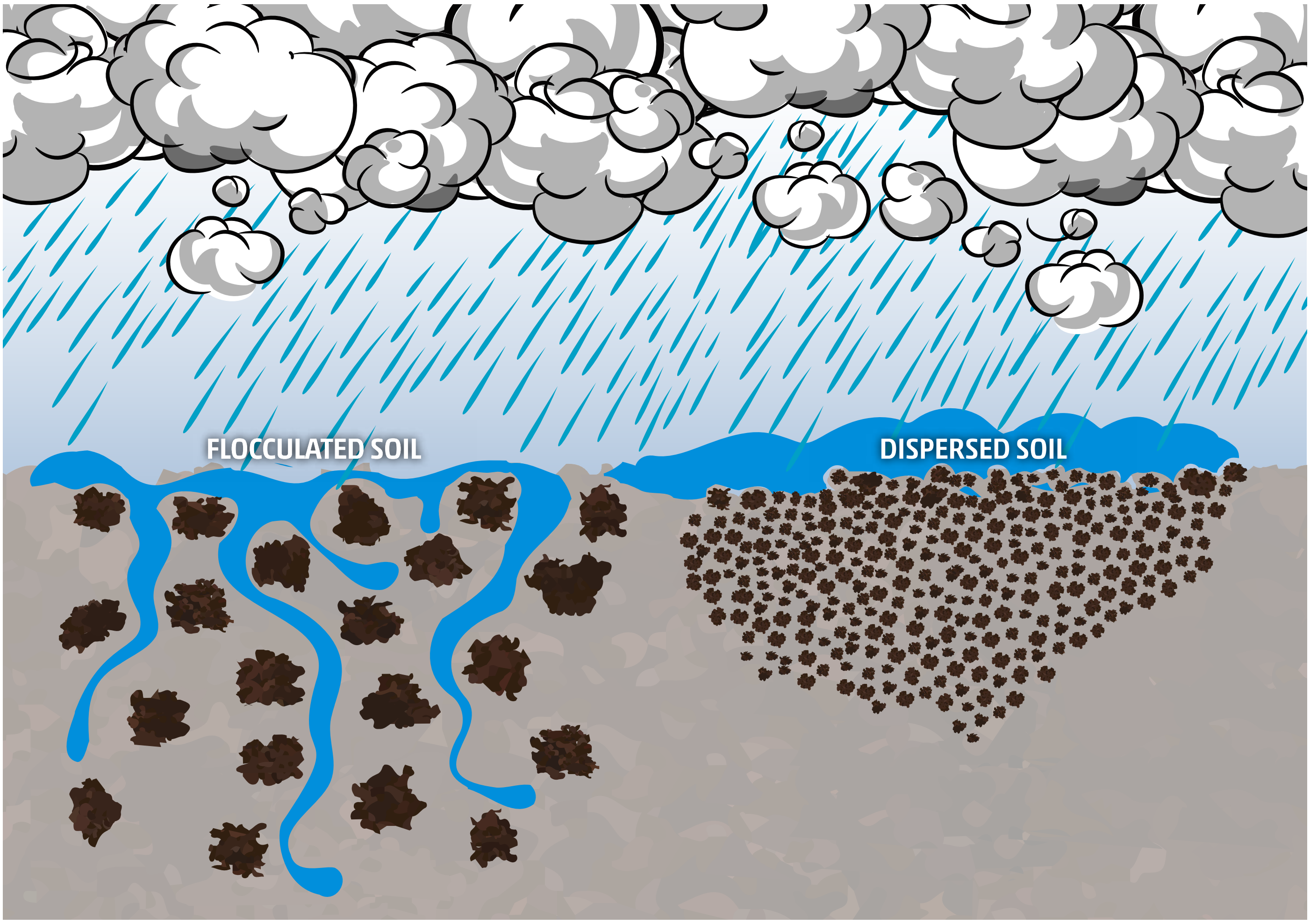

Figure 1.4 | The impact of soil dispersion in sodic soils on soil structure, porosity and water percolation

Source: Adapted from **Horneck, D.A., Ellsworth, J.W., Hopkins, B.G., Sullivan, D.M. & Stevens, R.G.** 2007. *Managing Salt-affected Soils for Crop Production*. Moscow, USA, University of Idaho, Corvallis, USA, Oregon State University, & Pullman, USA, Washington State University [Pacific Northwest Extension Publishing (PNW)]. *https://catalog.extension.oregonstate.edu/sites/catalog/files/project/pdf/pnw601.pdf*

Sodic soils have elevated amounts of exchangeable Na compared to the amounts of calcium and Mg measured as SAR >13 or ESP >15 but with a relatively lower salinity (EC <4 dS/m at 25 °C). The diagnosis of sodic soils varies between regions and academic schools. Some other criteria for defining soil as sodic could be: the excessive amount of exchangeable Mg (or the sum of Na and Mg); the specific (columnar) structure of sodic horizon; high dispersion; or the presence of specific microfeatures such as clay coatings.

Saline sodic soils have the characteristics of both saline and sodic soils, being high in salts with a high proportion of Na within soil particles (EC >4 dS/m at 25 °C and SAR >13 or ESP >15).

The variability of salt-affected soils is also defined by the depth of the upper saline or sodic horizon (surface, shallow, medium, and deep), the level of salinity (slight, moderate, strong, very strong, and extreme) as well as the chemical composition of salts (Pankova, Gerasimova and Korolyuk, 2018). Moreover, it is a typical feature of salt-affected soils that they combine with other nonsaline soils close by, forming patchy landscapes. This means that the proportion of salt-affected soils in an area can vary over the widest range, from one percent to covering 100 percent of the area. Therefore, when salt-affected soils are mapped, they are usually depicted by the percentage they represent of a larger area. This leads to an increased uncertainty in the estimates of the distribution and areas of salt-affected soils, especially in regions where they are patchy or dispersed across the landscape.

The latest comprehensive overview on the different classification schemes and methods used for the measurement of salt-affected soils is given by Zaman, Shahid and Heng (2018).

1.2 | Factors of soil salinization and sodification

Salinization and sodification are the processes of salinity and sodicity increase due to natural or humaninduced factors (Figure 1.5). Primary (or inherent) salinity and sodicity means the natural occurrence of salt-affected soils in the landscape, such as salt marshes, salt lakes, tidal swamps or natural salt scalds. Secondary salinity and sodicity are a result of the salinization of the soil, surface water or groundwater due to human activity such as urbanization and agriculture (irrigated and dryland) (DIINSW, 2009).

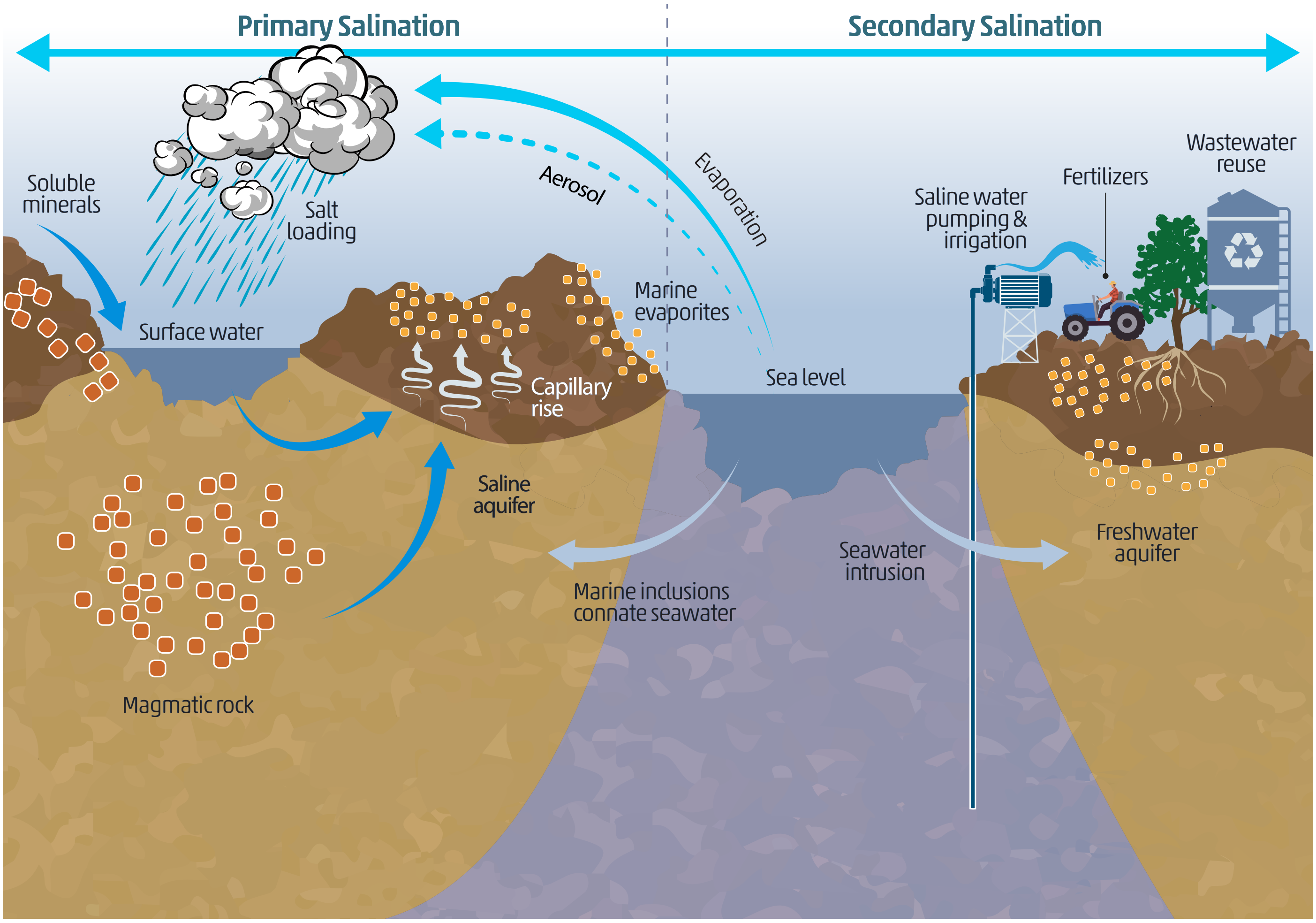

Figure 1.5 | Primary and secondary salinization

Source: Adapted from **Nachshon, U. & Levy, G.J.** 2023. Soil salination processes and management. In: D. Hillel, ed. *Encyclopedia of Soils in the Environment*, pp. 236–245. Amsterdam, Elsevier. *https://doi.org/10.1016/B978-0-12-822974-3.00014-8*

The sources of salts in soil are mainly from the weathering of saltbearing rocks or minerals, volcanic activity, seawater intrusion, and dry and wet aeolian input of salts from saline playas and coastal areas (Stavi, Thevs and Priori, 2021). Salts are mainly flushed from the topsoil by rainfall or irrigation. However, their accumulation may happen in specific locations due to restricted drainage either above the impermeable soil layers or within the topographic depressions under the condition of freshwater scarcity and climate aridity.

At present, increased **primary (natural) soil salinization and sodification** may be observed as the result of the following environmental factors:

- climate change and related phenomena (increasing aridity and freshwater scarcity, growing salinization of surface and groundwater, or permafrost thawing);
- increasing sea level rise; and
- tsunamis.

Increased **secondary (human-induced) soil salinization and sodification** may result from the following factors:

- irrigation with poor quality water;
- inadequate drainage or irrigation methods;
- deforestation and removal of deeprooted vegetation (dryland salinization);
- excessive water pumping in coastal and inland areas;
- overuse of fertilizers;
- use of de-icing agents; and
- mining activity.

Secondary soil salinization and sodification is considered separately in Chapter 2 of this report.

1.2.1 | Aridity trends

Arid regions occupy around 40 percent of the land surface (Gaur and Squires, 2018). However, the climatic aridity is not constant if considered as a time span. Paleoclimate reconstructions show that arid stages have occurred in all regions, including those being highly humid at present, such as Central Europe and East China (Figure 1.6).

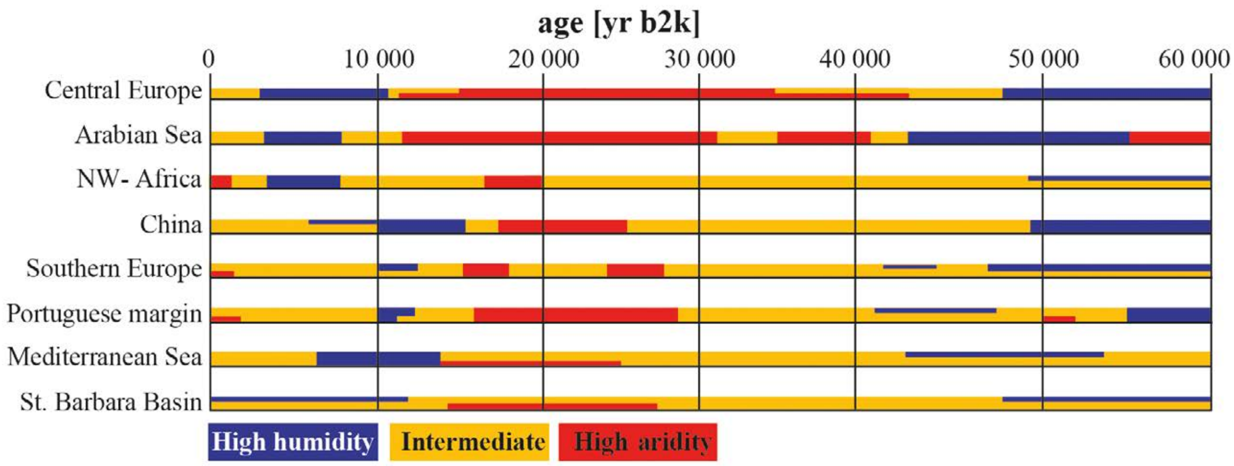

Figure 1.6 | Historic aridity trends

Source: **Fuhrmann, F., Diensberg, B., Gong, X., Lohmann, G. & Sirocko, F.** 2020. Aridity synthesis for eight selected key regions of the global climate system during the last 60 000 years. *Climate of the Past*, 16(6): 2221–2238. *https://doi.org/10.5194/cp-16-2221-2020*

The global aridity trend models predict that by the end of the twenty-first century, 24 to 32 percent of the total land surface may increase in aridity under the existing temperature trend (Huang *et al.*, 2016; Park *et al.*, 2018). As much as 80 percent of this aridification will occur in developing countries (Huang *et al.*, 2016). The Special Report on Climate Change and Land of the Intergovernmental Panel on Climate Change (IPCC) confirms that most global and regional models show an increasing trend in aridity (Mirzabaev *et al.*, 2019). Aridification will negatively affect topsoil moisture in most parts of the world as well as surface runoff in Europe, West Asia, the Near East, North America and the south of South America and Africa (Figure 1.7).

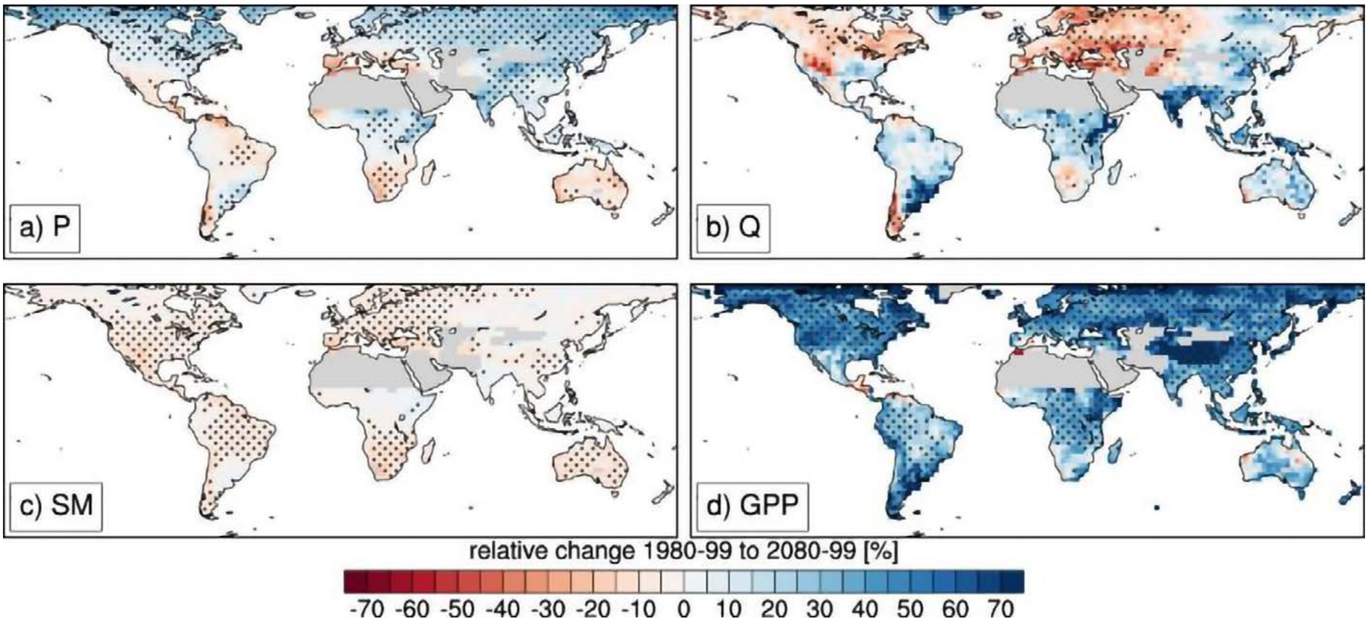

Figure 1.7 | Modern aridity trends

Note: These maps show the relative changes in hydroclimatological and agroecological variables related to aridity. Illustrated is the ensemble median change for between 1980 and 1999, and between 2080 and 2099 under the RCP8.5 (business-as-usual) emission scenario for: a) *precipitation (P)*; b) *runoff (Q)*; c) surface soil moisture (SM); and d) gross primary productivity (GPP). Stippling denotes regions where at least 75 percent of all climate models agree in sign. Grey colours mask regions with an ensemble-mean annual rainfall below 100 mm.

Source: **Greve, P., Roderick, M.L., Ukkola, A.M. & Wada, Y.** 2019. The aridity Index under global warming. *Environmental Research Letters*, 14(12): 124006. *https://doi.org/10.1088/1748-9326/ab5046*

Some global predictions of the effect of climate change on soil salinization have been postulated. According to Schofield and Kirkby (2003), the salinization potential will increase in Central Africa, Eastern Europe, southeast North America, South America, China, and Kazakhstan. New areas which were previously not affected, will appear in northeastern Europe and across large areas of northern parts of the Russian Federation. The areas with reverse trend (desalination) are predicted to occur in continental North America and Australia. Hassani, Azapagic and Shokri (2021) estimate that by the end of the twenty-first century, salinization will affect South America, southern and western Australia, Mexico, South Africa and the southwest of the United States of America. The opposite trend, or desalination, is predicted for Eastern Europe, the Horn of Africa, west Kazakhstan, Turkmenistan and the northwest of the United States (Figure 1.8).

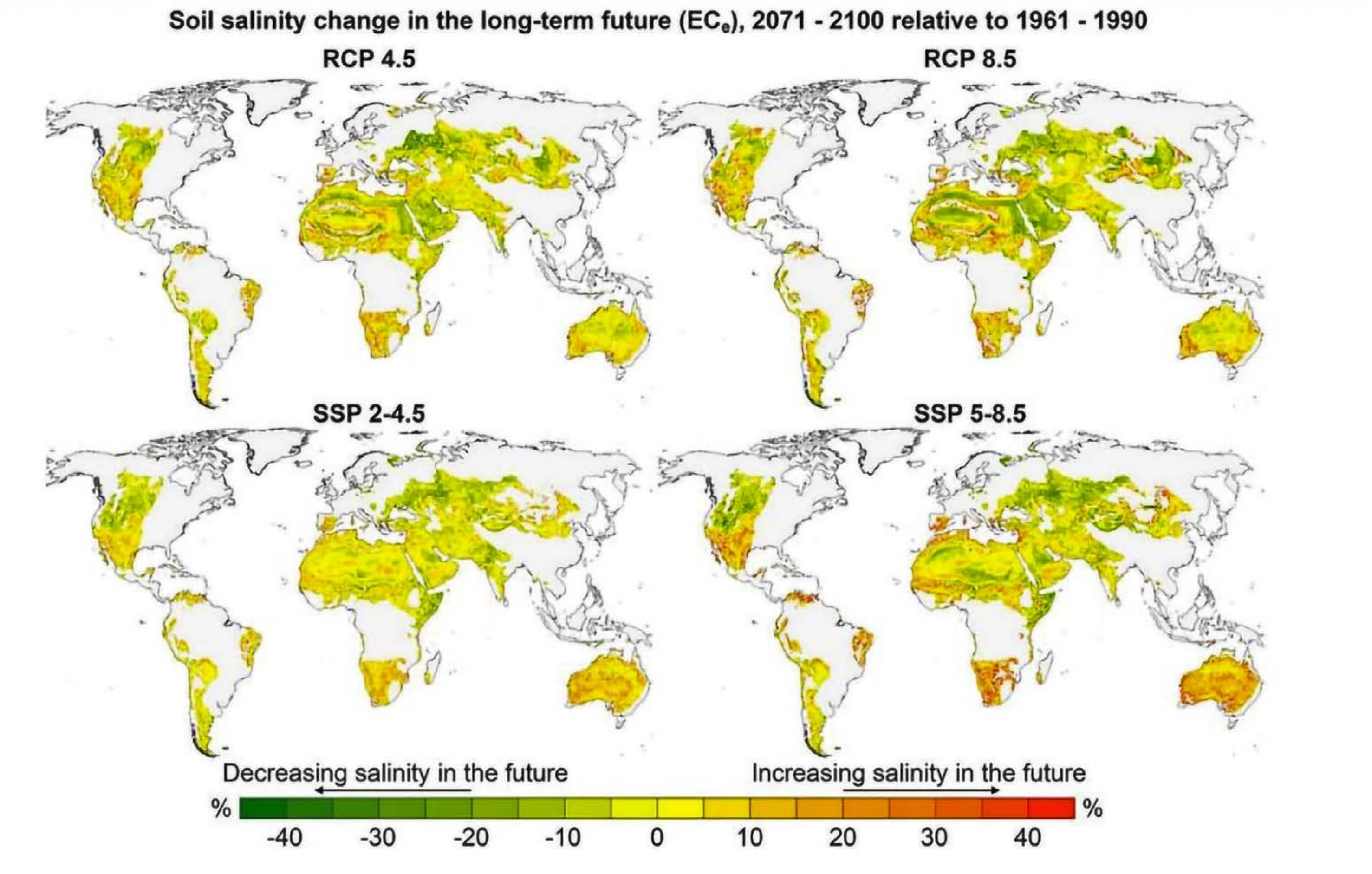

Figure 1.8 | Salinization trends under different climate change scenarios

Note: The RCP 4.5 and RCP 8.5 scenarios (Representative Concentration Pathways which result in a respective radiative forcing of 4.5 and 8.5 W/m^2 in year 2100, relative to pre-industrial conditions) are related to CMIP5 (Coupled Model Intercomparison Project Phase 5) data project, while the SSP 2–4.5 and SSP 5–8.5 scenarios (projections forced by RCP 4.5 and RCP 8.5 global forcing pathways for the Shared Socioeconomic Pathways 2 and 5) refer to CMIP6 (CMIP Phase 6).

Source: **Hassani, A., Azapagic, A. & Shokri, N.** 2021. Global predictions of primary soil salinization under changing climate in the 21st century. *Nature Communications*, 12(1): 6663. *https://doi.org/10.1038/s41467-021-26907-3*

1.2.2 | Fresh water scarcity

Global water use has increased by a factor of six during the twentieth century (Wada *et al*., 2016). Estimates by UN-Water show that 2.4 billion people – or 30 percent of the global population – already live in water-stressed countries (UN-Water, 2023). In 2050, this number will have increased and will affect 2.7 to 3.2 billion people (WWAP/UN-Water, 2018). The affected regions are mostly located in NENA, South Asia, northeast China, Peru, Spain, and western parts of the United States (Figure 1.9).

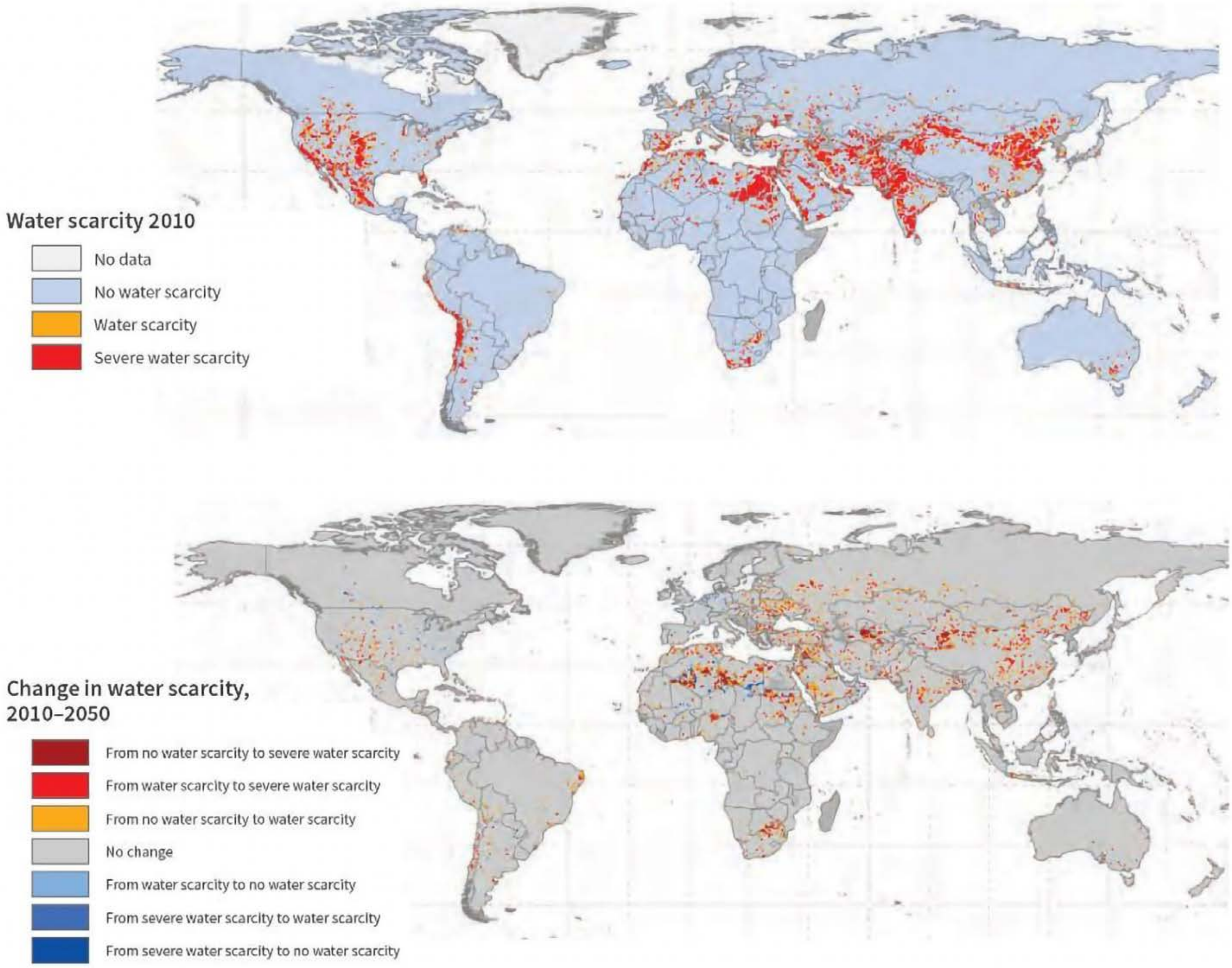

Figure 1.9 | Physical water scarcity in 2010 (upper figure) and projected change in water scarcity by 2050 (lower figure)

Note: Physical scarcity occurs when the demand of the population exceeds the available water resources of a region.
Source: **WWAP (United Nations World Water Assessment Programme)/UN-Water.** 2018. *The United Nations World Water Development Report 2018: Nature-Based Solutions for Water*. Paris, UNESCO.

Note: Dotted line represents approximately the Line of Control in Jammu and Kashmir agreed upon by India and Pakistan. The final status of Jammu and Kashmir has not yet been agreed upon by the parties. Final boundary between the Republic of Sudan and the Republic of South Sudan has not yet been determined.

At the same time, this growing trend of water demand is accompanied by the growing deterioration of water quality (Desbureaux *et al*., 2022; Kaushal *et al*., 2021). Globally, around 40 percent of water bodies are of poor quality, according to available data (UN-Water, 2021). The total area with occurrences of saline and brackish groundwater at shallow or intermediate depths approximates 24 million km², or 16 percent of the total land area on Earth (van Weert, van der Gun and Reckman, 2009). However, surface and groundwater quality data are not monitored in the majority of countries, which means that these numbers are most probably underestimated.

1.2.3 | Increasing sea level rise

Over one billion people inhabiting coastal zones are under threat of experiencing progressive flooding and salinization by the end of the twenty-first century (Kulp and Strauss, 2019). Low-lying areas will become submerged, shorelines will deteriorate, floods will worsen, and estuaries and aquifers will become more saline as a consequence of rising sea levels. Many developing countries are especially vulnerable to sea level rise because of their Low-lying terrain and a lack of resources available to make necessary adjustments in infrastructure (Box 1.2).

The most vulnerable nations are Small Island Developing States (SIDS), as well as Bangladesh, Djibouti, Indonesia, the Kingdom of the Netherlands, Thailand and Viet Nam, all of which have substantial populations in coastal regions (using estimates based on Kulp and Strauss [2019] focusing on nations with the highest percentage of population affected). More than 70 percent of the total number of people currently living on implicated land worldwide are in just eight Asian countries: Bangladesh, China, India, Indonesia, Japan, the Philippines, Thailand, and Viet Nam, (Kulp and Strauss, 2019).

Salinity intrusion is a problem that is increasing in severity in coastal locations all over the world, especially in Low-lying developing countries. Salt and tidal flooding reduce coastal agriculture's output or, in the worst cases, lead it to cease entirely (Nicholls *et al.*, 2007).

A lack of rainfall makes the problem worse since it inhibits soil salt from being leached away and increases the amount of salt in surface water, especially during the dry season. Climate change-related dangers such storm surge, cyclones, and sea level rise have all also contributed to increasing salt intrusion. The rise may be anticipated to be slightly greater in certain locations than in others, depending on a number of variables, including those that are both climate dependent (such as thermal expansion) and independent of the climate (such as land subsidence), although climatedependant variables have the greatest impact. The effects experienced by sea level rise vary geographically as well as socioeconomically (such as by population density, means of subsistence, inadequate infrastructure, and the effectiveness of policies and technology).

Box 1.2 | Salinization of coastal areas of Bangladesh due to increasing sea level rise

Bangladesh is particularly vulnerable to the risks posed by climate change since it is a low-lying alluvial fan region (Agrawala *et.al*, 2003). Bangladesh's coastline is subject to a number of natural calamities, including cyclones and tidal surges, saline intrusion, riverbank erosion, coastal recession, and others because of its almost flat topography and placement at the tip of the "funnel-shaped" Bay of Bengal (Haider, 1992). Although these threats are detrimental to agriculture, sea level rise is seen to be the greatest threat because of its ability to submerge land and allow saline water to intrude (Ahmed, 2006). The requirement for irrigation water is also significantly threatened by surface water salinity intrusion (Shahid, 2011), and plant development in coastal soil is impacted by salt accumulation in the soil's root zone (Yadav *et al.,* 2009). Soil salinity had caused varying degrees of damage to 8.3 million ha of land in coastal Bangladesh. With an estimated rise in sea level of 0.3 m, it is predicted that Bangladesh's coastal areas will lose a net 0.5 million tonnes of rice production by 2050 (World Bank, 2000). By the end of the twenty-first century, a 1 m sea level rise has been forecasted, which could potentially impact 17.5 percent of the nation's entire land mass (World Bank, 2000). A sea level rise of 88 cm, according to Miller (Miller, 2004), would submerge Bangladeshi deltas and lowland agricultural areas.

Salinity intrusion in coastal Bangladesh is occurring more quickly than was anticipated (Agrawala *et al.*, 2003). The impact of saline water ingression in estuaries and subterranean water is predicted to be enhanced by sea level rise, land subsidence, and low river flow conditions, according to the National Adaptation Programme of Action of Bangladesh (NAPA) (NAPA, 2009). The salinity front will move 60 km inland, with an additional 327 700 ha becoming a high saline water zone.

Sources: **Agrawala, S., Ota, T., Ahmed, A.U., Smith, J. & Aalst, M.V.** 2003. *Development and Climate Change in Bangladesh: Focus on Coastal Flooding and the Sundarbans*. Paris, Organization for Economic Co-Operation and Development (OECD). http://www.oecd.org/dataoecd/46/55/21055658.pdf

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1.2.4 | Permafrost thaw

With freshwater systems occupying over 16 percent of the northern permafrost area, the Arctic is a place abundant in water. However, the thawing of permafrost alters the lakes, streams, and rivers, while also generating new freshwater habitats (Vonk *et al.*, 2015). Wherever increasingly iceless waters degrade and inundate coastlines, the surface impacts of sea level rise in permafrost locations are evident. Sea level rise along coasts across the world is resulting in saltwater intrusion into terrestrial habitats as well as fresh water aquifers (such as through saltwater intrusion) (Guimond *et al.*, 2021). Largescale models so far only predict slow changes in seasonallythawed soil, despite the fact that the permafrost zone is projected to be a significant supplier of carbon to the atmosphere. Twenty percent of the permafrost zone would likely see an abrupt thaw, which might harm 50 percent of the permafrost carbon through landslides, fast erosion, and collapsing ground (Turetsky *et al.*, 2020).

The Arctic is more quickly affected by global warming than any other part of the planet, with temperature rises that are twice the world average (Mcbean *et al*., 2005). Temperature increases in Adventdalen (Svalbard, Norway) since 2000 have resulted in an increase of 0.6 cm per year in the thickness of the intermittentlydefrosted dynamic stack in sediments (Hanssen *et al*., 2019). A larger active layer increases the earth's capacity to absorb heat, which leads to heating and finally permafrost melting. Permafrost thawing causes the release of greenhouse gases (GHGs) such as carbon dioxide (CO_2) and methane (CH_4), which have a large and negative impact on global warming and harm the innate hydrology such as water drainage. The existence of cryopegs (zones of unfrozen cryotic soil that stay unfrozen owing to the presence of salts in the pore water) is aided by the concentration of pore water solutes (pore water salinity impacts the freezing temperature and mechanical behaviour of the soils, which complicates geotechnical conditions). Pockets of cryotic brine that have not yet frozen can be found in permafrost soils due to salts having been distributed differently in the soil's pore water. The soils' freezing point is greatly lowered by the salt concentration, dropping to as low as −6 °C.

In soils composed mostly of marine sediments, residual minerals from the time they were deposited are dispersed by porewater ejection throughout the development of permafrost. Salt concentrations near geological barriers produce enclaves of eutrophic soil (with salt concentrations of around 7 percent), which can melt at between −4 to −6 °C. (Gilbert *et al*., 2019). Because of the pressures produced by freezing and the weight of the earth on them, cryopegs are frequently under tremendous stress, with the pockets' diameters enlarging and altering in response to variations in soil temperature. As a result of the warming permafrost, and soil temperatures brought on by climate change, cryopegs are growing more widespread and larger. Drilling results from Longyearbyen (Svalbard, Norway) show the presence of unfrozen soil particles and liquid water within the permafrost, while cryopegs between 15 and 20 m deep were recently found during field studies in Adventdalen (Gilbert *et al*., 2019).

1.3 | Distribution of salt-affected soils

The global distribution of salt-affected soils has been reported by various publications at about 1 billion ha (Abrol, Yadav and Massoud, 1988; Squires and Glenn, 2004; Szabolcs, 1989; Wicke *et al*., 2011). Although these estimates are based on the FAOUNESCO soil map of the world (FAOUNESCO, 1977) and previouslyavailable global soil datasets, the input data has lacked consistency.

Estimates dating back to the 1980s and early 1990s stated that 45 million ha (19.5 percent) of irrigated land and 32 million ha (2.1 percent) of the world's rainfed croplands, totalling 77 million ha, were affected by salinity or sodicity (Oldeman, Hakkeling and Sombroek, 1991).

Investigating salinity levels under various land use and land management scenarios is crucial to ensure the sustainability and longterm viability of agricultural production. So in 2020, FAO's Global Soil Partnership (GSP) started a global initiative to improve information on salt-affected soils to coordinate and support countries in producing the first global map of salt-affected soils based on national data and following a country-driven process. More than 350 national experts were involved in the harmonization of the input data and methods for mapping salt-affected soils and were trained in stateoftheart methods for digital soil mapping (Omuto *et al*., 2020). Each country then produced its maps, following the agreed technical specifications (FAO, 2020).

The resulting GSASmap (FAO, 2021) is a product containing contributions from over 118 countries with 257 419 locations containing measured soil data (Figure 1.10). The GSASmap covers 75 percent of the total global land.

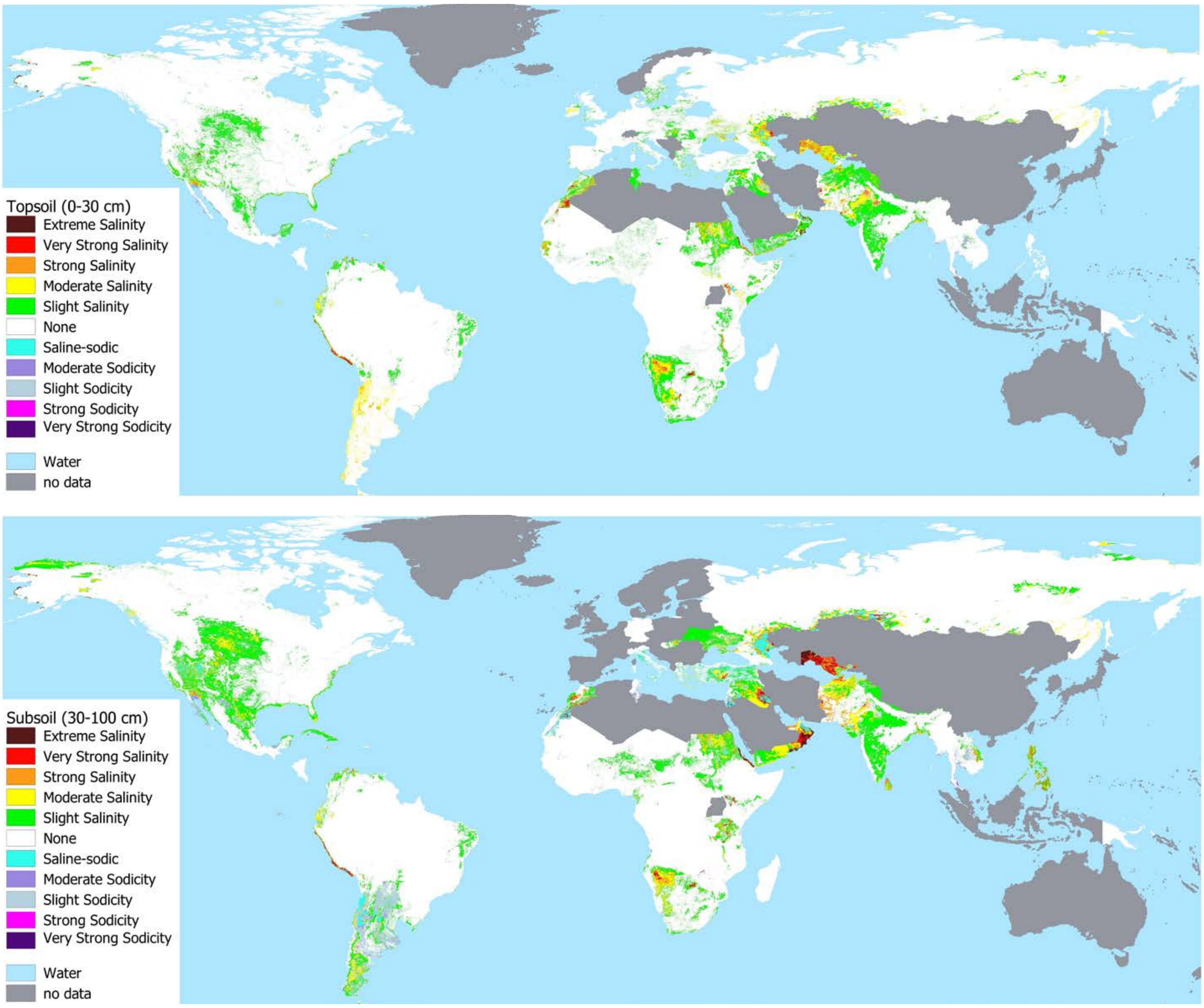

Figure 1.10 | Global map of salt-affected soils: a) topsoil (0–30 cm) and b) subsoil (30–100 cm)

Note: The designations employed and the presentation of material in the map(s) do not imply the expression of any opinion whatsoever on the part of FAO concerning the legal or constitutional status of any country, territory or sea area, or concerning the delimitation of frontiers.
Source: **FAO**. 2021. Global Map of Salt-affected Soils (GSASmap) v1.0. In: *FAO*. Rome. [Cited 2023]. *https://www.fao.org/soils-portal/data-hub/soil-maps-and-databases/global-map-of-salt-affected-soils/en/*

The map represents the spatial distribution of information at two depth intervals: 0–30 cm and 30–100 cm, and including EC, ESP, pH, and classes of salt-affected soils (Annex 1). The areas of salt-affected soils based on the GSASmap in the countries are provided in Annex 2 and Annex 3.

The published information for countries that are known to have extensive areas of salt-affected soils but did not provide their maps, is summarized in Annex 4 so that the affected areas can be estimated at the global level. **The total area of salt-affected soils of the world amounts to 1 381 million ha, or 10.7 percent of the total land area** (Table 1.1). The largest areas are observed in Australia (357 million ha), Argentina (153 million ha), Kazakhstan (94 million ha), the Russian Federation (77 million ha), the United States (73.4 million ha), the Islamic Republic of Iran (55.6 million ha), the Sudan (43.6 million ha), Uzbekistan (40.9 million ha), Afghanistan (38.2 million ha), and China (36 million ha). These ten countries account for 70 percent of the total global area of salt-affected soils. The countries most affected by salinity and sodicity are Oman (93.5 percent of total land area), Uzbekistan (92.9 percent), Jordan (90.6 percent), Kuwait (88.8 percent), Iraq (70.5 percent), the United Arab Emirates (60.5 percent), Afghanistan (58.6 percent), Argentina (56 percent), Australia (46.4 percent) and Eritrea (40.1 percent). **The area of soils potentially under risk of salinization (with an EC of 0.75–2 dS/m) amounts to 1 038 million ha**.

Table 1.1 | Areas of salt-affected soils at the regional level

Region*	Area of salt-affected soils** (km²)	Land area*** (km²)	%
Pacific	3 570 000	8 472 605	42.1
Europe and Eurasia	2 378 209	27 049 956	8.8
Latin America and the Caribbean	2 352 857	20 026 933	11.7
Near East and North Africa	2 303 461	13 033 953	17.7
Asia	1 543 269	20 722 790	7.4
Africa	883 795	22 046 043	4
North America	779 912	17 936 120	4.3
Total	**13 811 503**	**129 288 400**	**10.7**

Notes: *As per the GSP regions laid out in **FAO.** 2023. Global Soil Partnership. Regional Soil Partnerships. In: *FAO*. Rome. [Cited 2023]. *https://www.fao.org/global-soil-partnership/regional-partnerships/en/*
**The total areas of salt-affected soils in the countries are listed in Annex 2 and Annex 4, as per the GSP regions (see above).
***Land area of the whole GSP region.

1.4 | The Food and Agriculture Organization of the United Nations (FAO)s' work on salt-affected soils

For many decades, FAO has been a leading international organization working on the topics of irrigation and drainage, including salt-affected soils as the main threat to efficient management of irrigated cropland. In particular, the FAO Bulletin No 39 has been the guidebook for people working with salt-affected soils (Abrol, Yadav and Massoud, 1988), as well as the FAOproduced series of publications devoted to irrigation and drainage – the FAO irrigation and drainage papers – published by FAO from 1971 to 2014 (Nos 1–67). The first 56 volumes (1971–1998) can be found online (FAO, 1998).

In the periods 1994–2001 and 2007–2011, the Network on Sustainable Productive Use of Salt-affected Habitats (SPUSH) operated within FAO involving over 30 member countries in collaborative projects and national programmes. The network held eight thematic meetings (Manila 1995, Cairo 1997, Manila 1999, Izmir 1999, Bangkok 2000, Valencia 2001, Dubai 2007, and Valencia 2010) aimed at the management, measuring and monitoring of salt-affected soils as well as at improving dialogue between policymakers, scientists, and field experts (FAO, 2011).

In 2019, following the recommendation of the Intergovernmental Technical Panel on Soils (ITPS), the Seventh Plenary Assembly of the GSP endorsed the establishment of the International Network of Salt-affected Soils (INSAS) (FAO, 2019). The launch of INSAS took place during the Global Forum on Innovations for Marginal Environments in November 2019, in Dubai (ICBA and Food Security Office, 2019). The network aims to facilitate the sustainable and productive use of salt-affected soils for current and future generations. At present, INSAS is represented by 745 members from 125 countries.

The network operates through four working groups of experts: the SAS&Assessment group, focused on the mapping, assessing and monitoring of salt-affected soils; the SAS&SSM group, focused on the sustainable management of salt-affected soils (practices and policy); the SAS&Crops group, focused on halophyte agriculture and salt-tolerant crops; and the SAS&Water group, focused on the integration of soil and water management under saline and sodic conditions. These working groups contributed to the development of the relevant sections of the INSAS questionnaire, that were then distributed to 125 countries around the world. The responses to this questionnaire served as a basis for the regional summaries reported in Chapter 3 of this report. The entire *Global status of salt-affected soils* report has been made possible thanks to the inkind support of INSAS members who have contributed to its development and production.

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Chapter 2 | Human-induced soil salinization and sodification

Soil salinization and sodification, particularly in semi-arid and arid regions of the world, poses a huge threat to the longterm resilience of arable soils and, as a result, to food security. After soil erosion, it is the most prevalent kind of soil deterioration, costing the global agricultural sector at least USD 27 billion every year (Qadir *et al.*, 2014). Soil salinization is accelerated significantly by poor and inappropriate land management (Pessoa *et al.*, 2022) as well as improper drainage and insufficient irrigation (Zhou *et al.*, 2013). Soil salinization and sodification lead to a sharp decline in soil health, natural vegetation and biodiversity, affecting the soil's biotic components (Gorji *et al.*, 2020) and results in desertification (Peng *et al.*, 2019). Estimates dating back to the 1980s and early 1990s stated that 45 million ha (19.5 percent) of irrigated land and 32 million ha (2.1 percent) of the world's rainfed croplands, totalling 77 million ha, were affected by salinity or sodicity (Oldeman, Hakkeling and Sombroek, 1991). The new estimates performed on the basis of the FAO's *Global map of salt-affected soils* (GSASmap) (FAO, 2021) covering 75 percent of the total land indicate that 10 percent of irrigated cropland and 10 percent of rainfed cropland are affected by salinity or sodicity (see Chapter 4 of this report). Investigating salinity levels under various landuse and land management scenarios is crucial to ensure the sustainability and longterm viability of agricultural production.

2.1 | Secondary salinization due to unsustainable land and water management in agriculture

Salt-affected soils are present practically everywhere on Earth, from the humid tropics to Antarctic deserts, although they are more prevalent in arid and semiarid regions. Salt has an influence on more than 10 percent of the world's dry land, and may be found on all continents at altitudes ranging from 5 000 m (the Tibetan Plateau) to below sea level (the Dead Sea) (Szabolcs, 1994). The wide range of mechanisms that might cause secondary (humaninduced) soil salinization in agricultural lands are reflected in the large dispersion shown on Figure 2.1.

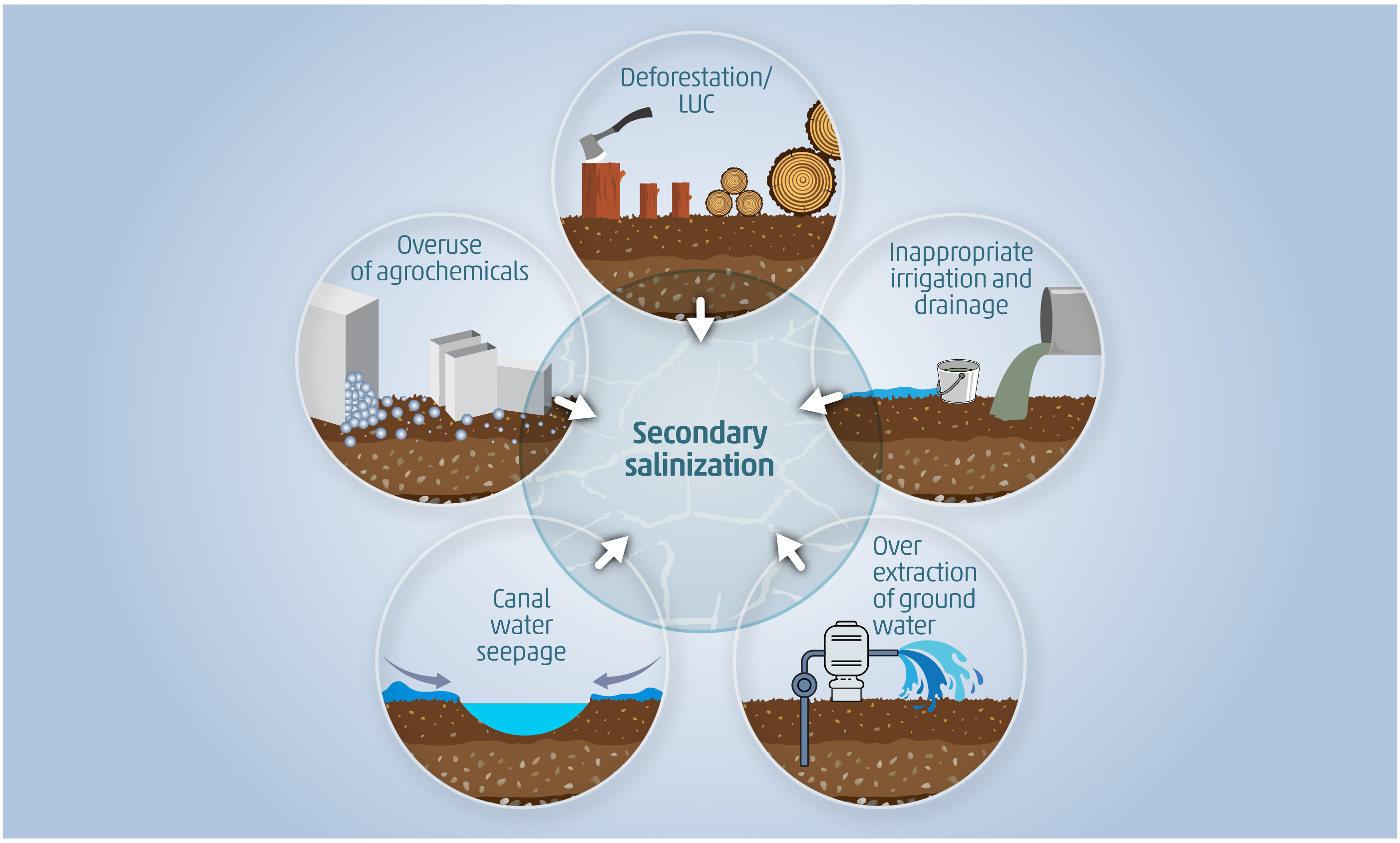

Figure 2.1 | Origins of secondary salinization in agriculture

2.1.1 | Deforestation and land use change

Soil may become salinized as a result of deforestation and the change from deep-rooted vegetation to shallow-rooted crops. Such a crop transformation changes the hydrological regime of a landscape, leading to reduced evapotranspiration and increased water recharge into the groundwater (Hatton, Ruprecht and George, 2003). Rising groundwater mobilizes the salt contained in subsurface layers and brings it up to the surface (Figure 2.2). This phenomenon is known from southwestern Australia where over 2 million ha of land were affected in the 1970s, giving rise to national programmes of dryland salinity control. There are over 1.8 million ha of land still salt-affected, with up to 8.8 million ha at risk by 2050 (Hatton, Ruprecht and George, 2003). Soil salinization due to deforestation has also been reported for other regions such as the Dry Chaco in Argentina, Paraguay, Bolivia (Maertens, 2021; Maertens *et al.*, 2022).and Thailand (Miura and Subhasaram, 1991).

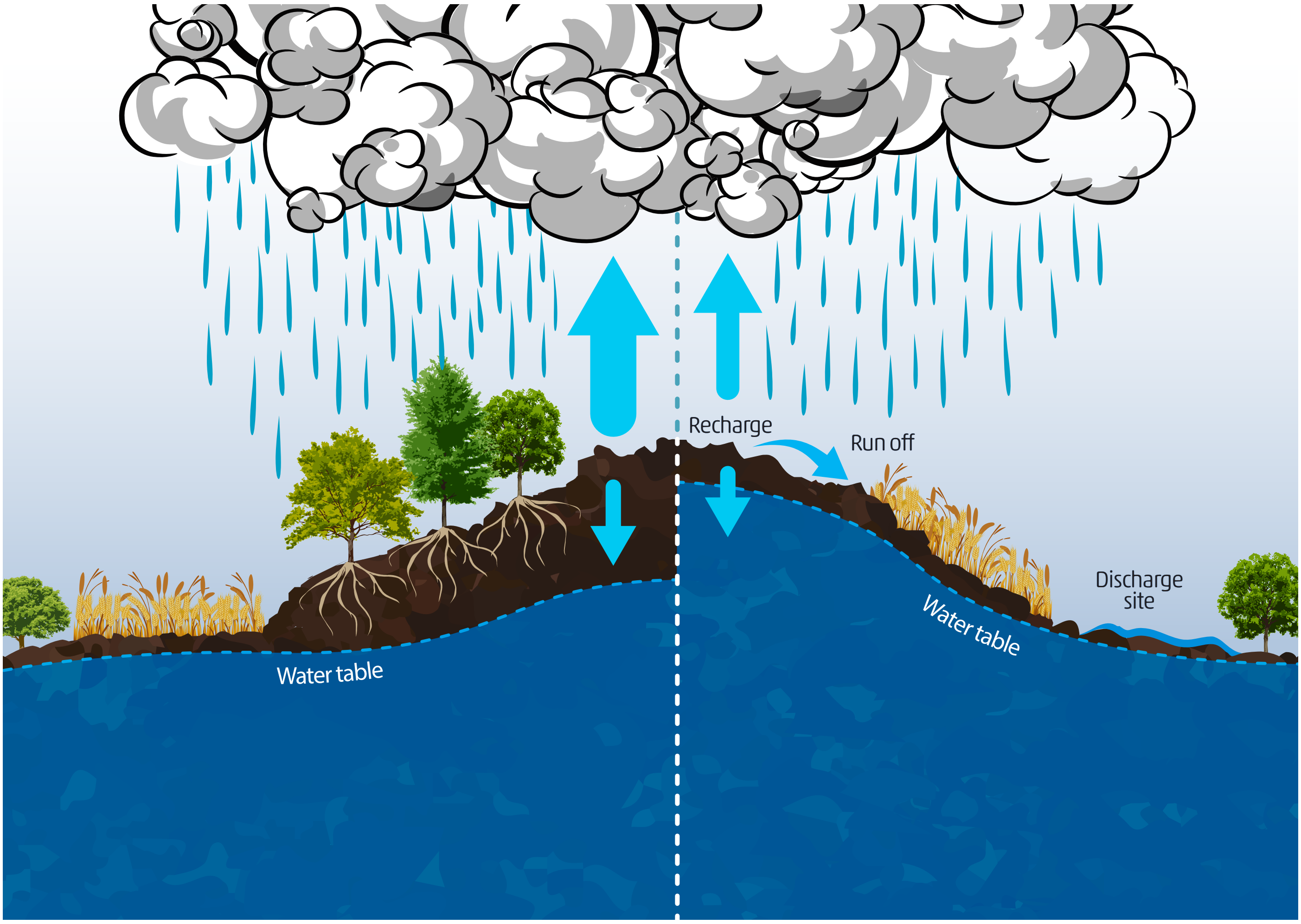

Figure 2.2 | Dryland (unirrigated) salinization caused by deforestation

Source: adapted from **DIINSW (Department of Industry and Investment of New South Wales).** 2009. Primefact 936. Dryland salinity – causes and impacts. Sydney, Australia, Government of New South Wales.
https://www.dpi.nsw.gov.au/__data/assets/pdf_file/0006/309381/Dryland-salinity-causes-and-impacts.pdf

2.1.2 | Inappropriate irrigation and drainage

Irrigation is an essential requirement to maintain sustainable yields in arid regions. Irrigated farmland occupies over 320 million ha or 20 percent of the world's cropland, and accounts for 70 percent of all freshwater withdrawals and 40 percent of the world's crop production (FAO, 2022). Around 100 million ha, or onethird of all irrigated areas suffer from inadequate drainage (Tyagi, 2014; Singh, 2019). In dry regions, modern agriculture uses between 500 and 1 000 mm of water annually, with some extreme situations using up to 2 000 mm (Döll and Siebert, 2002). Insufficient drainage and saline and sodic water are the main causes of human-induced soil salinization in agricultural areas. Fresh water is particularly scarce in dry regions, so brackish groundwater and treated wastewater are increasingly used for irrigation (Beltrán, 1999; Qadir *et al.*, 2007; FAO, 2022).

In dry environments, where human habitation and commercial activity need water, water shortage is a basic truth, sometimes at the expense of local habitats (Niu *et al.*, 2019). Inadequate management may still result in excessive irrigation, which might make the problem of soil salinization in dry environments worse (Scanlon *et al.*, 2006). Without adequate drainage, salts introduced by irrigated agriculture are able to persist in the crop root zone, while irrigation's deeper penetration and canal leaks can increase groundwater evapotranspiration, which then increases the amount of salt in the soil's top layer (Xue *et al.*, 2020).

The indiscriminate use of brackish and saltwater for irrigation, poor outflow, and rising groundwater levels are some of the causes of secondary salinization of land and water resources. Even longterm cultivation with very good quality water might cause salinization if there are insufficient soil–water–crop management approaches (Rao *et al.*, 2014). The salinization of coastal regions may also arise as a result of irrigation with seawater.

The equilibrium of the groundwater table is altered by declining plant cover and excessive irrigation water application (fresh or with added fertilizer), which exposes soils to salts (Perri *et al.*, 2018). Additionally, salts are deposited on soil as a result of frequent runoff or flooding from salt-affected areas (Krasilnikov *et al.*, 2013). Using saline water for irrigation continuously without using the proper drainage techniques might also cause soil salinization (Malash, Flowers and Ragab, 2005).

Two classic examples of secondary soil salinization caused by improper irrigation and drainage – despite being irrigated using good quality water – are the Hetao District of Inner Mongolia in China (Wu *et al.*, 2008) and the Golodnaya Steppe of Uzbekistan (Pankova, 2016). Improved drainage eventually reduced salinization through pumping (in China) and the installation of subsoil pipes (in Uzbekistan).

There are multiple case studies worldwide describing soil salinization caused by brackish irrigation water. One wellknown example is in India where good quality water available for irrigation purposes is scarce (Box 2.1).

Box 2.1 | Soil salinization due to insufficient drainage and the use of brackish water: The example from India

India has a salt-affected area of approximately 6.727 million ha, or 2.1 percent of its total geographic area, of which 2.956 million ha are saline and the remaining 3.771 million ha are sodic (Arora and Sharma, 2017). Gujarat (2.23 million ha), Uttar Pradesh (1.37 million ha), Maharashtra (0.61 million ha), West Bengal (0.44 million ha) and Rajasthan (0.38 million ha) make up about 75 percent of the country's salt-affected soils (Mandal *et al.*, 2018).

According to Shahid, Zaman and Heng (2018), 17 percent of the country's irrigated agriculture has experienced secondary salinization as a result of the use of brackish irrigation water. It is difficult to find highquality irrigation water throughout the country, so farmers are compelled to use a lot of brackish groundwater for irrigation in order to increase the amount of food they can grow on each available hectare of fertile land. According to groundwater evaluations, between 32 and 84 percent of the country's groundwater supplies are of low quality (Minhas, 1999). Due to the development of canal irrigation schemes without sufficient drainage systems, the cropland has become severely salinized. There are large salt-affected areas in a number of canal commands (Mandal *et al.*, 2010).

Continuous seepage from the canals has resulted in an increase in water tables, the movement of salts to the surface, waterlogging, the development of marshy fields, an increase in soil salinity, and a decrease in biodiversity. Two stark examples are the salinization of roughly 0.18 million ha in the Rajasthan region within a few years of the introduction of irrigation projects, and the salinization of roughly 0.37 million ha over the course of three decades in the Sharda Sahayak Canal Command region of Uttar

Pradesh (Singh, 2009). The possibility of degradation is present in many more sites with highquality aquifers as a result of unsustainable groundwater extraction. The salt-affected lands in India keep growing at an annual rate of 10 percent as a result of the installation of irrigation in new locations (Patel, Patel and Dave, 2011; Jamil *et al.,* 2011). If no preventive or ameliorative actions are taken, Sharma, Singh and Sharma (2015) predicted that by 2050, the salt-affected regions will increase from 6.74 to 16.2 million ha.

Sources: **Arora, S. & Sharma, V.** 2017. Reclamation and management of salt-affected soils for safeguarding agricultural productivity. *Journal of Safe Agriculture,* 1(1): 1–10.

Mandal, S., Raju, R., Kumar, A., Kumar, P. & Sharma, P.C. 2018. Current Status of Research, Technology Response and Policy Needs of Salt-affected Soils in India – A Review. *India Society Coastal Agricultural Resources*, 36(2): 40–53.

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Minhas, P.S. 1999. Use of Poor quality Waters. In: G.B. Singh and B.R. Sharma, eds. *50 Years of Natural Resource Management Research*, pp. 327–346. Karnal, India, CSSRI.

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https://www.researchgate.net/publication/305350773_Vision-2050

As a result of population growth, competition for water supplies between urban and agricultural use has increased. However, as urban populations grow, there is a greater chance of wastewater recycling due to the increased need for water, the necessity of costsaving measures or technological limitations (Lyu *et al.*, 2016). Although reusing treated wastewater (TWW) can aid in meeting agricultural water needs, there are agricultural and ecological hazards that need to be carefully evaluated (Levine and Asano, 2004). Treated wastewater can have a high concentration of salt, various trace quantities of dangerous substances, and many nitrogen (N) and phosphorus (P) components, and pathogens (Zhou *et al.*, 2014). Treated wastewater can thus offer both benefits and drawbacks. As a result of treated wastewater irrigation, the properties of soil and groundwater are altered, including nutrient supply, salinity, carbon content, and biochemical processes (Azouzi *et al.*, 2016). In addition to having an impact on crops, increased salinity can also have an impact on soil (Pedrero *et al.*, 2010). As a result of wastewater irrigation, the ESP increases due to enhanced electrical conductivity (EC), total dissolved solids (TDS), and principal electrochemical potential (Drechsel *et al.*, 2010). In research from the western United States, it was shown that golf courses that were irrigated with treated wastewater had their salinity (or EC) increase by 187 percent, and sodicity (SAR) increase by 481 percent (Qian and Mecham, 2005). Therefore, an area that is watered with treated wastewater tends to accumulate salts (Muyen, Moore and Wrigley, 2011), particularly in places with a high evaporative demand and little natural precipitation.

Salinization of the soil can also result through, for example, the usage of sewage sludge, untreated sewage effluent, and the dumping of industrial brine on the ground. The contamination of soils with heavy metals is particularly concerning (Gopal, 2019).

2.1.3 | Overwithdrawal of groundwater

Groundwater is often used to supply water for irrigation. Globally, 33 percent of water for irrigation comes from groundwater (FAO, 2022). Global groundwater withdrawals for irrigated agriculture have been continuously increasing in the twentieth and twenty-first century and have increased by 19 percent between 2010 and 2018, reaching 820 km^3/yr (FAO, 2022). The salinization of groundwater due to overexploitation of the aquifers occurs both in coastal areas as well as in arid and semi-arid regions (Greene *et al.*, 2016; Krishan *et al.,* 2020; Said, Salman and Elnazer, 2022). Understanding the dynamics of the groundwater system is crucial for irrigation, life, and the establishment of a healthy ecosystem in any irrigation region (Feng *et al.,* 2020). Groundwater is a priceless and dynamic natural resource of the planet, essential for all life and also plays a large role in our social and economic development. Since the 1970s, rising demand and climate change have caused a decline in this resource's availability in terms of quality and quantity as well as generating substantial spatial variability in groundwater depletion and accumulation (MacDonald *et al.,* 2016).

2.1.3.1 | Inland groundwater salinization

In arid and semi-arid regions, groundwater supply is heavily dependent on the availability of terrestrial freshwater lenses which develop above the more saline groundwater within the same aquifer (Laattoe *et al.*, 2017). As freshwater lenses are quite easily depleted, if the withdrawal of fresh groundwater exceeds freshwater recharge (due to a lack of precipitation), the risk of overexploitation is high (Wada, 2016) and leads to the salinization of groundwater and the soil rootzone (Kacimov and Obnusov, 2019; Stofberg *et al.*, 2017; Said, Salman and Elnazer, 2022) (Figure 2.3). While this phenomenon is widespread, it is less studied comparing to the salinization of coastal or island aquifers.

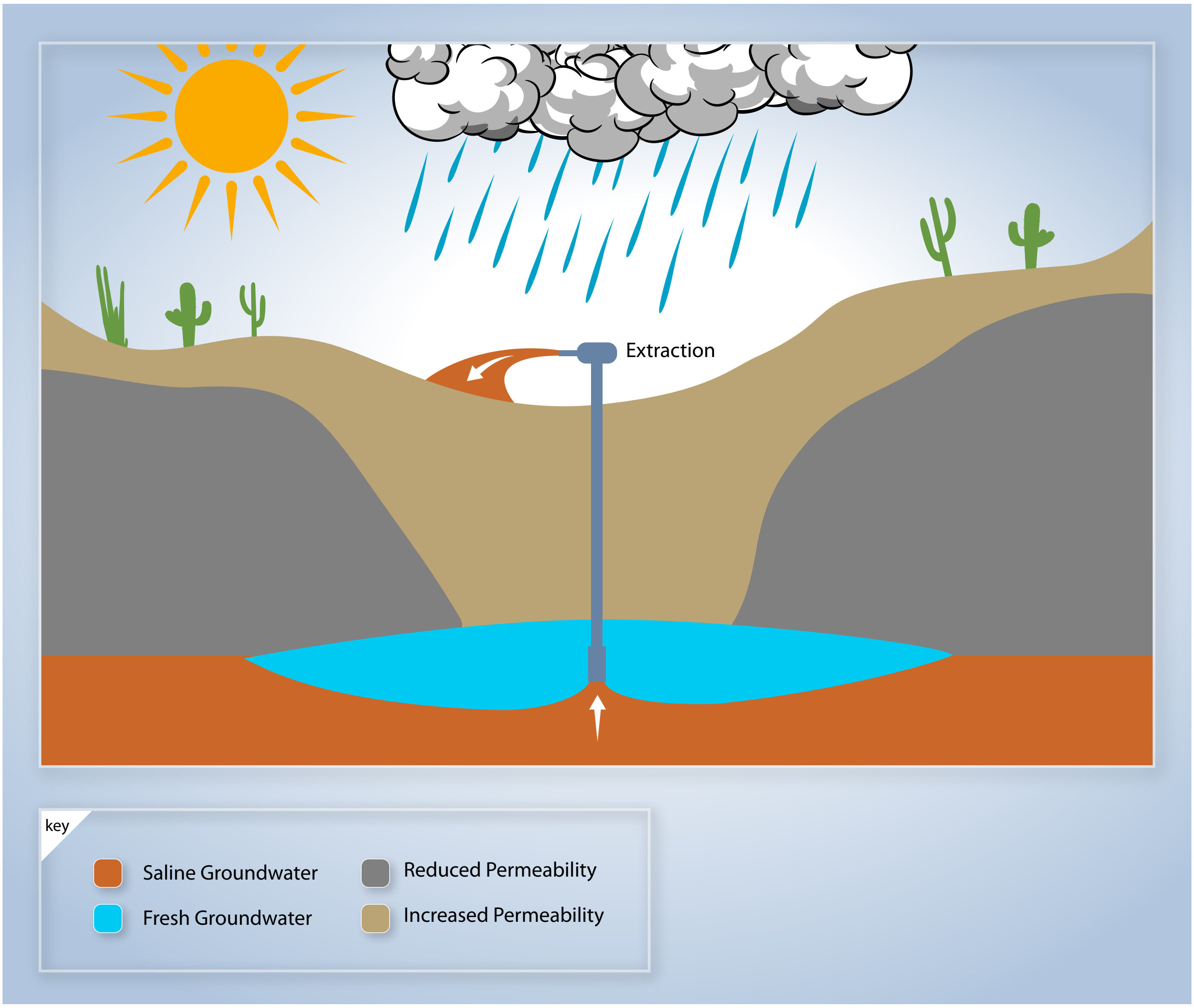

Figure 2.3 | Inland groundwater salinization due to freshwater lens depletion

Sanchez, F., Bashar, K., Janssen, M., Vogels, M., Snel, J., Zhou, Y., Stuurman, R. & Essink, O. 2015. SWIBANGLA: Managing salt water intrusion impacts in coastal groundwater systems in Bangladesh. A technical Report for the project SWIBANGLA No: 1207671-000-BGS-0016. Delft, Kingdom of the Netherlands, Deltares & IHE Delft Institute for Water Education, & Dhakar, Bangladesh, Jahangirnagar University.
https://publicwiki.deltares.nl/download/attachments/90430572/1207671-000-BGS-0016-r-SWIBANGLA%20def.pdf?version=1&modificationDate=1423653442000&api=v2

Laattoe, T., Werner, A.D., Woods, J.A. & Cartwright, I. 2017. Terrestrial freshwater lenses: Unexplored subterranean oases. Journal of Hydrology, 553: 501–507. https://doi.org/10.1016/j.jhydrol.2017.08.014

2.1.3.2 Coastal groundwater salinization

Coastal zones are among the areas with the highest population densities, with more than twice the global average (with an average demographic density of about 80 persons per km^2 [Kantamaneni *et al.*, 2017]). Along with an increase in population, these areas are also experiencing an increase in the demand for water due to continual improvements in living standards (Neumann *et al.*, 2015). The primary source of freshwater in coastal areas is groundwater – which is often utilised without proper management – so that the growing demand for water for domestic, agricultural, and industrial uses can be met (Hamed *et al.*, 2018). After any excessive groundwater removal, the seawater is drawn upward, and the hydrodynamic equilibrium between freshwater and seawater in the aquifer is disrupted (van Camp *et al.*, 2014).

The direction of seawater flow into the coastal aquifer is determined by the "Ghyben-Herzberg relationship": a wellknown mathematical correlation (Narayan, Schleeberger and Bristow, 2007). The ratio demonstrates that for every metre increase in the fresh groundwater table, the thickness of inland saltwater reduces by 40 m, and vice versa. A shift in the hydraulic gradient brought on by a decline in groundwater level below mean sea level forces seawater in the coastal aquifer to move inland (Nair *et al.*, 2013). Seawater intrusion is the inland migration of seawater into the coastal aquifer and is a significant contributor in the reduction of coastal groundwater resources (Figure 2.4). Seawater intrusion reduces both the region's potential for economic and agricultural growth and the quality of life for locals (Demirel, 2004).

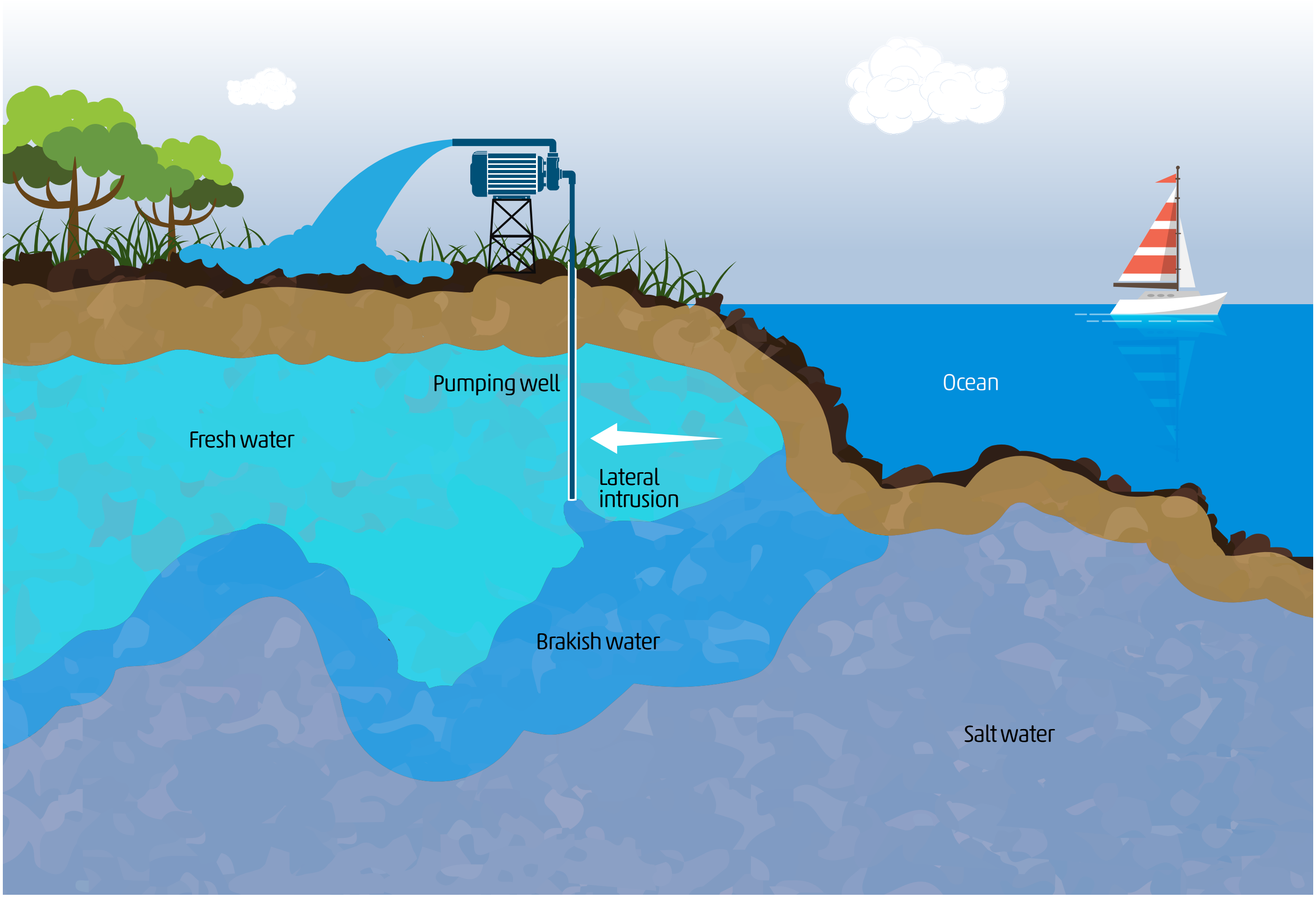

Figure 2.4 | Coastal groundwater salinization due to seawater intrusion

The world's coastal regions frequently experience salinization as a result of mean sea level rise (Chun *et al.*, 2018), which transports salt water and projects it onto continental lands, impacting their soil and water supplies (Kidwell *et al.*, 2017). Global salinization is already having an impact on the 600 million people who reside in lowelevation coastal zones (McGranahan, Balk and Anderson, 2007; Wheeler 2011). According to studies, if sea levels rise by at least one metre in the twenty-first century, by the year 2050, populations will have increased to almost one billion people (Hansen and Sato, 2012; Brecht *et al.*, 2012).

When the soil salinity is higher than a plant's salt tolerance, the salt that is concentrated in the root zone inhibits the plant's growth, leading to nutrient imbalances and yield loss. This has a great impact on agricultural production which can substantially decline unless specific measures are not undertaken (Pitman & Läuchli, 2002). River water salinization may result in significant economic loss through decreased crop yields, hindered industrial production, increased health risks, and decreased productivity of forest species (Haque, 2006). Due to seasonallyreduced upstream freshwater flow, the average soil salinity concentrations along the shore are greater in the low flow season than the high flow season. Waterlogging is another problem that can increase the soil salinity in the coastal zone (Awal, 2014). According to Karim and Mimura (2008), sluice gates of various polders (Low-lying tracts of land reclaimed from the sea or other water bodies) were allegedly sealed in the coastal regions of Bangladesh to stop silt deposition from rivers. This led to waterlogging and a salinated soil, as salinity from either the storm surge or high tide water had pooled in the polders but was unable to drain away effectively.

Several processes can cause a freshwater aquifer to become contaminated with saltwater, such as oblique invasion from the ocean, upswing incursion from deeper, more saltrich regions of an aquifer system, descending penetration from coastal regions, as well as storm or tidal-driven saltwater flash floods of coastal plains. Saltwater fouling might also occur via intrusion through open boreholes, deserted wells, poorlyconstructed or rotted boreholes, and syphoned networks (Metz and Brendle, 1996).

The amount of saltwater intrusion into an aquifer depends on several factors, including the rate of groundwater withdrawal from an aquifer in comparison to the rate of freshwater recharge, the distance between locales of groundwater sources, and the geologic structure of a natural drainage system (along with design characteristics like foibles, curving, and fractures) (Barlow and Reichard, 2009).

Groundwater flow paths range from a few kilometres to several hundred kilometres. How far freshwater in the aquifer may travel depends on many factors, including the volume of freshwater streaming throughout every aquifer, its density and hydraulic properties, and the location of saline surface water at any given time. The discovery of relatively fresh groundwater in some of the few aquifers along the Atlantic Coast (Meisler, 1989) has been connected to aquifer recharging occurring at times during the past 900 000 years when sea levels were lower than the present day.

Many countries have observed seawater intrusion, including Australia (Werner and Gallagher, 2006), Bangladesh (Nobi and Gupta, 1997), China (Cheng and Chen, 2001), Egypt (Sherif, Singh and Amer, 1988), India (Datta, Chakraborthy and Dhar, 2009), the Republic of Korea (Chang, 2014), and the United States (Johnson and Whitaker, 2004), as well as Belgium, southern Italy, the Kingdom of the Netherlands, and northeastern Spain (Custodio, 2010).

In the coastal regions of Bangladesh and Senegal, sea-level rise and the related seawater intrusion are the main causes of soil salinity (Thiam *et al.,* 2019; Khanom, 2016). Sea level rise is primarily responsible for encouraging saltwater intrusion into coastal freshwater aquifers, even in areas with little groundwater exploitation (Ketabchi *et al.,* 2016). In Bangladesh's coastal regions, Rahman *et al.* (2018) reported a steady increase in soil salinity from 1990 to 2015, and that improper farming practices and the rising sea level were the key contributors to this change. Highlysalinized soils increased from 1 percent of the overall area in 1990 to over 30 percent in 2015, with salinity levels rising in 46 percent of the entire area between 1995 and 2005 and in 44 percent of the entire area from 2005 to 2015. As a result of rising river levels, precipitation occasionally overflows the Meghna estuary deltas in coastal Bangladesh, and the region remains wet for most of the dry season, primarily due to subsidence. In addition, cyclones and storm surges frequently happen close to the Lower Meghna River. Bangladesh's coast (Hiron point) has experienced a 122 mm sea level rise between 1983 and 2003 (PSMSL, 2020). Even more land will be flooded as a result of rising sea levels, further preventing salts being washed away and so increasing soil salinity (Brammer, 2014).

Similar research on the Indramayu coastline in West Java, Indonesia found that the lands close to the beach had high to very high salinity levels, and that the salinity decreased, moving inland. Marine sediments were present in the samples taken from locations close to the coast, demonstrating that irrigation canals and rivers had been contaminated by seawater (Erfandi and Rachman, 2011). In a recent study carried out in Kuwait's desert regions, a relationship between the trend of salinity fluctuations and changes in climatic conditions was discovered (temperature and precipitation). It was found that the area of salt in the soil had increased as temperatures rose and precipitation decreased, and that this change in the spatial distribution of salinity had occurred gradually between 1987 and 2017 (Bannari and Al-Ali, 2020).

Storm surges are another effect of sea level rise, and they in turn raise soil salinity. Bangladesh is heavily impacted by tidal flooding and storm surges, due to the fact that 30 percent of its agricultural land is located along the coast (Haque, 2006) and that 1.056 million ha out of 1.689 million ha of coastal land have various levels of soil salinity (SRDI, 2010). According to Dunn *et al.* (2018), the GangesBrahmaputraMeghna, Mahanadi, and Volta deltas might not be able to keep up with current levels, making them susceptible to salinization and catastrophic threats. However, although the majority of studies have focused on the flooding and losses caused by rising storm surges, the increased salt content from seawater intrusion may currently be the most significant risk to community livelihoods and health due to its impacts on buildings, aquatic communities, farming, fish farming, and the freshwater supply water for residential and industrial use. In countries with vulnerable coastlines, planning for sufficient adaptation and understanding the physical and economic effects of saline spread are crucial for longterm development and the reduction of inequality (Brecht *et al.,* 2012). Twenty percent of India›s agricultural land is harmed by salt or sodicity, specifically in Jaisalmer, the coastline in Gujarat, and the Ganges basin. In Pakistan, 10×10^6 ha are affected, with 5 to 10 ha being lost due to salinity or waterlogging every hour in the irrigated Indus basin and coastal regions. In Bangladesh, 3×10^6 ha are no longer useable due to salinity. In Thailand, salt has had an impact on 3.58×10^6 ha (3.0×10^6 ha of arable land and 0.58×10^6 ha of coastline).

2.1.4 | Canal water seepage

Canal water seepage is a significant issue that contributes to the development of waterlogging and salinization along the canal banks in arid and semiarid regions.

The average seepage losses in irrigation systems vary from 5 to 50 percent, reaching their maximum of 90 percent in earthen, poorlylined or cracked concrete canals (Barkhordari and Hashemy Shahdany, 2022; Barkhordari *et al.,* 2020; Lund, Gates and Scalia, 2023). The excessive water mobilizes salts contained in the soil and leads to salt accumulation in arid conditions (Araki *et al.*, 2011; Cassel and Zoldoske, 2006). The secondary salinization caused by canal seepages creates a typical pattern of fringes with salt crusts or crop failures along canals (Figure 2.5).

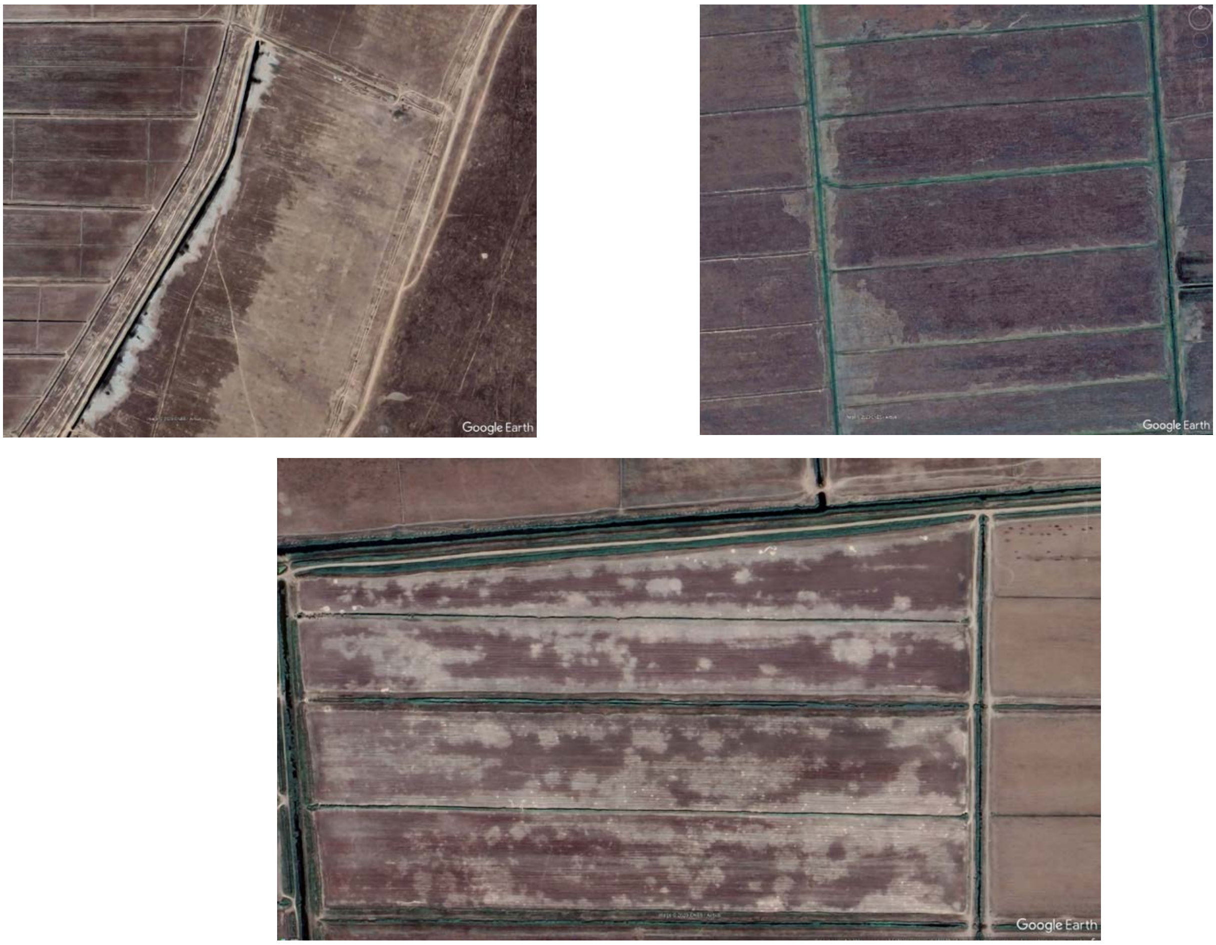

Figure 2.5 | **Fringes of secondary salinized soils due to canal water seepage (Kalmykia, Russian Federation)**
Source: **Google Earth**. 2023. Data from Google & CNES Airbus. In: *Google Earth*. Mountain View, USA, Google. [Cited 2023]. *https://earth.google.com/web/@0,0,0a,22251752.77375655d,35y,0h,0t,0r*

The proper maintenance of canals as well as the lining of canals with impermeable materials (such as concrete, geomembrane or bitumen) can help to reduce the water losses by 50 to 97 percent (Han *et al*., 2020; Zhang *et al*., 2017).

2.1.5 | Overuse of agrochemicals

All fertilizers contain salts but their concentration may differ depending on the type of fertilizer. The fertilizer salt index (A & L Canada Laboratories, 2013) is a measure to express the risk that fertilizer can induce for salinization of a soil solution (Table 2.1). When there is enough precipitation or fresh water irrigation, the risk of salinization is low. However, if the irrigation is limited and evaporation is high enough, then fertilizers with an index higher than 40 and 50 can cause secondary soil salinization and exert a negative impact on plant growth.

Table 2.1 | Salt index of fertilizer materials and soil amendments

Material and analysis	Salt index	Partial salt index*
Nitrogen (N)		
Anhydrous ammonia, 82% N	47.1	0.572
Ammonium nitrate, 34% N	104.0	3.059
Ammonium sulphate, 21% N, 24% S	88.3	3.252
Urea, 46% N	74.4	1.618
Urea-ammonium nitrate solution: 28% N (39% ammonium nitrate, 31% urea)	63.0	2.250
Urea-ammonium nitrate solution: 32% N (44% ammonium nitrate, 35% urea)	71.1	2.221
Calcium nitrate, 15.5% N	65.0	4.194
Sodium nitrate, 16.5% N	100.0	6.080
Phosphorus (P)		
Ordinary superphosphate, 20% P_2O_5	7.8	0.390
Triple superphosphate, 45% P_2O_5	10.1	0.224
Monoammonium phosphate: 11% N, 52% P_2O_5	26.7	0.405
Monoammonium phosphate: 10% N, 50% P_2O_5	24.3	0.405
Diammonium phosphate, 18% N, 46% P_2O_5	29.2	0.456
Ammonium polyphosphate, 10% N, 34% P_2O_5	20.0	0.455
Phosphoric acid, 54% P_2O_5		1.613 **
Phosphoric acid, 72% P_2O_5		1.754 **
Potassium (K)		
Potassium chloride, 60% K_2O	116.2	1.936
Potassium hydroxide, 83.6% K_2O		1.015
Potassium nitrate, 13% N, 44% K_2O	69.5	1.219
Potassium sulphate, 50% K_20, 18% S	42.6	0.852
Sulphate of potash-magnesia, 22% K_2O, 11% Mg, 22% S	43.4	1.971
Monopotassium phosphate, 52.2% P_2O_5, 34.6% K_2O	8.4	0.097
Potassium thiosulphate, 25% K_2O, 17% S	68.0	2.720
Sulphur (S)		
Ammonium thiosulphate, 12% N, 26% S	90.4	7.533
Ammonium polysulphide, 20% N, 40% S	59.2	2.960
Gypsum, 23% Ca, 17% S	8.1	0.247
Magnesium oxide, 60% Mg	1.7	0.002
Magnesium sulphate, 10% Mg, 14% S	44.0	2.687

Miscellaneous		
Calcium carbonate, (lime), 35% Ca	4.7	0.083
Dolomite, 21.5% Ca, 11.5% Mg	0.8	0.042
Manure salts, 20%	112.7	4.636
Manure salts, 30%	91.9	3.067

Note: * The salt index of a mixed fertilizer containing N, P and K is the sum of the partial salt index per unit (9.07 kg) of plant nutrient times the number of units due to each component in the formulation.

** Per 45.36 kg of H3PO4.

Source: A & L Canada Laboratories. 2013. Fertilizer Salt Index. Fact Sheet No. 141. London, Canada. *https://www.alcanada.com/pdf/Tech_Bulletins/Compost_Fertilizer_Manure/Levels/141-Salt_Index.pdf*

The continued application of some organic amendments can also induce soil and water salinization and sodification (Buvaneshwari *et al.*, 2020). The salts content varies between an average of 49.0 g/kg (chicken manure), 20.6 g/kg (pig manure) and 60.3 g/kg (pigeon manure), with a predominance of sulphates and chlorides of potassium and sodium, with Li-Xian *et al.* (2007) showing that their application increased the risk of secondary salinization, even in humid regions of China when applied in high rates. The average EC of cattle manure in semi-arid southern Alberta, Canada, studied by Hao and Chang (2003) was 23.4 dS/m, or 30.8 g of salts per litre, and its continued application has led to a significant increase in soil salinity (Figure 2.6).

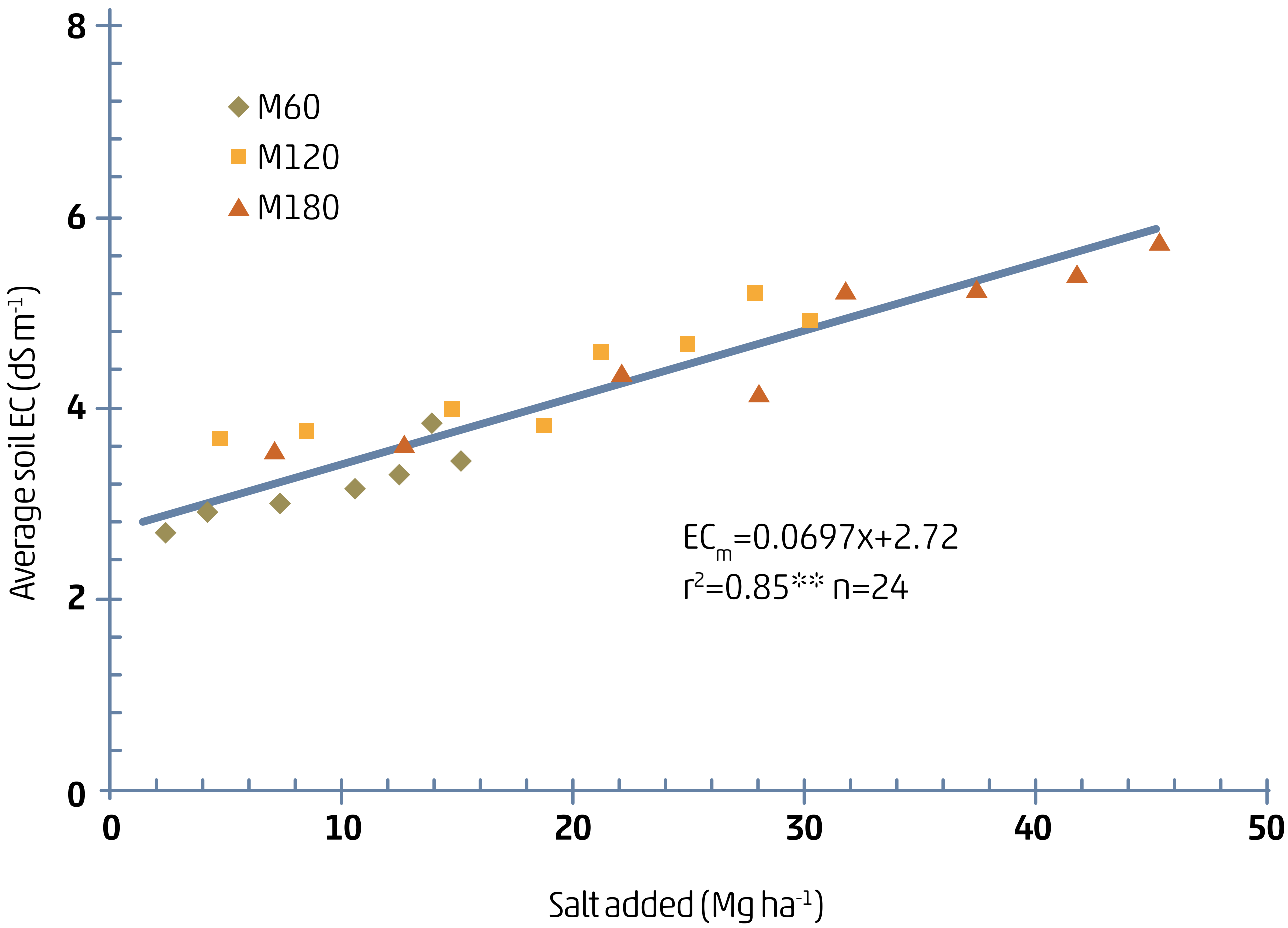

Figure 2.6 | The effect of continued manure amendments on soil salinity in semi-arid conditions

Note: M60, M120, M180 are different rates of cattle manure application in tonnes/ha.

Source: **Hao, X. & Chang, C.** 2003. Does long-term heavy cattle manure application increase salinity of a clay loam soil in semiarid southern Alberta? *Agriculture, Ecosystems & Environment*, 94(1): 89–103. *https://doi.org/10.1016/S0167-8809(02)00008-7*

Additionally, because farmers frequently apply fertilizers in quantities much greater than plant demand (a practise known as "fertigation"), the overuse of fertilizers through irrigation systems may also raise the concentration of solutes in the irrigation water and soil (Moreira *et al.*, 2014).

2.2 | Secondary salinization due to non-agricultural activity

2.2.1 | Road salts

The increased input of road deicing salts in many countries to meet the need for drivable roads yearround has resulted in the substantial eutrophication of freshwater environments (Findlay and Kelly, 2011; Hintz and Relyea, 2019). De-icing salt effects were once thought to be transient, only influencing ecosystems near roads during winter and spring thaw periods. However, current research shows that the effects of de-icing salts are ongoing, and year round (Tiwari and Rachlin, 2018). While de-icing salts are linked to the salinization of lagoons, waterways, and rivers (Schuler and Relyea, 2018), forested wetlands (which are ubiquitous ecosystems around the world and offer a variety of beneficial services like biodiversity sustenance, carbon confiscation, deluge storage, water value enhancement, and wildlife habitation), have received less attention (Brinson, Lugo and Brown, 1981).

Arboreal swamplands are coming under increasing threat from road fragmentation and urban expansion (two primary sources of road salt in the temperate north). The highest consuming road de-icing salt, sodium chloride (NaCl), splits into its ionic components (Na^+, Cl^-) in melted water (Mahoney *et al.*, 2015) which is then absorbed into road-adjacent soils where it can displace soil cations ($[NH_4]^+$, K^+, Ca^{2+}, and Mg^{2+}) via cation exchange, while Cl^-, being a mobile anion, tends to move down through groundwater (Schweiger, Audorff and Beierkuhnlein, 2015). Elevated soil Na^+ decreases hydraulic conduction and increases soil dispersal and dispersion (Kim and Koretsky, 2013). In wetland sediments where drainage is poor and saltenriched runoff may have lengthy residence times, ion exchange (i.e. Na^+ displacement of Ca^{2+}, Mg^{2+}, and K^+) may change the regional patterns of soil base cation availability. For example, organicallyrich wetland soils may improve Na^+ retention and displace other cations if macronutrients are leached out of the environment, or if dangerous amounts of Na^+ accumulate in plant tissues, thus decreasing the mineral nourishment of plants.

Secondary soil salinization by deicing agents is mainly observed in urban lawn soils and along roadside verges and has an ephemeral character, as salts are usually leached out by the beginning of the growing season (Gavrichkova *et al.*, 2020; Gerasimov, Chugunova and Polyak, 2021; Kostka *et al.*, 2019). However, it is possible that salts may cause an irreversible change to soil structure due to sodification, although such an effect is poorly studied.

Road salt contains cyanide as a small component, along with traces of phosphorus, sulphur, nitrogen, copper, and zinc (Environment Canada and Health Canada, 2001). Ferrocyanides like sodium ferrocyanide $Na_4Fe(CN)_6.10H_2O$ are also employed in road salt as anti-caking agents. When ferrocyanides are in solution and exposed to light, they dissociate to create cyanide ions,(CN^-), which then hydrolyze to produce hydrogen cyanide (HCN) and volatilize. However, ferrocyanides are not very soluble and often stay stable in the environment (Environment Canada and Health Canada, 2001).

Elevated salinity linked with deicing salts may also change ion uptake (Na^+ vs. K^+, Ca^{2+}, and Mg^{2+}), and lead to desiccation and stomatal conductance in wetland plant species, which may affect species composition and vigour (Cronk and Fennessy, 2001). According to Gałuszka *et al.* (2011), increased salinity can also cause the deprivation of leaves, foliar impairment, and preeminent Na tissue engrossment, which reduces the diversity of wetland plants, lowers flower and fruit yield, and increases the incidence of salt-tolerant species (Skultety and Matthews, 2017). As Cl^- gets excluded from the ice lattice and amasses beneath the ice, ice formation in shallow water wetlands can concentrate chloride levels to dangerous levels for marine life (Dugan, Helmueller and Magnuson, 2017). According to Hill and Sadowski (2016), it is likely that the chemical pollution caused by road salt on wooded wetlands changes with distance from the source of the salts, so wetland zones close to or hydrologically coupled to roadways are much more vulnerable than those further away.

Because groundwater frequently contributes significantly to the hydrology of wooded wetlands, it is particularly important to understand the regional dynamics of aquifers to comprehend patterns of road salt contamination in logged watersheds (Park, Wang and Kumar, 2020). First, depending on if groundwater has become more salinized (which is a common issue and one that is increasing in the regions of the United States where road salt is used [Cassanelli and Robbins, 2013]), groundwater discharge could either mitigate or worsen the consequences of road salt pollution. Second, since it is anticipated that Na^+ retention and exchange will play a significant role in the biogeochemical response to road salt effluence in organic marshland topsoils, groundwater – even when it is unpolluted – frequently has an surprisingly high base saturation (Winter *et al.,* 1998). Therefore, measuring the flow and biochemical silhouette of groundwater emancipation toward wooded swamps is crucial when separating out soil chemical patterns attributable to road salt.

2.2.2 | Mining

Substantial quantities of environmentallyhazardous waste are stored in association with mining operations, with up to 70 percent of excavated material frequently left behind as waste in potash mines (UNEP and IFA, 2001). Halitebased particulate waste is dumped in tailings heaps, consisting of over 95 percent NaCl. Pumps are used to move the insoluble portion of the fines as claysalt slurry, along with additional brines and clays, to slurry storage spaces. In the claysalt slurry, between 60 and 65 percent of the claysalt slurry consists of insoluble clay with watersoluble salts making up the remaining 35 to 40 percent. The elevated TDS concentration in waterways is caused by the high concentration of soluble salts in the salt tailing piles entering groundwater as brine. Many researchers have investigated the salinization of surface water and groundwater in potash mining regions (Arle and Wagner, 2013; Liu and Lekhov, 2013; Lucas *et al.,* 2010; Baure *et al.,* 2005; Bel'tyukov, 1996).

When assessing the ecological implications of potassium mining, an accurate indication of environmental and geological changes is through the examination of soil properties. According to one study evaluating soils in the floodplains of the Verkhnekamskoye salt deposit (Mitrakova and Khayrulina, 2019), salinization was noted throughout the soil profile and was shown to be the primary transforming factor. The zonal alluvial humic gley soils were changed into secondary saline alluvial clayloamsulphatechloridesodiumcalcium soil and saline alluvial gleyed humus chloridesodiummagnesiumcalcium soil as a consequence of the spreading of contaminated groundwater. The rise in the water table and mining subsidence were the main contributors to soil salinization.

Soil salinization and sodification caused by oilfield waste water are often observed in the regions of oil extractions (Fominykh, 2013; Gabbasova and Suleimanov, 2007; Nosova and Seredina, 2021). Oilfield waste water is highly saline (over 100 g/l) with a predominance of Na^+ and Cl^-, having a strong and longterm effect on soil deterioration, even in humid conditions.

2.2.3 | Industrial by-products

A compact waste residue created through the manufacturing of industrial soda ash is known as ammoniasoda residue (ASR), sometimes identified as ammonia-soda white mud (Ding and Mao, 2017). Soda ash (sodium carbonate [Na_2CO_3]) is an essential inorganic material, used extensively in the chemical, metallurgical, textile, printing and dyeing, paper, glass, enamel, medicinal, and food industries. Soda ash can currently be made using chemical or natural synthesis processes. The chemical synthesis procedure includes an ammonia-soda process and a combined soda process. The latter is known as Hou's process and involves the manufacture of ammonium chloride and sodium carbonate (Ding and Mao, 2017). Large amounts of industrial salt (NaCl), limestone ($CaCO_3$), and ammonia (NH_3) are used in the Solavy process, among the principal techniques for producing soda ash (Steinhauser, 2008). Low industrial salt utilization efficiency (around 70 percent) is a drawback of the ammonia-soda process (Ding and Mao, 2017). Although chlorine (Cl) is never used, Na is employed with a utilization efficiency of around 75 percent, with a significant amount of the left-over liquid condensation from the soda manufacture procedure comprising of $CaCl_2$ and NaCl (Pan, 2017). Ammoniasoda residue is the waste scum left over from the purification of the ammonia distillation left-over fluid (Kuang *et al.,* 2006). One of the main technical issues facing ammonia-soda plants is the dumping of ASR to avert contamination (Kuang *et al.,* 2006). Crops may be harmed by soil salinization and salinity due to the high Cl concentration in the ASR.

Research was done by Piernik, Hulisz and Rokicka (2015) in the city of Inowrocaw (Mtwy district) and the nearby town of Popowice in northcentral Poland. In 1.5 km^2 of waste ponds, waste had been deposited and without the necessary safety precautions. Being easily soluble salts, $CaCl_2$ and NaCl had then dissolved into the neighbouring shallow groundwater and urban arable soils. Urban and industrial agglomerations that have a high concentration of artefacts and have been considerably altered by humans are considered to have technogenic soils (IUSS Working Group WRB). In terms of origin, characteristics, and ecological services, soils impacted by technological processes clearly diverge from natural soils.

High spatial and temporal variability could be a result of the variety of technological materials (Huot, Simonnot and Morel, 2015). In a study conducted by Sylwia *et al.* (2023), it was determined that the main difference between the examined soils was the presence of technologicallycreated components. Nearly 70 percent of soils examined had been impacted by various technological soil transformations, including soil salinity, sodification, sturdy alkalinization, and augmentation with artefacts. It was shown that artificiallyinduced changes had altered the look and composition of soils, including Histosols, Gleysols, and Phaeozems, and contributed to the creation of Technosols and Solonchaks.

The study conducted by Hulisz *et al.* (2018) in Inowrocaw, Poland, focused on organic soils that had been damaged by salt and had thin mineral surface layers. The results showed that inorganic material had transferred from waste pools through the aeolian process, as well as through superficial overflow, and had established strata comprised of nearly 43 percent of carbonates. Additionally, it was shown that the way the tested soils performed in the landscape could be significantly affected by these presumably small variations in soil shape. The salinization- and sodification-related degradation of the water's quality and the consequent reduction in plant development were the most significant consequences in this regard. The study demonstrated the multiple effects of soda manufacturing waste on soil qualities, including those caused by saline groundwaters, and the aeolian supply of inanimate waste quantifiable from waste ponds, and, in some cases, superficial runoff. These processes had led to the development of soils with a complicated genesis, influenced by both natural (peat accumulation) and technological elements. All sampling sites showed an elevated soil salinity. However, only the organic soils found within 200 m of the waste ponds were distinguished by the existence of thin inorganic surface layers that were rich in carbonates and easilysoluble salts but low in organic carbon. These layers developed unfavourable water characteristics as a result of sodification, which restricted plant growth. According to the authors, while the World Reference Base (WRB) soil classification could effectively represent the pronounced detailed structures of the investigated soils, adding the option to indicate artefact types in the form of subqualifiers would supplementarily enhance the cataloguing scheme (Hulisz *et al.,* 2018).

As previously mentioned, ASR encompasses an important amount of soluble salts, such as major dissolved ions of sodium, chloride, and calcium as well as hydroxides, sulphates, and carbonates (Zhu and Liu, 2018). Additionally, the EC in its drenched solution can reach as high as 34 000 μS/cm (Pan and Xu, 2017). According to Maas (1990), plants that are sensitive to salt can typically endure EC values of around 1 500 and 3 500 μS/cm, respectively. As a result, the EC values in ASR saturated solutions are roughly 10 to 20 times greater than those that plants can tolerate. According to Wang, Yan and Li (2020), the use of ASR as a soil conditioner in agronomic areas has been on the rise. Few studies have examined the environmental impacts and risks of ASR, which has so far largely been the subject of studies on acid soil amendment in agriculture. It was shown that polluting substances include mercury (Hg), cadmium (Cd), copper (Cu), and fluorine (F) are present in ASR. The outcomes of the extraction tests also revealed that the levels of the constituents Hg, Cd, Cu, F, and Cl in the leachate of ASR exceeded the Class IV-V limitations of the Chinese Standard for Groundwater Quality. It is suggested that, without any pretreatment, ASR should not be used for soil remediation or conditioning of farmlands when wanting to lower dangerous contaminants, in order to ensure soil health, food safety, and environmental quality (Wang, Yan and Li, 2020).

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Chapter 3 | Status of salt-affected soils measurement, monitoring and management: regional assessments

Introduction

The regional assessments of the status of measurement, monitoring and management of salt-affected soils in the seven GSP regions (Africa, Asia, Europe and Eurasia, Latin America and the Caribbean, NENA, North America, and the Pacific) were carried out based on the responses of INSAS members to the survey distributed in 2023 amongst the network.

The INSAS survey, launched in 2023, consisted of 104 questions grouped in 19 blocks of questions in five sections:

1. General information;
2. *Status of measurement, mapping and monitoring salt-affected soils;*
3. *Status of sustainable management of salt-affected soils;*
4. *Status of crop and plant production in salt-affected environments; and*
5. *Status of sustainable water management in saline and sodic environments.*

In total, 59 questionnaires from 53 countries were filled out by 94 experts, and were received and analysed by the regional lead authors. The responses to the INSAS survey are given in Annex 5. The respondents were representatives of various organizations including research and educational organizations, private companies as well as representatives of governments. It is therefore important to note that they provided the responses to the best of their knowledge and expertise although in most cases were not validated with statistical offices of the respective countries, even though the references to the official national data sources were requested in the survey. In the Pacific Region, the experts from the region were invited to provide a summary report for this region.

3.1 | Asia

Introduction

Worldwide, over 20 percent of cultivated lands are salt-affected (Hayat *et al.*, 2020), with more than 77 million ha being human-induced. Seventy percent of these are exclusively in Asian regions (Shahid, Zaman and Heng, 2018).

Jamil *et al.* (2011) suggests that the soil salinization rate will increase up to 10 percent annually due to various factors such as global warming, malpractice in agricultural management, and inevitable natural processes. The varying degrees of soil salinity issues significantly impact agricultural industries by reducing the economic returns of cultivated land, causing the land to be barren and ultimately leading to mass land abandonment problems (Yasin *et al.*, 2018). Every minute, three hectares of arable land are degraded due to increasing soil salinity (Pisinaras *et al.*, 2010). Developing strategies to make use of saline land will be crucial for addressing the problem of insufficient cropland and meeting the challenge of providing food security for the projected global population of 9.3 billion people by 2050 (Liu and Wang, 2021).

Status of salt-affected soils in Asian countries

The total surface area of salt-affected soils in Asia is 1 543 269 km^2 (according to assessments given in Chapter 1). The assessment of the status of salt-affected soils given in this regional assessment was made for six Asian countries: Bangladesh, China, India, Malaysia, Pakistan and Thailand. As per the data provided by the experts from the respective countries, the extent of saline and sodic soils varied from 0.05 million ha in Malaysia to 36 million ha in China (Table 3.1.1). Unfortunately, in many of the countries, the official data pertaining to total salt-affected soils and the extent of their saline, sodic and saline sodic soils are unknown. There is therefore a demand for systematic surveying and compilation of data to gain a better understanding of the nature and extent of problem soils so that they can be managed sustainably.

Table 3.1.1 | Area of salt-affected soils in Asian countries

Name of country	Area of salt-affected soils (million ha)	Area of saline soil (million ha)	Area of sodic soils (million ha)	References
Bangladesh	1.056	n/a	n/a	No official data available
China	36.0	n/a	n/a	National Soil Survey Office (1998)
India	6.74	2.96	3.78	ICAR-CSSRI (2024)
Malaysia	0.050	0.050	–	No official data available
Pakistan	6.67	1.93	4.2 (saline sodic) 0.5 (sodic)	Khan (1998)
Thailand	0.806	n/a	–	No official data available

Sources: **National Soil Survey Office.** 1998. Soils of China (in Chinese). Beijing, China Agriculture Press.

ICAR-CSSRI (Central Soil Salinity Research Institute). 2024. Extent and distribution of salt-affected soils in India. In: CSSRI. Karnal, India. [Cited January 2024]. *https://cssri.res.in/extent-and-distribution-of-salt-affected-soils-in-india/*

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China has a total area of 36 million ha of salt-affected soils (about 4.88 percent of the available land area) (Yang *et al.*, 2022). These soils are mainly distributed in arid and semi-arid regions and coastal areas with an arid climate and little rainfall, high soil evaporation, a high groundwater table, and soluble salts (Zhang *et al.*, 2009; Wen *et al.*, 2021).

India has an agricultural area of 142 million ha (out of a total land area of 329 million ha), of which 6.74 million ha are affected by soil salinity (2.96 ha of saline soils and 3.78 ha of sodic soils). Similarly, Pakistan has an agricultural area of 22 million ha (out of a total land area of 79.7 million ha), of which 6.67 million ha (29.6 percent) are affected by soil salinity or sodicity. In Thailand, saline soils occupy 0.576 million ha in the coastal area and parts of the central plain, while potentially saline soils cover over 3.04 million ha. The severely affected coastal saline soils are used for salt making which involves heavy firewood consumption, thereby leading to extensive deforestation and environmental deterioration.

A survey of the literature was conducted to compile information regarding salt-affected soils in other Asian countries. In Malaysia, about 0.325 million ha of saline soils are found in the Malay Peninsula and in Sarawak, comprising 4.5 percent of the total area (Othman *et al.*, 1990).

Soil salinity is an enormous problem in coastal regions and the irrigated lands in the dry zones of Sri Lanka, with approximately 11 200 ha of coastal lands being affected. The Jaffna Peninsula, located in the northern most part of Sri Lanka, is one of the most salt-affected regions in Sri Lanka. About 32.8 percent of the soils in Jaffna Peninsula are affected by salinity. It has been established that since the turn of the twenty-first century, groundwater salinity has increased by 1.6-fold in the peninsula (Gopalakrishnan, Ansari and Athar Khan, 2020).

In Southeast Asia, Indonesia has 2.2 million ha of severely salt-affected soils. In Myanmar, approximately 1.4 percent of the land is affected by saline soils, occurring mainly in the coastal belt, deltaic and arid areas. Salinisation in the arid region occurs due to saline ground water evaporation, inadequate leaching and use of saline irrigation water. In the Philippines, an estimated area of 0.4 million ha is affected by salinity, occurring along the 18 000 km coastline. In Viet Nam, the coastal saline soils occupy 2 million ha – mostly along 2 500 km of the coastline – and are of great agricultural importance (Ponniah, 1998).

Table 3.1.2 | Chemical methods used to measure soil salinity in the Asian countries

Method	Bangladesh	China	India	Malaysia	Pakistan	Thailand
Electrical conductivity (EC) in saturated paste extract	√	–	√	–	√	√
EC at 1:1 soil to water ratio	√	–	–	–	–	–
EC at 1:2 soil to water ratio	–	–	√	–	–	–
EC at 1:2.5 soil to water ratio	–	–	√	–	–	–
EC at 1:5 soil to water ratio	√	√	–	√	√	√
EC at 1:10 soil to water ratio	–	–	–	–	√	–
Total dissolved solids (by gravimetric analysis)	–	–	–	–	–	–
Total soluble salts (calculated as the sum of Na^+, Mg^{2+}, Cl^-, SO_4^{2-}, HCO_3^-, and CO_3^{2-})	–	√	√	–	√	√
Content of soluble Na^+	–	√	–	–	–	√
Content of soluble Cl^-	–	–	–	–	–	–
Others	–	–	–	–	–	–

In Asian countries, the method commonly used for the determination of soil salinity and sodicity differs, as evident in Table 3.1.2. Electrical conductivity (EC) in saturated paste extract for the assessment of salinity is common in Bangladesh, India, Pakistan and Thailand while EC 1:5 is common in Bangladesh, China, Malaysia, Pakistan and Thailand. The sum of total soluble salts is also a common approach in the measurement of salinity in China, India, Pakistan and Thailand. As more than one method is being used, there is need for a uniform global assessment method.

Table 3.1.3 | Methods of soil sodicity measurement used in the Asian countries

Method	Bangladesh	China	India	Malaysia	Pakistan	Thailand
Exchangeable sodium percentage (ESP)	√	√	√	–	√	–
Sodium adsorption ratio (SAR)	√	√	√	–	√	√
Physical methods (specific swelling, low infiltration rate etc.)	–	–	–	–	–	–
Morphological methods (structure of sodic/ solonetzic horizon etc.)	–	–	–	–	–	–
Others	–	–	pHs (pH of saturation paste)	–	–	–

For the assessment of soil sodicity, the most common method used in Asian countries is ESP and SAR (Table 3.1.3) except in Malaysia and Thailand, and indicates the predominance of saline soils in these two countries. Among the various methods for determining exchangeable Na^+, the most prevalent approach in the Asian countries includes a three-step process: salt removal (step 1), cation exchange (step 2), and measurement of Na^+ (step 3). However, exchangeable Na determination in ammonium acetate extract is used in Bangladesh and India (Table 3.1.4). In Malaysia and Thailand, the measurement of exchangeable Na^+ and CEC was employed without salt removal.

Table 3.1.4 | Methods of determination of exchangeable Na^+ and their distribution in Asian countries

Method	Bangladesh	China	India	Malaysia	Pakistan	Thailand
Step 1. Salt removal. Step 2. Cation exchange. Step 3. Measurement of Na^+.	–	√	√	–	–	–
Without salt removal. Step 1. measurement of soluble Na+. Step 2. Cation exchange. Step 3. Measurement of Na^+. Step 4. Recalculation of exchangeable Na^+ based on the subtraction of soluble Na+ from total Na^+.	–	–	–	–	√	√
Without salt removal. Step 1. Cation exchange. Step 2. Measurement of Na^+.	–	–	–	√	–	–
Others	Ammonium acetate extract method	–	Ammonium acetate extract method	–	Ammonium acetate extract method	–

Among the methods of CEC determination in soils, ammonium acetate extraction (buffered at pH 7) is the most common method universally accepted in the assessed countries except for China, where ammonium chloride extraction is being adopted for determining CEC (Table 3.1.5).

Table 3.1.5 | Methods of measurement of CEC and their distribution among the Asian countries

Method	Bangladesh	China	India	Malaysia	Pakistan	Thailand
Ammonium acetate extraction (buffered at pH 7)	√	–	√	√	√	√
Ammonium chloride extraction	–	√	–	–	–	–
Triethanolaminebuffered barium chloride extraction (buffered at pH 8.2)	–	–	–	–	–	–
Hexamminecobalt (III) chloride extraction	–	–	–	–	–	–
Others (sodium acetate extraction)	–	–	–	–	–	–
Not applicable (CEC not measured)	–	–	–	–	–	–

There is no common method for the measurement of soil pH evident from the summary in Table 3.1.6, with pH (ratio 1:2.5 soil to water) being used in Bangladesh, India and Pakistan while in China and Malaysia, pH (1:5 soil to water ratio) is being commonly used. However, as no information was received for this measurement from Thailand, it suggests that soil salinity is the problem rather than sodicity.

Table 3.1.6 | Method of pH measurement and their application in countries of the Asian region

Method	Bangladesh	China	India	Malaysia	Pakistan	Thailand
Soil pH (extract of saturated paste)	–	–	√	–	–	–
Soil pH (1:1 soil to water ratio)	–	–	–	–	√	–
Soil pH (1:2 soil to water ratio)	–	–	√	–	–	–
Soil pH (ratio 1:2.5 soil to water)	√	–	√	–	√	–
Soil pH (1:5 soil to water ratio)	–	√	–	√	–	–
Soil pH ($CaCl_2$ at 1:2.5)	–	–	–	–	–	–
Total alkalinity, or content of alkaline anions (with methyl orange and phenolphthalein indicators)	–	–	–	–	–	–
Others	–	–	–	–	–	–

Table 3.1.7 | Map scales, used in the detailed saline and sodic soil maps in the Asian region at national scale

Map scale	Bangladesh	China	India	Malaysia	Pakistan	Thailand
1:5 000	–	–	–	–	–	–
1:10 000	–	–	–	–	–	–
1:20 000	–	–	–	–	–	–
1:25 000	–	–	–	–	–	√
1:50 000	–	–	–	–	–	–
1:100 000	–	–	–	–	–	–
1:250 000	–	–	–	–	–	–
1:500 000	–	–	–	–	–	–
1:1 000 000	√	–	–	–	–	–
No answer	–	√	√	√	√	–

Unfortunately, no proper responses were received for the map scale being used in Asian countries, except for Bangladesh and Thailand where 1:1 000 000 and 1:25 000 map scales are used for detailed saline and sodic soil map at a national level (Table 3.1.7).

Surface irrigation (basin/flood type) is commonly used in Asian countries followed by drip and sprinkler irrigation in some of the countries. In Bangladesh, pitcher irrigation is also prevalent, as evident from the information received and compiled in Table 3.1.8.

Table 3.1.8 | Irrigation method common in Asian countries

Irrigation method	Bangladesh	China	India	Malaysia	Pakistan	Thailand
Surface irrigation (basin/ flood irrigation subtype)	√	√	√	√	√	–
Surface irrigation (border irrigation subtype)	–	–	–	–	√	–
Surface irrigation (furrow irrigation subtype)	√	–	–	–	√	–
Surface irrigation (uncon-trolled flooding)	–	–	√	–	√	–
Sprinkler irrigation	–	–	√	√	√	–

Drip irrigation	–	–	√	√	√	–
Manual irrigation	–	–	–	√	–	–
Other (please specify which one)	√ pitcher irrigation	–	–	–	–	√

In general, an EC of 4 dS/m is considered as the threshold between saline and non-saline soils while >15 ESP is considered as the critical level for designating sodic and non-sodic soils (Table 3.1.9). The absence of information for the threshold of sodic and non-sodic soil from Bangladesh and Malaysia is indicative that salinity predominates rather than soil sodicity.

Table 3.1.9 | Thresholds level for saline and sodic soils

Threshold level	Bangladesh	China	India	Malaysia	Pakistan	Thailand
Threshold between saline and non-saline soils	2 dS/m	1 g/kg (0.1% salt)	4 dS/m	4 dS/m	4 dS/m	2 dS/m
Threshold between sodic and non-sodic soils	–	>20 ESP	>15 ESP >13 SAR	–	>15 ESP >13 SAR	>13 SAR

The services that are demanded by farmers and extension services in the six Asian countries to help manage salt-affected soils in a sustainable manner include training, soil and water analysis, and recommendations for the sustainable management of salt-affected soils (Table 3.1.10). This points towards the need for capacity building and awareness programmes to be implemented in Asian countries on a priority basis.

Table 3.1.10 | Services most demanded by farmers and extension services to help manage salt-affected soils in a sustainable manner in the countries of the Asian region

Services	Bangladesh	China	India	Malaysia	Pakistan	Thailand
Training about the management of salt-affected soils	√	√	√	–	√	√
Soil analyses	√	–	√	–	√	–
Interpretation of soil analyses	√	–	√	–	√	–
Irrigation water or groundwater analyses	√	–	–	√	√	√
Soil salinity and sodicity mapping	√	–	√	–	–	–
Recommendations on the sustainable management of salt-affected soils	√	√	√	–	√	√
Others	–	–	–	–	Seeds/ germplasm of salt tolerant plants	–

Table 3.1.11 | The most cultivated crops grown on saline and sodic soils in the countries of the Asian region

Crop	Bangladesh	China	India	Malaysia	Pakistan	Thailand
Rice	√	√	√	–	√	√
Cotton	–	√	√	–	√	–
Barley	–	–	√	–	√	–
Alfalfa	–	√	–	–	√	–
Sorghum	–	√	√	–	√	–
Tall wheatgrass	–	–	–	–	√	–
Halophytes (e.g. quinoa (*Chenopodium quinoa*), *Atriplex* sp., *Salicornia* sp., saltgrass (*Distichlis spicata*), etc.)	–	√	√	–	√	–
Non-conventional crops (amaranth or others)	–	–	√ (Sugar beet)	–	–	–
Millet	–	–	√	–	–	–
Date palm	–	–	–	–	–	–

In most of the Asian countries, rice is among the most dominant crop being cultivated in saline and sodic soils, as well as where there is saline irrigation water (Table 3.1.11 and Table 3.1.12), with barley and cotton also being popular in these areas. Halophytes and non-conventional crops like sugar beet are also cultivated in saline soils and where there is availability of saline water.

Table 3.1.12 | Some crops irrigated with brackish water in the countries of the Asian region

Crop	Bangladesh	China	India	Malaysia	Pakistan	Thailand
Rice	√	–	√	√	√	–
Cotton	–	√	√	–	√	–
Barley	–	–	√	–	√	–
Alfalfa	–	–	–	–	√	–
Sorghum	–	–	–	–	√	–
Tall wheatgrass	–	–	–	–	√	–
Halophytes (e.g. quinoa (*Chenopodium quinoa*), *Atriplex* sp., *Salicornia* sp., saltgrass (*Distichlis spicata*), etc.)	–	–	–	–	√	–
Non-conventional crops (amaranth or others)	–	–	√ (Sugar beet)	–	–	–
Salt-tolerant vegetable crops	–	–	–	–	√	–
Corn	–	√	–	–	–	–
Wheat	–	√	√	–	√	–
Date palm	–	–	–	–	–	–

Most of the Asian countries assess irrigation water quality using EC pH and SAR, as evident from Table 3.1.13. Unfortunately, no information on this aspect was received from Thailand. In Bangladesh, India and Pakistan, EC is a common criterion for measuring water salinity.

Table 3.1.13 | The criteria used to assess the irrigation water quality in Asian countries

Criteria	Bangladesh	China	India	Malaysia	Pakistan	Thailand
Water electrical conductivity	√	√	√	–	√	–
SAR of water	√	–	√	√	√	–
Total dissolved solids	–	√	–	√	√	–
Total soluble salts	–	–	√	√	√	–
pH	√	√	√	√	√	–
Toxic ions	–	–	–	√	√	–
Others	–	–	√ RSC	–	√ RSC	–

*RSC: residual sodium carbonate (RSC [meq/L] = [HCO_3^- + CO_3^{-2}] – [Ca^{2+} + Mg^{2+}]).

Table 3.1.14 | Type of drainage system implemented in the Asian region

Drainage system	Bangladesh	China	India	Malaysia	Pakistan	Thailand
Surface drainage (shallow ditches)	√	√	√	√	√	√
Subsurface drainage (deep open drains)	–	√	–	–	√	–
Subsurface drainage (buried pipe drains)	–	√	√	–	√	√
Controlled drainage	–	–	–	√	–	–
Others	–	–	Depending on soil texture & salinity	–	–	–

The most common type of drainage system implemented for salinity management is surface drainage (shallow ditches) preferred in Bangladesh, China, India, Malaysia and Thailand (Table 3.1.14). However, subsurface drainage is being implemented in Pakistan, either by using deep open drains or buried pipe drains. In India and Thailand, subsurface drainage using buried pipe drains is also being implemented.

The criteria used for designing the drainage systems in saline soils of Asian countries are illustrated in Table 3.1.15. It can be observed that soil parameters were considered by all four countries that responded (no response was received from Bangladesh and China).

Table 3.1.15 | The criteria used to design the drainage system in Asian countries

Criteria	Bangladesh	China	India	Malaysia	Pakistan	Thailand
Soil parameters	–	√	√	√	√	√
Water parameters	–	Water table	Water table	–	Water table	√
Soil hydraulic/physical properties (infiltration, compaction, soil layers)	–	√	√	√	–	–
Others	–	–	–	–	–	–

Based on the established drainage system, leaching stands out as the principal method for alleviating soil salinity. This crucial practice can be executed through various approaches. In the Asian region, the predominant form of leaching is through flooding. Regrettably, pertinent data from Bangladesh, China and Malaysia are absent, as illustrated in Table 3.1.16.

Table 3.1.16 | Type of leaching of saline soils used in the countries of Asian region

Leaching type	Bangladesh	China	India	Malaysia	Pakistan	Thailand
Flooding	–	√	√	–	√	√
Sprinkler	–	–	–	–	–	–
Drip	–	√	–	–	–	–
Others	–	–	–	–	–	–

Conclusion

Across the Asian region, the assessment of the status of salt-affected soils was made for six countries: Bangladesh, China, India, Malaysia, Pakistan and Thailand. The following conclusions were reached:

The soil salinization rate may increase by up to 10 percent annually due to climate change, malpractice in agricultural management and inevitable natural processes, and will pose a threat to food security for the region.

Salt-affected soils cover a wide area across the assessed Asian countries. The largest salt-affected areas occur in China (36 million ha), followed by India (6.74 million ha). The least affected country is Malaysia with an area of 0.05 million ha.

The most common methods used to measure soil salinity in the Asian region are soil EC in saturated paste extract and 1:5 soilto-water solution, followed by calculating the total soluble salts (Na^+, Mg^{2+}, Cl-, SO_4^{2-}, HCO_3-, and CO_3^{2-}). For sodicity, the exchangeable sodium percentage (ESP) and sodium adsorption ratio (SAR) are used in most countries except in Malaysia and Thailand.

The most prevalent approach to determine exchangeable Na^+ in the assessed Asian countries includes a three-step process: salt removal (step 1), cation exchange (step 2), and measurement of Na^+ (step 3). Ammonium acetate extraction (buffered at pH 7) is commonly used to determine cation exchange capacity (CEC).

The responses from the INSAS questionnaires indicate that no official mapping protocol exists for mapping salinity and sodicity in most countries except for Bangladesh and Thailand where 1:1 000 000 and 1:25 000 map scales were used for detailed saline and sodic soil maps at a national level.

An EC of 4 dS/m was considered to be the threshold between saline and non-saline soils while >15 ESP was considered as the critical level for designating sodic and non-sodic soils in the region.

Asian farmers and agricultural authorities have indicated that they need assistance in managing salt-affected soils in a sustainable manner via interventions through training, soil and water analysis, and recommendations on sustainable management practices.

The most cultivated crop in saline and sodic conditions is rice, followed by wheat cotton and barley. These crops are irrigated by brackish waters mainly in, Bangladesh, India, Malaysia, and Pakistan.

Sodium adsorption ratio and pH are commonly used to assess irrigation water quality. The dominant drainage system which is used is shallow ditches for saline and sodic soils and soil parameters is the common variable considered for designing drainage systems.

The management of soil salinity in most countries are done by leaching through flooding.

A critical gap was found across the surveyed countries within the Asian region whereby the crucial determination of national scale maps was absent in most countries except for Bangladesh and Thailand. To mitigate saline and sodic environments, baseline information on areas needing to be rectified is needed urgently.

As most countries have indicated that capacity building and awareness is needed to manage salt-affected soils, it is time for extension services to efficiently design resultoriented modules to assist farmers and agricultural authorities in enhancing food security, mitigate the effects of climate change and create a balance with sustainable soil management and conserving the environment in the Asian region.

3.2 | Europe and Eurasia

1 Introduction

Soil salinization occurs in the Europe and Eurasia region, posing a threat to food security and sustainability. Salt-affected soils are present in countries such as Hungary, Kazakhstan, the Russian Federation, Spain, Turkmenistan, Ukraine, and Uzbekistan. The area of salt-affected soils is increasing due to both natural and anthropogenic processes, including prolonged droughts, seawater intrusion into aquifers and improper irrigation practices. Some countries in the region have a long history of attempting to halt soil salinization while for others it is an increasingly new phenomenon, and preparing for a climate-proof future may prove challenging.

The current status of salt-affected soils in Europe and Eurasia impacts biodiversity and agricultural productivity and as a consequence, food production and farmer livelihoods and biodiversity as the salt content in the soil decreases yields by negatively affecting plant growth and productivity, leading to increased management costs and lower incomes for farmers.

The heterogenous scale and nature of salinization in the region means that addressing this challenge requires an approach that is both localized and, including cooperation between practice, science and public authorities, and environmental policies. This is especially visible in multiple initiatives and networks that are applying scientific and technical knowledge to mitigate and adapt to the progression of salinization and sodification.

An increased understanding of the status quo of salt-affected soils can contribute to the eventual design of improved management practices that protect farmer livelihoods and increase ecosystem protection.

2. Methodology note

The synthesis produced in this chapter is based on the survey distributed through the International Network of Salt-affected Soils (INSAS) among its members. The status of the measurement, mapping, and monitoring of salt-affected soils, sustainable soil management, crop production, and water management in saline and sodic environments are described based on these countrylevel surveys.
For Europe and Eurasia, 14 questionnaires were received from experts of 12 countries each of the following returned a single questionnare (Germany, Greece, Hungary, Israel, Italy, Kazakhstan, the Kingdom of the Netherlands, Poland, the Russian Federation, Spain, Ukraine, and the United Kingdom of Great Britain and Northern Ireland), while Israel and Spain submitted two questionnaires each. The respondents were voluntary representatives of various organizations, including public institutions, research institutes and private companies. It is therefore important to point out that the information given was not validated with statistical offices of the respective countries, although references from the official national data sources were requested.

3. Measurement, mapping and monitoring

The total area of salt-affected soils in Europe and Eurasia is 2 378 209 km^2 (according to assessments given in Chapter 1). However, the extent of salt-affected soils is not fully known, as many countries lack official data in this area, as indicated by the data provided by the national experts participating in the INSAS questionnaire (see Table 3.2.1). The reported areas range from a few thousand hectares to tens of millions of hectares, depending on the country. The lack of uptodate and comprehensive data on soil salinity in different countries poses a significant challenge in the understanding of the true extent of soil salinity issues in the region.

Table 3.2.1 | Area of salt-affected soils in the Europe and Eurasia region (according to available data from the INSAS survey)

Country	Area of salt-affected soils (ha)	Area of saline soil (ha)	Area of sodic soils (ha)	Saline sodic soil (ha)	Sources
Germany	n/a	n/a	n/a	n/a	n/a
Greece	4 019 385	3 975 129	44 256	0	Author's estimates
Hungary	1 413 460	1 388 450	25 010	n/a	Szatmári *et al.* (2020)
Israel	0.2	n/a	n/a	n/a	Eshel *et al.* (2022) and Ravikovitch (1969)
Italy	3 200 000	n/a	2 560 000	n/a	Dazzi and Lo Papa (2013)
Kazakhstan	93 982 300	35 817 000	58 164 900	n/a	MARK (2021)
Poland	10 000	Not specified	Not specified	Not specified	GDOS (2000); Hulisz (2008) and Pindral *et al.* (2023)
Russian Federation	66 441 000	43 377 600	n/a		Pankova and Gorokhova (2020) and MARF and DSSI (2024)
Spain	n/a	n/a	n/a	n/a	
Netherlands (Kingdom of the)	125 000	n/a	n/a	n/a	De Kempenaer, Brandenburg, and van Hoof (2007)
Ukraine	n/a	1 920 000	2 800 000	n/a	Getman and Shulga (2002)
United Kingdom	n/a	n/a	n/a	n/a	

Sources: **Szatmári, G., Bakacsi, Z., Laborczi, A., Petrik, O., Pataki, R., Tóth, T. & Pásztor, L.** 2020. Elaborating Hungarian Segment of the Global Map of Salt-Affected Soils (GSSmap): National Contribution to an International Initiative. Remote Sensing, 12(24): 4073. *https://doi.org/10.3390/rs12244073*

Eshel, G., Volk, E., Maor, A., Argaman, E. & Levy, G.J. 2022. Degradation of Agricultural Lands in Israel. In: P. Pereira, M. MuñozRojas, I. Bogunovic & W. Zhao, eds. Impact of Agriculture on Soil Degradation 1 (The Handbook of Environmental Chemistry, Volume 120), pp. 259–272. Dordrecht, Germany, Springer. *https://cris.technion.ac.il/en/publications/degradation-of-agricultural-lands-in-israel*

Ravikovitch, S. 1969. Distribution of soils affected by salinity in Israel (1: 500 000). In: ESDAC/JRC/EC. Brussels, Joint Research Centre (JRC), European Soil Data Centre (ESDAC) & European Commission (EC). *https://esdac.jrc.ec.europa.eu/content/distribution-soils-affected-salinity-israël-0*

Dazzi, C. & Lo Papa, G. 2013. Soil Threats. In: E.A.C. Costantini & C. Dazzi, eds. The Soils of Italy. pp. 205–245. World Soils Book Series. Dordrecht, Kingdom of the Netherlands, Springer. *https://doi.org/10.1007/978-94-007-5642-7_8*

MARK (Ministry of Agriculture of the Republic of Kazakhstan). 2021. Summary Analytical Report on the Status and Use of Lands in the Republic of Kazakhstan in 2021. Astana. *https://www.gov.kz/uploads/2022/4/11/b09469de9be9cc54d2cc0e9cc7a77e84_original.7131188.pdf*

GDOS (The General Directorate for Environmental Protection of Poland.) 2000. GDOS. Warsaw. [Cited 19 April 2023]. *http://www.gdos.gov.pl/*

Hulisz, P. 2008. Quantitative and qualitative differentiation of soil salinity in Poland. Conference presentation at The soils of the coast and their genesis in the area of tension between land use and climate change. 3–5 September 2008. Berlin, the German Society for Plant Sciences (DBG), Oldenburg, Germany, University of Oldenburg and Hannover, Germany, State Authority for Mining, Energy and Geology (LBEG). *https://eprints.dbges.de/66/1/Hulisz.pdf*

Pindral, S., Kot, R., Malinowska, A. & Hulisz, P. 2023. The effect of technogenic materials on fine-scale soil heterogeneity in a human-transformed landscape. CATENA, 221: 106772. *https://doi.org/10.1016/j.catena.2022.106772*

Pankova, E.I. & Gorokhova, I.N. 2020. Analysis of information about the alkaline soil areas in Russian Federation at the end of the XX and beginning of the XXI centuries. Dokuchaev Soil Bulletin, 103: 5–33. DOI: 10.19047/0136-1694- 2020-103-5-33

MARF & DSSI (Ministry of Agriculture of the Russian Federation & V.V. Dokuchaev Soil Science Institute). 2024. Unified State Register of the Soil Resources of Russia. EGRPR. Moscow. [Cited 19 April 2024]. *https://egrpr.esoil.ru/*

De Kempenaer, J.G., Brandenburg, W.A. & van Hoof, L.J.W. 2007. Het zout en de pap, een verkenning bij marktexperts naar langetermijnmogelijkheden voor zilte landbouw [The salt and the porridge, an exploration by market experts into long-term options for saline agriculture]. Technical report No. 07.2.154. Wageningen, Kingdom of the Netherlands, Wageningen University & Research.

Getman, A. & Shulga, A. (eds). 2002. Land Code of Ukraine. Kharkov, Ukraine, Odissei Publishing.

Regarding the determination of soil salinity and sodicity, there is some harmonization in the methods used, even though different countries apply varying approaches (as shown in Table 3.2.2). The most common method involves determining the electrical conductivity (EC) of an extract of a saturated paste (ECe), followed by calculating the total soluble salts (comprising of Na^+, Mg^{2+}, Cl-, SO_4^{2}, HCO_3^- and CO_3^{2-}).

However, it is worth noting that more than one method is often used within the same country. For example, in Italy, eight different methods are employed. Historically in the Kingdom of the Netherlands, salinity has always been expressed as the chloride concentration (mg/L) of water, and this habit is slow to change. The electromagnetic method is applied in relatively small areas (1–1 000 ha) in some countries such as Israel, Italy, Spain, and the United Kingdom.

Furthermore, diverse methods may be used by different actors in the analysed countries. For example, commercial labs, universities and private companies may all employ different methods. More detailed research is needed to specify the choice of methods in respective countries.

Table 3.2.2 | Chemical methods used in the Europe and Eurasia region to measure soil salinity (according to available data from the INSAS survey)

Method	Country											
	Germany	Greece	Hungary	Israel	Italy	Kazakhstan	Netherlands (Kingdom of the)	Poland	Russian Federation	Spain	Ukraine	United Kingdom
Electrical conductivity (EC) in saturated paste extract		√	√	√	√		√	√	√	√	√	
EC at 1:1 soil-to-water ratio				√						√		
EC at 1:2 soil-to-water ratio				√	√					√		
EC at 1:2.5 soil-to-water ratio	√				√							√
EC at 1:5 soil-to-water ratio	√				√			√	√	√	√	
EC at 1:10 soil-to-water ratio										√		
Total dissolved solids (by gravimetric analysis)		√			√		√		√			

Method	Country											
	Germany	Greece	Hungary	Israel	Italy	Kazakhstan	Netherlands (Kingdom of the)	Poland	Russian Federation	Spain	Ukraine	United Kingdom
Total soluble salts (calculated as the sum of Na^{+}, Mg^{2+}, Cl^{-}, SO_4^{2-}, HCO_3^{-}, and CO_3^{2-})	√				√	√	√	√	√	√	√	√
Content of soluble Na^{+}		√			√	√			√	√		√
Content of soluble Cl^{-}		√			√	√	√		√			√
Others				√							√	

In terms of soil sodicity determination, the most common methods in the Europe and Eurasia region are the determination of the exchangeable sodium percentage (ESP) and the sodium adsorption ratio (SAR), although SAR is not used in Kazakhstan, the Russian Federation (see SAIC, 1986; Aksenov and Grachev, 2008; Lyubimova, Salpagarova and Khan, 2016) or Ukraine. There are two different ways to calculate ESP found in the literature, so consensus on one method would be preferable. Other methods, such as the cation ratio of soil structural stability (CROSS) – that is believed to be the most comprehensive one parameter soil descriptor (Rengasamy and Marchuk, 2011) – are applied less often (Table 3.2.3).

Table 3.2.3 | Method of determining soil sodicity used in the Europe and Eurasia region (according to available data from the INSAS survey)

Method	Country											
	Germany	Greece	Hungary	Israel	Italy	Kazakhstan	Netherlands (Kingdom of the)	Poland	Russian Federation	Spain	Ukraine	United Kingdom
Exchangeable sodium proportion (ESP)	√	√	√	√	√	√	√	√	√	√	√	√
Sodium adsorption ratio (SAR)	√	√	√	√	√		√	√		√		√
Physical methods (specific swelling, low infiltration rate etc.)			√						√			
Morphological methods (structure of sodic/Solonetzic horizon etc.)			√			√			√		√	
Others							√			√		

For determining exchangeable Na^+, soil sodicity parameters are measured with different methods (Table 3.2.3). The most prevalent approach in the region involves a threestep process:

- salt removal;
- cation exchange; and
- measurement of Na^+.

However, some countries follow the procedure without salt removal (Table 3.2.4).

Table 3.2.4 | Methods of determination of exchangeable Na+ in the Europe and Eurasia region (according to available data from the INSAS survey)

Method	Country											
	Germany	Greece	Hungary	Israel	Italy	Kazakhstan	Netherlands (Kingdom of the)	Poland	Russian Federation	Spain	Ukraine	United Kingdom
Salt removal (step 1), cation exchange (step 2), measurement of Na^+ (step 3)	√	√		√	√			√	√			
Without salt removal, measurement of soluble Na^+ (step 1), cation exchange (step 2), measurement of Na^+ (step 3), recalculation of exchangeable Na^+ based on the subtraction of soluble Na^+ from total Na^+ (step 4)						√			√		√	
Without salt removal, cation exchange (step 1), measurement of Na^+ (step 2).			√							√		
Others												

When it comes to measuring the cation exchange capacity (CEC) in the Europe and Eurasia region, numerous countries did not disclose data on this process. For the countries that reported the measurement, the method of ammonium acetate extraction (buffered at pH 7) is the most widely used method for measuring the CEC (Table 3.2.5).

Table 3.2.5 | Method of measurement of the CEC in the Europe and Eurasia region (according to available data from the INSAS survey)

Method	Country											
	Germany	Greece	Hungary	Israel	Italy	Kazakhstan	Netherlands (Kingdom of the)	Poland	Russian Federation	Spain	Ukraine	United Kingdom
Ammonium acetate extraction (buffered at pH 7)		√		√	√			√				√

Method	Country											
	Germany	Greece	Hungary	Israel	Italy	Kazakhstan	Netherlands (Kingdom of the)	Poland	Russian Federation	Spain	Ukraine	United Kingdom
Ammonium chloride extraction												√
Triethanolaminebuffered barium chloride extraction (buffered at pH 8.2)	√		√		√				√			
Hexamminecobalt(III) chloride extraction												
Others (sodium acetate extraction)				√								
Not applicable (CEC not measured)							√					

In the region, the most common method for measuring the SAR is by measuring the content of Ca^{2+}, Mg^{2+}, and Na^{+} in the water-saturated soil paste extract and then calculating SAR using the following formula:

$$SAR = \frac{Na}{\sqrt{\frac{Ca + Mg}{2}}}$$

However, the Russian Federation uses a different approach. The essence of the method is to extract exchangeable and soluble sodium from the soil sample with a solution of ammonium acetate at a concentration of moles per cubic decimetre (M/dm^3) at a soiltosolution ratio of 1:20, followed by the determination of sodium in the extract using a flame photometer (simultaneously, soluble sodium in the aqueous extract is determined, and the exchangeable sodium is calculated based on the difference). In the Russian Federation, soil sodicity is assessed through physical methods, such as specific swelling (Lyubimova, Salpagarova and Khan, 2016) and the morphological method such as assessing the specific structure of the sodic and Solonetzic horizon (such as the hardness in the dry state, the presence of dark films on the edges of structural discontinuities, the nature of these dark films, and the degree of expression of structural columnar elements) (Shishov, ed., 2004; DSSI, 2008; Kust, 1987).

Soil alkalinity, or soil pH, can be determined using various methods, which differ in the preparation of the soil solution (from which the pH will be determined), and many are employed in the countries of the Europe and Eurasia region, as outlined in Table 3.2.6. The most prevalent technique for pH measurement in the region involves using an extract of saturated paste. However, in some countries such as Greece, Israel, and the United Kingdom, pH measurement is conducted on soil:water extracts with ratios of 1:1, 1:2, 1:2.5, and 1:5. In the Russian Federation, the 1:2.5 ratio and total alkalinity, or content of alkaline anions (with methyl orange and phenolphthalein indicators) are used (ARRIA, 2019; Vorobyova, 1998). There is a relative lack of harmonization in this regard among the countries in the region studied. However, In the Russian Federation, the conversion equations between the results of different methods for soil salinity and sodicity measurements are used (Sonmez *et al.*, 2008; Landon, 1991; Kopikova and Skulkin, 1990).

Table 3.2.6 | Methods of pH measurement in the Europe and Eurasia region (according to available data from the INSAS survey)

Method	Country											
	Germany	Greece	Hungary	Israel	Italy	Kazakhstan	Netherlands (Kingdom of the)	Poland	Russian Federation	Spain	Ukraine	United Kingdom
Soil pH (extract of saturated paste)		√		√			√	√		√		
Soil pH (soil:water 1:1)				√								
Soil pH (soil:water 1:2)	√	√		√								
Soil pH (soil:water 1:2.5)								√	√			√
Soil pH (soil:water 1:5)					√			√			√	
Soil pH ($CaCl_2$ 1:2.5)	√		√									
Total alkalinity, or content of alkaline anions (with methyl orange and phenolphthalein indicators)									√		√	
Others												

Saline and sodic soil classification systems used in the Europe and Eurasia region

Based on the questionnaire responses, it was found that each country uses a different classification system for soil salinity and sodicity. For example, the Kingdom of the Netherlands uses the FAO system (FAO, 1988), Ukraine uses their national standards (National Standards of Ukraine, 1999, 2015, 2016) and Spain refers to the US Salinity Laboratory (USSL Staff, 1954). There is also no harmonization regarding the thresholds, as while 4 dS/m is used most often as a threshold for classification, some countries such as Italy indicate thresholds of 2 dS/m, or 1 g/kg and 1.5 g/kg as indicated by the Russian Federation.

To give a more detailed example, the classification thresholds used by the Russian Federation are as follows:

- the depth of salinization of the saline horizon (position of the upper boundary) (Solonchak [0–30 cm], Solonchaklike [30–80 cm], deep Solonchaklike [80–150 cm], and deeply saline [>150 cm]);
- the degree of salinization, depending on the salinity chemistry (weak, moderate, strong, or very strong);
- the type of salinity chemistry (chloride and sulphatechloride, chloridesulphate, sulphate, soda and sodachloride, and sulphatesoda and sodasulphate).
- the content of exchangeable sodium in the Solonetz horizon (weakly sodic [<10 percent], slightly sodic [10–25 percent], moderately sodic [25–40 percent], and highly sodic [>40 percent]).

Regarding soil sodicity, many countries in the region (as per the questionnaire responses) use a threshold of >6 percent exchangeable sodium proportion (ESP) although there is a large variation with the use of >15 percent ESP and other approaches as well.

4. Status of soil salinity and sodicity mapping in the Europe and Eurasia region

Regarding soil salinity and sodicity mapping in the region, the responses from the INSAS questionnaire indicate that many countries do not conduct any mapping. Some that perform mapping use soil sampling, GIS tools or model estimations to generate relative maps. However, while the Russian Federation has an official protocol (Ministry of Agriculture, 1973), there are no standardized protocols across nations for organizing this process.

The depth of the mapped saline and sodic soils varies among countries. For example, for Ukraine, the measurements are taken at a depth of 200–300 cm (or to groundwater), for Spain the measurements are conducted at depths of 0–25 cm and 100 cm, in the Russian Federation they are taken at a depth of 200 cm and in Greece, at a depth of 0–30 cm. However, information on mapping methods and depths used in other countries in the region is lacking.

The scale of mapping used in different countries also varies considerably. For example, to map salt-affected soils and croplands, Kazakhstan uses a 1:10 000 scale, while Hungary uses a 1:25 000 scale. In the Russian Federation, a 1:50 000 scale is used for paper versions and a 1:2 500 000 scale for digital maps (Table 3.2.7).

In summary, soil salinity and sodicity mapping in the region varies greatly among the countries surveyed in the region. Additionally, due to the depth and scale of mapping differing significantly from one country to another, this also results in the produced maps having varied levels of detail.

Table 3.2.7 | Map scales used in the salt-affected soils mapping in the Europe and Eurasia region (according to available data from the INSAS survey)

Map scale	Country											
	Germany	Greece	Hungary	Israel	Italy	Kazakhstan	Netherlands (Kingdom of the)	Poland	Russian Federation	Spain	Ukraine	United Kingdom
1:5 000												
1:10 000						√ (SAS + crop-land)						
1:20 000				√ (SAS)								
1:25 000			√ (SAS + crop-land)								√ (crop-land)	
1:50 000									√ (pa-per)			
1:100 000												
1:250 000												
1:500 000												
1:1 000 000												
1:2 500 000									√ (digi-tal)			
No data	√	√			√		√	√		√		√

Note: SAS = salt-affected soils.

Soil salinity and sodicity monitoring systems are widely implemented in most countries in the region, according to the survey, with the other countries confirming the necessity of having such a system (except for Germany). While Israel and Italy have updated and modern systems, many other countries' systems are outdated.

As an example, water and soil amelioration monitoring and research in Ukraine is organized by the State Water Resources Agency of Ukraine. The monitoring of salt-affected and irrigated soils is based on observations and assessments of their condition parameters, which include hydrogeological, engineering-geological, soil reclamation, ecological-toxicological and agronomic criteria. All these parameters are determined simultaneously on specific key sites, which are chosen and recorded in a manner that allows for the comparison of ecological and agricultural characteristics of formerly and currently irrigated and non-irrigated lands. Hydrological criteria are the depth, hydrochemical composition and mineralization of groundwater. Engineering-geological criteria are based on the porosity coefficient and the degree of manifestation of exogenous geological processes.

Soil reclamation criteria are the degree of salinization and sodification, nutrient regimes, and irrigation water quality according to agronomic criteria. Ecological-toxicological criteria are concentrations of heavy metals and pesticides in soils, and water pollution with a great number of candidate pollutants.

In Hungary, on the other hand, following an initial and detailed baseline survey in 1992 and 1993, drilling has been carried out annually (NEBIH, 2024). The soil samples are averaged by drilling nine times in a 50 m diameter circle around the Soil Information and Monitoring System (SIMS) point at depths of 0–30 cm, 30–60 cm and 60–90 cm, which are then extensively tested by the Soil Protection Laboratories of the Directorate for Plant, Soil and Agro-environmental Protection of the National Food Chain Safety Office (the leading organization in Hungary).

In the Russian Federation, in areas most prone to salinity (irrigated zone), observations are conducted either annually or once every five years by the hydrogeological and reclamation regional monitoring team of the Ministry of Agriculture of the Russian Federation. They perform routine hydrogeological observations of the groundwater level, monitor the salt regime of soils, perform a reconnaissance survey of irrigated land, and monitor the quality of irrigation water. The annual compilation of a land reclamation cadastre provides information on the existence of land subject to reclamation, and the depth and mineralization of groundwater used for irrigation. The laboratory then conducts a quantitative chemical analysis of irrigation water, assessing salinity and contamination by humaninduced pollutants in water and soil. Based on this data, land reclamation specialists and agricultural entities formulate environmentallysound production policies.

5. Status of sustainable management of salt-affected soils

Across the surveyed countries in the region, the status of sustainable soil management of salt-affected soils exhibits a dynamic spectrum, varying from country to country based on their adopted practices. The practices employed in the analysed countries that responded to the questionnaire are delineated as follows:

Evaporation reduction techniques: These encompass strategies such as mulching and the utilization of interlayers composed of loose materials. Notably, these practices are prevalent in most surveyed nations, with the exceptions being Germany, Greece, and Ukraine.

Topsoil salt removal: Seven out of eleven countries reported that measures to remove salts from the topsoil (such as leaching, drainage and surface scraping) are used to combat soil salinity. These countries are Israel, Italy, the Kingdom of the Netherlands, the Russian Federation, Spain, Ukraine, and the United Kingdom. This roughly corresponds with the respondent countries where salinity is most prominently a problem.

Enhancing soil structure and infiltration: Greece, Israel (both respondents), the Kingdom of the Netherlands, the Russian Federation, Spain (both respondents), Ukraine, and the United Kingdom apply soil remediation methods (introducing organic matter such as compost and crop residues into the soil) to alleviate salt stress. This list of countries largely overlaps with the countries who remove topsoil salt through leaching, draining and surface scraping, as both those interventions are effective ways of alleviating salinity stress.

Biochar application: Only the Kingdom of the Netherlands and the Russian Federation responded that biochar is sometimes used to alleviate salt stress. In the Kingdom of the Netherlands, this has only been done on a very small and experimental scale.

Deep ploughing: Israel (both respondents), Italy, the Kingdom of the Netherlands, the Russian Federation, Spain (both respondents) and Ukraine all use deep ploughing as a measure to alleviate salt stress in salt-affected soils.

Chemical amelioration: Israel (both respondents), Italy, the Kingdom of the Netherlands, the Russian Federation, Spain (both respondents), the United Kingdom and Ukraine use the application of calciumcontaining compounds such as gypsum to alleviate the negative effects of salt-affected soils on crops.

Salt relocation and accumulation reduction: Greece, the Kingdom of the Netherlands, the Russian Federation, Spain (one respondent) and Ukraine practice land levelling and reshaping to avoid salt accumulation in certain areas.

Crop system management: Crop system management such as improved crop rotation, agroforestry and crop system diversification is practised by Germany, Hungary, Israel (both respondents), Italy, the Kingdom of the Netherlands, the Russian Federation, Spain (both respondents), Ukraine, and the United Kingdom. This is one of the most widespread methods to combat salinization, with the practices only not being applied in Greece and Kazakhstan.

Crop adaptation strategies: Crop adaptation strategies can be defined here as changing to growing halophytes or other non-conventional crops, breeding for salinity tolerance and genetic engineering, and the application of halopriming seeds. These methods are applied in Germany, Hungary, the Kingdom of the Netherlands, Spain (both respondents) and Ukraine. This list of countries is somewhat atypical compared to the other related adaptation strategies for salt-affected soils.

Agroforestry: Agroforestry as a means to adapt to salinity is practised in Greece, the Kingdom of the Netherlands, the Russian Federation, Spain (both respondents) and Ukraine.

Biotechnologies (including bioinoculants, and biofortification) are only implemented in the Kingdom of the Netherlands.

The variety of different methods to ameliorate the negative effects of salt-affected soils on crops underlines the need for better communication between countries and farming communities on effective methods to adapt to and mitigate soil salinity, and a better dissemination of knowledge. There are some countries where published data exist on in which areas specific measures to alleviate salt-affected soils have been applied (for example Israel, Italy, the Russian Federation and Ukraine) but many more countries could benefit from knowing which measures they can take and in which regions, to effectively deal with salt-affected soils.

Limited data is available regarding the implementation of practices for managing salt-affected soils across different regions. Only Israel and Italy reported the existence of such data.

Indicators of sustainable soil management (SSM)

Sustainable soil management (SSM) indicators employed for assessment exhibit variability across the region, with distinct practices in different countries. Greece and Italy adhere to the indicators outlined in the *Protocol for the assessment of Sustainable Soil Management* (FAO and ITPS, 2020). These encompass parameters like soil productivity (measured through biomass in dry matter), organic carbon content, bulk density, and soil respiration rate.

In contrast, Hungary adopts a broader array of indicators, extending beyond the FAO and ITPS SSM protocol recommendations. Apart from measuring soil organic carbon, bulk density, pH, and soil nutrients the Hungarian Soil Information and Monitoring System (NEBIH, 2024) also measures properties such as the CEC, base cations, the sum of soluble salts (percentage), and phenolphthalein alkalinity.

In the majority of countries who responded to the questionnaire, the indicators are not measured.

A vast majority of the countries do not have a comprehensive database cataloguing the implemented practices of sustainable soil management. In the Kingdom of the Netherlands and Israel (according to one questionnaire but not to the other), there is a database but it is incomplete and should be updated. Several countries indicated that it would be in demand.

Across the surveyed European and Eurasian countries, there are few policies governing the management of salt-affected soils. Some countries, such as Greece, the Russian Federation, Spain and the United Kingdom indicate a need for such regulations. Others such as Germany do not see them as necessary. In Hungary, this topic has been partly affected by the ”Soil protection action plan”, which is under development, led by the Hungarian Government’s National Food Chain Safety Office. Israel indicated that there is a policy but it needs improvements to become more efficient. The need or presence of the regulations may be related to the percentage of country’s area affected by salinity or sodicity.

To give an example, within the current policy documents of the Kingdom of the Netherlands, it appears that salinization is only marginally addressed in Dutch policy. It is mainly seen as a local spatial planning issue since the country currently still receives an annual surplus of precipitation (i.e. precipitation is higher than water loss through evapotranspiration). However, under climate change conditions this may change.

The Kingdom of the Netherlands does not have a specific governmental body dedicated solely to the monitoring and management of salt-affected soils. However, there are several governmental bodies and agencies involved in environmental management and agriculture that address soilrelated issues related to soil monitoring and management, including salt-affected soils. A significant portion of the salinity management governance is primarily focused on ensuring the availability of freshwater and combatting salinization in water bodies, rather than specifically addressing issues related to salt-affected soils.

The provinces also have a role to play in salinity management, and are involved through water management and infrastructure, particularly in areas where saline intrusion occurs. It is important to note that the specific roles and responsibilities of provinces in salinity management can vary, as each province has its own governance structure and approach. Therefore, the level of involvement may differ between provinces based on their geographical location, susceptibility to salinity intrusion, and local circumstances. Regional water authorities (Waterschappen) are responsible for managing water quantity and quality within their respective regions. These water authorities oversee water management, including salinity control, by implementing measures such as water supply management, freshwater retention, and maintaining water quality standards.

The question remains how and with what priority salinization will ultimately be defined as a policy problem: whether it will come down to the resistance of farmers, the relatively fragmented legal framework, the scientific uncertainties, or the uncertain nature of the policymaking processes in themselves.

The absence of policies addressing the sustainable management of salt-affected soils is a prevalent issue in most countries, often resulting from the lack of dedicated governmental bodies focused on this critical matter. However, there are noteworthy exceptions where proactive efforts are being undertaken.

The development of legislation and legal frameworks for the regulation and protection of saline environments as crucial biodiversity shelters remain underdeveloped in most countries of the region. Among those surveyed, only Germany, Hungary, Italy, the Kingdom of the Netherlands, Spain and the United Kingdom have established laws and legislative regulations. In Hungary, saline lakes are protected by law as natural areas of national importance. Law No. LIII of 1996 on Nature Protection (Hungary, 1996), while some parts of the area affected by salinity are national parks. In the Kingdom of the Netherlands, Spain and the United Kingdom, salt marshes are protected under the Ramsar Convention (Ramsar, 2023). In Poland, some coastal and inland saline areas are protected by Polish law as nature reserves due to the occurrence of unique fauna and flora. Other countries, including Greece, Israel and Kazakhstan indicated the presence of important ecosystems that need to be protected.

Extension services play a pivotal role in bolstering farmers’ efforts to effectively manage salt-affected soils, ensuring sustained productivity, and mitigating the adverse impacts on plant growth and agricultural output in the region. According to the responses to the questionnaire, the extension services are mostly not present, even though the majority of the respondents sees the need for them. Israel has a good geographic coverage and supports all aspects of salt-affected soils management (training, soil analysis, and recommendations). In the Kingdom of the Netherlands, services have a good geographic coverage but only support a few aspects of salt-affected soils management.

The specific services sought after by farmers and offered by extension services exhibit a dynamic and contextual variation within each country, as evidenced in the comprehensive breakdown presented in Table 3.2.8.

Table 3.2.8 | Services most demanded by farmers and extension services to help manage salt-affected soils in a sustainable manner in the Europe and Eurasia region (according to available data from the INSAS survey)

Extension services	Country											
	Germany	Greece	Hungary	Israel	Italy	Kazakhstan	Netherlands (Kingdom of the)	Poland	Russian Federation	Spain	Ukraine	United Kingdom
Training about the management of salt-affected soils			√	√			√		√			
Soil analyses				√			√		√			
Interpretation of soil analyses			√	√			√		√			
Irrigation water or groundwater analyses			√	√			√					
Soil salinity/ sodicity mapping				√			√		√			√
Recommendations on salt-affected soils management			√	√			√		√			
Others	No need	No, but demanded			No, but demanded	No, but demanded		No need		No, but demanded	No, but demanded	

6. Status of crop and plant production in salt-affected environments

Losses of crop yields resulting from soil salinization and sodification

Croplands stand as the most susceptible target of secondary soil salinity and sodicity ((i.e. caused by human activities). Based on the responses garnered from the questionnaire, two countries are considerably affected by salinity and sodicity. In Greece, as much as 4 124 807 ha is affected by salinity and sodicity. In Hungary, 878 985 ha of the cropland is affected by salinity and 1 847 ha by sodicity.

None of the countries reported any estimates for the losses of yields due to soil salinity or sodicity. Table 3.2.9 show the crops most cultivated in saline and sodic soils in the region.

Table 3.2.9 | Most cultivated crops grown in saline and sodic soils in the Europe and Eurasia region (according to available data from the INSAS survey)

Crop	Country											
	Germany	Greece	Hungary	Israel	Italy	Kazakhstan	Netherlands (Kingdom of the)	Poland	Russian Federation	Spain	Ukraine	United Kingdom
Rice						√			√	√		
Cotton		√		√						√		
Barley		√	√	√						√	√	
Alfalfa		√		√					√		√	
Sorghum									√	√		
Tall wheat-grass				√						√		
Halophytes (e.g. quinoa (*Chenopodium quinoa*), *Atriplex* sp., *Salicornia* sp., saltgrass (*Distichlis spicata*), etc.)							√					
Non-conventional crops (amaranth or others)									√			
Date				√								
Wheat			√				√				√	
Triticale			√									
Pepper				√								
Soybean											√	
Vegetables											√	
Beetroot							√					
Lettuce							√					
Carrot							√					
Combinable crops												√
Brassicas												√
Potato							√					√
Grazing pasture												√

Indicators used by crop scientists on salt-affected soils

The core soil parameters assessed by crop scientists for cultivating plants on salt-affected soils are the same as those employed by soil scientists in the vast majority of the countries, as evidenced by the responses to the questionnaire. Sometimes, as with Israel, additional indicators are used, such as SAR, EC, soil pH, sodium ions (Na^+), calcium ions (Ca^{2+}), and magnesium ions (Mg^{2+}).

Models of crop response to soil salinity and sodicity

The utilization of crop response models under varying stress conditions – particularly in the context of soil salinity and sodicity – is a pivotal tool in fostering sustainable crop production management. Within the region, insights gathered from responses to the questionnaire reveal that the deployment of such models is a practice only observed in Israel, the Kingdom of the Netherlands and Spain.

Using scenarios of crop production under different abiotic stresses in the region have a very limited distribution. While Germany, Hungary, Israel, and the Kingdom of the Netherlands indicated the presence of the scenarios, most of the surveyed countries did not give any response. Italy, the Russian Federation, Spain and the United Kingdom reported the absence of such scenarios.

Across the region, all of the surveyed countries reported the absence of assessments at the national or local level on the cost of inaction in case of growing salinity or sodicity.

7. Status of sustainable water management in saline and sodic environments

Areas of irrigated farmland and its exposure to salinization and sodification

Another important issue is the lack of official data about the extent of areas affected by both primary and secondary salinity and sodicity in irrigated farmland. The majority of the respondents indicated that there were no official data on the areas as well as no assessments, with the exception of Israel who had contrasting answers between the two questionnaires.

Table 3.2.10 shows the most common irrigation methods used in the region. Sprinkler and drip irrigation are prevalent in the region. In Greece, Italy and Spain, surface irrigation basin and flood irrigation subtype and furrow irrigation subtype are also used.

Table 3.2.10 | Most common irrigation methods used in the Europe and Eurasia region (according to available data from the INSAS survey)

Irrigation methods	Country											
	Germany	Greece	Hungary	Israel	Italy	Kazakhstan	Netherlands (Kingdom of the)	Poland	Russian Federation	Spain	Ukraine	United Kingdom
Surface irrigation (basin/ flood irrigation subtype)		√			√					√		
Surface irrigation (border irrigation subtype)					√							
Surface irrigation (furrow irrigation subtype)		√				√						
Surface irrigation (uncontrolled flooding)												
Sprinkler irrigation	√	√	√	√	√	√	√		√	√		√
Drip irrigation	√	√		√	√		√		√	√		√
Manual irrigation		√								√		
Others												

Irrigation water quality monitoring

When managed properly, brackish water can be used for irrigation. According to our survey, Germany, Greece, Israel, the Kingdom of the Netherlands, the Russian Federation, Spain (one out of two respondents), Ukraine and the United Kingdom use brackish water but there is no monitoring on the extent of the use of brackish water. Israel, Italy and Ukraine use brackish water and also monitor the extent of their use, while Hungary does not use brackish water and has no intention to do so. There was no data available from Kazakhstan.

The regulation on the use of brackish water also differs among the countries. In Israel, Italy and Germany there are strict regulations which are also followed, in contrast to the Russian Federation and Ukraine, where regulations exist but are not strictly followed. In the United Kingdom no such regulations are present but would be considered useful, although not urgent. This is in contrast to Greece and the Kingdom of the Netherlands who do not have regulations but consider the implementation of regulations to be very urgent. As Hungary does not use brackish water, there are also no regulations and they are not considered useful. No data was available from Kazakhstan. In the Russian Federation, the regulation specifies that the critical content of watersoluble salts in the soil should not exceed 0.1 percent for sodic salinity and 0.25 percent for other types of salinity (Ministry of Health of the Russian Federation, 1997). Regarding the granulometric composition of irrigated soils, the maximum concentration of total salts in wastewater should not exceed the following values:

- for heavy and medium loamy soils: 1 g/L (15 mmol eq./L);
- for light loamy soils: 2 g/L (30 mmol eq./L); and
- for sandy and loamy soils: 3 g/L (45 mmol eq./L).

The types of crops cultivated using brackish irrigation water in the countries covered in this report are summarized in Table 3.2.11.

Table 3.2.11 | Crops that are irrigated with brackish water in the Europe and Eurasia region (according to available data from the INSAS survey)

Crop	Country											
	Germany	Greece	Hungary	Israel	Italy	Kazakhstan	Netherlands (Kingdom of the)	Poland	Russian Federation	Spain	Ukraine	United Kingdom
Rice										√		
Cotton		√		√						√		
Barley		√			√						√	
Alfalfa		√		√	√					√	√	
Sorghum												
Tall wheat-grass				√								
Halophytes (e.g. quinoa (*Chenopodium quinoa*), *Atriplex* sp., *Salicornia* sp., saltgrass (*Distichlis spicata*), etc.)							√					

Crop	Country											
	Germany	Greece	Hungary	Israel	Italy	Kazakhstan	Netherlands (Kingdom of the)	Poland	Russian Federation	Spain	Ukraine	United Kingdom
Non-conventional crops (amaranth or others)	√											
Date												
Wheat		√			√						√	√
Triticale												
Pepper												
Soybean												
Vegetables												
Beetroot												
Lettuce												
Carrot												
Combinable crops												
Brassicas												
Potato												
Grazing pasture												
Maize		√		√	√						√	
Others				√								

Note: Crops mentioned under the "others" category in Israel are date, pepper, grape and melon.

For crop cultivation under saline conditions the answers were varied. No specific measures are taken in the United Kingdom and the Russian Federation. Spain uses improved drainage and leaching during certain times of the year. Improved drainage and irrigation is used in Germany, Israel, Italy and the Kingdom of the Netherlands, with Germany and Israel also employing mixing with fresh water.

To determine the quality of irrigation water, the United Kingdom measure the EC and the total dissolved solids., In addition to EC and total dissolved solids, Israel also measures the SAR, the pH and the presence of toxic ions, as does Hungary, apart from the measurement of toxic ions. One respondent from Israel also reported additionally measuring the chloride concentration. Spain reported measuring the EC, SAR, total dissolved solids, total soluble salts and the presence of toxic ions (specifically boron) and the pH, while Germany measures EC, the total dissolved solids, and pH. Ukraine measures total dissolved solids, pH and toxic ions. The Russian Federation measures total dissolved solids, and Greece measures the EC, SAR, total dissolved solids, total soluble salts and pH. The Kingdom of the Netherlands measures EC, the presence of toxic ions and harmful bacteria and chloride concentration, which is the national standard for expressing irrigation water quality. Italy measures all the parameters mentioned above, plus the presence of harmful bacteria.

When asked if the parameters were sufficient or if some were perhaps overlooked, Germany, Hungary, Israel, Italy, the Kingdom of the Netherlands, Spain, Ukraine, and the United Kingdom reported that nothing had been overlooked. Only Greece mentioned that it would be better if they also assessed the presence of toxic ions. These responses are of interest, given that almost all countries use a different combination of water quality indicators.

The United Kingdom has a water monitoring system in place at the local level. Israel, Italy, the Kingdom of the Netherlands and Ukraine have a water monitoring system in place at a national level. Germany, Greece, Hungary, Spain, and the Russian Federation do not have such a system in place but believe that they would benefit from one.

Only Israel (one of the two respondents), the Kingdom of the Netherlands and Ukraine describe their monitoring bodies in detail.

In Italy and Ukraine, the monitoring of water quality and the monitoring of soil salinity or sodicity are coordinated. In the other countries that responded, no such coordination exists, except for Israel, where one respondent mentioned that some efforts to coordinate the two are being made.

In Israel (one of the two respondents), Spain (one of the two respondents) and Ukraine, irrigation water is considered as a main factor leading to soil salinization. The Kingdom of the Netherlands mentioned it as a factor but a minor one (seawater seepage is a much larger contributor to soil salinization in the Kingdom of the Netherlands given the fact that about onethird of the country lies below sea level). All the other countries reported that there is no data on the contribution to soil salinization by irrigating with brackish water.

In the United Kingdom, as a measure to improve water quality, water is mixed. In Israel and the Russian Federation, water is desalinated along with secondary or tertiary treatments of treated wastewater, as well as desalination being applied in Israel (one respondent). In the Ukraine, water mixing and water desalination are applied. The Kingdom of the Netherlands reported constant monitoring as a measure to improve water quality. In Germany, Hungary, Italy and Spain (one respondent), no such measures are taken.

Groundwater monitoring

The survey asked about the presence of a groundwater monitoring system, integration with soil salinity and sodicity monitoring and the constructed irrigation systems protecting soils from salinization and sodification.

Most of the countries have a groundwater monitoring system. The European Union's Water Framework Directive (WFD 2000/60/EC) (European Union, 2024a) obliges Member States to set up monitoring networks to monitor the chemical and quantitative status of groundwater. In Germany, the federal states currently operate a total of 7 715 monitoring sites to monitor the quantitative status. For monitoring the chemical status, 7 869 monitoring sites are used. With all these monitoring sites, a total of 1 291 groundwater bodies with an average area of about 284 km^2 are currently monitored in Germany. The assessment results of these monitoring sites are reported every six years by the federal states to the European Union Commission via the federal and state information and communication platform "WasserBLIcK".

Furthermore, the German federal states run the European Environment Agency (EEA) monitoring network with currently 1 264 monitoring sites. The data from these sites are intended to provide a reliable and representative overview of groundwater quality in Germany and form the basis for Germany's annual status reports to the EEA and for reporting in accordance with the European Union's Nitrate Directive (91/676/EEC) (European Union, 2024b).

Greece stated that there is no monitoring system in place but that it should be established.

Groundwater monitoring is usually not integrated with soil salinity and sodicity monitoring with the exception of Italy, the Kingdom of the Netherlands, Spain and Ukraine.

In Hungary, groundwater is a leading factor of soil salinization and sodification (around 10 to 13 percent of the country's area (Tóth *et al.*, 2001) as well as in the Kingdom of the Netherlands. In Israel, Spain and the Russian Federation, it is a significant, but not leading factor in soil salinization and sodification. In Ukraine, it is an insignificant factor of soil salinization and sodification. Other respondents either indicated that there was no data or national assessments on this, or did not provide a reply.

Agrohydrological models to evaluate water management in salt-affected soils

Further questions focused on agrohydrological models that are used to predict water status and stress on salt-affected soils and soil salinization or sodification.

In Greece, in limited cases, FAO's AquaCrop model is used at farm scale to predict water status and stress on salt-affected soils. In Israel, HYDRUS or HYDRUS + MODFLOW models are used frequently in research (such as Kurtzman and Scanlon, 2011). In the Kingdom of the Netherlands, Soil Water Atmosphere Plant (SWAP) and WOrld FOod STudies (WOFOST) models are used. The SWAP model is an agrohydrological model used to simulate water flow, nutrient transport, and crop growth. It analyses the impact of water management and agricultural practices on yields, water use, and environmental factors. It helps optimize irrigation and promote sustainable land and water management. In Spain, AquaCrop and HYDRUS 1D are used to predict water status and stress on salt-affected soils and HYDRUS 1D and MODFLOW to predict soil salinization or sodification at field, farm and catchment area scales.

Leaching and drainage on salt-affected soils

The drainage system most commonly used for salt-affected soils is surface drainage with shallow ditches, followed by subsurface drainage (buried pipe drains) (see Table 3.2.12).

Table 3.2 12 | Types of drainage system used in the Europe and Eurasia region (according to available data from the INSAS survey)

Drainage system	Country											
	Germany	Greece	Hungary	Israel	Italy	Kazakhstan	Netherlands (Kingdom of the)	Poland	Russian Federation	Spain	Ukraine	United Kingdom
Surface drainage (shallow ditches)	√	√	√		√		√		√	√ paddy soils		
Subsurface drainage (deep open drains)					√							
Subsurface drainage (buried pipe drains)				√			√		√	√	√	√
Controlled drainage							√					
Others												

When designing drainage systems, water parameters are considered for Germany, the soil hydraulic or physical properties (infiltration, compaction and soil layers) are considered for Greece and Spain, and soil parameters, water parameters and soil hydraulic or physical properties are considered for Israel and Italy. Ukraine and the United Kingdom use soil parameters and water parameters. The Kingdom of the Netherlands additionally examines topography and elevation, land use, environmental impact, climate change and sea level rise, and legal and institutional frameworks. In Hungary, temporary surface drains are created to get rid of excess water that occasionally appears on heavy soils.

The most common leaching practice is through the use of sprinklers, followed by drip irrigation and flooding (see Table 3.1.13).

Table 3.2.13 | Types of leaching practice in the Europe and Eurasia region (according to available data from the INSAS survey)

Leaching system	Country											
	Germany	Greece	Hungary	Israel	Italy	Kazakhstan	Netherlands (Kingdom of the)	Poland	Russian Federation	Spain	Ukraine	United Kingdom
Flooding		√							√		√	
Sprinklers				√	√		√			√	√	
Drip irrigation				√			√			√		
Other												
No leaching is performed	√		√									

Conclusions and recommendations

1. It has not been possible to discover the full extent of salt-affected soils in Europe and Eurasia in this report, as many experts who participated in the INSAS questionnaire were not able to provide official data.

2. Different methods are used for the measurement of soil salinity and sodicity in the region. The most frequent method involves determining EC in a saturated paste extract, then analysing the total soluble ions. Data acquisition harmonization and the development of conversion equations from approaches that differ from the analysis results of the standard soil saturated paste extract are crucial for this region.

3. Electromagnetic methods were mentioned by the respondents in Italy, Spain and the United Kingdom where it has been used for many years. It is highly recommended that this mapping technique is disseminated among the countries of the region.

4. The mapping of salt-affected soils still needs to be improved and updated. Despite the efforts to digitize heritage soil salinity data and increase mapping with new remote and proximal sensing, this goal is still far to be fully achieved. Periodical monitoring of soil salinity changes is recommended.

5. The monitoring of salt-affected soils is not performed in most of the surveyed countries within the region, despite it possibly being beneficial for environmental design policies in some of the countries. It is likely that those countries that already have extensive areas of salt-affected soils will see these areas increase under increasing drought climate change scenarios.

6. Sustainable soil management indicators employed for assessment exhibit variability across the region, with distinct practices in different countries. However, in the majority of the countries who responded, these indicators were not standardized.

7. None of the countries reported on the extend of yield losses caused by soil salinity or sodicity. Similarly, no information was made available on the effectiveness of improved farming methods

8. However, national and supranational policies need this type of information for agricultural and environmental decision-making and policy design.

9. Several agrohydrological models (using data on climate, soil, plant, soil solution, and groundwater) are used across the region to study and predict soil salinization processes and underground waterflows. It is recommended that more extensive use is made of such models, although the complexity of the models, and their different aims, makes it difficult to standardize the approach and make a particular recommendation using any one model. Despite this, the modelled scenarios permit scientifaic insights into the development of salt-affected soils management and allow for their evolution to be predicted.

10. No country reported any specific national policies in place for managing salt-affected soils, although some countries had such policies for water management and maintaining adequate freshwater supplies for all users, including farmers, as well as long-existing policies for the protection of natural salt-affected environments.

11. Most of the countries reported on the use of brackish water and wastewater for irrigation, although without any systematic monitoring being put in place. There is a general consensus that establishing such monitoring systems would be necessary so that the long-term effects of such practices could be assessed.

12. Any missing or unavailable data or unvalidated data quality in this report should be addressed by soil specialists and governmental bodies in a future edition of the questionnaire.

3.3 | Latin America and the Caribbean

Introduction

The Latin American and the Caribbean (LAC) region has large areas covered with many different kinds of salt-affected soils. They are scattered across the region, although some areas have concentrated type-specific salt-affected soils. Salt-affected soils have either primary or secondary origins, but in most cases they are interrelated.

Salt-affected soils are found across many different areas: arid zones, humid areas, marshes and saline wetlands, irrigated areas, tropical regions, semiarid zones and coastal spaces. The salt-affected soils of the LAC region cover all taxonomical categories in the IUSS Working Group WRB (2022) and the United States of America soil taxonomy (Soil Survey Staff, 2022).

Primary or natural salinization – where saline soils are predominant – can be found in arid zones of the region. Those soils are found in a variety of taxonomical units, with the most noticeable areas being localized in western Argentina, the highlands of the Plurinational State of Bolivia, northern Chile, the Caribbean coast and the Andean intermontane valleys of Colombia, Northern Mexico, and coastal Peru.

Another primary salinization process – where mainly sodic soils are found – occurs in humid and subhumid temperate regions. These are large flat plains with shallow saline or sodic groundwater where soils with a natric horizon predominate, such as in some areas of the Pampas region of Argentina. The natural vegetation is a monotonous meadow, dedicated to cattle husbandry. In other countries there are similar but smaller areas affected. These soils are affected by water, including periodic waterlogging and flooding, combined with excesses of exchangeable sodium.

Coastal salt marshes can be found in countries like Colombia and the Bolivarian Republic of Venezuela, while large inland saltmarsh and saline wetlands can be found elsewhere, such as the Pantanal in southern Brazil, one of the largest wetlands of the world. Some coastal and swampy areas with saline acidic soils are also linked with salt marshes.

The different ecosystems are usually extremely vulnerable to degradation processes. The main cause of degradation of natural vegetation is overgrazing by sheep, goats, cattle and even South American camelids. Mining and oil extraction are also sources of salts. Attempts to introduce agriculture in these environments have generally failed and they are only grazed with a low animal load and is usually continuous. A common farming practice in these environments is the burning of vegetation to remove accumulated dry biomass, and promote better quality regrowth.

In the tropical high temperature areas of the semiarid and subhumid zones of northeastern Brazil, large areas have been degraded by salinization, and as degradation expands, desertification has become a problem. The native vegetation is a forest ecosystem known as “Caatinga”. Its deforestation for irrigated agriculture subsequently led to salinization problems which was exacerbated by high temperatures, alternating periods of extreme rain and drought, salt-laden soils and shallow groundwater. Areas of Colombia, Cuba, the Dominican Republic, the Bolivarian Republic of Venezuela and other countries have also experienced similar problems in areas with variable rainfall associated with shallow soils, low quality irrigation waters, lack of drainage and shallow groundwater.

Secondary salinization also occurs in irrigated areas in arid and semi-arid zones (mainly in Argentina, Chile, Mexico, and Peru), and also in humid areas (such as in Argentina, Brazil, Colombia, Cuba and the Dominican Republic). In these areas, intensive agriculture is practiced using a variety and different degrees of technologies.

The process of salinization and alkalinisation is mainly due to inefficient water management, poor drainage conditions, and poor irrigation water quality. In some areas, the installation of drainage systems and better irrigation techniques have significantly improved the situation, but in other cases, salinization and alkalinization processes continue to increase.

A recent and artificially-induced salinization process has been observed in semiarid areas of Argentina and Paraguay (known as Great Chaco). Due to the increase of crop (mainly soybean) prices, the agricultural expansion has led to initial deforestation and subsequent cultivation, which has altered the hydrological balance of the water table and has caused soil salinization.

This process of salinization is to some extent similar to the dryland salinity process found in Australia (Department of Environment and Climate Change, 2008). Research has focused on ways to alleviate the hydrological alteration process, such as through forest partitioning, or changes in cropping systems.

Excessive extraction of water for irrigation or urban use in coastal areas can lead to the ingress of seawater into aquifers. These marine ingressions are a hidden risk but have very serious consequences in the long term. They occur in several countries, such as Colombia and Cuba.

The accumulation of salts in soils can affect the native vegetation, degrading biodiversity and disturbing fragile ecosystems, and can have long-term ecological consequences. Salinity also affects crop productivity in agricultural areas, which then affects the economy of those areas.

In response to this complex and variable panorama, research and technology development has focused on two different areas: 1) classical approaches such as irrigation management, soil modification and crop adaptation, and 2) new approaches, like biosaline agriculture and phytoremediation (led by Brazil), and plant genetic modification (led by Argentina).

Status of measurement, mapping and monitoring salt-affected soils

Primary or secondary salinization and alkalinization affects the soils in all environments in LAC. The total area of salt-affected soils in the region is 2 352 857 km^2 according to assessments given in Chapter 1. Although the general focus is on arid and semi-arid regions around the world (Rengasamy, 2006), salt-affected soils occurs in all climate zones in LAC, particularly in humid areas (either temperate or tropical). Argentina and Paraguay have some type of salinity restriction over almost 30 percent of their territory, meaning that they are the two countries with the greatest restrictions in Latin America. In Brazil, there are also areas of salt-affected soils in the northeastern states.

Table 3.3.1 show the collected data of the area covered by saline and alkaline soils in the region. It is evident that there is a lack of current and accurate data on soil salinity in different countries. This absence poses a significant challenge to a global understanding of the true extent of soil salinity issues. However, new activity from the Food and Agriculture Organization of the United Nations (FAO), with the Global Map of Salt-affected Soils (GSASmap) (FAO, 2021) actualizes the area covered by salt-affected soils in the LAC. For instance, according to the GSASmap, the area of salt-affected soils in Argentina – measured using electrical conductivity [EC] as higher than 2 dS/m – is around 35.24 million ha at a depth of 0–30 cm, increasing to around 153.10 million ha at a depth of 30–100 cm.

Moreover, in addition to available data given in Table 3.3.1, there are 298 461 ha of salt-affected soils indicated at coastal Peru (Ramos, 2021).

Table 3.3.1 | Area of salt-affected, saline, sodic, and saline sodic soil in some LAC countries and percentage of total country area

Name of the country	Area of salt-affected soils (ha)	Area of saline soil (%)	Area of sodic soils (%)	Saline sodic soil (%)	References
Argentina	21 900 000 ha	60%	40%	n/a	Taleisnik and Lavado, eds. 2020; Rodriguez *et al.*, 2019
Brazil	n/a	n/a	n/a	n/a	Official data not available
Colombia	12 503 835,9 ha	6.3%	85.6%	8.1%	SIAC (2019)
Mexico	11 080 000 ha	53%	47%	n/a	SADER, 2021
	6 272 588.8 ha	n/a	n/a	n/a	SEMARNAT (2008)
	4 497 680.8 ha	80%	20%	n/a	INEGI (2022)
Paraguay	n/a	n/a	n/a	n/a	Official data not available

Sources: **Rodríguez, D.M., Shultz, G.A. & Tenti Vuegen, L.M**. 2019. Distribucion de suelos afectados por sales en Argentina [Distribution of soils affected by salts in Argentina]. Conference presentation at VI Congreso de la Red Argentina de la Salinidad (RAS) [sixth Congress of the Argentina Salinity Network (RAS)], 22–25 July 2019, School of Agriculture of the University of Buenos Aires (FAUBA), Buenos Aires, Argentina. Buenos Aires, RAS. https://redsalinidad.com.ar/inicio/reuniones-ras/vi-congreso-ras-buenos-aires-2019/publicacion/

SIAC (Environmental Information System of Colombia). 2019. SIAC Map Catalogue. [Accessed on 26 July 2024]. http://www.siac.gov.co/catalogo-de-mapas

SADER (Ministry of Agriculture and Rural Development). 2021. Mapa Agrícola de afectación por salinidad en México [Agricultural map of salt-affected soils in Mexico]. In: *Government of Mexico. Mexico City*. [Cited 26 July 2024]. https://www.gob.mx/agricultura/

When determining soil salinity and sodicity, while there is some harmonization in the methods used, some countries also employ other approaches, sometimes within the same country (as shown in Table 3.3.2). The most common method of measuring soil salinity involves determining the EC in a saturated paste extract, followed by determining the EC in 1:1 and 1:2.5 proportions.

Table 3.3.2 | Chemical methods are used in the LAC region countries to measure soil salinity

Method	Country				
	Argentina	Brazil	Colombia	Mexico	Paraguay
Electrical conductivity at 1:1 soil-to-water ratio		√	√		√
Electrical conductivity at 1:2 soil-to-water ratio					
Electrical conductivity at 1:2.5 soil-to-water ratio	√			√	
Electrical conductivity at 1:5 soil-to-water ratio		√			
Electrical conductivity at 1:10 soil-to-water ratio		√			
Total dissolved solids (by gravimetric analysis)					
Total soluble salts (calculated as the sum of Na^{+}, Mg^{2+}, Cl^{-}, SO_4^{2-}, HCO_3^{-}, CO_3^{2-})		√	√	√	
Content of soluble Na^{+}			√		
Content of soluble Cl^{-}					
Others		√			

In terms of soil sodicity determination, the most dominant methods in the LAC region are the sodium adsorption ratio (SAR), followed by the exchangeable sodium proportion (ESP) (Table 3.3.3).

Table 3.3.3 | Methods of soil sodicity measurement used in the LAC region

Method	Country				
	Argentina	Brazil	Colombia	Mexico	Paraguay
Exchangeable sodium proportion (ESP)	√	√	√	√	√
Physical methods (specific swelling, low infiltration rate etc.)					
Morphological methods (structure of sodic/solo-netzic horizon etc.)		√		√ (used for mapping sodic soils)	
Others					

The most prevalent approach in the countries of the LAC region involves a three-step process:

- salt removal;
- cation exchange; and
- measurement of Na+ mainly without salt removal.

The second most common approach involves a fourstep process with salt removal. Both methods and the countries that use them are documented in Table 3.3.4.

Table 3.3.4 | Methods of determination of exchangeable Na^+ and their distribution over the LAC region

Method	Country				
	Argentina	Brazil	Colombia	Mexico	Paraguay
Without salt removal, measurement of soluble Na+ (step 1), cation exchange (step 2), measurement of Na^+ (step 3), recalculation of exchangeable Na^+ based on the subtraction of soluble Na+ from total Na^+ (step 4)	√	√	√		
Without salt removal, cation exchange (step 1), measurement of Na^+ (step 2).					
Others					

The determination of cation exchange capacity (CEC) in the LAC region uses ammonium acetate extraction (buffered at pH 7) (Table 3.3.5).

Table 3.3.5 | Method of measurement of cation exchange capacity and their distribution among the countries of the LAC region

Method	Country				
	Argentina	Brazil	Colombia	Mexico	Paraguay
Ammonium chloride extraction					
Triethanolamine buffered barium chloride extraction (buffered at pH 8.2)					
Hexamminecobalt (III) chloride extraction					
Others (sodium acetate extraction)					
Not applicable (CEC not measured)					

In the LAC countries, the most common method for measuring the SAR is by calculating the content of Ca^{2+}, Mg^{2+}, and Na^{+} in a water-saturated soil paste extract. Sometimes the content of Ca^{2+}, Mg^{2+}, and Na^{+} is determined using other soil-to-water ratios.

Soil alkalinity, or soil pH, is mainly determined with saturated paste extract. However, measuring pH is also conducted on soil:water extracts with ratios of 1:2.5 (Table 3.3.6).

Table 3.3.6 | Method of pH measurement and their application in the LAC region

Method	Country				
	Argentina	Brazil	Colombia	Mexico	Paraguay
Soil pH (extract of saturated paste)	√	√	√	√	
Soil pH (soil: water 1:1)			√		√
Soil pH (soil: water 1:2)				√	
Soil pH (soil: water 1:2.5)		√		√	√
Soil pH (soil: water 1:5)					
Soil pH ($CaCl_2$ 1:2.5)				√	
Total alkalinity, or content of alkaline anions (with methyl orange and phenolphthalein indicators)					
Others					

Some countries have systematized analytical systems, like Argentina (MAGyP, 2003), Brazil (De Camargo *et al.*, 2009; Teixeira *et al.*, 2017), Colombia (IGAC, 2006) and Mexico (SEMARNAT, 2002).

In several countries soil laboratories are regulated, or at least checked by governmental bodies. For example, Colombia is regulated by the IGAC (Agustin Codazzi Geographical Institute) and the Colombian Soil Sciences Society.

Saline and sodic soil classification systems used in the LAC region

Based on the questionnaire responses, it was found that the United States classification system described by USSL Staff (1954) and the system adopted by FAO (FAO, 1988) are the most commonly used in the LAC region. However, there are differences in the thresholds used for classifying saline and nonsaline soils in different countries.

Regarding soil sodicity, most countries in the region (as per the questionnaire responses) use a threshold of >15 percent ESP, although some also use a threshold of >13 SAR. Another localized threshold for sodic soils in the LAC region is the Brazilian system of soil classification (Santos *et al.*, 2018)

The status of soil salinity and sodicity mapping in the LAC region

Regarding soil salinity and sodicity mapping in the region, the responses from the INSAS questionnaires indicate that most countries rely on conventional and traditional methods, which include soil sampling, description, and analysis. Geographic Information System (GIS) tools are also used to generate relative maps. However, standardized protocols for organizing this process are lacking across all countries. Most countries incorporate soil indicators like EC, pH, ESP, SAR, and salt ions, as well as additional data provided by remote sensing images, digital elevation models (DEMs), climate data (minimum and maximum temperature and precipitation), erosion data, and geology, land cover, hydrogeology, and soil maps, boundary and main town maps, and others.

The depth of the mapped saline and sodic soils varies among countries, either 0–25 cm, 0–30 cm, or 0–150 cm.

Furthermore, the scale of mapping used in different countries – and in different parts of the same countries – varies considerably, from 1:5 000 to more than 1:100 000, although the majority use a scale of 1:35 000 to 1:50 000.

Soil salinity and sodicity mapping in the region rely on both conventional methods and advanced techniques.

Status of sustainable management of salt-affected soils

Across the LAC region, the status of sustainable salt-affected soil management exhibits a dynamic spectrum, varying from country to country based on their adopted practices. The practices employed in the different countries can be shown as follows:

Evaporation reduction techniques: These encompass strategies such as mulching, and the utilization of interlayers composed of loose materials. Notably, these practices are prevalent for pastures in humid areas.

Topsoil salt removal: Methods involving the removal of salts from the topsoil, such as leaching, drainage, and surface scraping, are used in arid irrigated areas.

Enhancing soil structure and infiltration: Compost and residue incorporation are used to ameliorate soil salinity and sodicity in irrigated areas across the region, but in humid areas pastures are the main technique used.

Deep ploughing: Deep ploughing as a mitigation approach against soil salinity and sodicity is not common in the region.

Chemical amelioration: Chemical interventions are common in irrigated areas, such as the addition of gypsum and other calcium-containing amendments.

Salt relocation and accumulation reduction: Salt redistribution and accumulation practices encompassing land shaping and levelling are embraced in some areas but are not generalized.

Crop system management: This approach encompasses enhanced crop rotation, agrobiodiversity, and crop system diversification, and is distributed across multiple countries in the region.

Crop adaptation strategies: Crop adaptation – including the utilization of halophytes and nonconventional crops, breeding and genetic engineering, as well as halopriming – are mainly used in the saline areas of Brazil.

Agroforestry: It is a useful technology but so far has had limited implementation across the region.

Desalinization for irrigation water purification: This method is utilized in northern Brazil for intensively-grown crops, and to a lesser extent in other countries, also for intensively-grown crops.

Sustainable soil management (SSM): The LAC countries used different proportions of sustainable management of salt-affected soils across the LAC region.

Grazing management: Grazing management is a technology that avoids grazing pressure and trampling around water sources and is used in plots in humid areas.

Agrohydrologic management: Prevents, retains or delays the accumulation of water excesses, concentrating them in the less productive areas of the humid landscape.

Fertilization: This technique is the last stage in the productivity optimization phase for the recovery of pastures in halo-hydromorphic soils.

Revegetation of extremely saline areas: The productivity recovery of forage in sites affected by extreme salinity in areas with highly saline water tables (through natural processes, overgrazing or land clearing) can be very effective while difficult to achieve and presents a great technical challenge.

Further information for different countries can be found in Taleisnik and Lavado (2017), EMBRAPA (2013) and Filho and Pessoa (2022).

The services most demanded by farmers are given in Table 3.3.7.

Table 3.3.7 | Services most demanded by farmers and extension services to help manage salt-affected soils in a sustainable manner in the countries of the LAC region

Services	Country				
	Argentina	Brazil	Colombia	Mexico	Paraguay
Training about the management of salt-affected soils		√	√	√	
Soil analyses (please specify which analyses)		√	√	√	
Interpretation of soil analyses		√	√		
Irrigation water or groundwater analyses		√	√		
Soil salinity and sodicity mapping		√	√		
Recommendations on salt-affected soils management		√	√	√	
Others					

Indicators of sustainable soil management (SSM)

Sustainable soil management indicators used for assessment show variability across the region, with distinct practices in different countries. The indicators outlined in the SSM Protocol (FAO and ITPS, 2020) are used, including soil productivity (measured through crop biomass), organic carbon content, bulk density, soil respiration rate and others. Argentina also has a large database (INTA, 2019).

Brazil has developed a thorough and complete database of saline and sodic soils (EMBRAPA, 2013; Santos *et al.*, 2018), while Mexico has soft regulations (DOF, 2006; National Water Commission, 2022).

Across the surveyed LAC countries, noticeable differences are evident in policies governing the management of salt-affected soils. The occurrence of comprehensive policies is also dependent on the individual areas in each country. One country in particular, Brazil, shows targeted regulations (Gheyi da Silva Dias and de Lacerda, 2010; Castro and Santos, 2020; Brazil, 25 May 2012).

Status of crop and plant production in salt-affected environments

Losses of crop yields resulting from soil salinization and sodification

Irrigated croplands are at the most risk of experiencing secondary soil salinity and sodicity hazards within the region, with a multitude of factors converging to escalate these issues. The areas affected by salinization and alkalinisation range between 10 and 50 percent and are variable both between countries and within countries. For instance, in Argentina the percentage of salinization varies from 11 percent in the northwestern irrigated area to 36 percent in Patagonia.

The complex environments and differing climates in the LAC means that a wide range of crops are able to be grown, from tropical (such as banana), subtropical (such as citrus), temperate (such as wheat) and cold (such as apple). Another difference between countries is how their saline and alkaline soils are used, and which crops are grown for food, for industrial uses (cotton), or forage (tall wheatgrass). Although still in the initial stages of development, Brazil is the most advanced country in the cultivation of halophytes.

Table 3.3.8 | The most cultivated crops on saline and sodic soils in the LAC region

Crop	Country				
	Argentina	Brazil	Colombia	Mexico	Paraguay
Rice		√			
Cotton					√
Barley					
Alfalfa	√				
Sorghum		√		√	√
Tall wheatgrass	√				
Halophytes (e.g. Quinoa (*Chenopodium quinoa*), *Atriplex* sp., *Salicornia* sp., saltgrass (*Distichlis spicata*), etc.)		√			
Nonconventional crops (amaranth or others)		√	√	√	
Millet					√
Date palm					
Banana			√		

In the surveyed countries, there are insufficient data when assessing yield losses that can be attributed to soil salinity and sodicity in crops, livestock, forests and so on. The data for yield gains from the enhancements of salt-affected soils are also incomplete. An important issue concerning yield gains and losses is that many of the LAC countries are food exporters in a competitive world full of customs barriers and taxes. In competitive production areas, this situation forces production with low investments, which has led to the use of saline and sodic areas for animal husbandry and only growing salt-tolerant crops in times of good international prices. In other areas of the LAC there is subsistence agriculture, which is far from an innovative technology.

Indicators used by crop scientists on salt-affected soils

The soil parameters used to evaluate salt-affected soils for cultivation are the same to those employed by soil scientists across most countries. The analytical methodologies that were developed by USSL (EC, soil reaction [pH], ESP, and SAR) are the most common (USSL Staff, 1954). Other methodologies are little used.

Models of crop response to soil salinity and sodicity

The utilization of crop response models in the context of soil salinity and sodicity are not common in the LAC. These models are usually applied in crops developed on non-saline soils, such as the Water Evaluation And Planning (WEAP) system on nonsaline soils in Mexico (IMTA, 2019). Within the LAC region, Mexico responded positively about the use of crop response models in reference to soil salinity and sodicity, using georeferenced information on saline soils in agricultural censuses, to define particular strategies for an individual site, as managed by the National Institute of Statistics and Geography (INEGI) (INEGI, 2022). Colombia uses the SALSODIMAR model (Pla Sentis, 2014).

Status of sustainable water management in saline and sodic environments

Areas of irrigated farmland and its exposure to salinization and sodification

In the LAC region, the extent of secondary salinization in irrigated land varies across countries. The percentage of salt-affected soils in areas with total irrigation in Latin American countries (Taleisnik and Lavado, 2020), is as follows:

Argentina: 23.5 percent affected by various degrees of salinity or sodicity in average, varying from 11 percent in the north to 36 percent in the irrigated areas of the south.

Brazil: There is evidence of salinization processes that affect at least 25 to 30 percent of the irrigated area.

Cuba: It is estimated that around 50 percent of the irrigated area is affected by various levels of salinity and sodicity.

The Dominican Republic: it has been estimated that around 20 to 25 percent of the irrigated area – mainly in the eastern part of the country – is affected by some degree of salinity and sodicity.

Mexico: Different approaches indicate that between 10 and 20 percent of the irrigated area is affected by various degrees of salinity or sodicity.

Peru: Soil salinity is a problem that affects approximately 40 percent of the total agricultural area of the Peruvian coast.

The Bolivarian Republic of Venezuela: It is considered that between 25 and 30 percent of the irrigated area is affected by various levels of salinity and sodicity.

The Plurinational State of Bolivia, Chile, Colombia, Ecuador and other countries also have large areas affected by secondary salinization.

The irrigation methods in the LAC varied between countries and within countries, ranging from surface irrigation (such as basin and flood and furrow irrigation), to sprinkler and drip irrigation. Uncontrolled surface irrigation and border irrigation are also used on a small scale.

Irrigation water quality monitoring

The LAC region shows a very large variability in water availability and quality, but in general terms, the water-scarce areas coincide with limited water quantity and quality. However, despite the limited availability of water resources for irrigation in several countries, the use of brackish water for crop irrigation is only used to a small extent in certain areas of he Plurinational State of Bolivia, Mexico and some other countries (Table 3.3.9). Northeastern Brazil is one exception from this point of view, due to the widespread use of saline and brackish water (Taleisnik and Lavado, 2020; Ayrimoraes, 2020). There are no general statistics in the LAC about the extent of land irrigated using this method.

Table 3.3.9 | Some crops irrigated with brackish water in the countries of the LAC region

Crop	Country				
	Argentina	Brazil	Colombia	Mexico	Paraguay
Rice			√		
Cotton			√		
Barley					
Alfalfa					
Sorghum		√	√		
Tall wheatgrass					
Halophytes (e.g. quinoa (*Chenopodium quinoa*), *Atriplex* sp., *Salicornia* sp., saltgrass (*Distichlis spicata*), etc.)		√			
Non-conventional crops (amaranth or others)					
Salt-tolerant vegetable crops					
Corn		√	√		
Wheat				√	
Date palm					

Various strategies are employed across the countries to counteract soil salinity and sodicity problems coming from the use of brackish water irrigation, such as improving drainage systems, improving the technology of irrigation management and blending brackish water with fresh water. However, the most widespread way is to grow salt-tolerant crops, sometimes with local halophytes used as a food source. There are also examples of the use of zero tillage which leaves stubble mulch on the soil surface. Hydroponics and the use of reverse osmosis have also been proposed.

Some regulations on the use of brackish water for irrigation have been developed, such as CONOMA, (2011), DOF (2006) and the National Water Commission (2022).

Table 3.3.10 illustrates the criteria employed by LAC region countries to evaluate the suitability of water for irrigation. Across all surveyed nations, EC emerges as the predominant criterion, with SAR and pH also being widely utilized.

Table 3.3.10 | The criteria used to assess the irrigation water quality in countries of the LAC region

Criteria	Country				
	Argentina	Brazil	Colombia	Mexico	Paraguay
EC	√	√		√	√
SAR of water	√	√		√	
Total dissolved solids		√			
Total soluble salts					√
pH	√	√			√
Toxic ions		√			
Others			√		

The practice of water desalination to improve the quality of irrigation water is used mainly in northeastern Brazil, where reverse osmosis systems (to remove salts and minerals from water, making it suitable for irrigation purposes) are given to small farmers to produce watermelons (Taleisnik and Lavado, 2020). In the Colombian Caribbean coast, nitric acid is used in small quantities to reduce the pH levels of the irrigation water.

Other practices such as water mixing are not common, although there are some regulations in this area, such as in Mexico (IMTA and MMAyA, 2018). This approach involves the blending of different sources of water, often combining saline and freshwater in different proportions, to achieve a balanced water composition suitable for irrigation.

Other countries show an absence of any specific practices aimed at improving the quality of irrigation water.

Groundwater monitoring in the LAC region

Groundwater plays a significant and sometimes leading role in soil salinization and sodification processes. The elevation of the water table has a few different causes. In irrigated areas it comes from an excess of irrigation or the lack of a drainage system. In dryland areas the rise of the water table can be caused by the water equilibrium being disrupted due to vegetation changes (such as forest to crops), or an increase in bare soil surface (such as due to an excess of grazing). Having the water table near the soil surface can result in the excessive accumulation of salts within the root zone, which therefore needs to be monitored. This monitoring process is very useful for mitigating soil salinity and sodicity on agricultural lands. Some irrigated areas of Argentina, Brazil, Colombia, Mexico, and Peru, for example, have established comprehensive groundwater monitoring systems. However, there is a lack of available information provided regarding the occurrence of groundwater monitoring systems in other LAC countries.

The effectiveness of constructed irrigation systems varies across the region. Old, irrigated areas have usually lacked drainage systems, leading to soil salinization and sodification and have given rise to the late installation of drainage systems. This has led to issues such as high costs, friction between farmers, the unauthorized alteration of the original irrigation route, and poor drainage efficiency. On the contrary, new irrigation projects are designed to include drainage systems which make them less prone to salinization and alkalization processes. However, the flat topography of some areas, the limitations of drainage water disposal, or economic problems can hinder the effectiveness of some drainage systems.

Agrohydrological models to evaluate water management in salt-affected soils

Agrohydrological models represent a contemporary tool with significant potential for predicting, assessing, and mitigating water management challenges, as well as addressing soil salinization and sodification issues. These models offer a crucial avenue for enhancing the condition of saline and alkaline soils. However, within the LAC region, the adoption of these models remains limited. Some countries like Mexico use the Water Evaluation And Planning (WEAP) system, but not for saline soils (IMTA, 2019).

Risk assessments were implemented for new irrigation projects.

Leaching and drainage on salt-affected soils

Different drainage systems are employed in the countries in the LAC region, as detailed in Table 3.3.11. Among these systems, shallow ditches and subsurface drainage (deep open drains) emerge as the most prevalent methods.

Table 3.3.11 | Type of drainage systems implemented in the LAC region

Drainage System	Country				
	Argentina	Brazil	Colombia	Mexico	Paraguay
Surface drainage (shallow ditches)	√	√	√	√	√
Subsurface drainage (deep open drains)	√	√	√	√	√
Subsurface drainage (buried pipe drains)	√	√			
Controlled drainage		√			
Others			√	√	

The criteria used for designing the drainage systems are illustrated in Table 3.3.12. Soil parameters are the main criterion used in the region to design a drainage system.

Table 3.3.12 | The criteria used to design the drainage system

Criteria	Country				
	Argentina	Brazil	Colombia	Mexico	Paraguay
Soil parameters	√	√		√	√
Water parameters		√			√
Soil hydraulic/physical properties (infiltration, compaction, and soil layers)	√	√			
Others			√		

Based on the established drainage system, leaching stands out as the principal method for alleviating soil salinity. In the case of the LAC region, the predominant forms of leaching are flooding, followed by sprinkler irrigation, as illustrated in Table 3.3.13.

Table 3.3.13 | Type of leaching of saline soils used in the LAC region

Leaching type	Country				
	Argentina	Brazil	Colombia	Mexico	Paraguay
Flooding	√	√			
Sprinkler		√			
Drip					
Others			√		√

There are differences across the region regarding the quantity of leaching water used and the methodologies employed, such as FAO protocols (FAO, 1988), the USDA-ARS and USSL's approach (USSL Staff, 1954) or using the experience of technicians and farmers. There is also uncertainty about when to begin the leaching process, such as in relation to season, tillage or plant phenology.

Conclusion

Salt-affected soils have a wide distribution across the countries of the LAC region, ranging from humid to arid lands, from tropical to cold climates and from irrigated to rainfed agriculture. The level of salt-affected soil management varies from one country to another and within the countries.

Heterogeneity is the rule, as there are some areas managed with sophisticated technology, and other areas using primitive irrigation systems. The same heterogeneity applies to the measurement of soil salinity and sodicity in the region. Before the GSASmap became available for LAC, in 2021 (FAO, 2021), the mapping of salt-affected soils was uncompleted. The region is characterized by the limited use of salt-affected soil monitoring systems or crop models.

Drainage systems have been implemented for controlling soil salinity, mainly in irrigated areas. The use of different qualities of water and use of old technologies affect soil salinity and sodicity in irrigated areas, and several measures are taken to alleviate this problem, although with limited success.

In essence, concepts, categories, methodologies, technologies and economic principles developed for arid irrigated areas are not always suitable for application in the large areas of salt-affected soils in the region’s humid zones.

3.4 | Near East and North Africa

Introduction

Salt-affected soils pose significant challenges to agricultural productivity and environmental sustainability, particularly in the Near East and North Africa (NENA) region (Egypt, the Islamic Republic of Iran, Lebanon, Libya, the Syrian Arab Republic, Tunisia, Yemen and others). This region experiences a complex interplay of environmental factors that contribute to soil salinization. High evaporation rates, limited rainfall, improper irrigation practices, insufficient skills in the use of brackish, treated, and saline waters, and inadequate drainage systems have resulted in the accumulation of salts in the soil, rendering vast areas unsuitable for cultivation.

The status of salt-affected soils (SAS) in the NENA region is a pressing concern due to its profound impact on food security, rural livelihoods, and ecosystem health. Salinity affects crop growth and yield by disrupting root functions, water uptake, and nutrient absorption, ultimately reducing agricultural productivity. This agricultural decline exacerbates poverty, food insecurity, and rural–urban migration, posing serious regional social and economic challenges.

Moreover, the environmental consequences of SAS are farreaching. Excess salt in the soil can infiltrate in the groundwater, rendering it unfit for human consumption and irrigation, further jeopardizing water resources in an already waterscarce region. Additionally, the accumulation of salts can harm native vegetation, degrade biodiversity, and disrupt fragile ecosystems, leading to long-term ecological consequences.

Addressing the status of SAS in the NENA region requires a multifaceted approach that combines scientific research, technological innovations, and sustainable land management practices. Efforts are underway to develop and adapt salt-tolerant crop varieties, improve irrigation efficiency, implement proper drainage systems, and promote soil rehabilitation techniques. Collaborative initiatives (involving governments, research institutions, and local communities, taking the participatory approach), are crucial for implementing effective strategies to mitigate soil salinization and restore productivity.

In this questionnaire-based exploration of the status of SAS in the NENA region, we delve into the status of measurement, mapping, and monitoring of SAS, sustainable management, crop production, and water management in saline and sodic environments. By understanding the complex dynamics of SAS and fostering knowledgesharing and innovation, we can strive towards a more resilient and productive agricultural sector in the NENA region, ensuring people's wellbeing and the preservation of natural resources.

Status of measurement, mapping and monitoring salt-affected soils

The total area of salt-affected soils in the NENA region is 2 303 461 km^2 according to assessments given in Chapter 1. Soil salinity is undeniably one of the most prevalent hazards in the agricultural sector. The extent of SAS exhibits significant variations, as indicated by the data provided by national experts from 11 countries who participated in the INSAS questionnaire. The reported areas, as shown in Table 3.4.1, range from a few thousand hectares to tens of millions of hectares as well as showing the percentage of their country area. Indeed, it is evident that there is a lack of current and comprehensive data on soil salinity in different countries, particularly when it comes to national level data. The absence of uptodate and accurate information poses a significant challenge to global understanding of the true extent of soil salinity issues.

Table 3.4.1 | Area of salt-affected, saline, sodic, and saline sodic soils in some Near East and North Africa (NENA) countries in million ha, and percentage of total country area

Name of country	Area of salt-affected soils (Mha/%)*	Area of saline soil (Mha/%)*	Area of sodic soils (Mha/%)*	Saline sodic soil (Mha/%)*	References
Algeria	3.20/1.34	n/a	n/a	n/a	Szabolcs, 1989
Egypt	1.38/1.38	1.12/1.12	0.26/0.26	n/a	ICARDA, 2011; Hassan, 2012; Gehad, 2003;
Islamic Republic of Iran	55.6/31.81	55.1/31.52	0.50/0.29	n/a	Momeni, 2011; Banaei *et al*,. 2004
Kuwait	0.687/38.54	0.687/38.54	n/a	n/a	Burezq, Shahid and Carter, 2022
Lebanon	0.0015/0.014	n/a	n/a	n/a	Darwish *et al.*, 2005
Libya	0.86/0.46	0.86/0.46	n/a	n/a	Report on mapping project of Natural resources for agricultural use, 2007
Sudan	47.16/25	35.92/19	8.66/5	2.58/1	National SAS MAP of the Sudan, Land Water Res. Centre, ARC, MoAF, Sudan FAO, 2020a
Syrian Arab Republic	n/a	n/a	n/a	n/a	
Tunisia	n/a	1.64/10	n/a	n/a	Hachicha, 2007
United Arab Emirates	2.26/22.92	2.08/21.10	n/a	n/a	EAD, 2018
Yemen	0.50/9.47	n/a	n/a	n/a	Al-Mashreki, 2022

* Mha = million hectares. Percentage of SAS as a percentage of total country area.

Regarding the determination of soil salinity and sodicity, it is evident that some harmonization exists in the methods used, with different countries employing varying approaches (as shown in Table 3.4.2). The most common method involves determining electrical conductivity (EC) in saturated paste extract, followed by calculating total soluble salts (comprising Na^+, Mg^{2+}, Cl-, SO_4^{2}, HCO^{3-}, CO_3^{2-}). However, it is worth noting that more than one method can be used within the same country. For instance, in the Islamic Republic of Iran, both the EC in saturated paste extract and total soluble salts calculation are utilized. According to the responses, the electromagnetic method has limited application in the region. Algeria, the Islamic Republic of Iran and Tunisia are the only countries using this method on 1 265 ha, 200 000 ha and less than 1 000 ha, respectively.

In terms of soil sodicity determination, the most dominant methods in the NENA region are the sodium adsorption ratio (SAR) and exchangeable sodium percentage (ESP). Nevertheless, it should be noted that ESP is not applicable in the United Arab Emirates. Furthermore, despite the proven efficiency of various soil sodicity determination methods, it is evident that many of these methods are not commonly utilized across the NENA region, as shown in Table 3.4.3.

Table 3.4.2 | Chemical methods used to measure to measure soil salinity in the countries of the Near East and North Africa (NENA) region

Method	Countries										
	Algeria	Egypt	Islamic Re-public of Iran	Kuwait	Lebanon	Libya	Sudan	Syrian Arab Republic	Tunisia	United Arab Emirates	Yemen
Electrical conductivity (EC) in saturated paste extract	√	√	√	√	√		√	√	√	√	√
EC at 1:1 soil to water ratio				√		√		√			
EC at 1:2 soil to water ratio											
EC at 1:2.5 soil to water ratio				√	√		√	√			√
EC at 1:5 soil to water ratio	√	√		√			√		√		
EC at 1:10 soil to water ratio											
Total dissolved solids (by gravimetric anal-ysis)	√	√							√		
Total soluble salts (calculated as the sum of Na^+, Mg^{2+}, Cl^-, SO_4^{2-}, HCO_3^-, and CO_3^{2-})		√	√	√		√	√	√	√		√
Content of soluble Na^+			√						√		
Content of soluble Cl^-											
Others											

Table 3.4.3 | Methods of soil sodicity measurement used in the Near East and North Africa (NENA) region

Method	Countries										
	Algeria	Egypt	Islamic Republic of Iran	Kuwait	Lebanon	Libya	Sudan	Syrian Arab Republic	Tunisia	United Arab Emirates	Yemen
Exchangeable sodium per-centage (ESP)	√	√	√	√	√	√	√	√	√		√
Sodium ad-sorption ratio (SAR)	√	√	√	√	√	√	√	√	√	√	√
Physical meth-ods (specific swelling, low infiltration rate etc.)											
Morphologi-cal methods (structure of sodic/solo-netzic horizon etc.)									√		
Others											

Among the various methods for determining exchangeable Na^+, the parameters of soil sodicity mentioned in Table 3.3.3 are measured differently. The most prevalent approach in the countries of the NENA region involves a three-step process: salt removal (step 1), cation exchange (step 2), and measurement of Na+ (step 3). However, it is evident that there is currently no harmonization of this method across the countries in the region (Table 3.3.4.).

Table 3.4.4 | Methods of determination of exchangeable Na^+ and their distribution among the countries of the Near East and North Africa (NENA) region

Method	Countries										
	Algeria	Egypt	Islamic Republic of Iran	Kuwait	Lebanon	Libya	Sudan	Syrian Arab Republic	Tunisia	United Arab Emirates	Yemen
Step 1. Salt removal. Step 2. Cation exchange. Step 3. Measurement of Na^+.	√	√	√	√		√					√
Without salt removal. Step 1. measurement of soluble Na+. Step 2. Cation exchange. Step 3. Measurement of Na^+. Step 4. Recalculation of exchangeable Na^+ based on the subtraction of soluble Na+ from total Na^+.			√		√		√				√
Without salt removal. Step 1. Cation exchange. Step 2. Measurement of Na^+.					√			√	√		
Others										ESP calculation from SAR	

When it comes to measuring cation exchange capacity (CEC), for most countries in the NENA region, ammonium acetate extraction (buffered at pH 7) is the best approach for measuring cation exchange capacity (CEC) in the. Notably, the United Arab Emirates does not perform CEC measurements, while Algeria, the Islamic Republic of Iran and the Sudan utilize an additional method involving sodium acetate extraction. In Tunisia, triethanolaminebuffered barium chloride extraction (buffered at pH 8.2) is used. The methods are shown in Table 3.4.5.

Table 3.4.5 | Methods of measurement of CEC and their distribution among the countries of the Near East and North Africa (NENA) region

Method	Countries										
	Algeria	Egypt	Islamic Republic of Iran	Kuwait	Lebanon	Libya	Sudan	Syrian Arab Republic	Tunisia	United Arab Emirates	Yemen
Ammonium acetate extraction (buffered at pH 7)	√	√	√	√	√	√	√	√			√
Ammonium chloride extraction											
Triethanolaminebuff-ered barium chloride extraction (buffered at pH 8.2)									√		
Hexamminecobalt (III) chloride ex-traction											
Others (sodium ace-tate extraction)	√		√				√				
Not applicable (CEC not measured)										√	

In the NENA countries, the most common method for measuring the SAR is by calculating the content of Ca^{2+}, Mg^{2+}, and Na^{+} in the watersaturated soil paste extract. However, Algeria uses an additional approach, assessing the content of Ca^{2+}, Mg^{2+}, and Na^{+} in the 1:5 soil to water ratio. Notably, physical methods of soil sodicity measurement are not widely adopted in most NENA countries, except for Libya, where low hydraulic conductivity soil dispersion tests are preferred and in Tunisia, where low infiltration rate, low hydraulic conductivity, and soil dispersion tests are used. Additionally, the Sudan employs specific swelling and low infiltration rate methods in conjunction with the previously mentioned techniques. Morphological methods for assessing soil sodicity are not extensively used in the NENA region. Nevertheless, some countries such as Egypt, Libya, the Sudan, the Syrian Arab Republic and Yemen, utilize the specific structure of the sodic/solonetzic horizon method for this assessment. The Sudan has also adopted additional methods, including specific microfeatures of sodic/solonetzic horizon, observation of stunted plant growth, and identification of waterlogged soils.

Soil alkalinity, or soil pH, can be determined using various methods, and different approaches are employed in the countries of the NENA region, as outlined in Table 3.4.6. Among the methods known worldwide, it is apparent that the most prevalent technique for pH measurement in the region involves using the extract of saturated paste. However, in some countries, pH measurement is conducted on soil water extracts with ratios of 1:1, 1:2.5, and 1:5 (such as Libya and the Islamic Republic of Iran), while in the Sudan and Tunisia, soil water extracts with ratios of 1:2, and 1:5 are used, in addition to the saturated paste, which also used in the Islamic Republic of Iran. Indeed, harmonizing soil chemical analyses is crucial, even if some methods are already standardized. This harmonization would bring several benefits, which can be summarized as follows:

- enhancing the national and regional soil monitoring system;
- publishing in high-quality journals;
- improving communication and exchange of experience between scientists/practitioners;
- improving comparability of data in soil databases; and
- development of recommendations to farmers.

Table 3.4.6 | Method of pH measurement and their application in the Near East and North Africa (NENA) region

Method	Countries										
	Algeria	Egypt	Islamic Republic of Iran	Kuwait	Lebanon	Libya	Sudan	Syrian Arab Republic	Tunisia	United Arab Emirates	Yemen
Soil pH (extract of saturated paste)		√	√	√	√		√	√	√	√	√
Soil pH (1:1 soil to water ratio)			√			√					
Soil pH (1:2 soil to water ratio)			√						√		
Soil pH (ratio 1:2.5 soil to water)	√	√			√						√
Soil pH (1:5 soil to water ratio)	√		√					√	√		
Soil pH ($CaCl_2$ at 1:2.5)											
Total alkalinity, or content of alkaline anions (with methyl orange and phenolphthalein indicators)						√	√	√			
Others			pH of saturated soil paste	pH of saturated soil paste			Calculation of ESP				

An important observation to note is the limited use of conversion equations related to soil salinity and sodicity results obtained from the different methods. Notably, Lebanon is the exception, as it adopts the conversion equations proposed by Shahadat *et al.* (2020) and Seo *et al.* (2022). Notwithstanding, finding the proper conversion has its own challenges due to the different types of soils (such as calcareous and gypsiferous), with their different soil layer types and textural classes.

Saline and sodic soil classification systems used in the Near East and North Africa (NENA) region

Based on the questionnaire responses, it was found that the American classification system described by USDA (1954) and the system adopted by the Food and Agriculture Organization of the United Nations (FAO) is the most suitable for SAS classification in the region. However, there are differences in the thresholds used for classifying saline and nonsaline soils in some countries. For example, while Algeria, the Islamic Republic of Iran, the Sudan, and the United Arab Emirates use the 4 dS/m threshold suggested by USDA (1954), in the Islamic Republic of Iran, 2 dS/m is considered as the threshold, while Yemen and the Syrian Arab Republic use thresholds of 2 dS/m, 4 dS/m and 15 dS/m. In Lebanon, Kuwait, and Egypt, the threshold is 2 dS/m, while in Libya and Tunisia, it is 2 dS/m and 4 dS/m.

Regarding soil sodicity, most countries in the region (as per the questionnaire responses) use a threshold of >15 percent ESP. The only exception is Egypt, which uses a threshold of >13percent SAR. The Islamic Republic of Iran uses a threshold of >10 percent (ESP) and >13 (SAR), while the Sudan and Tunisia implement >15 percent (ESP) and >13 percent (SAR).

Status of soil salinity and sodicity mapping in the Near East and North Africa (NENA) region

Regarding soil salinity and sodicity mapping in the region, the responses from the questionnaires indicate that most countries rely on conventional and traditional methods, which include soil sampling, description, and analysis and Geographic Information System (GIS) tools to generate relative maps. In Tunisia, electromagnetic surveying and multispectral imagery are used for scientific research. Recently in the Islamic Republic of Iran, a digital soil mapping approach employing remote sensing data and machine learning algorithms has been used by several researchers, soil scientists, and students at a small scale. However, there are a lack of standardized protocols across countries for organizing this process, and the techniques used are often outdated and lack the modern mapping approaches. Apart from the Sudan, which adopted more contemporary methods recommended by Omuto *et al.* (2020), these methodologies were also implemented by ten other NENA countries during the elaboration of the *Regional action plan for sustainable soil management in the Near East and North Africa (NENA) region* (FAO, forthcoming) in the framework of the TCP/RAB/3802 project (2021–2022) (FAO, 2022). These modern approaches incorporate soil indicators like EC, pH, ESP and SAR, and soluble ions, as well as ancillary data such as remote sensing images, elevation (DEM), geology maps, climate data (minimum and maximum temperature, precipitation), land cover, hydrogeology maps, boundary and main town maps, soil maps, and erosion data. Egypt has also used the FAO protocol for SAS mapping (FAO, 2020b).

The depth of the mapped saline and sodic soils varies among countries. For example, Lebanon uses a depth of 0–25 cm or 30 cm, the Islamic Republic of Iran uses a depth of 0–100 cm, Algeria and Yemen uses a depth 0–30 cm. In Libya, the Syrian Arab Republic and Tunisia, the depth is set at 150 cm. The United Arab Emirates uses depths of 0–25 cm and 50–150 cm. The Sudan uses depths of 0–30 cm and 30–100 cm. Egypt uses depths of 0–30 cm, 30–60 cm, 60–90 cm, 90–120 cm, and 120–150 cm. However, there is a lack of information on mapping methods and depths used in other countries of the region.

The scale of mapping used in different countries also varies considerably (Table 3.4.7). Yemen, for instance, has maps with scales ranging from 1:5 000 to 1:500 000, whereas the Islamic Republic of Iran's most detailed maps are at a scale of 1:1000 000.

In summary, while soil salinity and sodicity mapping in the region predominantly rely on conventional methods and lack standardized protocols, some countries have started to adopt more advanced techniques. Additionally, the depth and scale of mapping differ significantly from one country to another, resulting in varied levels of detail in the maps produced.

Table 3.4.7 | Map scales, used in the detailed saline and sodic soil maps in the region at national scale

Map scale	Countries										
	Algeria	Egypt	Islamic Republic of Iran	Kuwait	Lebanon	Libya	Sudan	Syrian Arab Republic	Tunisia	United Arab Emirates	Yemen
1:5 000											√
1:10 000											
1:20 000					√ (crop-land)	√ (crop-land)				√ (crop-land)	√
1:25 000											
1:50 000					√	√ (crop-land)					√ (crop-land)
1:100 000										√	√ (crop-land)
1:250 000			√	√				√			√ (crop-land)
1:500 000										√	√ (crop-land)
1:1 000 000			√								
No answer	√	√							National scale		

Soil salinity and sodicity monitoring systems are not widely implemented in most countries in the region, although there is confirmation of the necessity of having such a system, as indicated by the responses from questionnaires.

In the Sudan, there is a local monitoring system for salinity and sodicity in areas of the country prone to such problems. While not a national monitoring system, the system in place at least ensures that these areas receive attention during soil studies.

In the Islamic Republic of Iran, there is a strategic plan for agricultural soil monitoring across the country based at the Soil and Water Research Institute of Iran. Soil samples from regions prone to salinity and sodicity issues are regularly collected and analysed to monitor salt accumulation or leaching. Parameters such as EC, pH, total dissolved solids (TDS), residual sodium carbonate (RSC), Na^{+}, K^{+}, Ca^{++}, Mg^{++}, Cl^{-}, CO^{3--}, HCO^{3-}, SAR, salinity hazard, and sodium hazard are typically examined to assess soil quality and guide decisions related to leaching requirements, gypsum application, and drainage management. There is also a traditional national soil monitoring programme which aims to provide relevant information on soil quality at national level. It only covers agricultural land and employs a comprehensive assessment of soil chemical and physical parameters, including soil salinity, pH, SAR, ESP, CEC, bulk density, and organic matter content. The monitoring is conducted annually at 3 000 sites throughout the country and the reference laboratory of the Soil & Water Research Institute holds INSO ISO/IEC 17025:2017 certification, ensuring its quality and reliability. In addition, more detailed monitoring projects had been carried out in the provinces of Khuzestan, Sistan (Sistan plain) and Baluchestan among many other provinces accounting for the assessment of the status and management of soil–water–crop interactions (irrigation, leaching, water supply, soil rehabilitation and crop selection) in SAS areas.

In Egypt, the local level monitoring system of soil analysis is strategically focused. It provides an in-depth exploration of land properties and water infiltration strata, assesses the crops' adaptability to saline soil conditions, conducts comprehensive studies spanning various vegetables and fruits, and thoroughly examines irrigation water quality. This initiative operates in conjunction with a comprehensive plan aimed at rehabilitating saline lands, and substantially reducing soil salinity levels before commencing planting activities. The central soil laboratory of the Ministry of Agriculture comprises of distinct departments, including the Department of Land and Water Chemistry, the Department of Land Characteristics, the Department of Irrigation and Agricultural Drainage, as well as the Department of Plant Nutrition and Physiology.

In the United Arab Emirates, there is also no national soil monitoring system, but a local initiative called the Abu Dhabi Soil Quality Monitoring Programme exists in Abu Dhabi. Launched in 2021, this programme aims to provide relevant information on soil quality in the Emirate and assess the impact of human activities, including residential, industrial, and agricultural practices. It covers approximately 30 percent of land currently in use, comprising of agricultural, industrial, and residential areas, and employs a comprehensive assessment of 35 soil parameters, including soil salinity, pH, and organic matter content. The monitoring is conducted annually at 600 sites throughout the emirate and holds ISO 16133:2018 certification, ensuring its quality and reliability. Although there is no integrated monitoring of irrigation water parameters for agricultural land use under the soil quality monitoring programme, field measurements of EC and pH are conducted separately. Additionally, a dedicated programme for monitoring groundwater is carried out by the Environment Agency - Abu Dhabi (EAD) but is not directly linked to the soil quality monitoring initiative. The information obtained from the soil monitoring system is utilized for crucial decisionmaking related to irrigation water management, the application of chemical amendments, and effective drainage management.

In Tunisia, there is monitoring of soil salinity and sodicity at the local level conducted by national research centres. They are used for irrigation water management (such as the amount of leaching water, regulation of quality of water and other water-related decisions).

To further enhance and develop the monitoring systems in these countries, there have been recommendations to incorporate remote sensing technology, which could offer valuable insights into soil and water conditions and facilitate more informed and efficient management strategies. While advanced monitoring systems may be absent in the region, Egypt and the Syrian Arab Republic have undertaken risk evaluations concerning secondary soil salinization and sodification within their irrigation and drainage projects. An exemplary initiative exists in North Sinai, Egypt, where a project focuses on the experimentation of diverse designs for covered agricultural drain fields and irrigation management. These designs are implemented in the Tina Plain's soil to assess their impact on enhancing agricultural drainage, ameliorating soil salinity, and subsequently, boosting productivity. The risk assessment incorporates comprehensive indices, including morphological characteristics like soil structure and salt crust formation, as well as quantitative indicators like laboratorybased soil salinity analysis.

Similarly, in the Syrian Arab Republic, strategic attention has been devoted to irrigation and drainage projects along the Euphrates, with a particular emphasis on the lower basin within Reqqa and Deir Azzour governorate. Governmental irrigation initiatives, alongside varied drainage systems, have been effectively implemented. In this context, the assessment of secondary salinity risk plays a pivotal role. This evaluation entails a comprehensive analysis of the efficiency of drainage systems, the groundwater table's dynamics, and the spatial distribution of salinity in both vertical and horizontal dimensions.

These commendable efforts in Egypt and the Syrian Arab Republic underscore a proactive approach to addressing soil salinization and sodification risks within the context of irrigation and drainage projects. By utilizing an array of assessment tools, from morphological observations to quantitative measurements, these initiatives contribute substantially to informed decision-making and the sustainable management of soil salinity issues.

The status of sustainable management of salt-affected soils

Across the countries of the NENA region, the status of sustainable SAS management exhibits a dynamic spectrum, varying from country to country based on their adopted practices. The practices employed in the ten countries that responded to the questionnaire are delineated as follows:

- **Evaporation reduction techniques**: These encompass strategies such as mulching and the utilization of interlayers composed of loose materials. Notably, these practices are prevalent in most surveyed countries, with the exceptions being Kuwait and Libya.
- **Topsoil salt removal**: Prevalent in the majority of countries, with the methods involving the removal of salts from the topsoil, such as leaching, drainage, and surface scraping. However, these techniques are not commonly implemented in Lebanon, Tunisia, the United Arab Emirates and Yemen, while are intensively used in the Khuzestan and Sistan (Sistan plain) provinces of the Islamic Republic of Iran.
- **Enhancing soil structure and infiltration**: Widely regarded as a cornerstone practice for ameliorating soil salinity and sodicity, these methods – including compost and residue incorporation – are consistently deployed across all surveyed countries except the United Arab Emirates.
- **Biochar application**: Egypt is the only country employing biochar as part of its soil management strategy. However, in some parts of the Islamic Republic of Iran, compost and biochar are used but just in small areas and at field level (data is limited on this matter).
- **Deep ploughing**: Implemented exclusively by Libya, the Sudan, and the Syrian Arab Republic, deep ploughing serves as a mitigation approach against soil salinity and sodicity. This method is advised in the Islamic Republic of Iran according to the soil type and status.
- **Chemical amelioration**: Egypt, the Islamic Republic of Iran, the Sudan, the Syrian Arab Republic and Tunisia all employ chemical interventions like the addition of gypsum and other calciumcontaining amendments.
- **Salt relocation and accumulation reduction**: Focusing on curtailing salt redistribution and accumulation, practices encompassing land shaping and levelling are embraced by half of the respondent countries, including the Islamic Republic of Iran, the Sudan, the Syrian Arab Republic, Yemen, and the United Arab Emirates.
- **Crop system management**: Distributed across multiple countries, including Egypt, the Islamic Republic of Iran, Lebanon, Libya, the Sudan, and the Syrian Arab Republic, this approach encompasses enhanced crop rotation, agrobiodiversity, and crop system diversification.
- **Crop adaptation strategies**: Egypt, the Islamic Republic of Iran, Lebanon, Libya, the Sudan, the Syrian Arab Republic, and the United Arab Emirates deploy strategies for crop adaptation, including the utilization of halophytes and nonconventional crops, breeding and genetic engineering, as well as halopriming.
- **Agroforestry**: With limited implementation across the region, the Sudan is the only nation that integrates agroforestry into its soil salinity management practices.
- **Desalinization for irrigation water purification**: This method is uniquely utilized in the United Arab Emirates as a means of purifying irrigation water. The use of private water desalination infrastructure in private agricultural areas and agriculturalindustrial companies across the country have been reported.

The intricate web of practices implemented within these countries underscores the diverse strategies employed to achieve sustainable management of SAS across the NENA region.

Limited data is available regarding the implementation of practices for managing SAS across different regions. Only four countries have reported the existence of such data.

In Egypt, a diverse range of practices have been adopted, spanning various sectors. Notable initiatives include a project funded by the United States Agency for International Development (USAID) in conjunction with the International Center for Biosaline Agriculture in Dubai (ICBA). This project focuses on cultivating and exporting agricultural crops. Another endeavour involves enhancing farming systems through the cultivation of forage plants in salt-affected environments within the Mediterranean basin (PRIMA). Efforts have also been directed towards optimizing land utilization impacted by salinity to uplift the livelihoods of small-scale farmers in selected villages of the Kafr El-Sheikh Governorate. An integrated farm model has also been established for producing milk, meat, and fish through the cultivation of seaweeds and halophytes in desert regions.

In Lebanon, specific areas have embraced these practices, particularly in response to crop challenges stemming from saltwater intrusion along the coastal regions. Studies have explored the salinity tolerance of strawberries (Perennial Fragaria) and evaluated the behaviour of salt-tolerant forage genotypes of millet (Atallah *et al*, 2022).

In the Sudan, El Mobarak (2007) highlighted various early practices for managing salt-affected areas, conducted by researchers across the different research stations of the Agricultural Research Corporation, as follows:

- Since 1920, the leaching of salt in Gezira state soils was achieved using Blue Nile irrigation water. In 1939, soil amendments like gypsum were introduced to mitigate sodiumrelated effects on Gezira soil physical properties. Saline-sodic soils in north Gezira were managed using leaching and alfalfa cultivation in 1977.
- In the River Nile state, the problems of SAS were addressed by employing salt-tolerant crops in 1977. Management practices also encompassed the application of gypsum and straw mulch (1974–1975).
- South Khartoum area's effective approach to managing severely saline soils involved cultivating crop varieties tolerant to oil.
- In the northern state, leaching emerged as the predominant practice for managing SAS due to the light soil composition.

Recently in the Islamic Republic of Iran, specific attention have been paid to the SAS of Golestan (to the north), Sistan and Baluchestan (to the southeast, on the border of Afghanistan), Khuzestan (to the southwest) as well as in the centre of the Islamic Republic of Iran such as the provinces of Isfahan, Yazd, Kerman and in the northeast, such as Khorasan.

The Soil and Water Research Institute (SWRI) in collaboration with the water and soil deputy of the Agricultural MinistryJihad and also the National Soil Salinity Centre (carrying out a saline agriculture mega project) have achieved several projects in those regions, under the supervision and coordination of SWRI. However, internal collaboration is crucial to implement the advanced monitoring system, to recognize good practices and to extend to the related regions.

Efforts in these countries illustrate the multifaceted nature of practices applied to address the challenges of SAS across different regions.

Indicators of sustainable soil management (SSM)

Sustainable soil management (SSM) indicators employed for assessment exhibit variability across the region, with distinct practices in different countries. Egypt, the Islamic Republic of Iran, and Lebanon adhere to the indicators outlined in the *Protocol for the assessment of Sustainable Soil Management* (SSM Protocol) (FAO and ITPS, 2020). These encompass parameters like soil productivity (measured through biomass in dry matter), organic carbon content, bulk density, and soil respiration rate.

The Islamic Republic of Iran, the Sudan and the United Arab Emirates all adopt a broader array of indicators, extending beyond the FAO recommendations. The Sudan focuses on security indicators, including average annual rainfall, residue management, and drought frequency. They also incorporate soil protection indicators, such as topsoil erosion, cropping intensity, and cropping pattern.

The Islamic Republic of Iran and the United Arab Emirates have undertaken a comprehensive approach, encompassing soil organic carbon and soil physical properties. Additionally, their assessment involves monitoring both inorganic and organic contaminants, serving the dual purpose of soil contamination assessment and soil quality evaluation.

Other countries that participated in the survey have chosen distinct pathways, veering away from the FAO SSM Protocol indicators. These countries have established their own unique measures and indicators to gauge SSM practices but the questionnaire did not record their response.

This diverse landscape of SSM indicators underscores the region's commitment to tailoring approaches based on local contexts, needs, and priorities. The result is a rich tapestry of methodologies that collectively contribute to the advancement of SSM across the region.

In the majority of countries who responded to the questionnaire, the establishment of a comprehensive database cataloguing the implemented practices of SSM remains an unmet need, often emphasized as a crucial requirement, Kuwait is the only country that spoke about the unnecessity of the database. However, notable exceptions were observed in the Sudan and the United Arab Emirates.

In the Sudan, significant progress has been made towards this goal, as evidenced by the partial creation of a national database initiated by El Mobarak (2007). Although this database may be incomplete, it signifies a step forward in consolidating information related to SSM practices within the country.

In contrast, the United Arab Emirates has achieved a commendable feat by developing a thorough and complete database for SSM. This comprehensive repository of data can be accessed through the web link *https://enviroportal.ead.ae/map/*. The availability of such a resource underscores the United Arab Emirates' commitment to transparency and accessibility of information pertaining to SSM practices.

These examples of database establishment in the Sudan and the United Arab Emirates serve as valuable models for other countries in the region. They highlight the potential benefits of having centralized repositories that house information on SSM practices, enabling informed decisionmaking, knowledge sharing, and collaborative efforts aimed at advancing SSM across the region.

Across surveyed NENA countries, a noticeable deficiency in policies governing the management of SAS is evident, despite a prevailing consensus on the necessity of such regulations. The absence of comprehensive policies in this domain is a widespread concern. However, an exception to this trend is observed in the United Arab Emirates, where a policy specifically targeting the management of soil, particularly SSM, has been established (EAD, 2019).

It is important to acknowledge that even in the United Arab Emirates where a policy is in place, there is room for further enhancement and refinement. The continuous improvement of existing policies and the formulation of new ones are essential to address the complexities and evolving challenges associated with the management of SAS.

The absence of policies addressing sustainable salt-affected soil management is a prevalent issue in most countries, often resulting in the lack of dedicated governmental bodies focused on this critical matter. However, there are noteworthy exceptions where proactive efforts are being undertaken. In Egypt, the Islamic Republic of Iran, and the Syrian Arab Republic, distinct organizations have taken on the responsibility of addressing salt-affected soil management, thereby demonstrating their commitment to tackling this significant challenge.

In the Islamic Republic of Iran, a governmental establishment, though unnamed, is dedicated to addressing salt-affected soil management, as indicated in the questionnaire responses. This underscores the recognition of the issue's importance within the country's agenda.

In the Syrian Arab Republic, a commendable collaborative approach is evident, with two ministries – the Ministry of Water Resources and the Ministry of Agriculture and Agrarian Reform – officially engaged in addressing salt-affected soil management. This joint effort highlights a comprehensive strategy for managing this complex challenge.

Egypt stands out due to the Egyptian Center of Excellence for Saline Agriculture (ECESA), an institution licensed under the Desert Research Center in Cairo. This centre plays a pivotal role in advancing expertise and research related to salt-affected soil management, thereby contributing to sustainable agricultural practices.

In the United Arab Emirates, multiple governmental institutions are actively involved in regulating diverse aspects of monitoring and managing SAS. This comprehensive approach is exemplified by the efforts of the Environment Agency - Abu Dhabi and the Abu Dhabi Agriculture and Food Safety Authority.

In Tunisia, there is one governmental institution: the General Directorate of Agricultural Land Development and Conservation (DGACTA), that regulates all aspects of monitoring and management of salt-affected soil.

These examples of governmental commitment and involvement underscore the importance of addressing salt-affected soil management at the policy and institutional levels.

The development of legislation and legal frameworks to regulate and protect saline environments as crucial biodiversity shelters remain underdeveloped in most countries of the region. Among those surveyed, only five countries have established laws and legislative regulations in this domain. Notably, the Islamic Republic of Iran, Kuwait, Libya, the Syrian Arab Republic, and the United Arab Emirates have taken steps toward enacting laws that focus on safeguarding saline environments and their biodiversity (no data was available for Kuwait and the United Arab Emirates).

The Islamic Republic of Iran has the Environmental Protection Law of 1974 [ILO, 2023] and the Soil Protection Law (2019; *https://qavanin.ir/Law/PrintText/265279)*, providing the regulation for the conservation and protection of soils. It is initiated to add some articles to the laws regarding SAS. There are soil and water research institutes and water and soil deputy of agricultural ministry as governmental institution that regulate all the aspects of monitoring and management of SAS.

In Libya, two distinct laws address this critical issue. The first is detailed in the Fourth National Report on the Implementation of the Convention on Biological Diversity (2010), as presented by the Environment Public Authority *(https://www.cbd.int/doc/world/ly/ly-nr-04-ar.pdf)*. This report signifies Libya's commitment to preserving biodiversity within saline environments, underscoring the nation's awareness of the ecological significance of such areas. The second law, known as the Law of Protecting the Environment No. (15) *(https://environment.gov.ly/law-no-15/)* provides a legal framework for the conservation and protection of natural resources, further emphasizing Libya's dedication to environmental preservation.

The Syrian Arab Republic stands as a noteworthy example of proactive legislative action. The Law of the Environment No. (50)/2003, presented in the link, serves as the official legislation for safeguarding diverse environments, with a particular focus on saline environments. This law demonstrates Syrian Arab Republic's recognition of the importance of protecting these unique habitats that harbour vital biodiversity. *http://www.parliament.gov.sy/arabic/index.php?node=201&nid=16193&ref=tree&*.

Additionally, Syrian Arab Republic's commitment to environmental conservation is reinforced by the Law of the State Ministry of Environmental Affairs No. (12)/2012 (in the upcoming link). This legal instrument signifies the nation's dedication to comprehensive environmental stewardship and emphasizes the importance of sustainable practices to ensure the continued well-being of both human and ecological communities. *http://www.parliament.gov.sy/arabic/index.php?node=201&nid=4323&ref=tree&*.

Extension services play a pivotal role in bolstering farmers' efforts to effectively manage SAS, while ensuring sustained productivity, and mitigating the adverse impacts on plant growth and agricultural output. In the NENA region (according to the responses to the questionnaires), these vital extension services have gained widespread prevalence in the majority of countries, with the exception of Libya, and are thoughtfully distributed geographically.

The specific services sought by farmers and offered by extension services exhibit a dynamic and contextual variation within each country, presented in Table 3.4.8. This intricate interplay underscores the need for tailored and responsive approaches that acknowledge the unique needs and aspirations of farmers across the region.

The collaborative partnership between farmers and extension services not only underscores the significance of knowledge dissemination and skill enhancement but also reflects the shared commitment to fostering sustainable agricultural practices amid the challenges posed by SAS.

Table 3.4.8 | Services, most demanded by farmers and extension services to help manage SAS in a sustainable manner in the countries of the Near East and North Africa (NENA) region

Services	Countries										
	Algeria	Egypt	Islamic Republic of Iran	Kuwait	Lebanon	Libya	Sudan	Syrian Arab Republic	Tunisia	United Arab Emirates	Yemen
Training about the management of SAS	√	√	√		√	√	√	√	√		√
Soil analyses		√	√	√ (ECe)	√	√	√ EC, pH, ESP, SAR, and soluble ions		√		√
Interpretation of soil analyses		√	√	√	√	√	√	√	√		√
Irrigation water or groundwater analyses	√	√	√	√ (ECe)	√	√	√		√	√	√
Soil salinity and sodicity mapping		√	√		√		√				√
Recommendations on SAS management	√	√	√	√	√	√	√	√			√
Others											

Losses of crop yields resulting from soil salinization/sodification

Cropland stands as the most susceptible target of secondary soil salinity and sodicity hazards within the region, with a multitude of factors converging to escalate these issues. The phenomenon is notably exacerbated by the imprudent utilization of water for irrigation, a practice that inadvertently fosters the accumulation of salts within the soil profile and triggers the ascent of saline groundwater.

Based on the responses garnered from the questionnaire, data from five countries furnish a clearer picture of the extent of cropland affected by soil salinity and sodicity. In Lebanon, an approximate expanse of 1 500 ha has been impacted, spanning the coastal regions where greenhouse production is prevalent, and in the semiarid northeastern sector of the Bekaa plain (Khatib, Darwish and Mneimneh, 1998; El Moujabber *et al.*, 2006, 2013; Atallah *et al.*, 2022).

In the United Arab Emirates, the afflicted cropland encompasses around 58 916 ha, accounting for the instances where soil EC exceeds 4 dS/m (an indicator of elevated salinity levels).

The Islamic Republic of Iran's landscape has been impacted far more severely, with an estimated 6.8 Mha of cropland (irrigated land) grappling with soil salinity issues, while an additional 0.5 Mha contend with the challenge of soil sodicity, as shown in Momeni (2011) and Banaei *et al.* (2004).

In Tunisia, the total area of cropland is around 1.5 Mha (Mzid *et al.*, 2023), but there is no information about the soil salinity or sodicity.

Lastly, Yemen is considerably impacted by SAS, with around 0.5 Mha of cropland succumbing to soil salinity, as documented by Al-Mashreki (2022).

The distinct climatic conditions prevailing across the region have engendered a rich array of crop diversity, presented in Table 3.4.9. Among these crops, barley is the most common, being grown in saline soils or thriving under irrigation with saline water across nearly all of the countries in the NENA region. Cotton, alfalfa, and sorghum are also common crops in much of the region.

More unconventional crops such as halophytes are also being grown in Egypt, the Islamic Republic of Iran, Kuwait, and Lebanon. This innovative approach underscores the region's commitment to exploring resilient and sustainable options for agricultural production in the face of challenging soil conditions. Libya, the Sudan, and Yemen are also experimenting with unconventional crops, such as Bonecam Mombasa and amaranth.

This variegated landscape of crops serves as a testament to the region's readiness to adapt and tailor its agricultural endeavours to harmonize with diverse climatic realities. Such diversified cultivation practices collectively contribute to the resilience and viability of the agricultural sector in the face of shifting environmental dynamics.

Table 3.4.9 | Crops, the most cultivated on saline and sodic soils in the Near East and North Africa (NENA) region

Crop	Countries										
	Algeria	Egypt	Islamic Republic of Iran	Kuwait	Lebanon	Libya	Sudan	Syrian Arab Republic	Tunisia	United Arab Emirates	Yemen
Rice		√									
Cotton		√	√				√	√	√		√
Barley	√	√	√	√	√	√	√	√	√		√
Alfalfa	√	√					√	√			√
Sorghum	√	√	√	√			√	√	√		
Tall wheatgrass						√					
Halophytes (e.g. quinoa (*Chenopodium quinoa*), *Atriplex* sp., *Salicornia* sp., saltgrass (*Distichlis spicata*), etc.)		√	√		√				√		
Non-conventional crops (amaranth or others)			√ Sugar beet, pistachio			√	√				√
Millet					√						
Date palm			√							√	

Regrettably, a critical gap persists across the surveyed countries within the region about the national assessment of yield losses attributed to soil salinity and sodicity. Similarly, the potential yield gains ensuing from reclamation efforts or other enhancements of SAS remain unknown. This significant absence of any assessment underscores the pressing need to extend support to the NENA countries in this crucial area.

Addressing this gap is of paramount importance, as such assessments provide invaluable insights into the economic and agricultural impacts of soil salinity and sodicity. By quantifying yield losses, countries can gain a deeper understanding of the magnitude of the challenge at hand. Similarly, gauging the yield gains achievable through reclamation or soil improvement endeavours provides a roadmap for sustainable growth and enhanced productivity.

It is imperative to recognize that such assessments extend far beyond the realm of data collection, as they serve as strategic cornerstones in formulating targeted policies, interventions, and resource allocations. Armed with accurate and comprehensive data, countries can steer their efforts more effectively, promoting efficient soil management, bolstered yields, and improved income for agricultural communities.

The absence of these assessments not only underscores an existing gap but also illuminates an opportunity. By rallying support to facilitate and promote comprehensive national assessments, it is possible to collectively advance the cause of SSM, drive productivity, and contribute to the overarching goal of fostering agricultural prosperity within the region.

Indicators used by crop scientists for salt-affected soils

The core soil parameters assessed by crop scientists in the NENA countries for cultivating plants in SAS are similar to those assessed in other regions, and offer essential insights and the requisite information and data for sustainably managing SAS. The Sudan relies on a comprehensive set of parameters, including electrical conductivity, pH, ESP, and SAR, as well as soluble cations and anions such as Na^+, K^+, Ca^{2+}, Mg^{2+}, Cl^-, HCO_3^-, CO_3^{2-}, SO_4^{2-}, and calcium carbonate equivalent. Similarly, Yemen's approach involves cultivating salt-tolerant crops like barley, okra, sesame, and alfalfa, tailored to the unique soil conditions, Egypt's focus extends to yield production, fruit weight, bunch weight, seed weight, and flesh weight, indicating an emphasis on quantifiable crop outcomes.

Algeria concentrates its assessments primarily on EC and pH, while the Libyan approach (similar in some respects to Algeria [EC and pH]), introduces an additional layer by incorporating carbonate content. While these parameters are integral to soil assessment, it is apparent that in certain contexts, they may fall short of providing the comprehensive information required by crop scientists. The complexity of agricultural ecosystems demands a holistic understanding that encompasses a broader spectrum of soil attributes.

Models of crop response to soil salinity and sodicity

The utilization of crop response models under varying stress conditions, particularly in the context of soil salinity and sodicity, stands as a pivotal tool in fostering sustainable crop production management. Within the NENA region, insights gathered from responses to questionnaires revealed that the deployment of such models is a practice observed in only four countries: the Islamic Republic of Iran, Lebanon, Libya, and the Sudan. However, it is noteworthy that while these models are not extensively adopted across the region, their significance remains undeniable.

In the Islamic Republic of Iran, a more robust utilization of models is evident, with the Soil Water Atmosphere Plant (SWAP) model, Aquacrop, and LEACHC playing instrumental roles. These models incorporate soil management practices as variables impacting crop growth. For instance, the filtration coefficient of the soil (Ks) value is manipulated to assess the influence of mulches on salt balance in the root zone. Parameters such as crop type, total soluble salts, soil physical properties, weather data, and irrigation management enrich the modelling process.

Libya's adoption of the Decision Support System for Agrotechnology Transfer (DSSAT) model is particularly noteworthy, addressing a spectrum of challenges encompassing genetic modelling, onfarm management, climate impact assessments, sustainability evaluation, and food security. While some soil management practices are integrated (including basic soil properties and nutrients), variables such as crop type, planting specifications, salinity and sodicity electrical conductivity, total soluble salts, climatic data, and crop management further contribute to the model's comprehensive scope.

In the Sudan, the application of models is primarily confined to research centres and universities, representing a potential avenue for broader implementation. However, where no information about the soil management practices in these models exist, some other variables are used, such as crop type, planting specifications, salinity and alkalinity. Lebanon, on the other hand, leverages models for the creation of a national soil salinity map, which draws on the GSP-FAO harmonization of national input data (FAO, 2020b), spatial modelling of soil indicators, and cross-validation data for soil classification. It is important to note that in Lebanon's model, factors such as soil management practices are currently excluded, warranting future consideration to comprehensively address secondary soil salinity dynamics.

The majority of surveyed countries did not respond regarding the utilization of crop response models for assessing the impact of soil salinity on crop yield.

In light of these findings, the limited application of crop response models highlights a potential avenue for enhancement and expansion. The broader adoption of these models holds significant promise, offering a structured approach to better comprehend the intricate interplay between soil conditions and crop performance. As the region navigates the intricacies of sustainable crop production, the strategic integration of these models could unlock valuable insights, empower informed decisionmaking, and ultimately drive resilient agricultural practices in the face of salinity challenges.

Scenarios of crop production under different abiotic stresses in the region have very limited distribution, and most of the surveyed countries did not provide any response. However, the Islamic Republic of Iran, Libya, the Sudan, and Yemen reported the absence of such scenarios, and only Lebanon had some data, as reported by Abdallah *et al.* (2013 and 2019) about flood risk and response to abiotic hazards.

Across the region, most of the surveyed countries reported the absence of assessments at the national or local level, despite the cost of inaction in case of growing salinity or sodicity. However, Algeria, Egypt, and the Syrian Arab Republic did not record any response about the assessments.

Areas of irrigated farmland and its exposure to salinization/sodification

The NENA region boasts one of the oldest areas with a history of irrigated civilization worldwide. However, the extent of irrigated land varies across countries. Based on collected questionnaire data, some countries have provided information on irrigated farmland areas. For instance, in Iran, 6.8 Mha of irrigated cropland is faced to different level of salinity, in Tunisia, the irrigation land area is around 0.496 Mha (MARHP, 2019), Libya's area is approximately 610 000 ha (according to the Land Resources Mapping for Agricultural Use project in 2007), Lebanon is around 113 000 ha (source: UNHCR), the United Arab Emirates covers 246 797 ha (data from the Environmental Agency Abu Dhabi), Syrian Arab Republic encompasses around 1 092 000 ha (Syrian Arab Republic Statistical Group, 2021), and Republic of Yemen spans roughly 500 000 ha (Al-Mashreki, 2022) and Egypt has around 3 Mha of irrigated farmland (Kotb *et al.*, 2000; USAID, 2023).

Nevertheless, official statistics concerning the impact of salinity and sodicity on irrigated farmland are scarce in most NENA countries. Egypt, the United Arab Emirates, and Yemen are exceptions, although Yemen's information is not publicly accessible, Egypt mentioned that about 25 percent of farmland is affected by soil salinity and sodicity

(http://www2.mans.edu.eg/projects/heepf/ilppp/cources/12/pdf).

The Syrian Arab Republic did not provide relevant information, and comprehensive national assessments of secondary salinized and sodified soil areas in these countries are limited. Lebanon (Darwish *et al.*, 2005) and Tunisia mention having a national assessment for secondary salinization.

The NENA countries primarily employ variations of surface irrigation (such as basin/flood and furrow irrigation), sprinkler, and drip irrigation, In Egypt, drip irrigation is the unique method used for irrigation (Organic Egypt, 2022). Manual irrigation is unique in Tunisia, while uncontrolled surface irrigation is prevalent in the Syrian Arab Republic and Yemen. Border irrigation is observed in the Islamic Republic of Iran and Kuwait.

Irrigation water quality monitoring

The NENA region is one of the most water-scarce areas globally, which drives the utilization of available water resources for irrigation, particularly brackish water. Based on questionnaire responses, many countries within the region choose brackish water irrigation, although statistics about the extent of land irrigated using this water type remain lacking. The United Arab Emirates has officially reported data on its use of brackish water, where nearly half of the shallow aquifer groundwater (44 percent) is categorized as saline water unfit for use, while 53 percent comprises of brackish water suitable to a certain degree for agriculture. Only 3 percent of shallow aquifer groundwater meets freshwater quality standards (TDS < 1 500 mg/l).

In Egypt, brackish water is used but there is no data on its area of use. Libya, the Sudan and Tunisia have confirmed their non-use of brackish water for irrigation. However, there is a planned adoption of such use in Libya. As for regulations governing irrigation using brackish water, the Syrian Arab Republic was the only country with a stringent framework (though unverified by questionnaire sources). Algeria and the United Arab Emirates lacked information on such regulations, while other countries indicated an absence of such provisions. Crops irrigated with brackish water are presented in Table 3.4.10.

Table 3.4.10 | Some crops irrigated with brackish water in the countries of the Near East and North Africa (NENA) region

Crop	Countries										
	Algeria	Egypt	Islamic Republic of Iran	Kuwait	Lebanon	Libya	Sudan	Syrian Arab Republic	Tunisia	United Arab Emirates	Yemen
Rice											
Cotton			√								
Barley	√		√	√					√		
Alfalfa	√										√
Sorghum	√		√	√					√		
Tall wheatgrass											
Halophytes (e.g. quinoa (*Chenopodium quinoa*), *Atriplex* sp., *Salicornia* sp., saltgrass (*Distichlis spicata*), etc.)		√	√						√		
Non-conventional crops (amaranth or others)			√ Sugar beet, pistachio					√			
Salt-tolerant vegetable crops					√						√
Corn									√		
Wheat			√						√		
Date palm			√							√	

Various strategies are employed across different countries to counteract soil salinity and sodicity resulting from brackish water irrigation. For instance, Algeria use enhanced drainage systems, while the Islamic Republic of Iran employs a comprehensive approach encompassing the development of irrigation systems, drainage networks, optimised leaching approach, deeprooted plant cropping, refined irrigation management, and the application of sand mulches to curtail salt accumulation. Kuwait focuses on refining water percolation and irrigation practices.

Lebanon has adopted the practice of blending brackish water with fresh water. Libya emphasizes the establishment of drainage networks and enhanced irrigation management. The Syrian Arab Republic combines the development of drainage systems with advanced irrigation management and the integration of fresh water. The United Arab Emirates employs the blending of brackish water with fresh water, and the Republic of Yemen employs a mixed approach involving the infusion of fresh water, restricted usage of coarse-textured soils, and hydroponics.

It is important to note that salinization and sodification threats are not uniformly addressed in these practices. The Sudan, as indicated by the questionnaire responses, currently does not require specific countermeasures in this regard. Egypt has adopted improved irrigation management, through mixing saline with fresh water and improved drainage, using both traditional open drainage and buried experimental drain tiles (Hassan *et al.*, 2017).

Table 3.4.11 illustrates the criteria employed by NENA region countries to evaluate the suitability of water for irrigation. Across all surveyed nations, EC emerges as the predominant criterion. Sodium adsorption ratio is widely utilized, though not in Lebanon and Kuwait. pH is considered in assessing water quality in Lebanon, Libya, the Sudan, Tunisia, and the United Arab Emirates. The Islamic Republic of Iran and the Sudan employ a more extensive set of criteria by providing used thresholds, including RSC (less than 2.25), boron (B) levels (1–2 ppm), salinity hazard, and sodium hazard. The United Arab Emirates is the only one of the surveyed countries in the region that uses the whole list of criteria suggested by the FAO methodology (FAO, 1988).

Table 3.4.11 | The criteria used to assess the irrigation water quality in Near East and North Africa (NENA) region countries

Criteria	Countries										
	Algeria	Egypt	Islamic Republic of Iran	Kuwait	Lebanon	Libya	Sudan	Syrian Arab Republic	Tunisia	United Arab Emirates	Yemen
Water electrical conductivity	√		√	√	√	√	√ (750–2 250 micromhos/cm)	√	√	√	√
SAR of water	√		√	√		√	√ (less than 10)	√	√	√	√
Total dissolved solids	√	√							√	√	
Total soluble salts	√		√							√	√
pH			√		√	√	√ (6.5–7.2)		√	√	
Toxic ions			√				√	√		√	
Others							√				

Furthermore, most of the countries considered that the abovementioned criteria are enough to avoid salinization and sodification when brackish water is used, but the Islamic Republic of Iran also suggested the Mg:Ca ratio.

While brackish water is used widely within the countries of the region, irrigation water monitoring systems are often not used, although there is agreement on their necessity. The only countries that implement the monitoring system are Egypt and the United Arab Emirates. In the United Arab Emirates, after the successful development of the Groundwater Quality Baseline Survey in 2019, in 2020, EAD started the Trend Assessment Phase of Groundwater Quality. As part of this phase, 155 groundwater samples were collected from target sites across the Emirate of Abu Dhabi and analysed in an accredited laboratory. The lab analysis covered the basic parameters of groundwater quality, in addition to a set of target potential contaminants relevant to all types of land uses, however, it is not integrated with the soil salinity and sodicity monitoring system, as they work separately, but there is some coordination or exchange of data (data sharing within the same organization). In Egypt and the Islamic Republic of Iran, there are four basic criteria for evaluating water quality for irrigation purposes:

- Total content of soluble salts (salinity hazard)
- Relative proportion of Na^{+} to Ca^{2+} and Mg^{2+} ions: SAR (sodium hazard)
- Residual sodium carbonates (RSC): bicarbonate (HCO^{3-}) and carbonate (CO_3^{2-}) anions concentration, as it relates to Ca^{2+} plus Mg^{2+} ions.
- Excessive concentrations of elements that cause an ionic imbalance in plants or plant toxicity.

To achieve the first three criteria, the following characteristics need to be determined in the irrigation water: EC, soluble anions (CO_3^{2-}, HCO_3^-, Cl^- and SO_4^{2-}) where Cl- and SO_4^{2-} are optional and soluble cations (Na^+, K^+, Ca^{2+}, Mg^{2+}) where K is optional. Finally, the B level must also be measured. The pH of the irrigation water is not an acceptable criterion of water quality because the water pH tends to be buffered by the soil, and most crops can tolerate a wide pH range. A detailed description of the techniques commonly employed for the analysis of irrigation water is available (USDA, 1954; Bresler, McNeal and Carter, 1982).

In the Islamic Republic of Iran, there are many cases of irrigation water with SAR values above 13 but in these cases the EC is high and using these types of water in irrigation is risk-free for sodification. Farmers and most experts are used to only considering the SAR value in interpolating the results and will therefore recommend reclamation methods. However, it is crucial to convince the applicants that they consider both indicators (EC and SAR), as recommended in FAO (1985).

The contribution of irrigation water quality on soil salinization/sodification is the main factor in increasing soil salinization and sodification in most countries of the region, however, there is no data available apart from in the United Arab Emirates (EAD, 2019). Libya considered the contribution of irrigation water quality on soil salinization/sodification significant, but not the leading one.

Soil and irrigation management practices, in addition to soil characteristics, determine the possibility of soil salinity and alkalinity. Lebanon and the Sudan reported about the absence of data about the contribution of irrigation water in the salinization and sodification, while in Egypt, around 30 to 40 percent of the land in the Nile Delta is salt-affected. The soils with moderate salinity levels (4–8 dS/m) have the best potential for the implementation of salt-tolerant crops (Al-Agha *et al*, 2015).

Practices employed within the surveyed countries in the NENA region to enhance the quality of irrigation water primarily fall into two categories:

- **Water desalination:** This practice is prevalent in several countries, including the Islamic Republic of Iran, Kuwait, Tunisia, and the United Arab Emirates. It involves the process of removing salts and minerals from water, making it suitable for irrigation purposes.
- **Water mixing:** Utilized in countries like Egypt, Libya, Lebanon, the Syrian Arab Republic, the United Arab Emirates, and Yemen, this approach involves blending different sources of water – often combining saline and freshwater – to achieve a balanced water composition suitable for irrigation.

Algeria and the Sudan have confirmed the absence of any specific practices aimed at improving the quality of irrigation water.

Groundwater monitoring in the Near East and North Africa (NENA) region

Groundwater plays a significant and sometimes leading role in contributing to soil salinization and sodification. The elevation of the water table can result in the excessive accumulation of salts within the root zone, thereby necessitating vigilant monitoring. This monitoring process serves as a crucial tool for mitigating soil salinity and sodicity on agricultural lands.

Findings from the conducted questionnaires reveal that only a handful of countries have established comprehensive groundwater monitoring systems. For instance, in Libya, the foundation of their groundwater monitoring mechanism is through the oversight of monitoring wells by either the General Authority for Water or the Ministry of Water Resources. The Industrial River Project also supervises groundwater wells to ensure effective monitoring.

In Egypt, the principles of a groundwater monitoring system were considered by applying a genetic algorithm and the factorial kriging method for nine variables – EC, TDS, Cl^-, Na^+, Ca^{2+}, Mg^{2+}, SO_4^{2-}, manganese (Mn), and iron (Fe) – for the optimal selection of monitoring wells (Yeh *et al*, 2006).

In Yemen, the General Authority for Water Resources, operating under the Ministry of Water and Environment, bears the responsibility of executing groundwater monitoring activities through a network of monitoring wells. This authority also holds the power to issue permits for the excavation of artesian wells, primarily employed for agricultural irrigation purposes.

In contrast, there is a lack of available information regarding the operational intricacies of groundwater monitoring systems in Kuwait and the United Arab Emirates. These aspects remain unexplored.

The majority of surveyed countries do not have functional groundwater monitoring systems in place, although a significant demand for their implementation is evident. Noteworthy exceptions include the Syrian Arab Republic, where the existence of such monitoring systems has not been reported.

It is important to note that groundwater monitoring systems usually operate in tandem with soil salinity and sodicity monitoring, but this integration is observed only in Egypt and Libya. However, in Kuwait and the United Arab Emirates, these systems function independently, albeit with some level of coordination, specifically within the United Arab Emirates.

The effectiveness of constructed irrigation systems varies across the region, with some notable patterns. In Algeria and Tunisia, these systems cover the entire area and effectively shield soils from salinization and sodification. In Egypt, around 30 to 40 percent of the land in the Nile Delta is salt-affected. The soils with moderate salinity levels (4 to 8 dS/m) have the best potential for the implementation of salt-tolerant crops, as the drainage systems do not work well enough to leach the majority of the salts. This area is characterized by a high ground water level (FAO, 2005; Al-Agha *et al.*, 2015). In the Sudan, they have been successfully implemented in a majority of the irrigated regions. However, in the other surveyed countries, there are significant challenges with the performance of constructed drainage systems that span vast stretches of irrigated farmlands. This disparity arises from diverse factors.

For instance, in Libya, the functionality of irrigation systems faces notable gaps. National agricultural reports highlight numerous soilrelated issues within these regions. These challenges are linked to irrigation systems, including their inefficiency and inadequate soil management within centre pivot irrigation, leading to soil compaction. Moreover, certain irrigation systems do not align well with the specific characteristics of the underlying soil.

In Lebanon, the Participatory Water Saving Management and Water Cultural Heritage country report of 2008 reveals that the majority of irrigation projects exhibit improper functionality.

Conversely, in the Islamic Republic of Iran, Kuwait, the Syrian Arab Republic, and Yemen, there is limited information available about the reasons behind the inadequate performance of irrigation systems. Additionally, the United Arab Emirates has not provided any reported data concerning the status of its irrigation systems.

Agrohydrological models to evaluate water management in salt-affected soils

Agrohydrological models represent a contemporary tool with significant potential for predicting, assessing, and mitigating water management challenges, as well as addressing soil salinization and sodification issues. These models offer a crucial avenue for enhancing the condition of saline and alkaline soils. However, within the NENA region, the adoption of these models remains limited.

According to the questionnaire responses, the utilization of such models is sparse. The Sudan stands out as a case where agrohydrological models are employed, particularly in conjunction with the Soil Information System Project. In the Sudan, the soil, climate, organisms, relief, parent materials, age and spatial location (SCORPAN) model assumes a prominent role, operating on a national scale to generate and predict maps of SAS. This model relies on data encompassing soil organisms, topography, parent material, and weather conditions, and establishes a mathematical correlation between the target soil attribute and its predictors, encapsulating the representation of soilforming factors. This model is underpinned by the Digital Soil Map (DSM) approach, as outlined by McBratney *et al.* in 2003.

In Egypt, the HYDRUS-3D model simultaneously solves transport problems in the soil volume and provides more realistic calculations of the soil water distribution around the drip emitter.

In addition, a successful water management scheme for irrigated crops requires an integrated approach that accounts for water, plant, soil, and field management. For that purpose, the SALTMED model has been developed. The model's input consists of climate data, soil data, crop data, irrigation data (system, amount, salinity), soil and crop parameters, and other model parameters. The daily potential and actual evapotranspiration were calculated using the Penman-Monteith equation (FAO, 1998). The model runs for a variety of irrigation systems, crops, soils, and water salinity levels. The daily model output (graphs and data files) includes yield, potential and actual water uptake, salinity, soil matric potential and soil moisture profiles, crop water requirements, leaching requirements, plant growth parameters, potential and actual evapotranspiration, bare soil evaporation and plant transpiration. The model is easy to use (Ragab, 2002).

In the Islamic Republic of Iran, the assessment of the irrigation systems (furrow and tape) was carried out in the Sistan plain using Hydrus 1/2/3D (a quasi3D modelling approach). The work also aimed to evaluate soil hydraulics, layers, the chemical composition and salinity and sodicity status for the short to long term (Rezaei, 2020, 2022, 2023; Rezaei *et al.*, 2023). The results demonstrate that drip irrigation is not a good practice to be extended in such regions and in similar areas.

Both Algeria and Yemen have explicitly stated the lack of implementation of such models. Furthermore, there is a notable absence of information regarding the utilization of these models in the remaining surveyed countries within the region.

The models used to evaluate the spatial variability of soil salinization consider ground or surface water, so soil management practices, water quality and management and crop specifics are either not applicable or no information was available, apart from the Sudan, who references Omuto *et al.* (2022).

When considering national or local water management scenarios, it is important to highlight that information regarding the existence of such scenarios was acknowledged by the countries that responded. Egypt, the Islamic Republic of Iran, Libya, and Lebanon, for instance, confirmed the presence of these scenarios in their respective contexts. However, there was a lack of information from Algeria, Kuwait, the Syrian Arab Republic, and the United Arab Emirates. Furthermore, the Sudan, Tunisia, and Yemen all stated the absence of such scenarios.

In the case of Libya, specific scenarios were outlined in the 2006 Water Resources in Libya report, published by the General Authority for Water. Similarly, in Lebanon, Darwish *et al.* (2002, 2006, 2015) highlighted the implementation of deficit irrigation strategies on potatoes as part of their water management approach. In Egypt, using the framework proposed by Molle *et al.* (2015), these scenarios are applicable.

Risk assessments that were implemented using hydrological models of soil salinization have limited application in the region. According to the questionnaire answers, Egypt and Tunisia are the only countries who use this method for their risk assessments. Egypt uses projected climate data and Tunisia uses remotelysensed data (LADA PROJECT).

Leaching and drainage on salt-affected soils

Distinct drainage systems are employed across the various countries in the region, as detailed in Table 3.4.12. Among these systems, shallow ditches and subsurface drainage (deep open drains) emerge as the most prevalent methods. Notably, controlled drainage is conspicuously absent in the countries that participated in the survey. The Islamic Republic of Iran initiated controlled drainage in the Gorgan region and Khuzestan provinces but limited information is available. Yemen reported a complete lack of any implemented drainage systems. On the other hand, the Syrian Arab Republic exclusively employs vertical drainage, with other techniques being implemented in a limited form. Libya and the United Arab Emirates have not provided any data about this topic.

Table 3.4.12 | Type of drainage system implemented in the Near East and North Africa (NENA) region

Drainage system	Countries										
	Algeria	Egypt	Islamic Republic of Iran	Kuwait	Lebanon	Libya	Sudan	Syrian Arab Republic	Tunisia	United Arab Emirates	Yemen
Surface drainage (shallow ditches)	√		√		√	No data	√	√	√	No data	No data
Subsurface drainage (deep open drains)	√		√	√		No data			√	No data	No data
Subsurface drainage (buried pipe drains)		√	√			No data		√		No data	No data
Controlled drainage						No data				No data	No data
Others			Sequential drainage			No data		Vertical drainage		No data	No data

Criteria used for designing the drainage systems are illustrated in Table 3.4.13.

Table 3.4.13 | The criteria used to design the drainage system

Criteria	Countries										
	Algeria	Egypt	Islamic Republic of Iran	Kuwait	Lebanon	Libya	Sudan	Syrian Arab Republic	Tunisia	United Arab Emirates	Yemen
Soil parameters		√	√	√		No data	√	√		No data	No data
Water parameters	Water table		Water table			No data	√	√	√	No data	No data
Soil hydraulic/ physical properties (infiltration, compaction, soil layers)			√		√	No data	√	√	√	No data	No data
Others						No data				No data	No data

Based on the established drainage system, leaching stands out as the principal method for alleviating soil salinity. This crucial practice can be executed through various approaches. In the NENA region, the predominant forms of leaching are through flooding and sprinkler irrigation. Regrettably, pertinent data from Lebanon, the United Arab Emirates, and Yemen are absent, as illustrated in Table 3.4.14.

Table 3.4.14 | Type of leaching of saline soils used in the Near East and North Africa (NENA) region

Leaching type	Countries										
	Algeria	Egypt	Islamic Republic of Iran	Kuwait	Lebanon	Libya	Sudan	Syrian Arab Republic	Tunisia	United Arab Emirates	Yemen
Flooding	√	√	√		No data		√	√	√	No data	No data
Sprinkler		√	√	√		√		√			
Drip		√		√							
Others						√					

Based on the responses to the questionnaire, the quantity of leaching water is typically determined through various methodologies, including the utilization of FAO protocols adopted in countries such as Algeria, Kuwait, the Sudan, and the Syrian Arab Republic. The USDA-ARS and U.S. Salinity Laboratory's approach (U.S. Salinity Laboratory Staff, 1954), as adapted by Rhoades (1974), is employed in Egypt and some areas of the Islamic Republic of Iran. In Lebanon and Libya, indigenous knowledge is applied, while experiences and water availability govern the process in the Islamic Republic of Iran. National protocols are followed in Tunisia. However, no data is available for Yemen and the United Arab Emirates. These leaching practices are conducted before sowing and tillage, as practiced in the Sudan and the Syrian Arab Republic, or during the growing season as practiced in Algeria, Egypt, Libya, Tunisia, and the Syrian Arab Republic.

Conclusions

- Salt-affected soils have a wide distribution across the countries of the NENA region, and according to the received information, the most extended SAS areas occur in Kuwait with 38 percent of the total country area, the Islamic Republic of Iran with 31.8 percent, and the United Arab Emirates with 22.9 percent.
- Different methods are used for the measurement of soil salinity and sodicity in the region. The most common method involves determining EC in saturated paste extract, followed by calculating total soluble salts. Data harmonization and development of conversion equations are crucial for this region.
- Electromagnetic methods have very limited use in the NENA region, where it is used only in the Islamic Republic of Iran and very locally in Algeria and Tunisia among the surveyed countries. It is highly recommended that this mapping technique is disseminated among the countries of the region.
- The mapping of SAS still needs to be improved and updated, as mapping is achieved with a mostly outdated method and maps are kept in a paper format.
- Monitoring of SAS is not performed in most of the surveyed countries within the region. Further information is needed and a meta-analysis of SAS monitoring of the management of this region is recommended.
- The SSM of SAS is used in the countries of the NENA region. However, there are no statistics available to understand its scale.
- A critical gap persists across the surveyed countries within the NENA region about the national assessment of yield losses attributed to soil salinity and sodicity. Similarly, the potential yield gains ensuing from reclamation efforts or other enhancements of SAS remain unexplored. By quantifying yield losses, countries can garner a deeper understanding of the magnitude of the challenge at hand. Similarly, gauging the yield gains achievable through reclamation or soil improvement endeavours can provide a roadmap for sustainable growth and enhanced productivity.

- Agrohydrological models have limited use across the region, although they provide contemporary tools with significant potential for predicting, assessing, and mitigating water management challenges, as well as addressing soil salinization and sodification issues. It is highly recommended that these are introduced and implemented widely in the NENA region.
- Across surveyed NENA countries, a noticeable deficiency in policies governing the management of salt-affected soil is evident, despite a prevailing consensus on the necessity of such regulations. The absence of comprehensive policies in this domain is of widespread concern. However, an exception to this trend is observed in the United Arab Emirates, where a policy specifically targeting the management of soil – particularly salt-affected soil – has been established.
- Brackish water is used widely within the countries of the NENA region. However, irrigation water monitoring systems are not used in most countries, although there is a consensus that establishing such monitoring systems is necessary.

3.5 | North America

Introduction

The status of salt-affected soils in the North American region (here to be taken as Canada and the United States of America) is a matter of significant environmental concern and scientific interest. These soils, often referred to as saline or sodic soils, represent a distinctive category within the broader spectrum of soil types found across the continent. Their presence and extent are influenced by various natural and anthropogenic factors, including climate, geology, land use, and agricultural practices. In this introduction, we will provide an overview of the current state of salt-affected soils in the North American region, highlighting their prevalence, causes, ecological implications, and ongoing research efforts.

Salt-affected soils are characterized by high concentrations of soluble salts, such as sodium, calcium, and magnesium ions, which can have detrimental effects on soil quality and plant growth. The North American region exhibits a diverse range of soil types due to its vast geographical extent and varying climatic conditions. Consequently, the distribution and severity of salt-affected soils vary across different regions within the North American region.

The causes of soil salinity in the North American region are multifaceted, with natural processes, such as geologic salt deposits and arid climates, contributing to the issue. However, human activities, particularly in agriculture and irrigation, have played a significant role both solving and in exacerbating soil salinity problems. The misuse of water resources, improper irrigation practices, and inadequate drainage systems have led to the accumulation of salts in the soil, affecting both crop productivity and the overall health of ecosystems.

Understanding the status of salt-affected soils in the North American region is crucial for sustainable land management, as these soils present unique challenges and opportunities for mitigation. Researchers, policymakers and land managers are actively engaged in studying these soils, developing strategies to combat salinity issues and promoting best practices in agricultural management. In this chapter we want to explore the status of measurement, mapping, and monitoring of salt-affected soils, the sustainable soil management, crop production and water management in saline and sodic environments, and the regional variations, ecological impacts, and ongoing efforts to address salt-affected soils in the North American region.

The synthesis produced in this chapter is based on the survey distributed through the International Network of Salt-affected Soils (INSAS). The questionnaire prepared within the network included 104 questions divided into 20 sections.

For the North American region, two questionnaires were submitted, one representing Canada, and the other, for the United States.

Measurement, mapping, and monitoring

The total area of salt-affected soils in the North American region is 77 991 200 ha, according to assessments given in Chapter 1. The total surface area of salt-affected soils in the United States of America according to Soil Survey Staff (2023) is 90.8 million ha. The area of salt-affected soils in Canada, according to this report (Annex 2) is 9.4 million ha of salt-affected soils at a depth of 0 to 30 cm depth and 45.8 million ha of salt-affected soils at a depth of 30 to 100 cm.

Table 3.5.1 | Area of salt-affected, saline, sodic, and saline sodic soils in the United States and Canada

Country name	Area of salt-affected soils (Mha)	Area of saline soils (Mha)	Area of sodic soils (Mha)	Saline sodic soils (Mha)	References
United States	90.805	68.067	4.198		Soil Survey Staff (2023)
Canada	9.4 (0–30 cm) 45.8 (30–100 cm)				this report (Annex 2), contributors to GSASmap: J. Juanxia He, X. Geng and B. VandenBygaart

Note: Mha + million hectares.

Sources: **Soil Survey Staff**. 2023. Gridded National Soil Survey Geographic Database (gNATSGO) for the Conterminous United States. Washington, DC., USDANRCS. [Cited 2023].
https://nrcs.app.box.com/v/soils

When it comes to assessing soil salinity and sodicity, there is some degree of standardization in the methods employed. However, as shown in Table 3.5.2, it is evident that the two countries often utilize different approaches, with varied methods being applied to measure soil salinity (Soil Survey Staff, 2022b; Miller and Curtin, 2007). The most prevalent approach involves measuring the electrical conductivity (EC) of an extract from a saturated paste, followed by the computation of total soluble salts, encompassing ions such as Na^+, Mg^{2+}, Cl^-, SO_4^{2-}, HCO_3^-, and CO_3^{2-}.

The electromagnetic method is utilized in both surveyed countries. In Canada, it encompasses a substantial land area of over 100 000 ha, whereas in the United States, it is applied to a far smaller area of less than 1 000 ha. Additionally, there is diversity in the devices used for the electromagnetic method. In the United States, sensor devices such as DUALEM-1S, EM38-MK2, and Profiler 400-EMP are employed, while in Canada, Geonics EM38-MK2 is used in Alberta and Saskatchewan, and Veris MSP3 in Manitoba.

Table 3.5.2 | Chemical methods that are used in the North American region to measure soil salinity

Method	Countries	
	United States	Canada
Electrical conductivity in saturated paste extract	√	√
Electrical conductivity at 1:1 soil-to-water ratio		√
Electrical conductivity at 1:2 soil-to-water ratio	√	√
Electrical conductivity at 1:2.5 soil-to-water ratio		
Electrical conductivity at 1:5 soil-to-water ratio	√	
Electrical conductivity at 1:10 soil-to-water ratio		
Total dissolved solids (by gravimetric analysis)		
Total soluble salts (calculated as the sum of Na^+, Mg^{2+}, Cl^-, SO_4^{2-}, HCO_3^- and CO_3^{2-})	√	
Content of soluble Na^+	√	√
Content of soluble Cl^-	√	
Others	√	

In terms of soil sodicity determination (Table 3.5.3), the most common shared method in Canada and the United States are the sodium adsorption ratio (SAR), while the exchangeable sodium percentage (ESP) and the morphological methods (such as the structure of the sodic and solonetzic horizon) are used in the United States (Soil Survey Staff, 1999, 2022b).

Table 3.5.3 | Methods of determining soil sodicity used in the North American region

Method	Countries	
	United States	Canada
Exchangeable sodium proportion (ESP)	√	
Sodium adsorption ratio (SAR)	√	√
Physical methods (specific swelling, low infiltration rate etc.)		
Morphological methods (structure of sodic/solonetzic horizon etc.)	√	
Others		

There are a few different ways for determining exchangeable Na^+ when measuring the parameters of soil sodicity (Table 3.5.3 and Table 3.5.4).

Table 3.5.4 | Methods of determination of exchangeable Na^+ and their distribution over the North American region

Method	Country	
	United States	Canada
Salt removal (step 1), cation exchange (step 2), measurement of Na^+ (step 3)		√
Without salt removal, measurement of soluble Na+ (step 1), cation exchange (step 2), measurement of Na^+ (step 3), recalculation of exchangeable Na^+ based on the subtraction of soluble Na+ from total Na^+ (step 4)	√	
Without salt removal, cation exchange (step 1), measurement of Na^+ (step 2).		
Others		

When measuring cation exchange capacity (CEC) (Table 3.5.5), in Canada, the most common methods used for measuring CEC are the ammonium acetate extraction method (buffered at pH 7) and ammonium chloride extraction method (Kalra and Maynard, 1991; Government of Canada, 1984). In the United States, the only method used is ammonium acetate extraction (buffered at pH 7) (Soil Survey Staff, 2022b).

Table 3.5.5 | Method of measurement of cation exchange capacity and their distribution

Method	Country	
	United States	Canada
Ammonium acetate extraction (buffered at pH 7)	√	√
Ammonium chloride extraction		√
Triethanolamine buffered barium chloride extraction (buffered at pH 8.2)		
Hexamminecobalt(III) chloride extraction		
Others (sodium acetate extraction)		
Not applicable (CEC not measured)		

The most common method for measuring the sodium adsorption ratio (SAR) in both Canada and the United States is by calculating the content of Ca^{2+}, Mg^{2+}, and Na^{+} in the saturated soil paste extract (Soil Survey Staff, 2022b). Both countries, also measure soil sodicity by using morphological methods such as the specific structure of the sodic and solonetzic horizon, as reported in the questionnaires. In Canada, some additional physical methods are used, such as hydraulic conductivity.

Various methods and different approaches are employed to determine soil alkalinity and soil pH by both countries (Table 3.5.6). The most prevalent technique for pH measurement involves using saturated paste extract and a soil:water extract at 1:1 (Soil Survey Staff, 2022b). In Canada, the soil pH is also measured in a solution of $CaCl_2$ at 1:2.5.

Table 3.5.6 | Method of pH measurement and their application

Method	Country	
	United States	Canada
Soil pH (extract of saturated paste)	√	√
Soil pH (soil:water 1:1)	√	√
Soil pH (soil:water 1:2)		
Soil pH (soil:water 1:2.5)		
Soil pH (soil:water 1:5)		
Soil pH ($CaCl_2$ 1:2.5)		√
Total alkalinity, or content of alkaline anions (with methyl orange and phenolphthalein indicators)		
Others		

Regarding the harmonization of soil analysis, as reported in the questionnaires, Canada has harmonization across the country, and do not have any difficulties when comparing data with the data from other countries. In the United States, no information about harmonization across the country was reported, and there are difficulties when comparing their data with the data from other countries and so the harmonization among countries is needed. Soil analysis harmonization for the United States is important when publishing in high-quality journals, communication and the exchange of experience between scientists/practitioners, and comparability of data in soil databases. In Canada, harmonization is important for the national and regional soil monitoring system, communication and the exchange of experience between scientists/practitioners, comparability of data in soil databases, the development of recommendations to farmers, and promoting standardization between commercial soil testing laboratories. It is worth mentioning that there are no widely established robust conversion equations used in either country between the results of the different measurement methods for soil salinity and sodicity.

Saline and sodic soil classification systems used in the North American region

Based on the questionnaire responses, it was found that each country uses a different classification of soil salinity and sodicity. For example, the United States uses the classification system as laid out in USSL Staff (1954) and Soil Science Division Staff (2017). In Canada, the system uses the Canadian System of Soil Classification (Agriculture Canada, 2016; Government of Alberta, 1993, 2000, 2023).

There is also no harmonization regarding the thresholds between saline and nonsaline soils. Canada uses a threshold of both 2 dS/m and 4 dS/m, (Alberta Agriculture, Food and Rural Development, 2004; Government of Alberta, 2001) while the United States only uses only 2 dS/m.

Regarding soil sodicity, (according to the questionnaire responses), in Canada, only the threshold of >13 sodium adsorption ratio (SAR) is used (Alberta Agriculture, Food and Rural Development, 2004) while in the United States, both the >15% exchangeable sodium proportion (ESP) and >13 SAR are implemented (USSL Staff, 1954; Soil Survey Staff, 1999).

Status of soil salinity and sodicity mapping in the North American region

Regarding soil salinity and sodicity mapping in the region, the responses from the INSAS questionnaires indicate that in Canada, field surveying and digital soil mapping are used (MSWG, 1981), while in the United States, soil map units are delineated by segmenting the landscape into repeatable units, with the composition of the resulting map units being described and occasionally sampled for laboratory analysis. The data are populated using all available data (including similar soils). New approaches based on digital soil mapping are also being produced at local and national levels (Soil Science Division Staff, 2017).

The depth of the mapped saline and sodic soils varies in both countries. In Canada the depth of mapping is 30 and 90 cm for saline soils and 30 cm for sodic soils, while in the United States the depth is at 0 to 200 cm. Taxonomically, most categories require a salic horizon within 100 cm, with sodic soils requiring 0 to 200 cm. Taxonomically, most categories require a natric horizon within 40 cm. It is worth mentioning that all saline sodic areas are mapped in the United States.

The scale and resolution of mapping used vary considerably. In Canada, while the resolution of mapping is 250 m by a digital surface model (DSM), no information was provided about the map scales. In the United States the scale and resolution used are 1:12 000/10 m.

Soil salinity and sodicity monitoring systems are widely implemented in Canada but not in the United States. In Canada, the work monitoring system combines soil and landscape characteristics, topography and climate data with statistics on farming practices to determine the risk of soil salinity in those regions where there is a potential for soil salinity. Water parameters include irrigation water quality monitoring with an EC of less than 4 dS/m and a SAR below 5, which are generally considered to be good quality for irrigation. Irrigation water with a lower EC (<1.5 dS/m) and high SAR (>5) can lead to increased sodium content in the soil, resulting in structural issues in the soil profile. All irrigation water with a very high SAR (>10) should be closely monitored for any potential impact on soil health.

The results of soil salinity and sodicity monitoring are used for the following:

- Analysing soil to determine EC or SAR helps to calculate gypsum requirements and leaching fraction. Drainage is usually required prior to adding gypsum due to the underlying internal drainage issues.
- Drainage management, EC and SAR along with electromagnetic mapping. These can assist in drainage design plans for farmers and where to locate drainage tiles. Electromagnetic mapping over subsequent years will also provide an indication if drainage and management plans are working.
- Providing the economic incentives to farmers or to calculate fees.
- Determining the suitability of the soil for irrigation. This can influence permits (access to irrigation water).

Land and water resources have provincial jurisdiction in Canada and results in incomplete or fractured sharing of data and standards nationally. Improvements in sharing soil and water data between provincial and federal jurisdictions should help in the development and implementation of monitoring and programming.

There is an uneven emphasis on the management of localized salinity associated with resource extraction and broadarea salinity on croplands. Nonagricultural industries are regulated, and strategies to avoid and manage spills are fairly well managed. In contrast, there is a limited capacity for assisting farmers and others in the agricultural industry to manage cropland salinization. Issues with salinization associated with irrigation seem to have lessened with improvements in infrastructure and engineering (so less unintended water leakage). Future pressures to improve water use efficiency could conceivably lead to increased salinity problems if irrigation water inputs are insufficient to leach salts from the surface layer.

In Canada, it is only necessary to establish the monitoring system of soil salinity and sodicity for croplands and hot spot areas. Canada needs a greater emphasis on landscape heterogeneity to support the multifunctional nature of agroecosystems nested within broader landscapes. Beyond the production of agricultural commodities, this might mean the retention of wetlands and coping with "bath-tub ring salinity" in the prairie pothole region, as these could be critical to protecting biodiversity, and related ecosystem services. Canada also has a vast area of non-agricultural soils at northern latitudes that may be especially vulnerable to salinization under the drastic climate shifts being experienced there (such as permafrost thawing).

Soil salinity and sodicity risk assessment used

In Canada, irrigation and drainage projects perform an evaluation of the risk of developing secondary soil salinization and sodification. This requires soil and water testing to determine the suitability of the land and water for irrigation purposes. If the land is susceptible to salinization or sodification, it will be denied development or conditionally approved with improvements in drainage and ongoing monitoring (sampling and mapping). Drainage is less regulated in provinces, with the main concerns being the volume and quality of discharge waters. The Canadian Agricultural Indicators Report assesses the risk of soil salinization through a performance index which includes EC and SAR among others (Agriculture Canada, 2016).

In the United States while there is no information about risk assessment within their drainage and irrigation projects, the Web Soil Survey (WSS) provide several interpretations for irrigation, which include salinity and sodicity as variables. The systems for categorizing prime farmland and land capability classification also include salinity and sodicity (Soil Survey Staff, 2022a; USDA-NRCS, 2017; Klingebiel and Montgomery, 1961).

Status of sustainable management of salt-affected soils

Across Canada and the United States, the status of sustainable salt-affected soil management exhibits a dynamic spectrum. The practices employed in the analysed countries that responded to the questionnaire are delineated as follows:

- **Evaporation reduction techniques**: These encompass strategies such as mulching and the utilization of interlayers composed of loose materials. These practices are prevalent in both countries.
- **Topsoil salt removal**: Canada and the United States report that procedures to remove salts from the topsoil such as leaching, drainage and surface scraping are used to combat soil salinity.
- **Enhancing soil structure and Infiltration**: Both countries apply soil remediation methods (introducing organic matter such as compost and crop residues into the soil) to alleviate salt stress.
- **Biochar application**: Information wasn't provided on this question for either country .
- **Deep ploughing**: Canada and the United States use deep ploughing as a measure to alleviate salt stress in salt-affected soils.
- **Chemical amelioration**: Both surveyed countries use the application of Ca containing compounds such as gypsum to alleviate the negative effects of salt-affected soils on crops.

- **Salt relocation and accumulation reduction**: Canada reported that land levelling and reshaping was used to avoid salt accumulation in certain areas.
- **Crop system management**: Crop system management such as improved crop rotation, agroforestry and crop system diversification were reported by Canada.
- **Crop adaptation strategies**: We define crop adaptation strategies here as changing to growing halophytes or other non-conventional crops, breeding for salinity tolerance, genetic engineering, and the use of halopriming seeds. These methods are applied in Canada and the United States.
- **Agroforestry methods:** Information wasn't provided on this question for either country.
- **Biotechnologies** (including bioinoculants and biofortification) are not implemented in Canada and the United States.
- **Intercept crops**: In Canada, strategies aimed at increasing plant transpiration to better manage shallow groundwater (intercept crops) are implemented.

The data regarding the area of implementation of practices for managing salt-affected soils across different regions of Canada is available in Agriculture Canada (2016) and in the United States is available in USDA-NRCS programmes (USDANRCS, 2022c).

Indicators of sustainable soil management (SSM)

Sustainable soil management (SSM) indicators employed in Canada and the United States for assessment adhere to the indicators outlined in FAO's SSM Protocol (FAO and ITPS, 2020), but Canada also uses other indicators (Agriculture Canada, 2016). A database of good practices for sustainable management of saline and sodic soils is available in Canada (Agriculture Canada, 2016; Government of Canada, 2007) and in the United States, there are Conservation Practice Standards (USDA-NRCS 2022a) and a Field Office Technical Guide (USDA-NRCS. 2022b).

There is no policy governing the management of salt-affected soils in the United States and consequently no governmental body focuses on this critical matter. While there is a lack of information from Canada, a governmental institution does regulate all aspects of monitoring and management of salt-affected soils (Agriculture Canada, 2016).

The development of legislation and legal frameworks are needed for the regulation and protection of saline environments as crucial biodiversity shelters, as there are some valuable and rare environments in the United States. No information was available from Canada.

Extension services play a pivotal role in bolstering farmers' efforts to effectively manage salt-affected soils, ensuring sustained productivity, and mitigating the adverse impacts on plant growth and agricultural output. In Canada (according to the responses to the questionnaires), all aspects of salt-affected soil management (training, soil analysis, recommendations, etc.) are supported but there is either lack of geographic coverage or poor accessibility for farmers. In the United States, extension services have good geographic coverage but few aspects of salt-affected soils management are supported.

The specific services sought by farmers and offered by extension services exhibit a dynamic and contextual variation within the two countries, as shown in Table 3.5.7.

Table 3.5.7 | Services most demanded by farmers and extension services available to help manage salt-affected soils in a sustainable manner in Canada and the United States

Extension services	Country	
	United States	Canada
Training about the management of salt-affected soils	√	
Soil analyses (please specify which analyses)		
Interpretation of soil analyses	√	
Irrigation water or groundwater analyses		
Soil salinity and sodicity mapping		
Recommendations on salt-affected soil management		√
Others		

Status of crop and plant production in salt-affected environments

Losses of crop yields resulting from soil salinization and sodification

Cropland is the most susceptible target of secondary soil salinity and sodicity. Based on the responses from the questionnaires, Canada has up to 0.6 million ha of croplands (both rainfed and irrigated) affected by secondary salinity (Phillips and Towns, 2017; Agriculture Canada, 2016) while the United States has 14.3 million ha of croplands affected (Soil Survey Staff, 2022a; Dewitz and USGS, 2021). Soil sodicity affects 1.9 million ha of cropland in the United States (no information was provided for Canada).

Table 3.5.8 shows the most cultivated crops in saline and sodic soils in the region.

Table 3.5.8 | Crops, the most cultivated on saline and sodic soils in the North American region

Crop	Country	
	United States	Canada
Rice		
Cotton		
Barley		√
Alfalfa	√	√
Sorghum		
Tall wheatgrass	√	√
Halophytes (e.g. quinoa [*Chenopodium quinoa*], *Atriplex* sp., *Salicornia* sp. and saltgrass [*Distichlis spicata*])		
Non-conventional crops (amaranth [*Amaranthus* sp.] and others)		
Kochia (*Bassia scoparia*)		√

A national assessment on the losses of yields due to soil salinity was conducted in Canada in 1998 and losses were about CAD 257 million annually (Forge, 1998) (Agriculture Canada, 2016) but no assessment was conducted for soil sodicity. In the United States, no assessment on losses of yields has yet been performed based on soil salinity or sodicity.

Status of sustainable water management in saline and sodic environments

Areas of irrigated farmland and its exposure to salinization and sodification

In the United States, the total area of irrigated farmland is around 23.478 million ha (USDA-NASS, 2019), and the area affected by both primary and secondary salinity and sodicity in irrigated farmland is around 23 774 ha (USDA-NASS, 2019). In Canada, the area of irrigated farmland is 0.605 million ha (Statistics Canada, 2021).

Table 3.5.9 shows the most common irrigation methods used in the region. Sprinkler irrigation is prevalent in the United States (USDA-NASS, 2019) and Canada, while in Canada, surface irrigation (a border irrigation subtype) and drip irrigation are also commonly used (Statistics Canada, 2023).

Table 3.5.9 | Most common irrigation methods used in the North American region

Irrigation methods	Country	
	United States	Canada
Surface irrigation (border irrigation subtype)		√
Surface irrigation (basin/flood irrigation subtype)		
Surface irrigation (furrow irrigation subtype)		
Surface irrigation (uncontrolled flooding)		
Sprinkler irrigation	√	√
Drip irrigation		√
Manual irrigation		
Others		

Irrigation water quality monitoring

When managed properly, brackish water can be used for irrigation. According to the survey, the United States use this water for irrigation (Dieter *et al.*, 2018; Stanton *et al.*, 2017; USGS, 2018) and Canada does not.

However, in the United States, there was no detailed information given about the regulation on the use of brackish water for irrigation.

In Canada, water EC and SAR are assessed to determine the quality of irrigation water, with the questionnaire indicating that the criteria are enough to avoid soil salinization and sodification. No information was provided for the United States.

Canada has a water monitoring system in place at the local level, where the provincial governments – usually within agricultural or environmental ministries – continually monitor irrigation water quality for irrigation and other uses (such as municipal or recreational). Groundwater applications are tested at the time of irrigation approval and may require ongoing monitoring as a condition of the license to irrigate (depending on the source). No data was provided about the contribution of irrigation water quality on soil salinization and sodification. In Canada there is work underway to improve irrigation water quality by mixing water, while no information was provided for the United States.

Groundwater monitoring

In both countries there are ground water monitoring systems in place in large regions of the country prone to salinity or sodicity problems. However, no information was available about the main principles of the systems and if the ground water monitoring was integrated with soil salinity and sodicity monitoring.

Groundwater is a leading factor in soil salinization and sodification in Canada (although there are no data or national assessments), and the constructed irrigation systems work as intended in protecting soils from salinization and sodification. In the United States no information was provided about this point.

Agrohydrological models to evaluate water management in salt-affected soils

No data was provided from either Canada or the United States.

Leaching and drainage on salt-affected soils

The last section focuses on the draining and leaching of salt-affected soils. The most commonly used drainage methods in Canada are surface drainage (shallow ditches), subsurface drainage (buried pipe drains), and controlled drainage. The criteria to design the drainage system are based on soil parameters and the soil's hydraulic and physical properties (infiltration, compaction, and soil layers). Sprinklers are used for leaching with the amount of water usually calculated using FAO drainage and irrigation papers, to be applied after harvesting. No information was provided for the United States.

3.6 | The Pacific

Overview

In this chapter, two related issues are unpacked: why Australian soils are inherently saline and why farmlands there are being increasing affected by secondary (dryland) salinity.

Australia's soils, especially those in the southwest, are inherently saline, as they lie in the path of a constant flow of westerly winds, laden with oceanic aerosols that have been deposited for millennia (Hingston and Gailitis, 1976). Added to this, aeolian dust storms have spread saline clay deposits (parna) across many Australian landscapes, following arid phases and megadroughts.

Thanks to a small amount of salt derived from ancient rocks and a pervasive semiarid climate, Australian subsoils have abundant natural salt stores. In southwestern Australia, salt loads of the order of ~1000 t/ha are common in the regolith (McFarlane and George, 1992). Cumulatively, 357 Mha of Australian soils in mostly inland areas are estimated to be naturally sodic and saline (*primary salinity*) (Northcote and Skene, 1972).

A further 2 Mha of saline soils (*dryland salinity*) occur in the hinterland between the arid and coastal regions and are caused by humaninduced clearing of native vegetation for agriculture. Most of this land has been salt-affected as a result of changes to the water balance of nonirrigated farmland. Following extensive clearing and aboveaverage rainfall starting in the 1950s, groundwater levels rose, and evaporation and salt accumulation started in previously arable areas. By the 1980s, dryland salinity had come to prominence in most southern Australian states.

In Western Australia, dryland salinity was first noticed when the catchment of Perth's first major reservoir was partly cleared, and tributary creeks became saline (Reynoldson, 1909). Investigations soon linked the clearing of forests with rapidlyrising water tables (Wood, 1924). Later in the 1970s, researchers defined the landscape processes responsible in detail (Peck and Williamson, 1987). Despite bans on the clearing of native vegetation from 1976 in water catchments, and the regulation of wider farmland clearing, 18 Mha of deep-rooted forests had already been replaced with short-lived, shallow rooted crops and pastures, and salinity had escalated (George *et al.*, 1997).

Between 1955 and 2002, the Australian Bureau of Statistics (ABS) surveyed farmers in Western Australia to determine the areas of previously arable land that were now salt affected. The surveys showed that salinity had increased from 74 000 ha in 1955 (Burvill, 1956) to over 1 Mha by 2002 (ABS, 2002), with some regions being more than 10 percent affected. Worse, salinization impacted the water quality in most streams, making them unusable for domestic purposes, and all but the most tolerant native species along these water courses died. Debates around salinity also highlighted the importance of the decline of remnant vegetation and biodiversity in lowlands, and the damage being done to infrastructure, like roads and the amenity and value of land in regional towns.

By the 1980s, all of the southeastern states (South Australia, Victoria, New South Wales and parts of Queensland) had also reported dryland salinity, but the extent was less certain and also by how much it was changing. Stream salinity levels were also noted to be rising in Australia's largest irrigation areas of the Murray–Darling Basin, with the issue being linked to land clearing in drylands and drainage from irrigation areas (MDBA, 2023).

Before today's topical issues like climate change, carbon and regenerative farming, it was the issue of escalating dryland salinity that had helped to galvanise farmers and conservationists to action through the "Landcare" movement. Salinity had become a huge problem and it was occurring on a national scale. From a farmer's perspective, the causal processes occurred underground and were invisible until, alarmingly, salinity appeared in a field, dam or waterway and took away the farm's income. Its extent and impact were unexpected at the time in these otherwise dry areas.

Policy and governance

Constitutionally, issues to do with land management and land condition assessment are a state issue in Australia. However, the recognition and importance of salinity as a significant constraint varied in timing between the states. By the 1980s, even though Western Australia had held several parliamentary enquiries and established programmes under its Soil and Land Conservation programme (Reid, 1988), and was gaining the attention of politicians in other states, it was yet to have a national voice.

National coordination to address dryland salinity finally came with the National Dryland Salinity Program (NDSP) (1993–2004) (van Bueren and Price, 2004). The NDSP led assessments of causes, research into various management strategies, and set up the first farmtocommunity network and education programmes. These programmes were groundbreaking for their time and were heralded for their effectiveness. Almost 15 percent of Australians watched when the Australian Broadcasting Commission (ABC) (Australia's major publiclyfunded television network) aired a four-part television series "Silent Flood",

The NDSP also linked the impact of dryland salinity to the water quality issues of the Murray–Darling Basin and lifted it to the status of the most pressing environmental problem Australia then faced.

The first Australiawide estimate of salinity was conducted by the Prime Minister's Science, Engineering and Innovation Council (PMSEIC, 1999) (Table 3.6.1), using a variety of data sources and methods. Western Australia's Land Monitor project endeavoured to assess risk by using satellite (25m pixel) and other digital data to map paddockscaled salinity (Caccetta *et al.*, 2022), while Victoria and South Australia used local air photo mapping, but most relied on regional estimates.

In 2001, a uniform approach to mapping was attempted, when the National Land and Water Resources Audit established the Australian Dryland Salinity Assessment. The audit assembled data using a "fitforpurpose" methodology and collated disparate information on salinity extent and risk across the country. However, in mixing highquality remote sensing data (e.g. satellite and aerial images) with sparse ground truth data, compromises were made and the variability between jurisdictions became homogenised. Physical differences in farming, landscapes and underlying processes were conflated and concepts of hazard and risk were entangled. Trends established in wet periods were extended into what became known as the "millennium drought" in Eastern Australia (2001–2009) (caused by the effects of a continuing El Nino weather pattern in the Pacific Ocean, natural climatic variability and accelerated anthropogenic impacts on climate).

The NLWRA reported the then current saline area at 5.7 Mha of land within aggregated regions at risk and forecast up to 17 Mha of land with a high future hazard (NLWRA, 2001). However, these numbers were widely misquoted and portrayed as areas of *actual* risk. In 2000, the Australian Conservation Foundation and the National Farmers Federation suggested the establishment of a programme to spend AUD 65 billion to address salinity. It was only later when the Academy of Sciences and Academy of Technological Sciences and Engineering were charged to look at salinity, that a realistic and comprehensive guide to estimation and risk was published (Spies and Woodgate, 2005).

By then however, the NLWRA results had become part of the Australian Government's AUD 1.4 billion National Action Plan for Salinity and Water Quality (2001–2008). Dubbed the "NAP", it delivered targeted research into revegetation systems and engineering, and enabled the implementation of some of the community programmes envisaged by the NDSP. However, it was also criticised for its cumbersome delivery and spreading money thinly without a clear understanding of its impact (ANAO, 2004). The NAP catalysed the formation of two major Cooperative Research Centres (CRCs) that addressed salinity management and engaged with 56 natural resource management (NRM) regions that had been developed to deliver the Government of Australia's programmes, many in partnership with Australian states. A smaller number of these remain today as the principal vehicles for the government to deliver environmental programmes.

More recent assessments

Following the issues created by the audit, a simpler approach was suggested. As part of a broader survey about the adoption of land management practices under the NAP, the Australian Bureau of Statistics asked a sample of 20 000 farmers from across all the states about salinity (ABS, 2002). This survey, similarly to the seven saltland surveys carried out in Western Australia (1955–1993) (McFarlane *et al.*, 2016), reported that dryland salinity affected 1.96 Mha of Australia's farmland, of which 1.2 Mha was in Western Australia (ABS 2002) (Table 3.6.1).

Six years later, in 2008, at the second International Salinity Forum in Adelaide (International Salinity Forum, 2008), scientists from the individual states revised these numbers. The numbers were largely qualifications of earlier work and affected by the span of investments of the NAP, including new work done in Tasmania. Since then, NSW (DECC NSW, 2009) and Western Australia have revisited the numbers, with the recent inclusion of 20 years of satellite data (Caccetta *et al.*, 2022; State representatives, personal communications, 2022) (Table 3.6.1).

Table 3.6.1 | Estimates of previously productive land now affected by salinity in the states and territories of Australia between 1999 and 2022

State	1999[1]	2002[2] Salinity/ha (% farms)	2008[3]	2022
NSW/ACT	120 000	124 000 (7.4%)	61 993[4]	not reassessed
Victoria	120 000	139 000 (13.4%)	149 912[5]	not reassessed
Queensland	10 000	107 000 (3.4%)	40 000	not reassessed
South Australia	402 000	350 000 (21.6%)	350 000	not reassessed
Western Australia	1 802 000	1 241 000 (51%)	1 077 000[6]	1 750 000[7]
Tasmania	20 000	6 000 (9%)	73 900	not reassessed
Northern Territory	n/a	2 000 (2%)	n/a	n/a
Total	**2 476 000**	**1 969 000**	**1 753 805**	

Sources:

1. **PMSEIC (Prime Minister's Science, Engineering and Innovation Council)**. 1999. *Dryland Salinity and its Impacts on Rural Industries and the Landscape*. Canberra.
https://kiriganaicom.files.wordpress.com/2016/09/pmseic_dryland-salinity-and-its-impacts-on-rural-industries-and-the-landscape.pdf

2. **ABS (Australian Bureau of Statistics)**. 2002. 4615.0 - Salinity on Australian Farms, 2022. In: *ABS*. Canberra. [Cited 2023].
https://www.abs.gov.au/ausstats/abs@.nsf/Latestproducts/4615.0Main%20Features12002?opendocument&tabname=Summary&prodno=4615.0&issue=2002&num=&view=

3. Unlinked figures collated by author based on state presentations at the second International Salinity Forum in 2008 in Adelaide, South Australia.

4. **DECC NSW (Department of Environment and Climate Change New South Wales).** 2009. *Salinity Audit: Upland catchments of the New South Wales Murray–Darling Basin*. Sydney, Australia.
https://www.environment.nsw.gov.au/research-and-publications/publications-search/salinity-audit-upland-catchments-of-the-new-south-wales-murray-darling-basin

5. **Allan, M.J.** 1994. *An assessment of secondary dryland salinity in Victoria*. Technical Report No. 14. Melbourne, Australia, Department of Conservation & Natural Resources.
https://www.ccmaknowledgebase.vic.gov.au/kb_resource_details.php?resource_id=2135 (Victoria total: 239 912 ha excludes areas of primary salinity).

6. **George, R., Kingwell, R., Hill-Tonkin, J. & Nulsen, B.** 2005. *Salinity Investment Framework: Agricultural land and infrastructure*. Report 270. Perth, Australia, Department of Primary Industries and Regional Development.
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7. **Caccetta, P.A., Simons, J., Furby, S., Wright, N. & George, R.** 2022. *Mapping salt-affected land in the SouthWest of Western Australia using satellite remote sensing*. Series Number EP2022-0724. Melbourne, Australia, Commonwealth Scientific and Industrial Research Organisation (CSIRO). *https://library.dpird.wa.gov.au/lr_publishedrpts/3/*

Land monitoring updated in 2018 (1.75 Mha includes public lands [30 percent of the total] and includes 670 000 ha of salt-affected soil that was not mapped in 2000).

Why has salinity stabilised in the east of Australia and kept growing in the west?

Recent hydrologic studies in the Murray–Darling Basin have shown that following a wetter phase in the midtwentieth century, when water tables rose steadily and salinity expanded, the hydrologic system has been replaced by mostly stable or falling water tables (DECC NSW 2009, Fu, Rojas and Gonzales, 2022). This was attributed climatically to the recent long phase of El Nino during the socalled "millennium drought". With some local exceptions in catchments with expanding salinity, salinity observed prior to the year 2000 was driven by multi-decadal patterns in rainfall and much less by land use and clearing.

In Western Australia, the driving force in most areas remains the legacy of the extent and timing of 18 Mha of clearing and the resultant orders of magnitude impact on the water balance (McFarlane *et al.,* 2016). More recently some areas have equilibrated, although this is variable depending on the hydrological zone and nature of the landscape (Raper *et al.*, 2014). In some places, especially latercleared sandy catchments, rising water tables and salinity continue to affect arable land. In addition, land use has changed. A doubling of the cropped area since the 1990s, adoption of soil moisture retention strategies and the use of chemical weed control as a water management tools, looks to have increased the leakage of rainwater into the regolith in recent wetter years. There has also been an increase in summer rainfall in some parts of the region (McFarlane *et al.*, 2020).

One hard lesson learned was that the purposeful adoption of various salinity management systems did not alter the areal extent of salinity as much as was hoped. In large part, this was due to climate being a much larger driver of salinisation than land management, although the relative lack of adoption (proportion of the landscape treated) was another contributing factor.

The dominant response of most communities affected by salinity in Australia was the adoption of salt-tolerant vegetation – both trees and halophytebased pastures – and in several states, engineering options such as deep open drains, groundwater interception and pumping (BarrettLennard and Norman, 2022; George *et al.*, 1997).

What have we learnt?

Australia is a big country and there is enough salt present in the subsoils under all but the highest rainfall areas to salinize land. In the east, multidecadal changes in rainfall have driven rapid, cyclic changes in the hydrology of aquifers and rivers, with land use adding to these larger forcing factors. In particular, the elevated risk of salinity was triggered by monitoring data that showed linear rates of rise, but had been collected in a dominantly wetter phase, without understanding the effect of long phases of drying (DECC NSW, 2009; Fu, Rojas and Gonzales, 2022).

Understanding the hydrologic response of complex aquifer systems is now even more important in the context of climate variability and the need to maintain food production.

In addition, in heavytextured soil during drought, a new form of salinity is becoming evident. Dubbed "transient salinity", it is unrelated to shallow water tables and has been found to be common in crops on sodic, alkaline soils, especially in dry seasons (Rengasamy, 2002; Barrett-Lennard *et al.*, 2021). Its causes are regionally specific, but typically a mix of soil chemistry and water relations.

Dryland salinity has taught the hydrologic community about response times in natural and modified systems, and how to look sceptically at short measurement records, especially when projecting those into a future climates and changing land uses. It has also shown that physical processes can change, with systems crossing boundaries due to nonstationarity.

More significantly it has shown that to return functions of a landscape changed by largescale impacts such as land clearing, most of the landscape has to be changed. Where agricultural businesses exist because of this alteration, adoption will rarely be able to bring back hydrologic function and maintain previous productivity.

With hindsight, it might be easy to say that the threat of salinity was exaggerated. However, this is too blunt an assessment and fails to account for the variability seen within Australia. The issue of timing can also be considered here, because if the millennium drought had not occurred when it did, it is probable that salinity would be a far worse problem in the east of the country, with major implications for the water quality of rivers that supply irrigation in the Murray–Darling Basin. In Western Australia, salinity impacts 1.75 Mha of land, despite there having been reduced rainfall over the last 30 years. In fact, reduced rainfall has decreased runoff by ~70 percent in forested catchment areas and in some areas have increased river salinity (McFarlane *et al.*, 2020). Contrary to this, in nearby farmland, aquifers continue to fill and saline areas grow. City water resource managers are turning to the sea to extract drinking water through desalination, and inland farmers are trialling similar techniques from recentlycreated aquifers to do the same.

We are all aware that climate variability and change is forecast, that require altered land uses and hydrologic responses. The learning created by monitoring and managing hydrologic systems due to the risks posed by dryland salinity will form a sound base for managers to learn from and enable future adaptive systems and responses.

3.7 | Sub-Saharan Africa

Introduction

Salt-affected soils affect agricultural production and sustainable environmental management globally, including the Africa region counties of Benin, Cameroon, Djibouti, Ethiopia, Ghana, Kenya, Liberia, Mauritania, Mozambique, Nigeria, Sierra Leone, South Africa, the United Republic of Tanzania, Togo, Uganda and Zimbabwe. Salt-affected soils result from natural and anthropogenic activities, including high evaporation rates, limited rainfall, improper irrigation practices, and inadequate drainage systems. Salt-affected soils originate from various sources and drivers, acting either alone or in combination, such as climate, parent material and human activities.

The status of salt-affected soils in the Africa region is of great concern and significantly affects food security, rural livelihoods, and ecosystem health. Highly soluble salt concentration at or within the root zone reduces crop growth and yield by disrupting water uptake and nutrient absorption. Poverty, food insecurity, and rural–urban migration pose social and economic challenges for the region and result from low agricultural production.

Salt-affected soils have direct and indirect effects on surface and ground water and contribute to water scarcity and pose human health hazards. Available land for cultivation is decreasing, thereby exacerbating conflict over land.

It is essential that a multi-stakeholder approach (scientific research, technological innovations, and sustainable land management practices) is engaged in tackling salinity and sodification. The joint efforts and mutual collaboration of governments, research institutions and local communities are also required. However, the level of interventions needed to solve the challenges of salt-affected soils varies in the region. Approaches currently under consideration or employed include developing salt-tolerant crop varieties, improving irrigation efficiency, implementing proper drainage systems, and promoting soil rehabilitation techniques.

Status of measurement, mapping and monitoring salt-affected soils

The total area of salt-affected soils in the sub-Saharan Africa region is 883 795 km^2 according to assessments given in Chapter 1. Soil salinity is one of the major factors militating against the agricultural sector. The extent of salt-affected soils – as indicated by the data provided by national experts from 16 countries who participated in the INSAS questionnaire – exhibits significant variations. Table 3.7.1 shows that eight out of the sixteen countries have data on this subject. The areas range from a few thousand hectares to tens of millions of hectares. Current and comprehensive data on soil salinity in different countries are lacking, particularly at the national level, limiting the global capacity to understand the true extent of soil salinity.

Table 3.7.1 | Area of salt-affected, saline, sodic, and saline sodic soil in some Africa countries

Country	Area of salt-affected soils (ha)	Area of saline soils (ha)	Area of sodic soils (ha)	Saline sodic soils (ha)	References
Benin	–	–	–	–	
Cameroon	1 891 560	472 890	1 481 670	–	Ngachie (1992)
Djibouti	–	–	–	–	
Ethiopia	44 000 000	33 000 000	–	–	Borena and Hassen (2022), Tesfaye, Petros and Zeleke (2014) and Seid and Genanew (2013)
Ghana	318 000	200 000	–	118 000	FAO (1988) and Allotey *et al.* (2009)
Kenya	24 000 000	1 920 000	–	–	Mugai (2004) and Wanjogu *et al.* (2004)
Liberia	–	–	–	–	
Mauritania	–	–	–	–	
Mozambique	–	–	–	–	
Nigeria	–	–	–	–	
Sierra Leone	208 000		–	200 000	UNDP and FAO (1979)
South Africa	37 619 316	94 050		463 686	Nell *et al.* (2015)
United Republic of Tanzania	2 000 000	1 700 000	300 000		FAO (2000)
Togo	–	–	–	–	
Uganda	1 586 279				Chenery (1960)
Zimbabwe	–	–	–	–	
Total					

Sources: **Ngachie, V.** 1992. A general assessment of soil resources and soil fertility constraints in Cameroon on the basis of FAOUNESCO soil map analysis. Tropicultura, 10(2): 61–63. *http://www.tropicultura.org/text/v10n2/61.pdf*

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Determination of soil salinity

Table 3.7.2 illustrates the methods used in the region to determine soil salinity, and show that a certain level of harmonization exists, although different countries employ varying approaches. The most common method is the electrical conductivity (EC) of saturated paste extract, followed by calculating the total soluble salts (comprising of Na^{+}, Mg^{2+}, Cl-, SO_4^{2-}, HCO_3-, CO_3^{2-}).

Table 3.7.2 | Chemical methods used in the Africa region countries to measure soil salinity

Method	Country															
	Benin	Cameroon	Djibouti	Ethiopia	Ghana	Kenya	Liberia	Mauritania	Mozambique	Nigeria	Sierra Leone	South Africa	United Republic of Tanzania	Togo	Uganda	Zimbabwe
Electrical conductivity (EC) in saturated paste extract		√	√	√	√	√		√		√		√	√			√
EC at 1:1 soil:water ratio				√	√	√	√			√	√		√			
EC at 1:2 soil:water ratio							√					√				
EC at 1:2.5 soil:water ratio				√		√			√		√	√	√			
EC at 1:5 soil:water ratio		√	√		√		√				√			√		
EC at 1:10 soil:water ratio																√
Total dissolved solids (by gravimetric analysis)		√		√												√
Total soluble salts (calculated as the sum of Na^{+}, Mg^{2+}, Cl^{-}, SO_4^{2-}, HCO_3^{-}, and CO_3^{2-})			√	√					√			√				√
Content of soluble Na^{+}			√		√					√	√				√	√
Content of soluble Cl^{-}			√						√					√		
Others															√	

Determination of soil sodicity

The determination of soil sodicity in the Africa region is shown in Table 3.7.3. The most common methods are the sodium adsorption ratio (SAR) and exchangeable sodium percentage (ESP).

Table 3.7.3 | Method of soil sodicity used in the Africa region

Method	Country															
	Benin	Cameroon	Djibouti	Ethiopia	Ghana	Kenya	Liberia	Mauritania	Mozambique	Nigeria	Sierra Leone	South Africa	United Republic of Tanzania	Togo	Uganda	Zimbabwe
Exchangeable sodium percentage (ESP)		√	√	√	√	√			√	√		√	√			√
Sodium adsorption ratio (SAR)		√	√	√	√	√				√	√	√	√		√	
Physical methods (such as specific swelling, and low infiltration rate)															√	√
Morphological methods (such as structure of sodic/solonetzic horizon)					√							√			√	
Others							√									

The methods of determining exchangeable Na^+ are almost equally distributed across the countries (Table 3.7.4) with the most prevalent approach involving a four-step process (without salt removal). Across the Africa region, the most common method for measuring the SAR is by calculating the content of Ca^{2+}, Mg^{2+}, and Na^+ in a water-saturated soil paste extract.

Table 3.7.4 | Methods of determination of exchangeable Na^+ and their distribution over the Africa region

Method	Country															
	Benin	Cameroon	Djibouti	Ethiopia	Ghana	Kenya	Liberia	Mauritania	Mozambique	Nigeria	Sierra Leone	South Africa	United Republic of Tanzania	Togo	Uganda	Zimbabwe
Salt removal (step 1), cation exchange (step 2), measurement of Na^+ (step 3)			√	√	√			√			√					
Without salt removal, measurement of soluble Na+ (step 1), cation exchange (step 2), measurement of Na^+ (step 3), recalculation of exchangeable Na^+ based on the subtraction of soluble Na+ from total Na^+ (step 4)				√`				√	√			√	√	√	√	
Without salt removal, cation exchange (step 1), measurement of Na^+ (step 2)		√			√		√	√					√			
Others																

Method of measurement of cation exchange capacity (CEC) and distribution

Table 3.7.5 illustrate the methods for measuring cation exchange capacity (CEC) in the region. The method of ammonium acetate extraction (buffered at pH 7) is the approach most used for measuring CEC in most Africa region countries. Cation exchange capacity is not measured in Liberia and no information was provided by Benin or Mauritania.

The most common method for measuring the SAR is by calculating the content of Ca^{2+}, Mg^{2+}, and Na^+ in a water-saturated soil paste extract. Notably, physical methods are also adopted in most of the countries, where low hydraulic conductivity soil dispersion tests are most common. Additionally, Ethiopia and Uganda employed specific swelling and low infiltration rate methods in conjunction with the previously mentioned techniques.

Morphological methods for assessing soil sodicity are also used in the Africa region, with most countries such as Cameroon, Djibouti, Ethiopia, Ghana, Kenya, Liberia, South Africa, the United Republic of Tanzania and Uganda utilizing the specific structure of sodic or solonetzic horizon method. South Africa also adopts additional methods, including measuring specific microfeatures of the sodic and solonetzic horizon and Zimbabwe adopts physical methods such as specific swelling and a low infiltration rate.

Table 3.7.5 | Method of measurement of cation exchange capacity (CEC) and distribution over the Africa region

Method	Country															
	Benin	Cameroon	Djibouti	Ethiopia	Ghana	Kenya	Liberia	Mauritania	Mozambique	Nigeria	Sierra Leone	South Africa	United Republic of Tanzania	Togo	Uganda	Zimbabwe
Ammonium acetate extraction (buffered at pH 7)		√	√	√	√	√			√	√	√	√	√	√	√	√
Ammonium chloride extraction											√					
Triethanolamine-buffered barium chloride extraction (buffered at pH 8.2)																
Hexamminecobalt (III) chloride extraction										√						
Others (sodium acetate extraction)																
Not applicable (CEC not measured)																

Method of pH measurement and their application in the Africa region

Table 3.7.6 illustrates the most common method for measuring soil alkalinity, or soil pH. Different approaches are employed in the region. Soil pH measurement in soil:water extracts with ratios of 1:2.5 is the most widely used. Soil pH measurement in 0.01 M $CaCl_2$ is used in Cameroon, Nigeria and Zimbabwe, and this method has been reported to remove any seasonal effects. However, there is a need to harmonize methods.

Table 3.7.6 | Method of pH measurement and their application in the Africa region

Method	Country															
	Benin	Cameroon	Djibouti	Ethiopia	Ghana	Kenya	Liberia	Mauritania	Mozambique	Nigeria	Sierra Leone	South Africa	United Republic of Tanzania	Togo	Uganda	Zimbabwe
Soil pH (extract of saturated paste)				√		√		√			√	√				
Soil pH (soil:water 1:1)					√		√				√				√	
Soil pH (soil:water 1:2)							√									
Soil pH (soil:water 1:2.5)	√	√		√	√				√	√	√	√	√	√		
Soil pH (soil:water 1:5)																

Method	Country															
	Benin	Cameroon	Djibouti	Ethiopia	Ghana	Kenya	Liberia	Mauritania	Mozambique	Nigeria	Sierra Leone	South Africa	United Republic of Tanzania	Togo	Uganda	Zimbabwe
Soil pH ($CaCl_2$ 1:2.5)		√								√						√
Total alkalinity, or content of alkaline anions (with methyl orange and phenolphthalein indicators)					√			√								
Others																

Saline and sodic soil classification systems used in the Africa region

Based on the questionnaire responses, it was found that the most widelyused threshold for classifying saline and non-saline soils is 4 dS/m. Mauritania uses thresholds of 2, 4 and 15 dS/m, Mozambique uses a threshold of 15 dS/m, and Togo uses a threshold of 2 dS/m. No information for the use of thresholds was provided for Benin and Zimbabwe.

Regarding soil sodicity, most countries in the region use a threshold of >15 percent ESP. A threshold of >10 percent ESP is used by Sierra Leone, South Africa uses a threshold of >6 percent ESP, and no information was provided for Benin and Liberia.

Status of soil salinity and sodicity mapping in the Africa region

Regarding soil salinity and sodicity mapping in the region, the responses from the INSAS questionnaires indicate that there are no standardized protocols across the region for organizing this process. The techniques used are outdated and lack modern mapping approaches, with most countries relying on conventional and traditional methods, including soil sampling, description, and analysis (Table 3.7.7). Additionally, Geographic Information System (GIS) tools are used to generate relative maps. However, South Africa reported that at the farm level, grid sampling, electromagnetic induction (EMI) and remote sensing are used, while on a country scale, a combination of soil analysis, geology, vegetation, topography and climate are used with the help of remote sensing and GIS.

Table 3.7.7 | Map scales used in the detailed saline and sodic soil maps in the Africa region

Map scale	Country															
	Benin	Cameroon	Djibouti	Ethiopia	Ghana	Kenya	Liberia	Mauritania	Mozambique	Nigeria	Sierra Leone	South Africa	United Republic of Tanzania	Togo	Uganda	Zimbabwe
1:5 000																
1:10 000												√				
1:20 000																
1:25 000					√										√	
1:50 000																

Map scale	Country															
	Benin	Cameroon	Djibouti	Ethiopia	Ghana	Kenya	Liberia	Mauritania	Mozambique	Nigeria	Sierra Leone	South Africa	United Republic of Tanzania	Togo	Uganda	Zimbabwe
1:100 000																
1:250 000		√														
1:500 000																
1:1 000 000						√										
No data	√		√	√			√		√	√						

The measured depth of the mapped saline and sodic soils varies among the countries and is inconsistent. Most countries use a depth of 0–15 cm, 0–20 cm, 0–30 cm, 0–40 cm or 0–60 cm while Cameroon, Kenya and Mozambique use a depth of 0–100 cm. Information on mapping methods and depths used in Benin is not available. Mauritania indicated that all areas prone to salinity or sodicity are mapped.

Most countries in the Africa region have no data on the scale of mapping used. The available data varies considerably. South Africa had maps of 1:10 000, Ghana had maps with scales ranging from 1:5 000, Cameroon had maps with scales ranging from 1:250 000, whereas Kenya had most detailed maps at a scale of 1:1 000 000. Cameroon uses a digital soil mapping approach with machine learning. The main methodology of mapping soil salinity and sodicity by farmers in Mozambique involves local sensory evaluation of soil water characteristics (salt crusts, plant symptoms, and indicator plants).

Soil salinity and sodicity monitoring systems are not widely implemented in most countries in the region, although the questionnaire responses confirmed the necessity of such systems. Water parameters are not as widely measured as soil parameters. The results of soil salinity and sodicity monitoring are used for irrigation water management and other decision-making processes. Most scientists who responded to the questionnaires did not have enough knowledge in this area to suggest ways of improving the monitoring systems.

Soil salinity and sodicity risk assessment used

Out of the region, only Ghana, Kenya, South Africa and Zimbabwe have performed evaluations of the risk of developing secondary soil salinization or sodification in their irrigation and drainage projects. In South Africa it was mandatory as early as 1922, to conduct soil surveys for any irrigation scheme development (reconnaissance scale [1: 50 000] and detailed scale [1:6 000 to 1:10 000]). When performing soil surveys for irrigation planning and rehabilitation, South Africa mostly uses the 5 Class Irrigation Suitability System, which has been adapted for South African conditions. In Zimbabwe, soil surveys are done for the potential area to be covered by each project by digging and categorizing soil profiles for each different soil type. Samples of each horizon in each profile are then taken to the lab and analysed, enabling salt-affected soils to be identified. The irritability class is then determined by the chemical and physical properties of the soils.

Status of sustainable management of salt-affected soils

Across the region, the status of sustainable salt-affected soil management exhibits a dynamic spectrum, varying from country to country, based on their adopted practices. The practices employed in the sixteen countries that responded to the questionnaire are as follows:

- **Evaporation reduction techniques**: These encompass strategies such as mulching and the utilization of interlayers composed of loose materials. Ghana, Mozambique, Nigeria, South Africa, Togo and Uganda do not practice this method.

- **Topsoil salt removal**: Methods involving the removal of salts from the topsoil, such as by using leaching, drainage, and surface scraping. However, these techniques are not commonly implemented in Cameroon, Ethiopia, Liberia and South Africa.
- **Enhancing soil structure and infiltration**: Widely regarded as a cornerstone practice for ameliorating soil salinity and sodicity, the methods, including compost and residue incorporation, and are consistently deployed across all surveyed countries except for Ghana, Nigeria, South Africa and Uganda.
- **Biochar application**: Cameroon, Kenya, Liberia, Togo and Zimbabwe employ biochar as part of their soil management strategies.
- **Deep ploughing**: Deep ploughing serves as a mitigation approach against soil salinity and sodicity, and is implemented by Cameroon, Kenya, South Africa and Zimbabwe.
- **Chemical amelioration**: Djibouti, Ethiopia, Kenya, Nigeria, South Africa and Zimbabwe employ chemical interventions like the addition of gypsum and other calciumcontaining amendments.
- **Salt relocation and accumulation reduction**: Practices encompass land shaping and levelling and focus on curtailing salt redistribution and accumulation (only employed by Cameroon and Kenya).
- **Crop system management**: Enhanced crop rotation, agrobiodiversity, and crop system diversification are approaches common in Cameroon, Djibouti, Kenya, Liberia, Mozambique, Sierra Leone, Togo and Zimbabwe.
- **Crop adaptation strategies**: Cameroon, Ethiopia, Kenya, Liberia and South Africa deploy strategies for crop adaptation, including the utilization of halophytes and nonconventional crops, breeding and genetic engineering, as well as halopriming.
- **Agroforestry**: Kenya and Zimbabwe integrate agroforestry into its soil salinity management practices.
- **Desalinization for irrigation water purification**: This method is only utilized in Kenya as a means of purifying irrigation water.

Generally, practices implemented within these countries to achieve sustainable salt-affected soil management across the Africa region were varied and there were no in-depth data.

Indicators of sustainable soil management (SSM)

A wide gap exists in the sustainable soil management (SSM) indicators employed for assessment, and exhibit variability across the Africa region. Ethiopia, Ghana, Kenya, South Africa, the United Republic of Tanzania, Togo and Zimbabwe adopt the indicators outlined in the FAO SSM Protocol (FAO and ITPS, 2020). These encompass parameters like soil productivity (measured through biomass in dry matter), organic carbon content, bulk density, and soil respiration rate. Most other countries do not have indicators for assessment but acknowledged that it was necessary to measure them.

Considering the database of salt-affected soils management practices, only Ghana and Kenya reported any national or international database of good practices for sustainable management of saline and sodic soils. While Kenya said that their database was sufficient, Ghana indicated that the database was incomplete and should be updated.

Most countries have lack of policies addressing sustainable salt-affected soil management due to the low commitment of governmental bodies focused on this critical matter. Kenya and South Africa have policies, although their policies need improvements to become more efficient, while South Africa mentioned the Conservation of Agricultural Resources Act 43 of 1983 (South Africa, 1983) and Soil Conservation Act 76 of 1969 (South Africa, 1969).

It is important to have governmental institutions that can regulate all aspects of the monitoring and management of salt-affected soils. However, only Benin, Ghana, Kenya and South Africa have government institutions that fulfil this function. Generally, there was no coordination between governmental institutions responsible for monitoring and management of aspects of salt-affected soils.

Services most demanded by farmers and extension services to help manage salt-affected soils in a sustainable manner in the countries of the Africa region

Table 3.7.8 contains data on the extension services with a good geographic coverage that provide support for all aspects of salt-affected soil management, such as training, soil analysis, and recommendations. There is a wide variation in the specific services sought by farmers and offered by extension services.

The importance of extension services in empowering farmers to effectively manage salt-affected soils – ensuring sustained productivity, and mitigating the adverse impacts on plant growth and agricultural output – cannot be over emphasized. Ghana, Kenya and the United Republic of Tanzania have good geographic coverage and support with all aspects of salt-affected soils management while Togo and Zimbabwe have good geographic coverage but few aspects of salt-affected soils management are supported. Access to training about the management of salt-affected soils and Irrigation water or groundwater analyses are the two things most demanded by farmers.

Table 3.7.8 | Services most demanded by farmers and extension services to help manage salt-affected soils in a sustainable manner in the countries of the Africa region

Services	Country															
	Benin	Cameroon	Djibouti	Ethiopia	Ghana	Kenya	Liberia	Mauritania	Mozambique	Nigeria	Sierra Leone	South Africa	United Republic of Tanzania	Togo	Uganda	Zimbabwe
Training about the management of salt-affected soils	√	√		√	√		√		√	√	√	√	√	√		√
Soil analyses (please specify which analyses)	√						√		√	√	√	√	√	√		√
Interpretation of soil analyses	√	√		√		√			√	√	√	√	√			√
Irrigation water or groundwater analyses		√		√	√	√	√		√	√	√	√	√	√		√
Soil salinity and sodicity mapping	√			√	√	√	√		√	√	√	√	√			
Recommendations on SAS management		√		√	√	√	√		√	√	√	√	√			√
Others																

Status of crop and plant production in salt-affected environments

Losses of crop yields resulting from soil salinization and sodification

Crop growth and yields are adversely affected by salinization or sodification (Table 3.7.9). The results of the survey showed that most counties have no data on the total area of cropland affected by salinity or sodicity, except Sierra Leone with 200 000 ha of cropland and South Africa with 94 050 ha of cropland. The most common crop grown on salt-affected soils is rice (particularly by Ghana, Mozambique, Sierra Leone and Togo), followed by sorghum (Cameroon, Ethiopia, and Zimbabwe). Ethiopia grows cotton while Liberia grows tall wheatgrass.

Some countries are growing other unconventional crops such as sweet potatoes Mozambique), vegetables (Togo) and pasture (Zimbabwe). Assessments of crop yield loss and the yield gains due to reclamation or other improvements of salt-affected soils are not available in most countries.

Table 3.7.9 | Crops, the most cultivated on saline and sodic soils in the Africa region

Crop	Country															
	Benin	Cameroon	Djibouti	Ethiopia	Ghana	Kenya	Liberia	Mauritania	Mozambique	Nigeria	Sierra Leone	South Africa	United Republic of Tanzania	Togo	Uganda	Zimbabwe
Rice		√			√				√		√		√	√		
Cotton		√		√												
Barley																
Alfalfa			√													
Sorghum		√		√												√
Tall wheatgrass							√									
Halophytes (e.g. quinoa (*Chenopodium quinoa*), *Atriplex* sp., *Salicornia* sp., saltgrass [*Distichlis spicata*], etc.)						√										
Non-conventional crops (amaranth or others)	√						√									
Millet																
Date palm																

Indicators used by crop scientists on salt-affected soils

The main soil parameters which are assessed by crop scientists (and similar specialists) for growing crops and plants on salt-affected soils in Cameroon and Nigeria are similar to those used when studying soil, but they are not enough for crop scientists to prepare their recommendations and decisions.

In Djibouti and Ghana, the main soil parameters assessed by crop scientists are different from those used when studying soil. While they provide sufficient information for crop scientists, in Ethiopia, the parameters should be amended when studying soil. In Sierra Leone, the parameters are different to those used with soil, (such as the sprouting of halophytic plants indicating the ideal time for cropping, and sensory evaluation by tasting the water) and they give enough information for crop scientists. In South Africa, soil analyses and visible methods are used (salt precipitation and discolouring of leaves).

Models of crop response to soil salinity and sodicity

There is a wide variation in the models that are used in the countries of the Africa region or in research in those countries to predict crop and plant responses to salinity and sodicity. No data was available in most of the countries that responded to the questionnaire. Kenya reported on a study on plant material germination assay and salinity treatment on relative water content and chlorophyll and proline contents determination with six finger millet varieties (GBK043124, GBK043122, GBK043137, GBK043128, GBK043094 and GBK043050) grown in different agroecological zones (Mukami *et al.*, 2020). The detailed model used was not included.

In South Africa, even though various models are available both worldwide and in South Africa for integrating and estimating the processes involved in water and salt movement along the soil-plant-atmosphere continuum (SPAC) pathway, researchers have found it difficult to decide which appropriate model to use. While the most suitable models are a combination of empirical and mechanistic models where the governing equations are solved analytically or numerically, the research models or mechanistic water and salt transport models are generally not suitable for management purposes. However, they do comprehensively integrate the knowledge of the processes controlling soil water and salt movement. Empirical water and salt transport models are less intensive and are commensurately less quantitative in their ability to predict water and salt movement under field conditions, and are therefore mostly used as management models. Water and salt balance models are therefore generally favoured because of their conceptual basis, which makes them equally applicable as research or management models. From several water and salt balance models that are available, the specific application, accuracy of prediction, inputs required, and experience of the user of the model need to be the fundamental factors determining the most appropriate water and salt balance model to use.

The model used in Togo to predict crop and plant responses to salinity or sodicity is provided by AquaCrop (FAO, 2023).

Soil management practices included into this model as variables affecting the crop and plant growth

There is a wide variation in the soil management practices included in the model as variables affecting the crop and plant growth. Soil management practices included into this model in Kenya include proper drainage, plant salt tolerant crops, biochar application and proper irrigation. In Togo, soil management practices include initial conditions, field and irrigation, and where it is possible to set up amendment and irrigation options and quantities, soil parameters are used. As reported by the respondent from Djibouti, there is no need for soil management practices to be included into the model as variables.

Variables that are used in this model

Crop type (such as wheat, rice or barley), cultivar characteristics (the specific properties of a crop), other soil conditions and soil organic matter content are all variables used in Cameroon. Kenya and Sierra Leone use crop type (such as wheat, rice and barley), cultivar characteristics (the specific properties of a crop), salinity or sodicity level (grades of salinity or sodicity), EC and the content of total soluble salts.

There are examples of national and more localized scenarios of crop production under different abiotic stresses (such as droughts, salinity or temperature extremes). There is currently no information available for Cameroon, Djibouti, Ethiopia and Ghana. In Zimbabwe, agroecological zones are used to provide an estimate of the different meteorological and soil conditions in different parts of the country. They can also suggest the potential likelihood of different extreme weather events.

Assessments of the cost of inaction in the case of growing salinity or sodicity at the national or local level are available in Kenya. However, they can be of great importance for improved salinity and sodicity management in all the countries in Africa region.

Status of sustainable water management in saline and sodic environments

Areas of irrigated farmland and its exposure to salinization and sodification

Table 3.7.10 illustrates the total irrigated area across the region. Kenya uses surface irrigation (basin or flood irrigation subtype), surface irrigation (border irrigation subtype), surface irrigation (furrow irrigation subtype), surface irrigation (uncontrolled flooding), sprinkler irrigation, drip irrigation and manual irrigation.

In Libera, surface irrigation (uncontrolled flooding) and manual irrigation are the most commonly used methods. In South Africa, sprinkler irrigation and drip irrigation are widely adopted.

Table 3.7.10 | The total area of irrigated farmland in the Africa region

Country	Total irrigated area (ha)	References
Benin	2 823	Ministry of Agriculture and Food (2016)
Cameroon	290 000	Knoema (2020)
Djibouti	600	FAO (1997)
Ethiopia	1 110 000	Chandrasekharan, Subasinghe and Haileslassie (2021)
Ghana	–	
Kenya	151 000	Knoema (2021)
Liberia	–	
Mauritania		
Mozambique	118 120	
Nigeria	–	
Sierra Leone	–	
South Africa	1 500 000	
United Republic of Tanzania	777 280	United Republic of Tanzania Ministry of Agriculture (2023)
Togo	–	
Uganda	–	
Zimbabwe	–	

Sources: **Ministry of Agriculture and Food.** 2016. Benin. Contexte Agricole et relations internationales [Agricultural context and international relations]. In: Ministry of Agriculture and Food. Paris. [Cited 2023]. *https://agriculture.gouv.fr/benin*

FAO. 1997. Irrigation in the near east region in figures. Djibouti. Rome. *https://www.fao.org/4/W4356E/w4356e0b.htm*

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Knoema. 2020. Cameroon - Irrigation potential. In: Knoema. New York, USA. [Cited 2023]. *https://knoema.com/atlas/Cameroon/topics/Water/Irrigation-Water-Management/Irrigation-potential#:~:text=Between%201977%20and%202019%2C%20Cameroon,at%20around%20290%20thousand%20ha*

Knoema. 2021. Kenya. Total area equipped for irrigation. In: Knoema. New York, USA. [Cited 2023]. *http://knoema.com/atlas/Kenya/topics/Land-Use/Area/Total-area-equipped-for-irrigation?mode=amp*

United Republic of Tanzania Ministry of Agriculture. 2023. HOTUBA YA MHESHIMIWA HUSSEIN MOHAMED BASHE (MB), WAZIRI WA KILIMO WAKATI WA KUHITIMISHA HOJA YA MAKADIRIO YA MAPATO NA MATUMIZI YA FEDHA YA WIZARA YA KILIMO KWA MWAKA 2023/2024 [SPEECH OF THE HONORABLE HUSSEIN MOHAMED BASHE (MB), MINISTER OF AGRICULTURE DURING THE CONCLUDING MOTION ON THE ESTIMATES OF INCOME AND EXPENDITURE OF THE MINISTRY OF AGRICULTURE FOR THE YEAR 2023/2024]. In: United Republic of Tanzania Ministry of Agriculture. Dodoma. [Cited 2023]. *https://www.kilimo.go.tz/resources/view/hotuba-ya-mheshimiwa-hussein-mohamed-bashe-mb-waziri-wa-kilimo-wakati-wa-kuhitimisha-hoja-ya-makadirio-ya-mapato-na-matumizi-ya-fedha-ya-wizara-ya-kilimo-kwa-mwaka-2023-2024-08-may-2023-16*

Crops mainly used under irrigation with brackish water

Rice is the main crop used under irrigation with brackish water, followed by cotton, then corn (Table 3.7.11). Brackish water is a significant, but not leading factor of soil salinization and sodification in most countries.

Table 3.7.11 | Crops that are mainly used under irrigation with brackish water in the Africa region

Country	Crop
Benin	–
Cameroon	Cotton, rice, and sorghum
Djibouti	Alfalfa
Ethiopia	Non-conventional crops (amaranth or others)
Ghana	Rice
Kenya	Wheat, corn, cotton, sorghum and tall wheatgrass
Liberia	Rice
Mauritania	Non-conventional crops
Mozambique	–
Nigeria	Wheat
Sierra Leone	Rice
South Africa	Cotton
United Republic of Tanzania	–
Togo	Rice
Uganda	–
Zimbabwe	–

Irrigation water quality monitoring

Country responses to the use of brackish water for irrigation fall into four major categories. Cameroon, Djibouti, Liberia, Ghana, South Africa and Togo use brackish water for irrigation but there are no data on the land area under this system. Kenya does not use brackish water but there are plans to start using it. Nigeria does not use brackish water because it is believed that there is enough good quality water available for irrigation, while Ethiopia, Sierra Leone, Uganda, United Republic of Tanzania and Zimbabwe do not use brackish water and have no plans to start using it. Regulations on the use of brackish water for irrigation is available in Kenya and it is strictly followed (Ministry for Environment and Natural Resources, 2006).

The agronomic practices mainly used under irrigation with brackish water so that soil salinization and sodification are minimised or avoided include improved drainage, the application of biochar and deep ploughing, improved irrigation management (such as through avoiding overirrigation and irrigation scheduling), reduced salt build up and surface accumulation and mixing with fresh water. However, there is some variation, such as in Sierra Leone, where agronomic practices include improved drainage, improved water percolation, improved irrigation management (avoiding overirrigation and irrigation scheduling, reduced salt build-up and surface accumulation).

The criteria used to assess the quality of water for irrigation include the following, with little variation among the countries:

- water electrical conductivity;
- SAR of water;
- total dissolved solids;
- total soluble salts;
- pH; and
- toxic ions.

Most of the responses to the questionnaire indicated that water quality indicators are overlooked. Only Kenya has a comprehensive data on irrigation water monitoring system functioning and irrigation water monitoring integrated with soil salinity and sodicity monitoring.

There is a national irrigation water monitoring in place for the whole of Kenya (MWI, 2012). The main principles of its work (the organizations and ministries in charge, and including coverage, indicators, periodicity, etc.) are as follows:

- designing a national water quality monitoring programme;
- supporting drinking water quality surveillance;
- development of a sampling programme;
- supporting laboratories;
- procurement of laboratory equipment;
- drinking water quality protection;
- control of water treatment chemicals and materials;
- development of surface water protection programmes;
- development of ground water protection programmes;
- protection of coastal and marine waters;
- protection of urban and rural water supplies;
- supporting data collection and information management;
- capacity building for water quality management; and
- providing an institutional framework for the implementation of the National Water Quality Management Strategy (NWQMS) (MWI, 2012).

The contribution of irrigation water quality on soil salinization and sodification is significant in Kenya, but not the leading factor of soil salinization and sodification. No data was available for the other countries.

Measures used to improve the quality of irrigation water

Kenya uses water mixing and water desalinization while Sierra Leone and South Africa use only water mixing. Other countries do not have any method.

Groundwater monitoring system functioning

In Kenya, the groundwater monitoring system works efficiently. The main principles include the organizations or ministries in charge, coverage, indicators, periodicity (Bakker, 1997).

Agrohydrological models used for evaluating water management in salt-affected soils

Agrohydrological models are used to predict soil salinization or sodification (Table 3.7.12).

Sierra Leone use the AquaCrop model (FAO, 2023) as demonstrated by the Sierra Leone Agricultural Research Institute (SLARI) in a soil salinity project with the International Centre for Biosaline Agriculture (ICBA).

The scale of application applied was as follows:

- Field scale
- Farm scale
- Catchment area
- Regional scale
- National scale
- Variables used in the model in Kenya were:
- crop type and characteristics related to water potential;
- irrigation water composition (anions or cations);
- ground water composition (anions or cations);

- soil profile information (soil depth, soil layers etc.);
- salinity and sodicity level (grades of salinity or sodicity);
- electrical conductivity; and
- content of total soluble salts.

Crop type and characteristics related to water potential in Sierra Leone were:

- irrigation water composition (anions or cations);
- ground water composition (anions or cations); and
- soil profile information (soil depth, soil layers etc.).

Other soil conditions were:

- weather data;
- water management (method of irrigation, scheduling); and
- boundary conditions (ground water fluctuations, etc.).

Table 3.7.12 | Agrohydrological models to evaluate water management in salt-affected soils in the Africa region

Variables that are used in this model	Country															
	Benin	Cameroon	Djibouti	Ethiopia	Ghana	Kenya	Liberia	Mauritania	Mozambique	Nigeria	Sierra Leone	South Africa	United Republic of Tanzania	Togo	Uganda	Zimbabwe
Crop type and characteristics related to water potential		√			√				√		√		√	√		
Irrigation water composition (anions/cations)		√		√								√	√			
Ground water composition (anions/cations)												√				
Soil profile information (soil depth, soil layers etc.)			√									√				
Salinity or sodicity level (grades of salinity/sodicity)		√		√							√	√				√
Electrical conductivity							√				√	√				
Content of total soluble salts						√										
Other soil conditions (specify which ones)	√						√									
Weather data																

Variables that are used in this model	Country															
	Benin	Cameroon	Djibouti	Ethiopia	Ghana	Kenya	Liberia	Mauritania	Mozambique	Nigeria	Sierra Leone	South Africa	United Republic of Tanzania	Togo	Uganda	Zimbabwe
Water management (method of irrigation, scheduling)																
Boundary conditions (ground water fluctuations, etc)																

Kenya uses models from Bakker (1997) to evaluate the spatial variability of soil salinization at local, regional and national levels considering the ground or surface water.

The modelling projected changes in the soil water budget in coastal Kenya under different long-term climate change scenarios. The remotesensing proxies used for risk assessment were Climate Hazards Group InfraRed Precipitation with Station (CHIRPS 2.0) and Tropical Rainfall Measuring Mission - Multi-satellite Precipitation Analysis (TMPA) 3B42 version 7 (TRMM), one gauge interpolated product (Global Precipitation Climatology Centre (GPCC) and one reanalysis product (Modern-Era Retrospective Analysis for Research and Application (MERRA).

Leaching and drainage for salt-affected soils

The most common methods of drainage system used in Kenya include surface drainage (shallow ditches), subsurface drainage (deep open drains), subsurface drainage (buried pipe drains) and controlled drainage.

The criteria used to design the drainage system in Kenya is measuring the hydraulic or physical properties of soil (infiltration, compaction, and soil layers) while soil parameters are also included in Zimbabwe. The types of leaching practices include flooding and sprinkler irrigation. There are no details given for the other countries.

Calculation of amount of water for leaching

Calculating the amount of water required for leaching is only carried out in Kenya using national and international protocols. South Africa uses the same approach, with the addition of indigenous knowledge. Other counties did not provide any information.

Conclusion

Across the Africa region, the following conclusions were reached:

- Salt-affected soils have a wide distribution across the countries of the Africa region, and according to the received information, the most extended salt-affected areas occur in Cameroon with 39.8 percent of the total country area, Ethiopia with 39.6 percent, and South Africa with 30.8 percent.
- Different methods are used to measure soil salinity and sodicity in the Africa region. Certain levels of harmonization exist in the methods used, although different countries employ varying approaches. The most common method was the determination of the soil EC in saturated paste extract and 1:1 soil:water solution, followed by calculating total soluble salts (comprising Na+, Mg^{2+}, Cl-, SO_4^{2-}, HCO_3-, and CO_3^{2-}).
- Electromagnetic methods have very limited use in the Africa region. It is highly recommended that this mapping technique is employed by the countries of the region.
- The responses from the INSAS questionnaires indicate that no official mapping protocol

exists, with most countries relying on conventional and traditional methods, including soil sampling, description, and analysis. Techniques are mostly outdated and lack modern mapping approaches. However, South Africa reported that at the farm level, digital soil mapping and EMI techniques are used.

- Monitoring of salt-affected soils is not performed in most of the surveyed countries within the region. Kenya and South Africa have regulating bodies for soil monitoring at the national level, but they lack proper coordination.
- Sustainable salt-affected soils management practices are used in the countries of the Africa region, but there are no statistics available to understand its scale. Apart from Ghana and Kenya, all countries that participated in the survey reported that they had no national or international database of good practices for the sustainable management of saline and sodic soils. Kenya said that its database was sufficient, while Ghana stated that the database was incomplete and should be updated.
- A critical gap persists across the surveyed countries within the Africa region about the national assessment of yield losses attributed to soil salinity and sodicity. The results of the survey showed that most counties have no data on the total area of cropland affected by salinity, apart from Sierra Leone with 200 000 ha of cropland and South Africa with 94 050 ha of cropland. Rice is the most common crop grown on salt-affected soils (particularly by Ghana, Mozambique, Sierra Leone and Togo), sorghum (Cameroon, Ethiopia, and Zimbabwe) while Ethiopia and South Africa grow cotton and Liberia grows tall wheatgrass. Some countries are growing other unconventional crops such as sweet potatoes (Mozambique), vegetables (Togo) and pasture (Zimbabwe). Assessment of crop yield loss and the yield gains due to reclamation or other improvements of salt-affected soils are not available in most countries. Similarly, gauging the yield gains achievable through reclamation or soil improvement endeavours provides a roadmap for sustainable growth and enhanced productivity.
- Agrohydrological models have limited use across the region as yet, although they provide contemporary tools with significant potential for predicting, assessing, and mitigating water management challenges, as well as addressing soil salinization and sodification issues. It is highly recommended that they are introduced and implemented in the Africa region.
- The lack of policy addressing the sustainable management of salt-affected soils is dominant in most countries of the Africa region due to the low commitment of governmental bodies focused on this critical matter. Only Kenya and South Africa have policies. However, these need improvements to become more efficient.
- Generally, there is a lack of data on the area of irrigated land in the region. Irrigation methods most common in Kenya include surface irrigation (all types), sprinkler irrigation, drip irrigation and manual irrigation. In Libera, surface irrigation (uncontrolled flooding) and manual irrigation are the most common. Surface irrigation (uncontrolled flooding), sprinkler irrigation, drip irrigation and manual irrigation are the most common methods across the region. In South Africa, sprinkler irrigation and drip irrigation have been widely adopted. Rice is the main crop used under irrigation with brackish water across the region, followed by cotton, then corn.
- Brackish water is used within the countries of the Africa region. The use of brackish water for irrigation falls into four major categories. Cameroon, Djibouti, Ghana, Liberia, South Africa and Togo use brackish water for irrigation but there are no data available on the land areas. Kenya does not use brackish water but there are plans to start using it. Nigeria does not use brackish water because it is believed that there is enough good quality water for irrigation, while Ethiopia, Sierra Leone, Uganda, United Republic of Tanzania and Zimbabwe do not use brackish water and have no plans to start using it while regulations on the use of brackish water for irrigation are available. Most of the responses to the questionnaire indicated that water quality indicators are overlooked. Only Kenya has comprehensive data on irrigation water monitoring system functioning and irrigation water monitoring, integrated with soil salinity and sodicity monitoring. There is also a national irrigation water monitoring scheme that covers the whole of Kenya.
-

- The contribution of irrigation water quality on soil salinization and sodification is significant in Kenya, but it is not the leading factor of soil salinization and sodification. No data are available for other countries.
- Kenya uses water mixing and water desalinization while Sierra Leone and South Africa only use water mixing. Other countries do not employ any method.
- The most common methods of drainage system used in Kenya include surface drainage (shallow ditches), subsurface drainage (deep open drains), subsurface drainage (buried pipe drains) and controlled drainage.
- The criteria used to design the drainage system in Kenya is measuring the hydraulic and physical properties of soil (infiltration, compaction, and soil layers) while soil parameters are also included in Zimbabwe. The type of leaching practice includes flooding and sprinkler
- Calculating the amount of water for leaching is carried out only in Kenya using FAO protocols and national protocols. South Africa uses the same calculations with the addition of indigenous knowledge. Other counties did not provide any information.

Conclusions derived from the International Network of Salt-affected Soils (INSAS) survey

The main conclusions of the INSAS survey can be summarized as follows:

- The extent of salt-affected soils is not fully known, as in many countries there are no official data on this or the data are controversial. The monitoring of salt-affected soils is not performed in most of the surveyed countries. Many experts reported that the mapping of salt-affected soils still needs to be improved and updated, as mapping is achieved with mostly outdated methods and maps are still kept in a paper format.
- Different methods are used for the measurement of soil salinity and sodicity. The most common method involves determining EC in saturated paste extract, followed by calculating TSS. Data harmonization and the development of conversion equations (pedotransfer functions) are crucial.
- The use of electromagnetic methods to assess salinity is, as yet, limited across the regions, although it is a method that gives quick and reliable results when mapping salinity at the field level (FAO, 1999). It is highly recommended that this mapping technique is disseminated among the countries through training sessions.
- Several sustainable management practices for salt-affected soils are implemented in the surveyed countries. However, there are no statistics available to understand their scale of adoption and assess their efficiency.
- A critical gap remaining is the lack of national assessment of yield losses attributed to soil salinity and sodicity. Similarly, the potential yield gains ensuing from reclamation efforts or other enhancements of salt-affected soils remain unexplored. By quantifying yield losses, countries can gain a deeper understanding of the magnitude of the challenge at hand. Similarly, gauging the yield gains achievable through reclamation or soil improvement endeavours can provide a roadmap for sustainable growth and enhanced productivity.
- The use of agrohydrological models is, as yet, limited across all regions, although they provide contemporary tools with significant potential for predicting, assessing, and mitigating water management challenges, as well as addressing soil salinization and sodification issues. It is highly recommended that these are introduced and implemented widely through awareness raising and training sessions.
- Across surveyed countries, a noticeable deficiency in policies governing the management of salt-affected soils is evident, despite a prevailing consensus on the necessity of such regulations. The absence of comprehensive policies in this domain is of widespread concern. However, some exceptions are observed, where a policy specifically targeting the management of soils – particularly salt-affected soils – has been established.
- Brackish water is used widely in most of the surveyed countries. However, irrigation water monitoring systems are not used in most countries, although there is a consensus that establishing such monitoring systems is necessary.

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Chapter 4 | Effect of salinization and sodification on food production (based on GSASmap calculations)

The estimates based on FAO's GSASmap (FAO, 2021) and ESA CCI land cover map (ESA, 2017) indicate that around 10% of irrigated cropland, 10% of rainfed cropland and 8% of agricultural land worldwide is affected by salinity or sodicity (Table 4.1).

Table 4.1 | Areas of salt-affected soils under different land uses (M ha)

	Topsoil (0-30 cm)		Subsoil (30-100 cm)	
	Area of salt-affected soils (SAS)	% of SAS	Area of salt-affected soils (SAS)	% of SAS
Agricultural lands	132.261	4.2	243.19	7.8
Croplands	79.549	4.5	152.086	8.6
Irrigated croplands	19.789	8.6	24.316	10.5
Rainfed croplands	41.269	5.0	81.903	10.0

*The coverages of different land categories have been taken from ESA CCI v. 2.0 (ESA, 2017). The total areas are: Agricultural (codes 10+20+30+40+130) = 3130.036 M ha; Cropland (codes 10+20+30+40) = 1759.936 M ha; Irrigated (Code 20) = 230.648 M ha; Rainfed (Code 10) = 817.988 M ha.

**The statistics is provided based on the submitted data covering 73% of the total land area

The potential yield losses caused by soil salinity were assessed on the basis of a geospatial analysis of the GSASmap (FAO, 2021) and the Global Spatially-Disaggregated Crop Production Statistics Data (mapSPAM) (IFPRI, 2019). The calculations were performed for the countries included in the GSASmap (120 countries in total). The topsoil (0–30 cm) salinity (ECe) was considered. The mapSPAM provided the spatial distribution of 42 different crops and groups of crops (Table 4.2). The potential yield losses were estimated for 15 crops as provided by the salt tolerance parameters in FAO (2002) (Table 4.3). The relative yield loss is available online at *this link* and was calculated according to Formula 1, as follows:

Yield loss (%) = a * (EC − b) *(Formula 1)*

where a is a slope, and b is a threshold (as per Table 4.1).

Table 4.2 | Mapped crops

Type of crop	Name of crop	mapSPAM name	Threshold (dS/m)	Slope
Food crops #				
1	Wheat	whea	6	7.1
2	Rice	rice	3	12
3	Maize	maiz	1.7	12
4	Barley	barl	8	5
5	Pearl millet	pmil	–	–
6	Small millet	smil	–	–
7	Sorghum	sorg	2.8	4.3
8	Other cereals	ocer	–	–
9	Potato	pota	1.7	12
10	Sweet potato	swpo	1.5	11
11	Yam	yams	–	–
12	Cassava	cass	–	–
13	Other roots	orts	–	–
14	Bean	bean	1	19
15	Chickpea	chic	–	–

Type of crop	Name of crop	mapSPAM name	Threshold (dS/m)	Slope
Food crops #				
16	Cowpea	cowp	2.5	11
17	Pigeon pea	pige	–	–
18	Lentil	lent	–	–
19	Other pulses	opul	–	–
20	Soybean	soyb	5	20
21	Groundnut	grou	–	–
22	Coconut	cnut	–	–
37	Banana	bana	–	–
38	Plantain	plnt	–	–
39	Tropical fruit	trof	–	–
40	Temperate fruit	temf	–	–
41	Vegetables	vege	–	–
Non-food crops #				
23	Oil palm	oilp	–	–
24	Sunflower	sunf	4.8	5
25	Rapeseed	rape	9.7	14
26	Sesame seed	sesa	–	–
27	Other oil crops	ooil	–	–
28	Sugar cane	sugc	1.7	5.9
29	Sugar beet	sugb	7	5.9
30	Cotton	cott	7.7	5.2
31	Other fibre crops	ofib	–	–
32	Arabica coffee	acof	–	–
33	Robusta coffee	rcof	–	–
34	Cocoa	coco	–	–
35	Tea	teas	–	–
36	Tobacco	toba	–	–
42	Rest of crops	rest	–	–

Sources: **IFPRI (International Food Policy Research Institute).** 2019. Global Spatially-Disaggregated Crop Production Statistics Data for 2010 Version 2.0. In: Harvard Dataverse. Cambridge, USA. [Cited 16 November 2023]. *https://dataverse.harvard.edu/citation?persistentId=doi:10.7910/DVN/PRFF8V*

Salt tolerance parameters (threshold and slope) according to **FAO**. 2002. Agricultural Drainage Water Management in Arid and Semi-Arid Areas. FAO Irrigation and Drainage Paper 61. Rome. *https://www.fao.org/3/y4263e/y4263e00.htm#Contents*

According to these estimates – covering an area of 644 million ha – the total relative yield loss is 0.5 percent, ranging from 0.03 percent (soybean) to 5.05 percent (bean) (Table 4.3). However, in the countries most affected by salinity of the cropland, the potential yield losses caused by salinity stress are much higher. Here, potential crop losses due to salinity stress are up to 72 percent for rice, 68 percent for bean, 45 percent for sugar cane, 40 percent for potato, 38 percent for sweet potato, 37 percent for maize, 15 percent for wheat, 14 percent for barley, 12 percent for sorghum, 11 percent for cowpea, and 4 percent for cotton and sunflower (Table 4.4). The full estimates are given in Annex 6.

Table 4.3 | Relative potential yield loss due to salinity stress (by crop)

Crop	Crop area (ha)	Area affected by salinity (ECe >4 dS/m) (ha)	Relative yield loss (%)
Wheat	144 194 726	4 247 037	0.28
Maize	114 839 712	375 291	0.32
Soybean	86 920 777	46 404	0.03
Rice	79 623 314	1 414 523	0.69
Barley	39 654 032	557 141	0.08
Sorghum	37 266 043	182 642	0.09
Cotton	24 620 428	1 596 099	0.21
Bean	23 700 140	143 906	5.05
Rapeseed	23 077 346	663 166	0.03
Sunflower	22 011 576	301 239	0.15
Sugar cane	20 422 832	185 954	0.40
Potato	11 681 203	293 579	1.93
Cowpea	8 778 301	50 990	0.19
Sugar beet	4 007 546	14 168	0.05
Sweet potato	3 127 151	4 758	0.12
Total	**643 925 126**	**10 076 898**	**0.47**

Table 4.4. Relative potential yield loss due to salinity stress in the countries most affected by cropland salinity (descending order)

Country	Total area occupied by crops (ha)	Area of cropland affected by salinity (EC >4 dS/m) (ha)	Area of cropland affected by salinity (EC >4 dS/m) (%)	barl	bean	cotton	cowp	maiz	pota	rape	rice	sorg	soyb	sugb	sugc	sunf	swpo	whea
Uzbekistan	2 948 951	1 991 365	67.5	0.5	0.3	3.8	–	37.5	39.9	0.4	72.2	12.0	0.8	0.5	–	3.9	–	11.7
Namibia	73 499	37 679	51.3	0.0	68.4	1.4	–	28.3	24.0	–	–	9.5	0.0	–	14.3	2.5	37.7	2.7
Kuwait	2 848	1 453	51.0	1.6	–	–	–	31.2	25.8	–	2.9	–	–	–	–	–	–	4.6
Oman	2 926	760	26.0	13.9	–	–	–	4.2	15.8	–	–	8.4	–	–	44.7	–	–	14.8
Senegal	647 082	112 269	17.4	0.0	0.6	0.0	11.4	7.0	1.3	–	3.8	1.4	0.0	0.0	11.7	–	18.5	–
Iraq	2 199 892	214 692	9.8	0.0	9.5	0.0	3.3	11.7	5.9	0.0	3.7	2.9	0.0	0.0	0.0	0.0	–	0.1
Morocco	5 376 400	297 306	5.5	0.3	0.0	0.0	–	3.0	7.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.7	0.7
Syrian Arab Republic	3 191 968	172 289	5.4	0.0	7.0	0.0	0.0	5.7	2.3	–	0.0	0.6	0.0	0.0	–	0.2	0.0	0.1
Afghanistan	2 688 343	139 121	5.2	0.0	4.8	0.1	–	5.6	7.0	0.0	0.8	6.1	0.0	0.1	4.9	0.1	0.0	0.1
Pakistan	17 208 008	807 945	4.7	0.0	11.3	0.0	–	0.3	0.4	0.0	3.5	0.3	0.2	0.0	2.9	2.8	0.7	0.0

Notes: The full names of crops are given in Table 4.2. The endash means that this crop is not present on mapSPAM in this country.

References to Chapter 4

ESA (European Space Agency). 2017. *Land Cover CCI Product User Guide Version 2.* Technical Report. In: *UCL*. Paris. [Cited 15 May 2024]. http://maps.elie.ucl.ac.be/CCI/viewer/download/ESACCI-LC-Ph2-PUGv2_2.0.pdf

IFPRI (International Food Policy Research Institute). 2019. *Global Spatially-Disaggregated Crop Production Statistics Data for 2010 Version 2.0*. In: *Harvard Dataverse*. Cambridge, USA. [Cited 16 November 2023]. https://dataverse.harvard.edu/citation?persistentId=doi:10.7910/DVN/PRFF8V

Chapter 5 | Pathway towards the sustainable management of salt-affected soils

5.1 | Policy and legal frameworks on sustainable management of salt-affected soils

The sustainable management of salt-affected soils is based on five components (Figure 5.1):

1. Science and technology;
2. Data and knowledge sharing (information);
3. Institutions;
4. Economic feasibility (economics); and
5. Policy (Baliuk *et al.*, 2020).

The latter component – namely effective policies and legal frameworks – is vital to promote social action and attract various forces to make concerted efforts in support of other pillars.

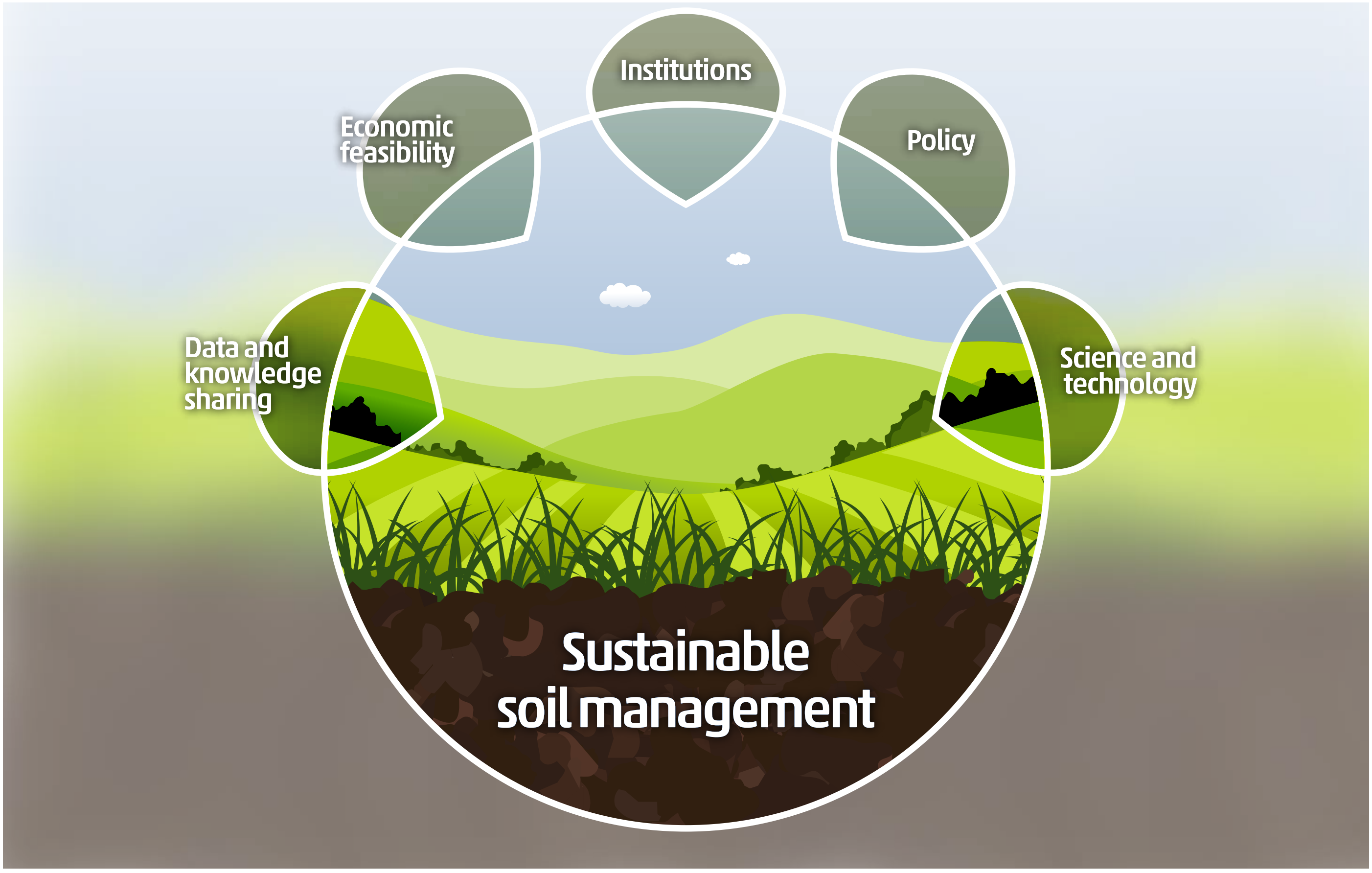


Figure 5.1 | The main components of sustainable soil management

In the SoiLEX (soil related legal instruments and soil governance) database, 32 countries are reported as having the legislative documents related to soil salinization and sodification (FAO, 2024a). The documents (52 in total) do not directly mention salt-affected soils and are mainly focused on combatting desertification (eight documents), water management (six documents), irrigation (nine documents) and overarching laws concerning fertility, soil protection, environment and soil reclamation (26 documents). There was only one document in the database where soil salinity (salinity measurement) is the focus of legislation (FAO, 2024b).

5.1.1 | The status with policy regulation over salt-affected soils according to responses to the International Network of Salt-affected Soils (INSAS) questionnaire

Most of the surveyed experts (76 percent out of 50 countries) reported that there was no specific policy regulating the use and management of salt-affected soils in their countries and that there was a need to develop such a policy. Only 4 percent of respondents agreed with a statement that there was no need in such a policy. It is worth mentioning that they were from the countries not suffering from salinity and sodicity problems. There were no responses confirming that there was any efficient regulation in place.

Half of those countries (25 countries out of 50) did not have a governmental body to undertake the responsibility of monitoring and managing salt-affected soils, although when necessary, some functions concerning the management of salt-affected soils and monitoring had been assigned to the existing governmental body or bodies. Thirtyfour percent of respondents confirmed that such an institution existed in their countries, with 22 percent saying that there was a sole institution responsible, and 12 percent (six countries) describing several institutions undertaking this function. When several institutions existed in the same country dealing with the management of salt-affected soils, no coordination usually existed between institutions, although it would be beneficial to ensure proper management and use of resources.

Countries not suffering from salinity and sodicity problems did not have any institution or regulation in place and did not consider their establishment as a priority.

5.1.2 | Key actions to improve the policy in the sustainable management of salt-affected soils

Salt-affected soils are of high importance in terms of conservation of vulnerable and highly biodiverse ecosystems as well as for food security especially in countries severely affected by salinization and sodification. There are several key actions proposed to improve the protection and sustainable management of salt-affected soils:

Implement the ecological priority and green development model. As salt-affected soils are often located in ecologicallyfragile areas, maintaining respect for natural laws and establishing the concept of sustainable use of natural resources are crucial to maintain the health and functioning of the local environment. A green development model that integrates resource development with resource protection, capacity building, and more sustainable industrial chains is required in the management of salt-affected soils. For instance, conserving the natural heritage of saline areas is vital to ensure the sustainable use of salt-affected soils. It is of strategic and practical significance to develop ecologicallyoriented integrated management practices and technologies that match the natural resources and socioeconomic conditions of salt-affected areas.

Introduce preferential policies and strengthen pilot guidance for reclamation efforts. Introducing preferential policies can mitigate reclamation costs, thereby increasing the investor attractiveness of reclamation endeavours. For example, mechanisms such as tax exemptions and favourable loan interest rates have the potential to attract a larger pool of investors and capital, fostering greater involvement in the restoration of saline and sodic lands and thereby facilitating the seamless advancement of such projects.

Pilot guidance serves as an empirical platform through which reclamation initiatives can systematically explore diverse methodologies and technologies. The implementation of pilot initiatives in specific locations offers the possibility to showcase tangible outcomes and acquired wisdom from reclamation activities, consequently inciting interest and engagement from stakeholders in analogous contexts.

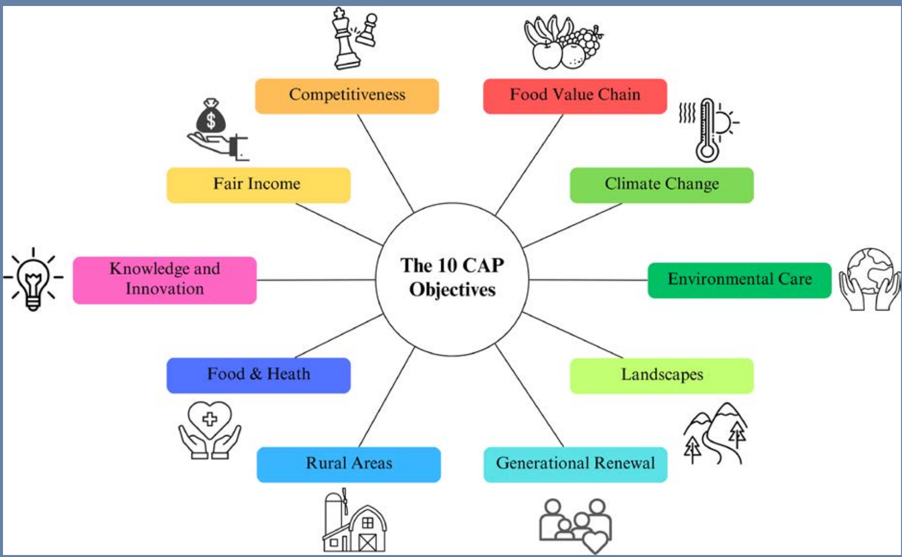
The integration of preferential policies and pilot guidance can strengthen social support for reclamation initiatives. Active engagement and endorsement by governmental entities can heighten public cognizance and confidence, catalyzing a unified commitment across multifarious sectors to participate in the comprehensive rehabilitation of salt-affected soils. Preferential policies coupled with pilot guidance mechanisms can also expedite the reclamation timeline, thereby hastening the realization and culmination of projects. This acceleration contributes to the prompt amelioration of the ecological milieu and soil integrity of salt-affected soils, thereby furnishing substantial backing for agricultural productivity and ecological preservation.

Box 5.1 | The European Union's policy landscape concerning salt-affected soils

As of 2023, policy and legal instruments which deal with sustainable management and monitoring of salt-affected soils are limited at the European Union level. However, the theme is intertwined amongst several European Union governance documents.

The supranational European Union policy framework, known as the Common Agricultural Policy (CAP), is a partnership between agriculture and society with a policy cycle of four years (EC, 2023a). The latest CAP strategic plans initiated in January 2023 encompass three main measures: 1) income support; 2) market measures, and 3) rural development measures (with the CAP's budget among them). It furthermore divides the key policy objectives for 2023–2027 over ten objectives.

The Common Agricultural Policy's ten key objectives



Source: Author's own elaboration from **EC.** 2023. Key policy objectives of the new CAP. In: *European Commission*. Brussels. [Cited 4 January 2023].
https://agriculture.ec.europa.eu/common-agricultural-policy/cap-overview/new-cap-2023-27/key-policy-objectives-new-cap_en

The first European Union strategy linked to a CAP objective that mentions salt-affected soils is under the objective of "climate change" (EC, 2023b). In the objectivespecific policy brief, a decrease in the agricultural potential for areas in coastal regions due to salinization of aquifers is stressed. However, most measures linked to this objective focus on the mitigation of greenhouse gases (GHGs). This limited scope prevents concrete policy development explicitly linked to attenuate salt-affected soils. Salinization is mentioned as a major contributor for soil degradation and biodiversity loss under the CAP's objective of "environmental care" (EC, 2023c). For that respective policy brief, salinization is labelled as one of the main threats to European soils, land and biodiversity, with the main strategies being discussed under this objective focus on agroecology and precision agriculture. Unfortunately, no interventions are mentioned under precision agriculture that are linked to salinity mitigation (e.g. leaching, drainage and precision irrigation) under these strategies. Soil salinity is not explicitly mentioned in the policy brief of CAP's objective on "landscapes" (EC, 2023d), which is striking, as salinity is linked to biodiversity loss under the strategies of other CAP objectives.

In 2020, the European Green Deal was initiated, framed as "a package of policy initiatives, which aims to set the European Union on the path to a green transition, with the goal of reaching climate neutrality by 2050" (European Parliament, 2019). Part of the European Green Deal is the Farm to Fork (F2F) strategy, which consists of a set of policy targets for 2030 regarding food security and environmental protection (European Commission, 2019).

Agriculture and rural areas are central to the European Green Deal. Neither the European Green Deal, nor the F2F strategy explicitly mention salt-affected soils or saline agriculture. The Biodiversity Strategy and the Soil Strategy for 2030 both address the issue of soil salinization and of saline agriculture and contribute to reaching the goals of the European Green Deal. The EU Soil Strategy for 2030 stresses the importance of active restoration measures to recover salinized soils (European Commission, 2021). Remarkably, salinity adaptation or prevention is not covered in the strategy. In the EU Biodiversity Strategy for 2030, the European Commission proposed legallybinding nature restoration targets to restore degraded ecosystems, in particular those with the most potential to capture and store carbon and to prevent and reduce the impact of natural disasters (European Parliament, 2021). This once again hints at a carbon sequestration focus, as seen in the strategies for the CAP's objectives.

Policy gaps and opportunities at the European Union level

Legal instruments on salt-affected soils are not specified per se at the European Union level, but are present at some European Union member states' national levels according to the SoiLEX database (FAO, 2024). Although salt-affected soils are addressed in some European Union strategy documents, concrete supranational policies and frameworks are left much to be desired.

Saline agriculture could fit in all three measures of the CAP. Income support can provide an incentive to adopt saline agriculture and would cover the loss of yields due to farming on salt-affected lands (Daliakopoulos *et al*., 2016). Market measures include the promotion of European products through subsidies, which can provide necessary support to create a market for saline agriculture products. Rural development includes sharing and encouraging uptake of knowledge, innovation by farmers through improved access to technology and training. Due to the fouryear policy cycle of the CAP, there is ample opportunity to give salt-affected soils a more prominent place on the CAP for 2027. Saline agriculture could furthermore get a more prominent place on the strategies for the CAP's objectives: "fair income", "rural areas" and "knowledge and innovation".

The EU Soil Strategy for 2030 (EC, 2021) and the EU Biodiversity Strategy 2030 (European Parliament, 2021) briefly hint at salt-affected soils being integrated into the strategy to mitigate the respective ecological challenges, but it is limited to restorative action. Hence, an opportunity arises to integrate policies supporting salinity adaptive or wider mitigative measures into policy at the European Union level. It is advised to frame salinity issues and solutions in a wider perspective and to prevent a carbon tunnel vision from arising, to support a wide, inclusive sustainable transition.

Opportunities arise for policymakers to give saline agriculture a more prominent place on the future European Union policy agenda to ensure food and water security, prevent degraded lands and sustain biodiversity. In literature on saline agriculture, scholars emphasize the need to look at salinization issues from a participatory research perspective and call to include stakeholders that are most affected by salt-affected soils (De Waegemaeker and Rogge, 2021). It is therefore crucial that sustainable intensification strategies consider the local context and that they are inclusive for all stakeholders involved.

Sources: **EC (European Commission).** 2023a. The new common agricultural policy: 2023-27. In: *European Commission*. Brussels. [Cited 2 January 2023].
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De Waegemaeker, J. & Rogge, E. 2021. The International Farmers' Café on Salinization and Saline agriculture. In: J. De Waegemaeker & E. Rogge. *Future of Sustainable Agriculture in Saline Environments*, pp. 323–372. Milton Park, UK, Taylor and

Strengthen cross-sectoral communication and engagement within and between governments at all levels to form an efficient management model. The sustainable management of salt-affected soils involves comprehensive development, encompassing water conservancy, agriculture, finance, and other departments, which requires the cooperation of all the relevant departments of government. If different ministries or departments do not communicate enough or lack collaboration mechanisms, this could result in scattered funds and impaired efficiency of salinity management. Hence, a collaborative mechanism is needed to determine the responsible subjects, improve governance efficiency, promote cooperation between various departments involved in the governance of salt-affected soils, and establish a coordination mechanism to ensure efficient operation.

Strengthen the capacities of relevant scientific and technological talents and promote academic platforms and technology development. Improving salt-affected soils requires the strengthening of multidisciplinary crossfertilization research and enhancing the cooperation between academia and the private sector involved in technology development. In addition, strengthening the present platforms is needed to attract and gather talents. Particularly, the focus should be on developing local scientific and technological talents, as they would be able to serve the local community for a longer period and be more familiar with the local conditions. By using these platforms to vigorously introduce highlevel talents and projects, a wide range of cooperation channels between industry, academia, and research institutions can be catalyzed. Research platforms can provide new technologies, such as biomediated methods, which can offer technical support and reserves for the high-quality development of largescale industries that can help manage salt-affected soils.

Establish a legal framework for soil salinization and sodification supervision and accountability. It is necessary to develop and implement a legal framework at national level related to the management and administration of salt-affected soils and their ecological protection. This framework should include a system of assessment, inventorying, monitoring, utilization, supervision, and management of saline and sodic lands. The current legal system of each individual country requires the incorporation of soil protection into the existing land management and land (soil) monitoring laws and other legal instruments. In addition, it is necessary to establish a responsibility system for land salinization and sodification, strengthen the accountability system for governments at all levels to fulfil their responsibilities for land protection in accordance with the law, and clarify the legal responsibilities and forms of responsibility for safeguarding land resources protection.

5.2 | Conservation of natural saline and sodic soils

5.2.1 | Key ecosystem services provided by salt-affected soils

Ecosystem services describe all the benefits that humans can derive from natural ecosystems for their physical, social, and economic wellbeing, including provisioning services (e.g. providing food and water), regulating services (e.g. controlling floods and diseases), cultural services (e.g. spiritual, recreational, and cultural benefits), and supporting services (e.g. maintaining nutrient cycling for the living environment of life on Earth) (Postel *et al.*, 2012). As a crucial part of those ecosystems, saline and sodic soils are often regarded as a "free" gift, providing a diverse array of ecosystem services to humanity. Currently, a lot of research has been conducted on the ecological service function of other ecosystems, but the ecological service function of saline and sodic soils is often undervalued or overlooked.

First, as a whole, **saline and sodic ecosystems have great carbon sequestration capacity**. Saline soils have a strong ability to absorb CO_2, and that high soil salinity degrees can inhibit the mineralization rate of soil organic matter and therefore increase the CO_2 uptake capacity of soils (Wang, Fan and Guo, 2019). Saline wetlands are an important component of saline and sodic ecosystems, as they also have a high carbon sequestration capability (Olsen *et al.*, 1996). Saline wetland ecosystems (composed of salt marshes and mangroves) have a greater carbon sequestration capacity and offer more ecosystem service functions than most other terrestrial ecosystems, and therefore are crucial resources for addressing the current climate change problem faced by humans (Bonan, 2008). Globally, salt marshes cover an area of approximately 6.23×10^4 km^2 (Bunting *et al.*, 2018), which allows them to capture and store large quantities of carbon. Studies have indicated that the top metre of salt marsh wetlands approximately stores 917 tonnes of CO_2 equivalent per hectare, with the annual carbon sequestration being about 8.0 ± 8.5 tonnes of CO_2 equivalent per hectare (Sapkota and White, 2021). The carbon burial rate of saline and sodic marsh soils has been estimated as 218 ± 24 g C/m^2/yr, which is about 40 times higher than that of forest ecosystems (Macreadie *et al.*, 2019; Mcleod *et al.*, 2011).

Carbon sequestration by mangroves plays a significant role in the carbon sequestration of halophyte ecosystems and thus it is an integral part of the carbon cycle on Earth. Despite the fact that mangroves only cover 0.1 percent of the earth's surface, they are able to sequester 5 percent of the CO_2 from the atmosphere (Duarte *et al.*, 1998). It has been found that mangrove sediments can bury about 38.3 Tg C/yr (Wang *et al.*, 2021), which is much higher than the carbon sequestration capacity of salt marshes. Accordingly, mangroves are considered to be the most effective of the coastal blue carbon ecosystems for the sequestration of carbon (Box 5.2).

Box 5.2 | Tropical mangrove soils

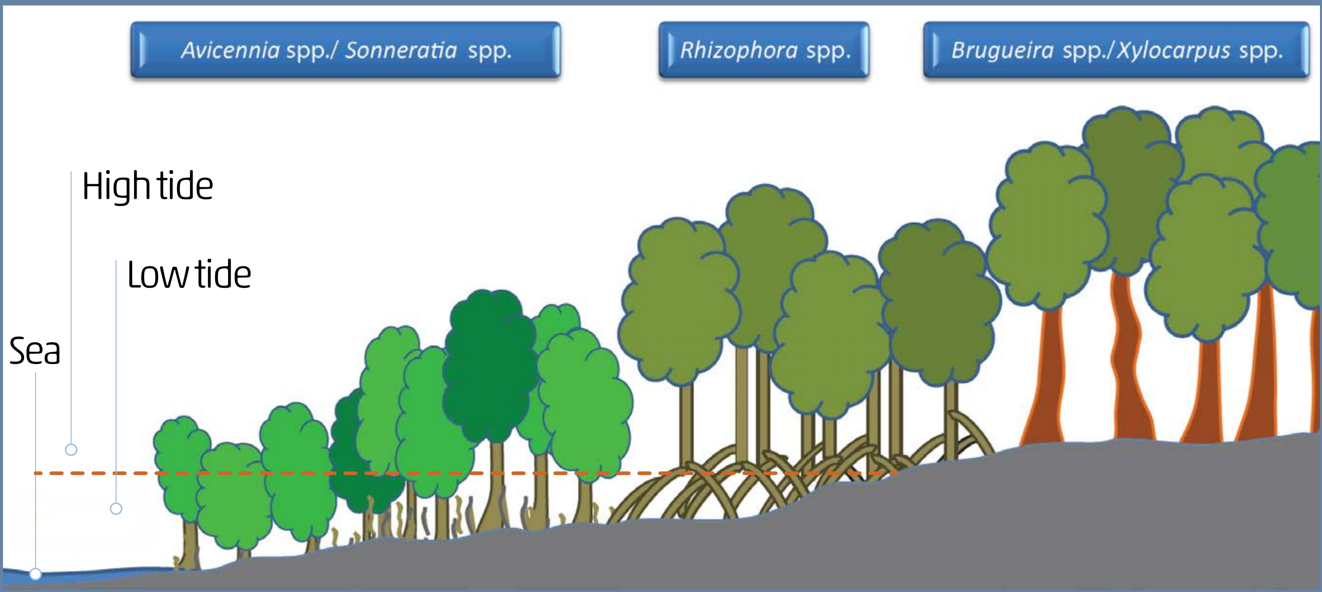
Mangroves are found in the tropical and subtropical regions of the world, forming a substantial belt between land and sea. Mangroves are susceptible to tidal change and salinity, enabling the exchange of sediments, organic matter and gases between water, land and atmosphere (Hutchings and Saenger, 1987; Duarte *et al*., 1998; Biber, 2006). Rocks, sands, minerals, organic matter and marine clay are common substrates of tropical mangrove soils. Salt-affected soils such as those associated with mangroves are unique in the sense that they support important mangroveassociated vegetation that are able to thrive on saline conditions, support faunal communities, store carbon, provide coastal barriers, assist pollution mitigation and support cottage industries (Jeyanny *et al*., 2021). However, despite their niche in the coastal ecosystem, mangrove soils are poorly investigated. The December 2004 Indian Ocean tsunami was a pertinent gamechanger in shifting awareness to the importance of saline soils such as mangroves and their ecosystem services to human, wildlife and nature. Since then, soil scientists have investigated many aspects of saline soils, including soil profiling, erosion, remediation, microbiology, quality, and amendments.

Beneath the soil, in the mix of mud and water, a significant variety of fish, crustaceans and molluscs thrive, with the soils functioning as a breeding ground for these aquatic creatures. In Malaysia, at least 65 percent of finfish and shellfish harvested are associated with mangroves, and over 30 percent of shellfish and finfish landed by commercial operators each year are mangrovedependent (EJF, 2004).

The vegetation composition in mangrove forests is closely related to the substrate characteristics and quality of the salt-affected soils. The presence of rather selective mangrove species discovered at various localities in Malaysia is governed by several factors such as soil structure, soil texture composition and salinity level (Jeyanny and Wan Rasidah, 2015).

Mangrove species can be very site specific, where species adaptability very much depends on the substrate types, such as clay mud or sandy mud, as well as soft or firm substrates. The stilt- and buttresslike architecture of roots such as pneumatophores (aerial roots), are variable according to different physical soil properties. Species succession is a common feature when substrate properties change, with soil profiles becoming deeper and firmer going inland, and so being capable of supporting larger and more robust trees.

Distribution of mangrove species from coastline to inland in Peninsular Malaysia



Source: Adapted and modified from: **Mohamad Fakhri, I. & Wan Rasidah, K.** 2015. Vegetation and soils. In: K. Wan Rasidah, M. Mohamad Zaki, & I. Mohamad Fakhri, eds. *Muddy Substrates of Malaysian Coasts.* Kuala Lumpur, Forest Research Institute of Malaysia.

Mangroves evolve according to the ecological conditions limiting their tolerance to soil salinity and salt water inundation regime. Thus, if durations of daily inundation were to be modified, mangrove species either readjust to the new conditions through recovery or succumb to the unsuitable conditions through mortality (Chan and Baba, 2009). Sonneratia sp. and *Avicennia* sp. can tolerate salinity more than 25 parts per thousand (ppt) with heights above chart datum (0–2.4 m) whereas Rhizophora sp. and Brugeira sp. can withstand salinity between 15 and 25 ppt with heights above chart datum (3.4–4.0 m).

The saline soils in Kuala Sepetang, Perak, Malaysia represent a wellestablished mangrove soil which could be deemed healthy in terms of providing balanced nutrients and physical properties.

Profile of a marine clay soil in Matang Mangrove Reserve, Perak

Well established Rhizophora apiculata trees in Matang Mangrove Reserve, Perak

As can be noted in the soil profile photo, the soil is somewhat imperfectly drained with very dark brown (10 YR 2/2) colour according to the Munsell colour chart, consistent up to a 1.2 m depth. Matang mangroves have a suitable clay and silt composition that ranged from 20–50 percent clay to 10–30 percent silt, falling under the silty clay loam texture. The soils have pH ranging between 6 and 7, with a moderate soil structure and display the electrical conductivity of the saturated paste (ECe) ranging from 7.5 to 9.2 dS/m (Jeyanny and Wan Rasidah, 2015) which is far below the salinity threshold suggested by Chan and Baba (2009) (35 dS/m). Soils display high C values (between 7.6 and 8.6 percent), comparable to a luxuriant mangrove ecosystem in the Vellar and Coleroon estuaries (Kathiresan, 2002) and suitable for mangrove growth and productivity. The cation exchange capacity (CEC) values here range from 30–50 cmol(+)/kg, which are adequate for mangrove growth and productivity.

Salt-affected soils in the mangrove forests support fragile ecosystems that are constantly affected by tidal waves, changing climate, natural erosion and anthropogenic activities such as aquatic farming, infrastructural development and illegal felling that further change the dynamics of soils and mangrove productivity. Despite the need to determine the physical and chemical properties of saline soils, future work should also elucidate the role of soil biodiversity that determines tree species adaptability (Jeyanny *et al.*, 2020) and their overall functions in the biogeochemical cycles that govern the ecosystem.

Besides providing a medium for crop growth, saline and sodic soils provide a natural wave breaker, a buffer for heavy metal and plastic pollution, provide habitat for marine biodiversity and enrich local cottage industries via their raw materials and products. Thus, the protection and conservation of mangrove ecosystems are vital for present and future generations.

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Second, **saline and sodic ecosystems increase the global biodiversity**. In addition to being an important component of the Earth's ecosystem, saline and sodic ecosystems provide a restricted but unique environment for animals, plants, and microorganisms that are especially adapted to it. Through the process of "two-way selection", species have coevolved with their saline and sodic ecosystems, creating highly biodiverse environments. Numerous studies have shown that saline and sodic environments may have an increased diversity of animals and halophytes (Hu *et al.*, 2021; Liu and Wang, 2021). Not surprisingly, saline and sodic environments are also home to numerous salt-tolerant and even halophilic microbial groups, including archaea, bacteria, actinomycetes, and eukaryotes (Zhang *et al.*, 2018). The activity of such microorganisms not only changes the physical and chemical properties of the saline and sodic soils, but the microorganisms have been influenced and changed in return. Due to their adaptation to the high saline and sodic environments, they exhibit physical and chemical characteristics and physiological functions (e.g. cell structures and genetic characteristics) that hugely differ from those of less extremophile microbes. Consequently, the biodiversity of saline and sodic environments is very valuable not only regarding the amount but also the specificity of the genetic reserve contained in the animals, plants, and microorganisms they host (Box 5.3).

Box 5.3 | Soils of the hypersaline inland wetlands in Monegros (Northeast Spain)

The inland saline wetlands of the semiarid region of Monegros (Central Ebro Basin, Northeast Spain) occur in endorheic depressions produced by the karstification of the gypsum and limestone strata on a Miocene structural platform. These depressions have been filled up by sediments from their catchments, mostly as a result of human intervention (Valero-Garcés *et al*, 2000). They are ephemeral and shallow playa lakes, subject to intermittent periods of flooding and drying with no clear seasonal pattern, due to the influence of the irregular and scarce rains, groundwater, surface runoff, and subsurface flows. Hypersaline inland wetlands (with a salt concentrations exceeding that of seawater, up to saturation) have a fluctuating salinity with a non-marine (continental) origin and a chemical composition different from seawater. The 149 saline wetlands of the semiarid region of Monegros cover 19.16 km^2, or 9 percent of the area of the Miocene structural platform (~220 km^2).

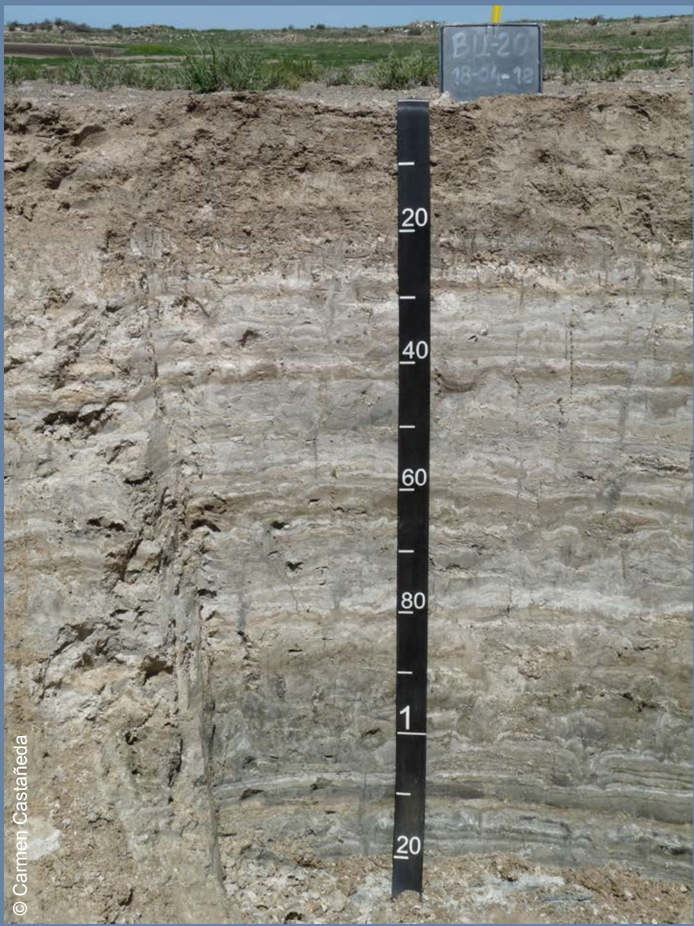
The soils are Gypsic Aquisalids or Gypsic Haplosalids (Soil Survey Staff, 2014), or (frequently Gleyic) Sodic Gypsic Fluvic Solonchaks (Clayic to Siltic, frequently Sulfatic, Evapocrustic, Gypsiric or Hypersalic) (IUSS Working Group WRB, 2022). The redox status of the soil horizons varies from sulphidic to redoxic. Vesicular crusts – made up of crystals of gypsum, halite, thenardite, and bloedite – develop with a polygonal pattern during dry periods on the bare soil surface of the lake.

Apart from the ubiquitous gypsum, mineral occurrences in the soil include synsedimentary authigenic magnesite, diagenetic authigenic dolomite, and most likely allogenic sepiolite (Mees, Castañada and van Ranst, 2011). A microbial mat of cyanobacteria, algae, archaea, and eubacteria appears below the crust only when the surface texture of the soil is relatively coarse.

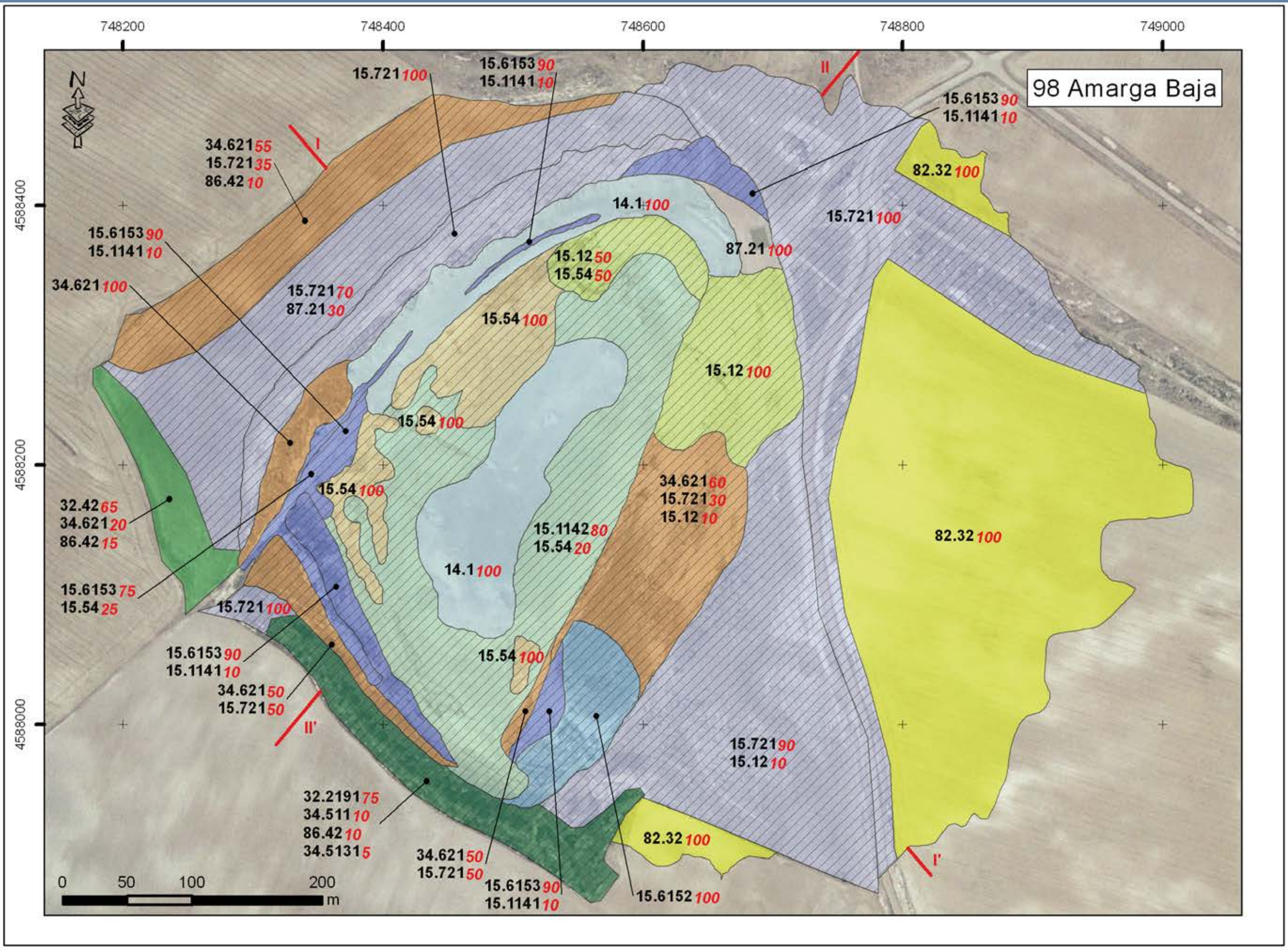
Soils hold different microbial communities involved in the main biogeochemical cycles (nitrogen, sulphur and carbon) (Bourhane *et al*, 2023). Soils with an electrical conductivity (ECe) ranging from 30 to 80 dS/m in the upper 20 cm develop perennial prairies of plant communities with *Arthrocnemum macrostachyum* being the most saltresistant of the vascular plants living on these soils (*A. macrostachyum* is protected under the European Union Habitats Directive 92/43) (Conesa, Castañada and Pedrol, 2011; Dominguez-Beisiegel, Castañada and Herrero, 2013). The surface mineral horizons of these soils have organic matter contents of between 1.3 and 5.2 percent, reflecting significant processes of biological activity despite the harsh environmental conditions. While calcium carbonate content rarely exceeds 20 percent, gypsum contents are higher than 30 percent in all soil horizons and reach over 80 percent in some cases of cemented horizons, appearing below 50 cm depth.

About 60 percent of the wetlands have already been converted to agriculture or urban use, and many of those remaining are under threat due to the expansion of agriculture in their surroundings (Dominguez-Beisiegel, Herrero and Castañada, 2013). Irrigation projects, even if not developed in the immediate vicinity, would produce significant inputs of nonsaline water with an intense disturbance of the irregular pattern of flooding and drying that partially creates these singular environments.

Gypsum-rich layered soil profile in Amarga Baja



Amarga Baja: Example of habitats map corresponding to the Annex I Directive 92/43/CEE



Habitat[1]	HCI[2]	Description
14.1		Mud flats and sand flats in endorheic basin, unvegetated
15.1142	1310	*Salicornia* swards of temporarily inundated salt basins and *Microcnemum* formations
15.12	1310	Mediterranean halonitrophilous pioneer communities
15.54	1410	Interior Iberian salt pan meadows
15.6152	1420	*Arthrocnemum* formations of Iberian interior salt basins
15.6153	1420	Interior woody seablite prostrate scrubs
15.721	1430	Interior, extensive and varied, halonitrophilous scrubs of the Ebro basin and salt lakes
32.2191	5210	Formations of *Quercus coccifera* of the Ebro Basin
32.42		Formations, usually relatively tall, dominated by *Rosmarinus officinalis*
34.621		*Lygeum spartum* dominated formations of the Ebro basin
82.32		Traditionally and extensively cultivated crops
87.21		Ruderal communities

[1]: CORINE Paleartic Code; [2]: Habitat of Community Interest code

Prairie of the halophyte Arthrocnemum macrostachyum in Pito

Soil profile showing sulphidic redox conditions in Salineta

Salt crust in Salineta

Soil profile in Guallar

Sources: **Valero-Garcés, B.L., Navas, A., Machín, J., Stevenson, T. & Davis, B.** 2000. Responses of a Saline Lake Ecosystem in a Semiarid Region to Irrigation and Climate Variability. *Ambio*, 29(6): 344–350. https://doi.org/10.1579/0044-7447-29.6.344

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Box 5.4 | The agropastoral use of sodic soils in Ukraine

One of the provisioning services employed in the management of saline and sodic soils (characterized by unfavourable physicochemical properties for plant growth), is their use in the production of fodder and the development of animal husbandry. Through an adequate biological reclamation it is possible to improve the ecological condition of saline and sodic soils, increase their fertility, and ensure the functioning of ecosystems and the supply of ecosystem services.

The effectiveness of improving the properties of saline and sodic soils is enhanced through the following series: annual leguminous grasses – perennial cereal grasses – perennial leguminous grasses – grass mixtures in crop rotations – longterm grass mixtures (Baliuk, Romashchenko and Truskavetsky, eds., 2015). In particular, perennial grasses have a powerful and beneficial effect, and are therefore considered to be good soil improvers.

Agropastoral ecosystem on sodic soils in Ukraine

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In Ukraine, significant areas (92 200 ha) are occupied by sodic soils. Their reclamation in terms of reversing their conditions has been ineffective and their conversion to arable land is economically unprofitable (Baliuk, Romashchenko and Stashuk, eds., 2013). It is recommended that soilscapes containing saline and sodic soils in more than 50 percent of the area are avoided as croplands.

The most economicallyeffective and ecologicallysafe management of such soils consists of selecting adapted and valuable types of crops to create productive perennial multicomponent agrocenoses (cultural hayfields and pastures) with high fodder value, a pronounced phytomelioration effect, and low resource inputs.

Therefore, phytobiological reclamation measures adapted to these soils would allow them to sustain a specific agricultural production with a significant saving of energy and matter resources, while at the same time significantly improving the soils' physical and physicochemical properties, preserving and increasing their agroecological potential, and sustaining several ecosystem services.

Sources: **Baliuk, S., Romashchenko, M. & Truskavetsky, R**., eds. 2015. *Land reclamation (systematics, prospects, innovations).* Kherson, Ukraine, Grin.

Baliuk, S.A., Romashchenko, M.I. & Stashuk, V.A., eds. 2013. *A complex of anti-degradation measures on irrigated lands of Ukraine,* p. 160. Kyiv, Agrarian Science.

5.2.2 | The status of the protection of salt-affected soils with valuable ecosystems according to responses to the International Network of Salt-Affected Soils (INSAS) questionnaire

Many countries surveyed did not have a **specific law or regulation** to protect natural salt-affected soils, despite the importance and urgent need to protect some valuable and rare environments (such as marshes and mangroves) at risk of extinction. Thirty-two percent of surveyed countries reported that there was such a protective regulation in place (Table 5.1). The list of regulations is provided in the full report. Some of the respondents mentioned that such a protection was in place under the Ramsar Convention (Ramsar, 2023). Only 6 percent of respondents stated that there was no need for such a law as there were no valuable ecosystems with salt-affected soils in their respective countries. It is therefore of primary importance to raise awareness among respective governmental bodies about the value of such wetland ecosystems, and beyond.

Table 5.1 | Laws protecting saline environments with valuable ecosystems (summary from responses to INSAS questionnaire)

Country	Regulation
Benin	Law No. 2018-10 of 2 July 2018 related to the protection, development and raiding of the coastal zone in the Republic of Benin (Government of the Republic of Benin, 2018).
Botswana	National Biodiversity Strategy and Action Plan 2016 (DEA, 2016).
Brazil	Federal Law 12.651 2012 (Chamber of Deputies, 2012). Establishes norms for the protection of native vegetation, including forest conservation and exploitation areas. This law protects only vegetation in saline environments.
Cameroon	Law No. 96/12 of 5 August 1996 RELATING TO ENVIRONMENTAL MANAGEMENT (National Assembly of Cameroon, 1996).
Germany	Several laws depending on federal states in respect to protect salt marshes of the Wadden Sea World Heritage.
Hungary	Saline lakes are protected natural areas of national importance «ex lege», natural areas declared protected by law (Act LIII of 1996 on the Protection of Nature [National Assembly of Hungary, 1996]). Some parts of the area affected by salinity are national parks.
Italy	COUNCIL DIRECTIVE 92/43/EEC of 21 May 1992 related to the conservation of natural and semi-natural habitats and wild flora and fauna (OJ L 206, 22.7.1992, p. 7) (Italian Parliament, 1992).
Kenya	The environmental management and coordination (wetlands, river banks, lake shores and sea shore management) regulations, 2009 (Ministry for Environment and Mineral Resources, 2009).
Libya	The Fourth National Report on the Implementation of the Convention on Biological Diversity, 2010 (EPA, 2010). Law No. 15 of 2003 on the protection and improvement of the environment (General People's Congress, 2003).
Mexico	Only for sites declared as protected natural areas (Government of Mexico, 2018, 2023; Unknown Mexico, 2023).
Kingdom of the Netherlands	Ramsar Convention, protection laws for biodiversity in the wetland areas (Ramsar, 2023).
South Africa	National Environmental Management: Biodiversity Act 10 of 2004 (South African Government, 2004).
Spain	Ramsar Convention, protection laws for biodiversity in the wetland areas (Ramsar, 2023).
Tunisia	Descriptive sheet on wetlands Ramsar (FDR) (Ministry of Agriculture and Hydraulic Resources, 2007).
The United Kingdom	Many wetland and estuary habitats are protected by Natural England, the Royal Society for the Protection of Birds (RSPB), and other stakeholders (Natural England, 2023). Water is regulated by European Union Water Framework Directive (WFD).

Sources: **Government of the Republic of Benin**. 2018. *Law No. 2018-10 of 2 July 2018 related to the protection, development and raiding of the coastal zone in the Republic of Benin*. Cotonou, Benin. *https://sgg.gouv.bj/doc/loi-2018-10/*

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5.3 | Sustainable management practices of salt-affected soils

Soil salinity and sodicity cause major reductions in crop productivity and quality, reduce the area of land available for cultivation, and present devastating environmental stresses for humanity (Yamaguchi and Blumwald, 2005; Shahbaz and Ashraf, 2013). The world population is increasing rapidly and global food production has to be continually increased to maintain the current levels of food supply. Given that salt-affected soils represent at least 10 percent of arable land, the sustainable management of these soils is crucial to meet food demand, which FAO has identified as a critical strategy to increase agricultural productivity (FAO, 2017). Salt-affected soils limit crop growth due to their excessive salt content, limiting water availability to crops, and excessive exchangeable Na, leading to poor soil structure. These soils usually lack soil organic carbon and available nutrients, particularly N, P, and K.

Both mitigation and adaptation strategies can be applied to sustainably manage salt-affected soils for agricultural production. Mitigation strategies are aimed at the reduction of salinity levels in the root zone whereas adaptation strategies are aimed at coping with existing salinity levels (Figure 5.2). Most widespread practices are summarized in this chapter. Many of them are not independent but are used in combination with each other.

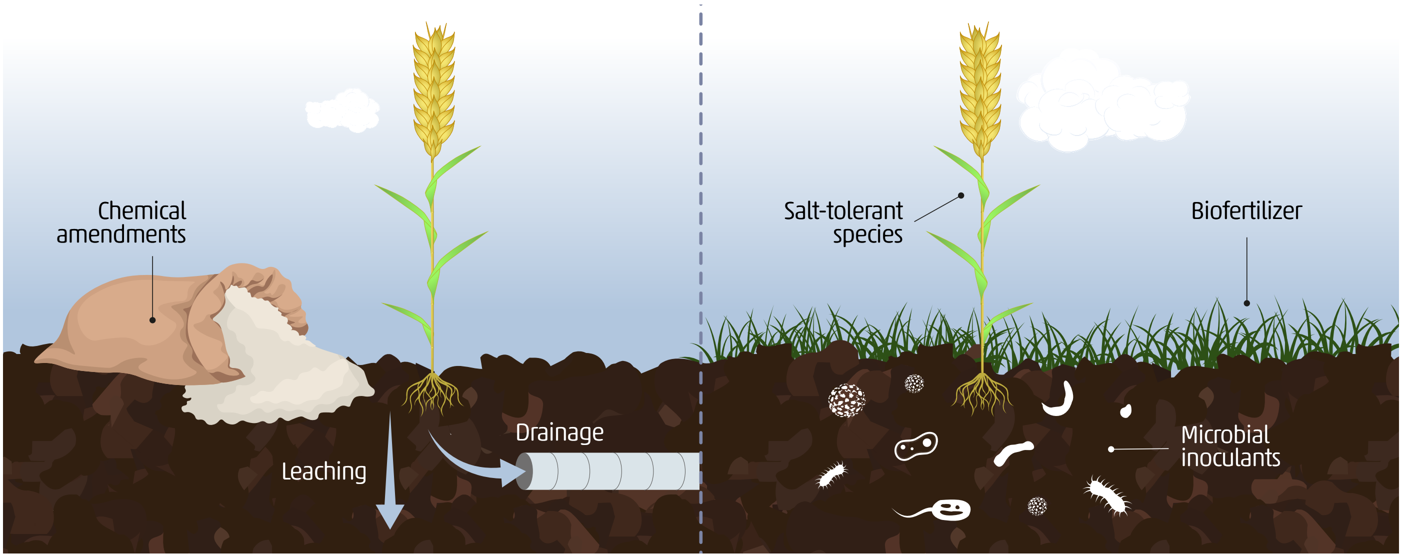

Figure 5.2 | Examples of mitigation (left) and adaptation (right) strategies

5.3.1 Mitigation strategies

Physical measures

Mulches

Mulch is any material that is used to cover the soil's surface. By forming a barrier on the surface or around the plant root, mulch can protect soil, water, and plants in a variety of ways (Kardavani *et al.*, 2013). The mulching of the surface can attenuate the evaporation of water from the ground and prevent the upward movement of salts, thus inhibiting the accumulation of salts on the soil surface (Figure 5.3).

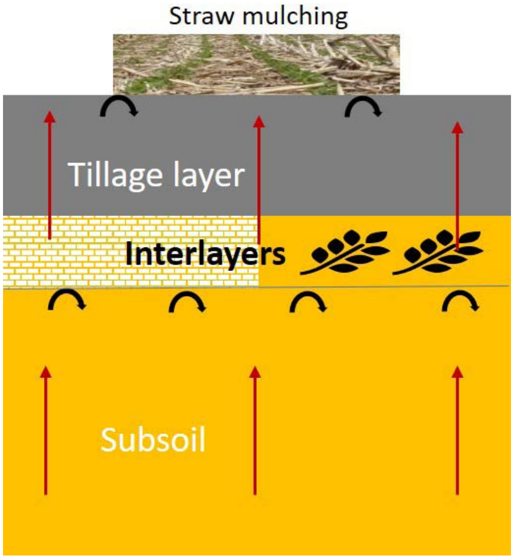

Figure 5.3 | Schematic diagram of practices aimed at reduced evaporation (interlayers and straw mulching)
Source: Author's own elaboration. Photo © Lidong Ren.

Mulches have mainly positive effects in reducing water evaporation, salt accumulation, lowering soil temperature, and increasing water efficiency (Benz, Sandoval and Willis, 1967; Bezborodov *et al.*, 2010). Their use improves soil structure (Cong *et al.*, 2019) and helps regulate microbial activity (Li *et al.*, 2016). Mulching results in an increased number of leaves, plant height, leaf surface area, and plant performance (Awopegba, Oladele, and Awodun, 2017).

There are two types of mulches used in agriculture: organic and inorganic (Tahan *et al.*, 2015). Inorganic (plastic) mulches do not decompose or slowly break down after a long period of time and thus they are not recommended due to their negative effects on the environment (UNEP and GRIDArendal, 2021). Moreover, inorganic mulches inhibit soil moisture retention in winter time. Organic mulches decompose over time, adding nutrients back into the soil and help to retain moisture in the soil. They can also help degrade pesticides and other contaminants while contributing to the nutrient availability and the soil carbon content of the soil (Gan *et al.*, 2003).

Kumar and Goh (2000) highlighted that incorporating crop residues after harvesting significantly increased the soil's physical properties, nitrogen content, soil water storage and grain yield. Pang *et al.* (2010) examined the impact of brackish water and straw mulching on soil profile salinity and crop development and showed a reduced amount of salinity in the first 100 cm of soil under mulch treatment. A recent study on sunflower crops in the Ganges Delta reported that the application of rice straw mulch at 5 t/ha on the soil surface led to a higher soil water content and lower soil salinity, thus increasing the soil solute potential and contributing to an increased sunflower yield (Paul *et al.*, 2020b). Another study implemented in the same area demonstrated that rice straw mulch significantly reduced soil compaction and cracking which related to better sunflower root development (Paul *et al.*, 2021a). The crop conditions and soil status under rice straw mulch and nomulch treatment are shown in Figure 5.4.

Figure 5.4 | Soil and crop condition under nomulch (left) and rice straw mulch (right) in the coastal area of Bangladesh

Limitations for scaling up. Different mulches have different effects on water movement. Due to the inhibition of water movement between the soil and above-ground, black plastic limits soil water recharge (Banko and Stefani, 1991). Mulching with materials such as plastics, geotextiles, finetextured organic mulches, and compounds with waxy components may lead to increased soil compaction or cause hydrophobic conditions that will limit recharge. Hence, although these materials may initially improve soil water retention, due to a decrease in evaporation (Lakatos *et al.*, 2000), over the long term they will create abnormally dry soils. The use of oil mulch has a quick and immediate effect on soil stabilization from wind erosion and can be implemented quickly and over a wide area, but its use is not nature-friendly as the oil contains heavy metals which can cause environmental damage (Salehi Morkani *et al.*, 2022).

Economic aspects: Many decades of study have shown that mulching increases crop growth and yield (Zare *et al.*, 2022). The use of organic mulches is therefore recommended due to their environmental friendliness, safety and cheap price.

Interlayers from loose materials

An interlayer is a layer of any material (such as sand, pebbles, or straw) in the subsoil that is used to improve the hydrological and physical properties of soil. It has proved to be an effective barrier to capillary movement and in preventing the upward movement of salts from the subsoil and groundwater in saline–alkali areas (Akudago, 2009; Wang *et al.,* 2019). Soil salinity is also consistently decreased as the straw thickness is increased, as the thicker the interlayer, the longer the retention time of the capillary water within and the more effective the interlayer is at inhibiting water evaporation (Aubertin *et al.*, 2009). However, there is an upper limit on the thickness index of the barrier that prevents water and salt movement (Qian, Huo and Zhao, 2010). It is important to note that a thicker straw layer can also accelerate salt accumulation in the straw layer and increase secondary soil salinization (Zhang *et al.*, 2020).

Changing the soil structure increases the infiltration of salts in the upper layer. Tillage can cut the capillaries in the soil and inhibit the rise of salts, while increasing the porosity, aeration and permeability of the soil, which is conducive to salt leaching (Jayawardane and Chan, 1994; Xong *et al.*, 2011; Yao *et al.*, 2023). In addition, straw return (the ploughing in of crop residue) can improve soil structure by increasing soil organic matter, which in turn increases soil infiltration capacity and promotes salt leaching from the topsoil (Zhang *et al.*, 2020). However, those tillage methods can reduce the beneficial effects and even lead to losses if not properly applied, as well as risking subsoil compaction by heavy machinery (Botta *et al.*, 2006; Ren *et al.*, 2022).

Burying a layer of straw in the soil also has a potentially helpful effect on the management of soil water and salt (Wang *et al.*, 2012). Based on the report by Cao *et al.* (2012), the application of a straw layer limits the evaporation of groundwater and reduces the accumulation of salts in the topsoil. According to Wang *et al.* (2012), additional advantages of deep burial of straw layers in saline soils were lower soil pH and bulk density, increased soil organic matter, and plant earliness.

Box 5.5 | Integrated salinity management for smallholder vegetable production: Case studies from Mozambique

Overview and context

The presented integrated salinity management is based on experiences gained in salt-affected intensive vegetable production systems in Maputo, southern Mozambique. Local vegetable production predominantly takes place in coastal wetland environments with a varying influence of seawater intrusion or historic saline soils and subsoils. It is dominated by smallholder farmers and thus characterized by small plot sizes, manual land preparation and irrigation. Typically, although farmers have a low financial and technological resource endowment, they have a comparatively high labour availability. This allows for salinity management solutions with a low-cost extensive resource input but a comparatively high labour and management demand. A recent applied research initiative piloted and compared several promising agronomic salinity mitigation strategies under local conditions (Herrmann *et al.*, 2022). Its preliminary results are presented here, assuming replicability in similar agroecological and socioeconomic context around the globe.

Target: Both soil salinity and soil sodicity can be treated with this approach. Local soil conditions are quite variable, specifically in terms of texture, organic matter content and actual levels of salinity. Sodicity, as well as high soil pH, have been identified as complementary constraints.

Type of cropland: Irrigated. Irrigation is conventionally done manually with watering cans. Irrigation water is retrieved from simple boreholes or from surface drainage channels.

Practice 1. Leaching, improved drainage, and mulching

Necessary equipment and activity needed to introduce the practice:

- access to quality (non-saline) irrigation water;
- simple irrigation equipment (e.g. watering can); and
- mulching material (e.g. dried grass or reeds).

Economic aspects: No economic or monetary evaluation was made. There was a higher labour input compared to conventional production strategies, and a high investment would be required if longdistance transportation of quality water was to be considered.

Brief description of the practice

The key objective of this approach is the (temporary) removal of salts from the upper soil layers and root zone of the vegetable crops produced. The principal prerequisite is the access to quality (nonsaline or low salinity) irrigation water. Local mapping and monitoring of water resources revealed that a high variability exists in terms of water quality between different irrigation water sources, even on a small scale (e.g. boreholes only a few metres apart from each other). Ideally, simple measuring devices should be used in order to monitor irrigation water quality parameters in critical zones (e.g. electrical conductivity [EC] meters, made available through extension services). Alternatively, it is possible to resort to local knowledge and monitoring techniques (e.g. physical tasting of the water). After land preparation, and before seeding or transplanting, the raised vegetable beds should be intensively watered in order to wash out any salts present in the upper soil layer of the beds. Especially in areas with high groundwater tables, the beds should be intentionally elevated and furrows laid out, in order to improve drainage of the leaching water and prevent subsequent capillary rise of soil water containing salts. If feasible, irrigation quantity should be kept above actual crop demands during the first few phases of crop establishment. One complementary measure – which aims to reduce evaporation and thus reduce irrigation demand or the risk of salt accumulation on the soil surface – is the application of mulching material on top of the vegetable beds. Complementary benefits are an enhanced soil life and the suppression of weeds. Generally, suitable local materials, such as dried grasses or reeds, are readily available.

The outlined management approach was applied in a pilot demonstration trial at the beginning of the warm/wet season in November and December 2022, using beetroot as the study crop. The salinity of the upper soil layers was monitored with a handheld EC meter. Salinity levels proved to be lower under the improved treatments described previously, compared to conventional treatments (lower beds, less irrigation, and no mulching). Equally, better crop emergence and initial development was recorded for the piloted management approach. These results correspond well with the available scientific literature, which reports a reduction of salinity and sodicity levels and yield increase under integrated salinity management approaches, including appropriate leaching requirements and raised bed planting methods (Velmurugan *et al.*, 2016; Aiad *et al.*, 2021), as well as mulching (El-Mageed, Semida and Abd El-Wahed, 2016). The practice itself is rather simple. It does not necessarily require significant additional material input and can be easily understood by farmers. The main limitations could be the increased labour requirement, the nonavailability of quality irrigation water in sufficiently close proximity, as well as the nonavailability of measuring equipment for precise and efficient monitoring of water quality or salinity dynamics in the root zone.

Raised bed preparation and initial leaching before seeding

Beetroot seedling development after four weeks of direct seeding, showing a clear difference in germination success and plant development between improved and conventional irrigation and drainage approaches

Practice 2. Application of tolerant crop varieties and green manures

Necessary equipment and activity for introducing practice: Access to quality seeds of salt-tolerant crop varieties.

Economic aspects: No economic or monetary evaluation made.

Brief description of the practice

In general terms, conventional vegetable crops are mostly classified as being sensitive towards salinity stress . Beetroot and Swiss chard are comparatively salt-tolerant and are both successfully exploited by local farmers on salt-affected plots. There also exists some "indigenous leafy vegetables" with a comparatively high salinity tolerance. In the local context these include different amaranth species and New Zealand spinach (Herrmann, 2019). However, they are often of minor economic relevance in local markets and thus do not constitute a viable alternative to conventional cash crops. Depending on the actual level of salinity, farmers may also draw on more resistant cultivars of a given crop species. The scientific literature highlights the intraspecific variability of vegetable crops with regard to salt tolerance (De Vos *et al.*, 2016; Su *et al.*, 2013). However, respective knowledge and practical experience under local conditions are limited, as well as having access to seeds of alternative cultivars. The presented project initiative therefore initially piloted small variety trials in farmers' fields, with crops such as Swiss chard, beetroot and leafy brassicas. Repetition and expansion of the trials are necessary in order to obtain conclusive results. Additional efforts should be made to introduce promising cultivars for testing under local conditions and eventually introduce them into the portfolio of local commercial seed providers.

Multiple benefits can be gained by further diversifying the vegetable cropping system through the introduction of complementary salt-tolerant crops. These may be shortterm catch crops (cover crops planted between main plantings for green manuring), or perennial woody species that are then integrated into a vegetable agroforestry system. Several species have been suggested as suitable candidates by the scientific literature, such as Kallar grass (*Leptochloa fusca*) or *Sesbania* spp. (Jesus *et al.*, 2015; Qadir *et al.*, 2007). The presented project initiative introduced and piloted *Sesbania sesban* and *Sesbania bispinosa* as promising candidates for the local cropping system. While the former is applied as a perennial agroforestry crop for biodrainage and green manure coppicing, the latter serves as a shortterm green manure catch crop during the warm/wet season. *Sesbania* spp. offers a considerable remediation potential for salt-affected soils, principally based on the following mechanisms:

- improved leaching conditions based on plant root effects on soil physical characteristics;
- increased dissolution of calcite due to root respiration and root proton release, which results in higher calcium availability and replacement of sodium from the exchange complex; and
- plant uptake of sodium and other salt ions, and their accumulation in the above ground biomass.

Further benefits are an increase of soil organic matter and microbial activity, as well as an improvement of soil fertility (Jesus *et al.*, 2015; Qadir *et al.*, 2007).

***Pilot trial.* Sesbania applied as a perennial biodrainage and green manure crop in a vegetable agroforestry system**

***Pilot trial*. Sesbania applied as green manure catch crop in individual raised beds**

Sources: Velmurugan, A., Swarnam, T., Ambast, S. & Kumar, N. 2016. Managing waterlogging and soil salinity with a permanent raised bed and furrow system in coastal lowlands of humid tropics. Agricultural Water Management 168: 56–67. https://doi.org/10.1016/j.agwat.2016.01.020

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Leaching

Leaching is the washing out of material from the soil, both in solution and suspension. Leaching reduces the salt content of soil by irrigating a certain amount of water on salt-affected land and washing salt from the soil into the groundwater. Leaching is effective on soils with good internal drainage due to a favourable structure or light texture.

The restoration of large areas of farmlands with salt accumulation requires a combination of methods that need to be economical and sustainable. Initially, to recover salt-affected soils, drainage is required (the process where water is able to freely flow downward, taking salts dissolved in water away from the topsoil). The relatively low salinity subsoil is also then accessible to plants when the salt layer is removed, improving yield.

The best method to avoid harmful salt build up in the soil profile is to leach excess salts while maintaining a good salt balance. To achieve this while protecting groundwater reserves, it is important that the correct amount of fresh water is applied so that salts are able to diffuse below the root zone (Mohamed, 2016), as salt accumulation and distribution are significantly influenced by the irrigation method and amount of water used. In dripirrigated plots, dissolved salts in the water are concentrated as the water evaporates and moves away from the emitter. Water flows through capillary flow from the furrow into the bed in furrowirrigated plots and salts then gather in the middle of the interstitial bed when nearby furrows are irrigated. To prevent salt damage in furrowirrigated row crops, beds can be shaped differently and plants can be placed in different ways (Mohamed, 2016). Total water consumption is also reduced in periodic seasonal leaching compared to continuous leaching.

Limitations for scaling-up. A widelyused and traditional method of salt leaching is flood irrigation, but this method requires a large amount of fresh water and is not applicable in areas where water resources are scarce. To collect more fresh water, the brackish water can be desalinated by freezing and thawing in winter (applicable for cold regions). Since salts are less soluble in ice, freezing ice tends to restrict salts to the unfrozen water. The concentrated salt water is then the first to drain out of the thawing ice, thus achieving water desalination over freezing and thawing cycles (Wang *et al.*, 2023).

Water quality, soil characteristics and crop sensitivity together with expected productivity and farm economic return are some important determining factors in improving the efficiency of leaching. Moreover, drainage should be practiced in parallel with irrigation to provide yields and for environmental safety. Drainage problems arise from impermeable soils, the highwater table in depression areas, and side hill seepage (Ritzema, Kselik and Fernando, 1996). When discussing drainage, a separation needs be made between the drainage of groundwater and the drainage of surface water. Groundwater drainage helps to control soil salinity for irrigated lands (Ayars, Richard and Evan, 2003) while surface drainage may be necessary to remove excess rainfall or increase irrigation water, especially for soils with low leakage rates (Brouwer, Goffeau and Heibloem, 1985; Abdel-Dayem, 2000; Sharma and Tyagi, 2004). The advantage of surface water drainage is that it can move a large amount of water at the surface when there is both shallow groundwater and a flat topography. The disadvantages are that it requires a lot of space, it is inconvenient for farm management and dangerous for cattle. Periodic maintenance may also be needed due to weeds blocking waterways or soil erosion (UNESCAP and UNDP, 1990).

Groundwater is often saline in arid lowlands, and often the salinity is increased with depth. Deep vertical drainage wells will produce highlysaline water, unsuitable for reuse and difficult to dispose of (Smedema *et al.*, 2004).

Drainage

Drainage is the natural or artificial removal of surplus surface water and groundwater and dissolved salts from any area in order to enhance crop growth. In the case of natural drainage, the excess waters flow from fields to lakes, swamps, streams and rivers. In an artificial system, surplus ground or surface water is removed by means of natural or artificial subsurface or surface conduits.

Irrigation and drainage management is the most widely used method in mitigating salt-affected soils. Effective management is able to control or lower the groundwater level, which maintains the soil water and salt balance in the cultivated layer and further promotes soil salt discharge. An irrigation and drainage strategy includes lowering the groundwater level, irrigation with pumping water, and drainage desalination (Figure 5.5).

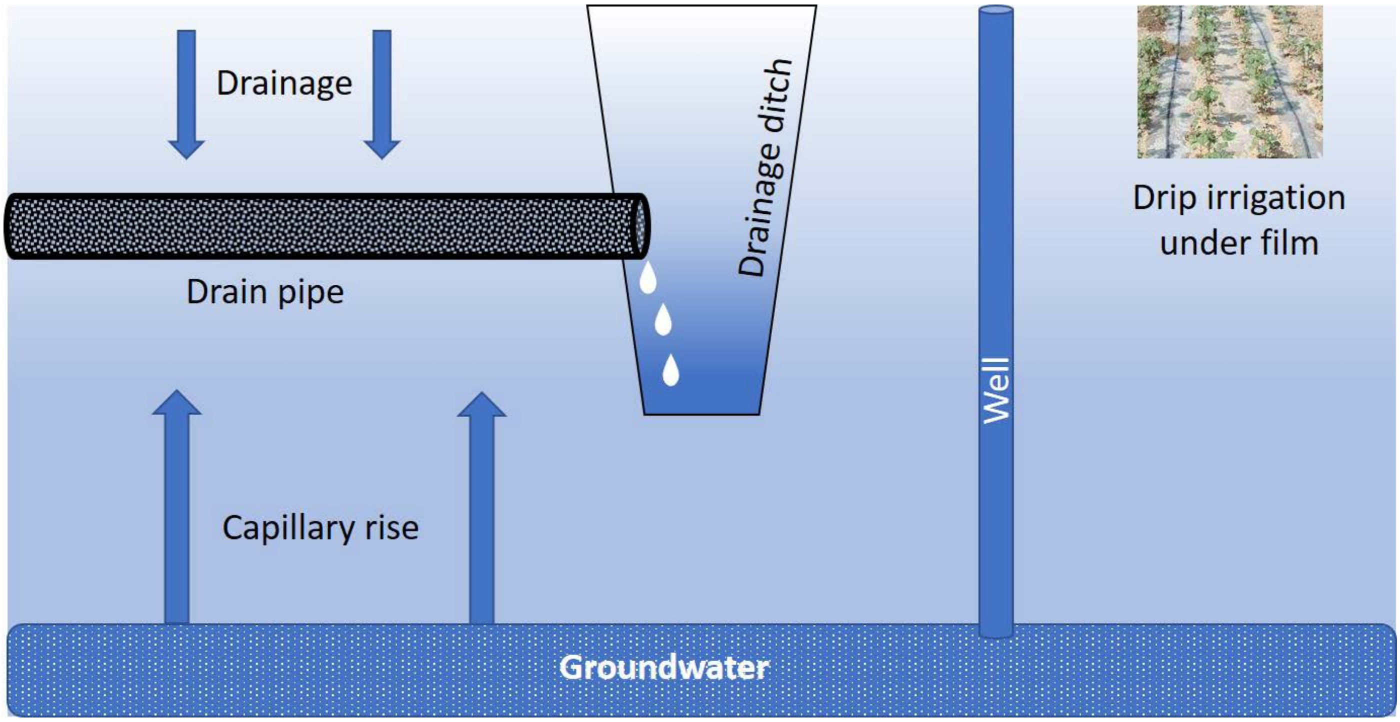

Figure 5.5 | Schematic diagram of main irrigation and drainage mitigation strategies on salt-affected soil
Source: Author's own elaboration.

Lowering the groundwater level can be done with **vertical wells**. In saline areas, the water table is generally shallow (mostly <5 m deep), and groundwater is able to rise to the crop root zone through capillary water rise suction. Therefore, vertical wells could lower the groundwater level and irrigate any nearby field with the pumped water. Vertical wells only take up a small area and have the extra benefit of low cost, while providing a large volume of water, along with being easy to maintain and providing flexible regulation of the groundwater level. The efficiency of the vertical drainage depends on engineering design capabilities, area planning and area management.

Drainage desalination is mainly achieved through contained open ditch drainage and subsurface pipe drainage. **Open ditch** drainage has a relatively long history and is a way to remove salt by digging ditches of a certain depth at certain distances in the field (Dagar *et al.*, 2019). The open ditch system is often in the form of a network, consisting of a main ditch and branch ditches perpendicular to the main ditch, which can drain both surface water and groundwater. It is suitable for areas that are salineheavy, with a shallow water table and drainage outlet locations. The depth should be more than 1.5 m to facilitate soil desalination and prevent the return of salinity. While this method can be effective, it takes up more space than vertical wells, the ditches collapse easily, and the open ditch depth limits the effect of salt drainage. Drainage ditchs are also easily blocked by silt and the repair and maintenance costs are high.

Subsurface pipe drainage is a relatively widelyused method in water conservancy projects that involves laying a perforated plastic pipe at a certain depth underground to drain water after irrigation or rainfall (Ritzema *et al.*, 2008). Subsurface pipes cannot directly remove the surface water, and so it needs to be combined with open ditch drainage. The burial depth of pipe is usually between 1.5 and 2.5 m, with the burial depth determined by the critical depth of the water table. The spacing of the pipe is also determined by the burial depth, as well as the permeability of the soil and the drainage standard (Liu *et al.*, 2021). Various factors, such as the length of the pipe, the burial depth, pipe spacing, the amount of irrigation water, soil characteristics, drainage time, and so on, determine the pipe's inner diameter. Wang *et al.* (2019) suggested a subsurface drainage pipe spacing of 15 m for use in practical applications to reduce soil salinity in China's inland arid saline sodic lands.

As well as taking up a lot of space and being costly, these traditional irrigation and desalination techniques require large amounts of water, and are therefore not suitable for application in arid and semi-arid areas where water resources are scarce. Alternative water-saving methods are needed in these cases.

Mulched drip irrigation is a water-saving method to control salt, where water continuously drips into the soil and drenches the soil. Due to the point source nature of drip irrigation, the salts in the soil will be pushed to the edge of the wetted area by the water, thus forming a desalination zone cantered on the drip head, which is beneficial to crop growth (Wang, Fan and Guo, 2019). At the same time, mulching attenuates surface evaporation, making soil resalinization much lower. Moreover, drip irrigation wastes very little water, and so is very water-efficient. Most of the water in the soil is removed through crop transpiration, which has less impact on the dynamic balance of groundwater and can avoid the problem of salt accumulation in the topsoil in spring due to the rise of the water table in arid and semiarid areas. Compared with the construction of traditional drainage systems, mulched drip irrigation does not take up a lot of space, saves costs and removes the pressure on freshwater. Furthermore, it is easy to operate and maintain.

In general, irrigation and drainage management is an effective strategy for mitigating salt-affected soils, but it is less suitable for developing countries in arid and semiarid regions where freshwater resources are scarce and funds are insufficient.

Surface scraping

The topsoil of many saline soils has the highest salt concentration due to a shallow groundwater table and ongoing evaporation. Therefore, some farmers practice the removal of the topsoil by scraping it off and removing any spots of efflorescence on the surface. Endo and Kang (2015) reported that soil scraping and leaching of the scraped surface soil are useful in remediating saltdamaged farmlands as evidenced by the soil's ESP, EC and ion content. Scraping is a temporary cure rather than a solution however, and salinity may develop again if other methods are also not followed simultaneously. In addition, the practice of removing the salty soil and transporting it from the field to adjacent areas merely transports the problem, as it leads to increased salinization of the storage area instead.

Compost and plant residue incorporation

Organic matter amendment is a good solution for increasing productivity of salt-affected soils. It can effectively reduce salinity and sodicity obstacles by improving soil structure, water holding capacity and fertility level.

The application of organic matter is shown to be one of the most efficient ways of repairing soils that have been negatively impacted by salt by altering their chemical, physical, and biological properties (Cha-um and Kirdmanee, 2011; Lakhdar *et al.*, 2009). Organic matter enhances the bonding of soil particles into aggregates (Amini *et al.*, 2016). According to Tejada *et al.* (2006), adding organic matter (OM) to soils that have been affected by salt can increase water infiltration, waterholding capacity and aggregate stability, while decreasing ESP and EC and speeding up the leaching of Na^+. Based on the results of Lakhdar *et al.* (2010), the application of different biosolids (sewage sludge and municipal wastewater compost) in salt-affected soils significantly improves the biophysicochemical properties of the soil. Composts, farmyard manures, and other organic materials can all be used as amendments to improve and maintain the overall soil fertility.

Limitations for scaling up. In drylands and lowincome regions, organic materials are rarely available for soil purposes. Not all sources of organic matter are suitable for soils prone to salinity and sodicity in the case of low water supply, due to aridity, low biological activity and surface accumulation. Compost maturity is beginning to be more recognized as a significant parameter to evaluate compost. In storage, immature composts may become anaerobic, which frequently causes odours, the emergence of toxic substances, bag swelling, and bursting. Continued active decomposition when these composts are added to soil or growth media may have negative impacts on plant growth due to reduced oxygen in the soil root zone, reduced available nitrogen, or the presence of phytotoxic compounds (Brinton, 2000). Additionally, lowquality compost can result from a lack of stability and an abundance of salt and heavy metals (Murillo *et al.*, 1995)

The chemicals that have been recognized as problems in amendment-derived sewage sludge include heavy metals, polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), and polychlorinated dioxins and furans (PCDD/Fs) (Harrison *et al.*, 2006). Surfactants and some of their metabolites are not readily biodegraded in nonaerated environments and may also cause adverse environmental impacts when they enter sewage systems at high loads and accumulate in sludge (Düring and Gäth, 2002). Conversely, as the production of organic wastes mainly occurs in urban areas, using these wastes as green manure to improve saline and sodic soils is both beneficial to the city and economically affordable (Liu *et al.*, 2009). Therefore, because the sources, collection, and utilization of sewage sludge and other wastes in agriculture both present solutions along with issues concerning their negative environmental and health effects, its use needs to be carefully considered (Cai *et al.*, 2007).

Biochar

Biochar is a carbonrich soil amendment produced through pyrolysis, a process in which organic material is exposed to high temperatures in the absence of oxygen. Biochar as a soil amendment has the potential to ameliorate soil and alleviate drought and salinity stress. It has considerable potential for use in carbon sequestration, as it does not degrade easily and remains in the soil for a long period of time. Enhancing soil quality and enabling the sustainable use of natural resources are two of the main benefits of carbon sequestration (Lal, 2008).

Biochar is a specific organic soil amendment that can improve the physical, chemical and biological properties of salt-affected soils, such as:

- soil organic carbon content (Glaser, Lehmann and Zech, 2002);
- water holding capacity (Hien *et al.*, 2021; Ahmad Bhat *et al.*, 2022; Mousavi, Srivastava and Cheraghi, 2022);
- cation exchange capacity (CEC) (Luo *et al.*, 2017; Das *et al.*, 2021);
- soil aeration and porosity (Major *et al.*, 2009; Rattanakam *et al.*, 2017; Ahmad Bhat *et al.*, 2022; Singh *et al.*, 2022);
- saturation of the soil base;

- retention and availability of nutrients and fertilizer (Laird, 2008; Mousavi, Srivastava and Cheraghi, 2022);
- stimulation of soil microbes, microbial biomass, and activity (Thies and Rillig, 2009; Singh *et al.*, 2022);
- crop growth and yield (Xu *et al.*, 2015; Zhang *et al.*, 2015; Gopal *et al.*, 2020; Mousavi, Srivastava and Cheraghi, 2022);
- a decrease in anthropogenic greenhouse gas (GHG) fluxes; and
- carbon sequestration (Lal, 2011).

Limitations for scaling-up. Some studies indicated that the addition of biochar, particularly at the highest level of biochar application, had a detrimental effect on plant growth (e.g. Mohawesh *et al.*, 2018), and recommended the application of biochar at application rates of <2.5 weight percent. A study by Dahlawi *et al.* (2018) showed an increase in soil salinity after a high rate of biochar application.

The application of biochar has some specificities in salt-affected soils. Typically, biochar has a high alkalinity and, when applied to salt-affected soils (which normally have pH >7.5), it can impact the pH status. In order to avoid this situation, the pyrolysis needs some modifications (low temperature or shorter time of pyrolysis) or postprocessing with water or composting to reduce alkalinity before soil application. Based on the report of Salem *et al.* (2019), mixing biochar with farmyard manure is an efficient, economical and environmentallysound solution in alkaline soils comparing to solely using biochar.

The high cost associated with the production of biochar together with high application rates remain significant challenges to its widespread use in areas affected by salinity or sodicity. It is also important to note that there is still relatively limited information on the longterm behaviour of salt-affected soils with biochar amendment.

Economic aspects. Biochar has received particular attention as a lowcost technology in the countries with cheap energy, as it is a renewable modifier, a smart solution for recycling organic residues, and environmentally friendly (Lehmann and Joseph, 2015). Considering the problem of the availability of phosphorus in calcareous and saline soils (high soil pH), such a management method (the application of biochar) can increase the short- and longterm availability of phosphorus in calcareous and saline soils in arid and semiarid areas. This reduces the consumption of phosphorus fertilizer, which is both economical and avoids environmental pollution.

Low rank coal

Lowrank coal (LRC) is a type of organic matter that is high in lignin and low in cellulose and hemicellulose. It is typically derived from sources such as peat, lignite, or brown coal. Low rank carbon has been shown to be an effective treatment option for salt-affected soils in many studies (Sakai, Nakamura and Wang, 2020; Cubillos-Hinojosa, Valero and Melgarejo, 2015). It has the potential to enhance soil composition, improve the soil's ability to retain water, and increase the availability of nutrients.

The addition of humidified organic matter (HOM) to soil has been frequently used to contribute to the rehabilitation of degraded lands (Ros, 2003). Lowrank coals such as lignite have a soft, friable consistency, opaque appearance, a humidity of 30–45 percent, a high ash content, and low fixed carbon content (low energy content) (WCI, 2005). Lowrank coal is rich in a wide range of macro- and microelements and is also a valuable source of organic matter, while having a low degree of carbonification so is a great source of humic substances (HS) (Peña-Méndez, Havel and Patočka, 2005; Giannouli *et al.*, 2009).

Humic acid production is one of the primary ways through which LRC enhances soil characteristics in saline and sodic soils. Low rank coal is characterized by a significant content of humic substances (HS), accounting for 90 percent of its dry weight (Dong *et al.*, 2009; Anemana *et al.*, 2020).

Humic substances are relatively stable complexes with a variety of functional groups that help to improve the formation of soil aggregates, the activity of microorganisms, the functionality of enzymes, the storage of carbon, the retention of nutrients, and the immobilization of pollutants (MikosSzymaska *et al.*, 2019; Amoah-Antwi *et al.*, 2020). Humic acids can also aid in lowering soil salinity by binding cations like sodium and calcium. Upon ionization in a solution, the majority of functional groups in lignin that contain oxygen lead to a decrease in pH levels. Consequently, LRC can exhibit efficacy in soils that range from neutral to alkaline conditions (Qi *et al.*, 2011). According to Cubillos-Hinojosa, Valero and Peralta Castilla (2017), the application of LRC at a rate of 5 kg/m^2 resulted in a decrease in the electrical conductivity and the SAR of soils with high salinity and sodicity. These studies have shown that crops grown in soils amended with LRC have higher yields, better root development, and increased tolerance to stress caused by salinity and sodicity.

Limitations for scaling up. The application of LRC to saline and sodic soils must be performed with caution. If not applied at the appropriate rate, LRC can enhance soil compaction, resulting in decreased infiltration and higher runoff. It is important to conduct soil tests before applying LRC to determine the appropriate application rate.

In a study conducted by PantojaGuerra, Ramirez-Pisco and Valero-Valero (2019), the impact of different LRC concentrations on soil aggregate formation was investigated. The highest dosage of 4 Mg/ha resulted in a 12 percent increase in soil aggregate formation compared to the control and lowest dosage, attributed to lignite's porous nature and its role in soil aggregation (O'Keefe *et al.*, 2013). The introduction of LRC notably increased the size of soil pores.

According to Ortiz and Ramirez (2022), the addition of LRC resulted in a significant reduction in soil heat conductivity and an increase in maize plant survival of 36 percent with a 2 t/ha application of LRC compared to 1 percent for the control. Lowrank charcoal was applied to saline sodic soil, resulting in a reduction in the soil's thermal conductivity. A medium dose of LRC (2 t/ha) was shown to be more effective in fostering plant development (Figure 5.6).

Figure 5.6 | Field trial. Emerging (A-B) and established plants (C) in the low-rank coal application trial to a saline sodic soil in Colombia

Low rank coal is a successful amendment for saline sodic soil restoration. It can lessen soil salinity and sodicity, while also enhancing soil structure, water-holding ability, and nutrient availability. Depending on origin and quality, LRC may itself contain elevated levels of organically-bound chlorides and inorganic constituents, implying a conceivable risk of soil contamination by polycyclic aromatic hydrocarbons, and heavy metals (Binner *et al.*, 2011; Domazetis, Raoarun and James, 2006). The selection criteria for LRC amendment should integrate environmental and agronomic factors, such as soil quality, material availability, economic accessibility, cost, application needs, safety compliance, and sustainability (Amoah-Antwi *et al.*, 2021). To prevent adverse effects, LRC must be applied carefully and at appropriate rates. Further investigation is required to ascertain the long-term effects of LRC application on soil characteristics and crop growth in saline sodic soils.

Deep tillage

Ameliorative deep tillage methods include **deep ploughing**, when the topsoil and subsoil are reversed, **deep mixing** when the topsoil and soil are well mixed and **subsoiling** when the field is partially tilled and the soil is generally not reversed (Figure 5.7). They are specific reclamation practices applied to sodic soils with ploughing to 30 cm and deeper in order to mix Ca-containing subsoil rich in $CaCO_3$ or gypsum with sodic horizons. The exchangeable Na in the sodic horizon is exchanged with Ca which leads to a decrease in ESP, SAR and soil bulk density, and a sharp increase in water permeability (Bazykina and Olovyannikova, 1996; Havrylovych and Drozd, 2006; Novikova 1984; Sandoval and Jacober, 1977). Soluble salts that may be present in saline sodic soils are leached out more easily with irrigation or rain water after deep ploughing (Gabchenko, 2008; McAndrew and Malhi, 1990), and the yield substantially increases (Ladnykh and Vorotyntseva, 2006; McAndrew and Malhi, 1990).

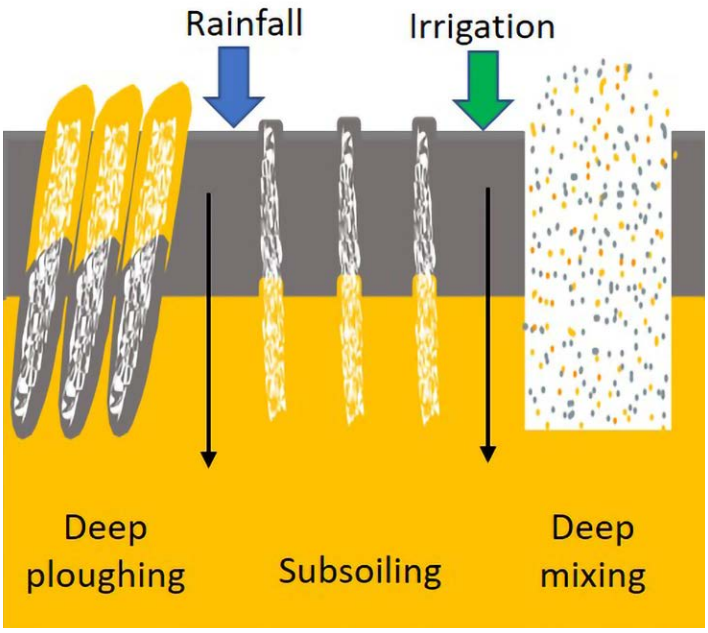

Figure 5.7 | Schematic diagram of ameliorative deep tillage practices
Source: Author's own elaboration.

Limitations for scaling up. Deep tillage is an expensive technique as it requires specific machinery and high fuel consumption. This practice is not recommended for soils rich in organic matter as the topsoil becomes buried after deep ploughing. If the subsoil contains calcium carbonate rather than gypsum, reclamation may take longer (up to several years) due to the lower solubility of $CaCO_3$. Deep tillage should be avoided on saline soils as the practice brings salts up to the soil surface. For strongly saline soils, zero tillage should be considered.

Land shaping

The land shaping technique is a unique technology for addressing key challenges like soil salinity, drainage congestion and scarcity of fresh water for irrigation, and has the potential to enhance production. Land shaping like farm pond, deep furrow and high ridge, paddy-cumfish cultivation have been developed in India for the restoration and productivity enhancement of degraded (saline) coastal land. These techniques reduce the process of land degradation by alleviating soil salinity and waterlogging problems as well as creating irrigation resources in coastal regions (Subhasis *et al.*, 2013).

Limitations for scaling-up. The adoption of land shaping techniques requires a high initial investment and needs an area of land at a distance from the residential village.

Economic aspects. The economics of the land shaping models depend on actual field level data from the farmers' fields (Subhasis *et al.*, 2013).

Land levelling

Salt damage in the root zone can be reduced by constructing flat microtopography. Salinity usually accumulates at higher topographic sites because of the high evaporation rate, showing patchy salinization. A difference in elevation of a few centimetres may result in significant differences in salt distribution, leading to uneven desalination if not graded. Land levelling can make the water obtained from precipitation and irrigation infiltrate evenly, enhancing the effect of leaching salts, and eliminating the local accumulation of salts, so it is an important terrain reconstruction measure (Eckert, Dimick and Clyma, 1975; Khan *et al.*, 2007).

Limitations for scalingup. Land levelling can reduce soil fertility as it removes topsoil (0–15 cm) (which has a high content of organic carbon and available nutrients) and decreases structural stability. Compaction of the soil during land levelling is another limitation of using this technique (Criddle and Haise, 2010).

Economic aspects. The land levelling strategy needs considerable financial resources for operating equipment. During this process, the fertile topsoil is buried and replaced with infertile subsoil, increasing soil erodibility and sometimes reducing the ability of plants to grow (Khan *et al.*, 2007).

Chemical measures

Gypsum and other calcium-containing amendments

Chemical amelioration for sodic soils is used by applying chemical amendments that help to reduce soil sodicity, improve soil structure and promote the growth of plant roots. Typical chemical amendments are gypsum ($CaSO_4$), lime or calcium carbonate ($CaCO_3$), calcium chloride ($CaCl_2$), pyrite (FeS_2), sulphur (S), hydrochloric acid (HCl), sulphuric acid (H_2SO_4) and nitric acid (HNO_3) (Ahmad, Qureshi and Qadir, 1990; Gupta and Abrol, 1990). Chemical amendments are classified as soluble ($CaCl_2$), sparingly soluble ($CaSO_4$ and $CaCO_3$) and acids or acidforming chemicals (ferrous and ferric sulphate, aluminium sulphate, sulphur, pyrite, etc.) (Gupta and Abrol, 1990). Gypsum, lime and calcium chloride have calcium (Ca^{2+}) which can substitute sodium ions (Na^+) through a cation exchange process (Oster, 1982) promoting the aggregation of soil particles and thus improving soil porosity and permeability (Ilyas, Miller and Qureshi, 1993; Oster and Frenkel, 1980). Calciumcontaining amendments can replace exchangeable Na directly whereas pyrite, sulphur and acids ameliorate soil sodicity indirectly by dissolving calcite contained in soil and making it available for exchange reaction (Abdel-Fattah, 2018; Amezketa, Aragüés and Gazol, 2005).

Gypsum is the most commonly used chemical amendment for sodic soil amelioration because of its abundant availability and low cost. Calcium chloride is the most effective but its high cost prohibits its use.

Gypsum is mined as an ore and also available as a byproduct from many chemical industries in the form of phosphogypsum. Phosphogypsum is produced in phosphoric acidmanufacturing industries. As an amendment, gypsum should be 80 percent pure or more (Ayers and Westcot 1985; Choudhary, Kaur and Benbi, 2007) (Figure 5.8).

Figure 5.8 | Broadcasting of gypsum in sodic soil by the farmers under a trial on management of salt-affected soil in India (left) and Thailand (right)

The dose of amendments is calculated on the basis of initial and final desired levels of ESP and the depth of the soil to be reclaimed. The achievable level of ESP and soil depth for reclamation is chosen on the basis of crop, CEC and the soil's texture. The requisite gypsum for reclamation is known as gypsum requirement (GR), with the type of amendments being decided on the basis of availability and economics. However, chemical amendments are not equally effective. The relative effectiveness of amendments with respect to gypsum as a reference amendment is summarized in Table 5.2.

Table 5.2 | Common amendments and equivalent quantity for reclamation of sodic soil

Amendments	Relative quantity
Gypsum ($CaSO_4.2H_2O$)*	1.00
Calcium chloride ($CaCl_2.2H_2O$)*	0.85
Sulphuric acid (H_2SO_4)*	0.57
Sulphur (S)*	0.19
Iron sulphate ($FeSO_4.7H_2O$)	1.62
Pyrite (FeS_2)**	0.63

Notes: *The quantity of amendment is based on 100 percent purity. **S content is 30 percent.

Sources: **Anonymous.** 2004. Reclamation and Management of Salt-Affected Soils. Karnal, India, Central Soil Salinity Research Institute (CSSRI).

Choudhary, O.P. & Kharche, V.K. 2018. Soil salinity and sodicity. In: Soil Science: An Introduction, pp. 353–384. New Delhi, Indian Society of Soil Science.
https://www.researchgate.net/publication/327824188_Soil_Salinity_and_Sodicity

Chemical amendments have a positive effect on soils after one use and there is usually no need to apply them repeatedly. Field tests on the sodic soils of India demonstrated that application of half the required gypsum, or 10–15 t/ha at a soil depth of 0–15 cm is sufficient to start the reclamation of sodic soils and to cultivate shallowrooted crops like rice, wheat, barley and berseem (*Trifolium alexandrinum*). According to field investigations, applying gypsum at shallower depths was preferable than applying at deeper depths (Khosla *et al.*, 1973).

Limitations for scaling-up. Some amendments may contain pollutants and lead to secondary soil pollution. Application of acidic amendments can lower soil pH, which is positive for alkaline soils but will have a negative impact on soils with neutral pH. Thus, the applications of amendments should be carefully evaluated. In some cases, if a soil is compacted and has low drainage capacity, Na ions are not readily displaced by gypsum's Ca ions and the leaching of Na ions by irrigation water or rainfall can be largely ineffective, meaning that the salinity of the soil water can actually increase (Ilyas, Qureshi and Qadir, 1997; Zia-ur-Rehman *et al.*, 2016).

Adjustment of planting time and place

Planting times are an important consideration for crop cultivation in saline areas. Many crops are not able to tolerate salinity in their germination and early seedling period but can tolerate salinity later, during the vegetative, reproductive, and grainfilling stages. In the saline environment, failure of germination and lower plant density is a usual problem that in turn produces lower yield. Mondal *et al.* (2015) have shown that early crops have a better germination rate and escape initial salt injury.

One way to help to increase the germination percentage and plant density is to implement freshwater irrigation before sowing to wash out the surface salts (Minhas and Tyagi, 1998). Planting in a raised bed can also mitigate salinity and ensure crop establishment. Seeds sown at the centre of a raised bed can often have low germination due to two wetting fronts of the furrow leading to more salt accumulating in the centre of the bed (Francois and Maas, 1999). To mitigate salt deposits in this example, alternative furrows called doublerow raised beds can provide a practical solution. Another method is to sow the seeds in the midcentre of the raised bed slope, as demonstrated in Figure 5.9. In the case of low or moderate levels of salinity, each furrow should be irrigated. In the case of high levels of salinity, alternate furrows should be irrigated.

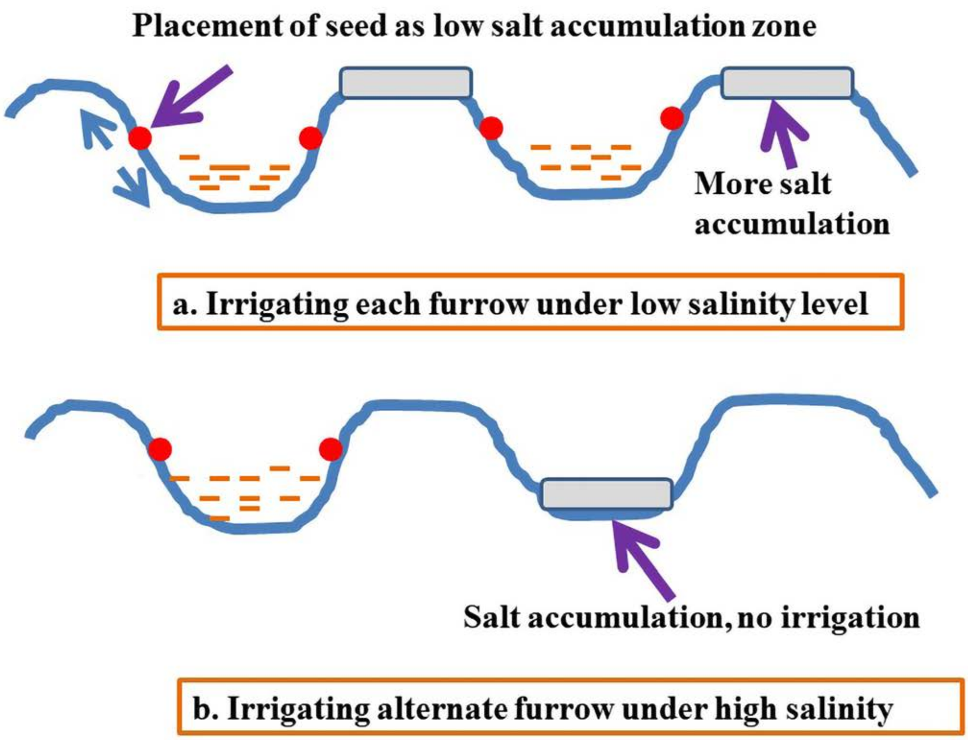

Figure 5.9 | Schematic diagram showing the pattern of salt build-up and seed placement on beds: (a) under low salinity level; and (b) under high salinity level

Notes: (a) Irrigate each furrow. The seed should be placed on the ridge slope as accumulation of salt is minimal at this zone and thus any adverse impact of salt on seed will be less. (b): Irrigate alternate furrows. This way, the maximum amount of salt will accumulate in the nonirrigated furrow. The seed should be placed on the ridge slope of the irrigated furrow.

Source: Author's own elaboration.

One of the measures for regions with a long growing season (tropical and subtropical) is to choose a planting time adjusted for the minimum levels of salinity. Paul *et al.* (2021b) demonstrated that early sowings of sunflower (before 15 December) had bigger heads, more seeds per head, and higher seed weight and grain yield. In the same report, they showed that the lower yield from late sowing was connected to the dry soil surface, higher soil resistance and soil salinity.

In the coastal area, early sowing is limited by a high soil water content (wet soil) due to a tidal lowland topography, with a shallow groundwater depth and heavy textured soil. Therefore, the best method of establishing sunflowers in a high moisture or wet soil is through dibbling (no tillage). If the gravimetric soil water content is less than 30 percent weight for weight (w/w), rotary tillage (two or three passes) would be suitable for dibbling (Paul, 2020; Paul *et al.*, 2020a). Figure 5.10 shows the crop performance of both an early and late sowing of sunflowers.

Figure 5.10 | Sunflower growth condition for early sowing (left) and late sowing (right) in the saline area of Bangladesh

Crop system management: Improved crop rotation, agrobiodiversity, crop system diversification

Crop system management can be considered both as a mitigation and adaptation strategy for managing salt-affected soils. Growing crops such as leguminous grasses that can improve soil structure and permeability can also help to decrease the salinity and sodicity levels of soils. At the same time, crop diversification leads to improved soil biodiversity and the growth of beneficial microorganisms that help crops to tolerate drought and salinity.

An environmentallyfriendly means of managing salt-affected soils is through the use of appropriate **crop rotations**. However, recommendations for suitable crop rotations for salt-affected land are site specific and should be developed through longterm field experiments (Kaur, Malik and Paul, 2007).

In order to adapt crop rotation to salinity, it is necessary to include salt-tolerant crops. Saltresistant crops include barley *(Hordeum)*, rapeseed (*Brassica napus*), millet (*Panicum*), sugar beet (*Beta vulgaris*), brome grass (*Bromus*), Sudanese grass (*Sorghum bicolor* **subsp.** *drummondii*), sweet clover (*Melilotus*), and birdfoot (*Lotus*). Mediumresistant crops include wheat (*Triticum L.*), sorghum (*Sorghum*), soybean (*Glycine max*), corn (*Zea mays*), sunflower (*Helianthus annuus*), tomato (*Lycopersicon*), potato (*Solanum tuberosum*), pepper (*Piper)*, carrot (*Daucus carota*), pea (*Pisum*), alfalfa (*Medicago sativa*), and sainfoin (*Onobrychis*) (Baliuk, Romashchenko, and Stashuk, eds., 2013)).

Agrobiodiversity is another costefficient method. For example, mixed cropping[2] with trees or the planting of forage crops within the interspaces of salt-tolerant perennials can alleviate the accumulation of sodium and other salts in the upper soil layers (Sakadevan and Nguyen, 2010; Yamaguchi and Blumwald, 2005).

The effectiveness of farming systems around the world is increased by **diversified crop rotation** (DCR). It has the potential to enhance soil quality and increase system output. In a variety of crop rotations, improved soil properties (such as greater soil water uptake and storage and a greater number of beneficial soil organisms), may also increase yield tolerance to drought and other difficult growing conditions. Farmer benefits include a decrease in production risk and uncertainty, improved soil and ecological sustainability, and increased crop yields from crop

[2] Mixed cropping is a system of sowing two or three crops together on the same land, with one being the main crop and the other(s) being the subsidiary/subsidiaries.

rotations with a variety of crops. Plant nutrients are also restored when specific crop species are added to the crop rotation, reducing the need for chemical fertilizers. Crop rotation is therefore an efficient strategy for sustainable agriculture (Shrestha *et al.*, 2021)

Soil salinization is strongly associated with the use of ineffective cropping systems (e.g. crop choices, crop rotations, tillage practices, irrigation, and pest and nutrient control tactics applied to a given field for a period of time). Consequently, soil improvement is necessary to end the vicious cycle of degradation, increased inputs, increased costs, and environmental damage (Sørensen *et al.*, 2014). This requires the emergence or development of soilimproving cropping systems (SICS) that increase the soil's capacity to perform its functions, such as the production of food and biomass, the capacity for buffering and filtration, and the provision of other ecosystem services (Lahmar, 2010). In this way, SICS can lower the accumulation of undesirable salts, thereby reducing salinization and improving soil structure.

Limitations for scaling up. Crop system management has a significant effect on the status of soil salinization. However, any concrete recommendation should be based on local knowledge and longterm field experiments. For example, if the soil has a poor structure and limited drainage, in cottonbased rotations, salinization of the root zone may happen, even when irrigated with goodquality water (Weaver *et al.*, 2003). To highlight the effectiveness of rotations, Cao *et al.* (2004) reported that soil salt content more than doubled when paddy rice (*Oryza sativa* L.) in rotation with a wheat or oilseed rape was converted into intensive cultivation of vegetable crops.

Economic aspects. By implementing diversified crop rotations, farmers may be able to increase the variety of their income sources. Furthermore, the distinct structure, purpose, and relationship of the plant community with the soil in DCR contribute to the longterm development of soil health by lowering the incidence of insects, weeds, and diseases and enhancing the physicochemical structure of the soil. As a technique to maintain sustainable crop production, DCR is gaining popularity (Shah *et al.*, 2021). For economic reasons, tree planting is not a preferred option, although trees have commercial value as fruit trees.

Agroforestry

Agroforestry is the landuse system and technology in which woody perennials (such as trees, shrubs, palms or bamboo) and agricultural crops or animals are used deliberately on the same parcel of land in some form of spatial and temporal arrangement.

Treebased land management approaches can play a vital role both in the productive use of salt-affected lands and reducing the extent of salinity and sodicity. According to Zhong (1998), agroforestry is an important strategy to combat salinization. The growing of trees on farms increases the amount of organic matter (OM) and field capacity, available potassium, available phosphorus, soil carbon stocks, and lowers bulk density (BD) (having the effect of retaining water like a sponge through increasing the water holding capacity (WHC) and then slowreleasing the water to plants (Chatterjee *et al.*, 2018; Hailu, 2015; Schroth and Burkhard, 2003; Surki *et al.*, 2020).

Organic matter plays a significant role in soil aggregation and the lowering of BD. Reducing BD aids in air circulation, water distribution in the rhizosphere, groundwater recharge, and improving the nutrient quality of the soil (Surki *et al.*, 2020). The trees and shrubs create a specific microclimate under their canopy, reducing overheating and evaporation from the soil surface (Rolo *et al.*, 2023) and so reducing the build-up of salts in the subsoil.

Due to low crop yields and the high costs of physically removing salts, both farming conventionally on highly saline soils and irrigating with highly saline water are not economically viable (Qadir and Oster, 2004). However, saline agroforestry systems may be another option for these soils, due to the fact that some tree species can remove salts from the soil and remediate it, being tolerant of extreme salinity or sodicity (Dagar, Pandey and Chaturvedi, 2014).

Certain plant species – from salt shrubs to large trees – are suitable for growing on salt-affected soils. Every time the root system of a salt-tolerant plant comes into contact with groundwater, the main physiological characteristic is considerable transpiration. It has been demonstrated (Dagar *et al.*, 2016), that several tree species can thrive and grow in salty and waterlogged soils, and these species are now being used more frequently to reclaim and use saline and waterlogged areas. Technologies were also developed by Dagar *et al.* (2016) for the successful organization and better development of woodland and fruit trees, herbs, agricultural, nonconventional medicinal, and aromatic plants in agroforestry systems that use saline water for irrigation.

Perennial trees were found to be promising for planting in highlysodic soils (Table 5.3). Growing leguminous trees like *Prosopis, Acacia*, and *Casuarina* improve these soils considerably and more quickly than nonleguminous trees. *Prosopis juliflora* and *Acacia nilotica* were found to be the best in terms of biomass production (Singh, Abrol and Cheema, 1994). Longterm experiments have shown that *Prosopis* and *Acacia* can restore the productivity of sodic soils (Singh, Singh and Bhojvaid, 1999) and Singh and Gill (1992) show that agroforestry is able to reclaim extremely sodic soils so that agricultural crops, including rice, can be planted.

Table 5.3 | Ameliorating effects of tree plantation on sodic soils and their biomass production (India)

Species	pH		Organic C (%)		Biomass production, kg/tree
	Initial	After 20 years	Initial	After 20 years	
Prosopis juliflora	10.3	9.18	0.12	0.58	156
Acacia nilotica	10.3	9.03	0.12	0.55	129
Albizia lebbeck	10.3	8.67	0.12	0.47	–
Eucalyptus tereticornis	10.3	9.18	0.12	0.33	–
Terminalia arjuna	10.3	8.15	0.12	0.58	–

Source: **Dey, P., Mongia, A.D & Singh, G.** 2004. Bio-amelioration of sodic soil. In: Extended Summaries: International Conference on Sustainable Management of Sodic Lands, p. 387388. Lucknow, India, Uttar Pradesh Council of Agricultural Research (UPCAR).

A planting technique that draws power from a tractor's PTO drive shaft has been standardized for breaking through *kankar* ($CaCO_3$) pan in India, with soil from each auger bore then being mixed with gypsum (8 kg), farmyard manure (FYM) (10 kg) and river sand (20 kg). This has led to the successful growing of salt-tolerant fruit species such as *Emblica officinalis*, *Zizyphus mauritiana*, *Psidium guajava* and *Carissa carandus* (Singh *et al.*, 1996). It was further established that intercropping of medicinal and aromatic crops inside such a fruit orchard is also possible with *Plantago ovata* and *Matricaria camomila* in a soil with pH <9.5.

The mechanism of carbon sequestration and nutrient dynamics under agroforestry systems with high ESP was demonstrated by Dey (2009), Dey and Singh (2008) and Mongia, Dey and Singh (1998).

Limitations for scaling-up. Relatively low soil salt concentrations (ECe up to 5 dS/m) do not affect the survival and growth of many tree species. However, salt concentrations of 10 dS/m or higher – usual in saline drainage water – would significantly reduce the growth and water use of pulpwood species, particularly on clayey soils (Dagar and Minhas, 2016).

Economic aspects. From an economic and environmental point of view, agroforestry practices have significant advantages. Agroforestry can increase farm profitability in several ways, including:

- the combined yield per unit area of trees, crops, and livestock is greater than that of any single component alone (Marcar *et al.*, 1999); and
- livestock and crops protected from wind damage are more productive (Zhang, 1997).

According to their salt tolerance, trees can also lower the water table, reduce salinity, and stop seepage, according to numerous other studies, such as Dagar *et al.* (2008).

Bioremediation

Bioremediation is the use of living organisms (bacteria, fungi, plants or animals) to remove, destroy or sequester hazardous substances from the environment. In the case of salt-affected soils, bioremediation helps to remove salts from topsoil in saline soils or improve permeability of sodic soils. Bioremediation is an environmentally- and economicallybeneficial measure among biological methods for the conservation and improvement of soil fertility. It is between five and ten times cheaper than chemical melioration.

Planting and sowing plants resistant to adverse conditions on saline and sodic soils contribute to their gradual desalinization and improvement of properties (Imadi *et al.*, 2016; Truskavetsky and Tkach, 2018). Phytoremediation should be used in conjunction with agrotechnical and engineering methods to improve the ameliorative state of saline soils. Crops tolerant to soil sodicity, such as white sweetclover (*Melilotus alba*), have a dense root system that is able to loosen a compacted sodic horizon. This improves the structure of the soil and decreases soil bulk density.

Plants that can be used for bioremediation of saline soils are, for example, European saltwort (*Halocnemum*), *Brassica napus* L. subs., *Atriplex littoralis, Atriplex cana*, white gooseberry (*Ribes uvacrispa*), *Bassia hyssopifolia*, Gerard rush (*Scirpus georgianus)*, *Seriphidium maritimum, Seriphidium santonicum*, Ural licorice (*Glycyrrhiza uralensis)* and others.

Bioremediation is a cheaper and more efficient technique for the remediation of salt-affected soils than other methods and can be used for vast areas. Rhizosphere bacteria are the most usually used microbes in bioremediation and can promote plant growth under serious constraints, such as salinity stress (Arora and Vanza, 2017). The plants used for bioremediation of salt-affected soils can be used as forage, fuel, and a source of income, as well as for ecological restoration (Arora, Singh and Sahni, 2017).

Limitations for scaling-up. Some important limitations of the bacteria used in bioremediation include the bacterial inocula's lower flexibility, inoculation procedures, decreased bioavailability, and higher toxicity of pollutants toward plants and microbes (Rayu, Karpouzas and Singh, 2012). Phytoremediation is timeconsuming and also limited to certain soil depths and reduces sodicity more slowly than chemical remediation techniques. Furthermore, when a soil is highly sodic, the efficacy of phytoremediation is constrained.

Economic aspects. Compared to other remediation techniques, bioremediation is less costly and more environmentally friendly.

5.3.2 | Adaptation strategies

Breeding of salt-tolerant crops (including genetic engineering)

The ability of certain plants to tolerate high levels of salt is due to the development of specific molecular mechanisms or special cellular structures to tolerate high concentrations of salt. Harnessing this ability by using or breeding salt-tolerant crops can greatly increase the area of land able to be cultivated while decreasing the salinity present in the soils. It is the most effective way to adapt to a salt-affected soil (Dagar *et al.*, 2016). Since the 1990s, tremendous efforts have been made in understanding the mechanisms of salt stress tolerance in plants. However, applying this fundamental knowledge to improve the tolerance of field crops to salt stress is a slow and challenging process. With advances in gene editing techniques and effective genetic transformation of different species, it will become increasingly feasible to improve salt stress tolerance in crops.

Significant progress is being made in permissive genotypic screening compared to conventional breeding (Chiconato *et al.*, 2019). The genetic diversity of most crop species has been assessed using DNAbased molecular markers, and quantitative trait loci (QTL) have been identified for a variety of traits using these markers (Mondal *et al.*, 2019). Better genotypes with a high tolerance to salt stress are crucial for growing under salt stress (Kaashyap *et al.,* 2017). Complex molecular mechanisms – including genes and their signalling pathways – allow plants to adapt to salinity stress. To find tolerant genes to increase salt tolerance in plants, a large gene pool is required (Jha *et al.*, 2019).

The most widespread and saltresistant crops can be found listed in Box 5.6.

Limitations for scaling-up. In the past century, plant breeding has mainly been used as a means of breeding plants that are tolerant to abiotic stress, and many salt-tolerant varieties for different crops have been developed. However, the use of this method is limited by the reproductive barriers and limited genetic variations found in food crops. Numerous salt-tolerant crop cultivars and lines have been developed through breeding, such as the CSR10, CSR13, and CSR27 rice cultivars created at the Central Soil Salinity Research Institute in Karnal, India. Breeding is limited by the small amount of variation found in the gene pools of most crops. Due to the extremely small size of the genes, the ineffective methods for isolating, removing, and transferring them, as well as the limited ability to regenerate new plants (*in vitro*) from single cells, there is little information available about the genetics involved in salt-tolerant traits of crops.

Due to a decline in genetic diversity and increased climatic stress on crops, these traditional breeding methods have been unable to keep up with crop yield in the postgreen revolution (Tilman *et al.*, 2002). Additionally, traditional breeding methods have a number of drawbacks, including genetic drag, hybridization incompatibilities, timeconsuming screening procedures, and the fact that new crop varieties take between 15 and 20 years to develop (Breseghello and Coelho, 2013). Salinity stress tolerance is also a polygenic trait, and conventional breeding techniques take a long time and are expensive to improve (Shahbaz and Ashraf, 2013).

Domestication of halophytes and other non-conventional crops

Halophytes[3] are salt-tolerant plants that exist in the natural environment. There is an arbitrary line between plants that can tolerate different level of salts in the soil: those able to tolerate 80 to 200 mM NaCl are salttolerant, whereas those that can tolerate (and in many cases prefer) >200 mM NaCl are called halophytes (Flowers and Colmer, 2008). Plants adopt some morphological adaptations to salinity stress through taking up excessive salts by storing in their vacuoles or other parts, while salts may also be excreted by salt glands or by the shedding of leaves (Aslamsup *et al.*, 2011; Ayub *et al.*, 2020).

There are around 625 species of halophytes which makes up 0.2 percent of plant species (Flowers and Al-Azzawi, 2022). These plants are the genetic basis for a salt response in nature that can be used in agriculture (Rozema *et al.*, 2015). For the selection of salt-tolerant crops, plants can either be directly selected in the saltstressful environments or by the mapping of QTL which represents the regions of a genome that are associated with the variation of a quantitative trait of interest (Flowers, 2004). However, the drawbacks of using QTL are the effects of undesirable traits because of the large size of the regions of chromosomes (Asins, 2002).

Halophyte plantations can be considered for fodder production, soil remediation, bioenergy production, landscaping, carbon sequestration, and several other useful purposes in those extreme soil or water salinity conditions where no crops of agricultural interest can be grown (Sardo and Hamdy, 2005). The issue of food production, particularly in developing countries, may be made worse in the upcoming decades by rising temperatures, escalating climatic variation, and extreme weather events. Those negative effects are probably more evident in the already stressed, salttolerant, and droughtprone semiarid and desert regions of the world (NASA and NOAA, 2017).

The International Center for Biosaline Agriculture (ICBA) created a germplasm bank of halophytes and salt-tolerant species, by selecting the most promising cultivars (ICBA, 2020). Aronson (1989) estimated that as a minimum, 50 different species of seedbearing halophytes could be used as sources of grain and oil. The eHALOPH database (Al-Azzawi and Flowers, 2023) recently revised the potential uses of halophytes in agriculture.

Although many species have long been used as various food ingredients, scientific study of these species only began in the second half of the twentieth century (Panta *et al.*, 2014).

To overcome specific genetic challenges, domestication may be essential. This entails improving a diverse natural ecosystem's capacity, forging strong ties between specific ecological niches and crops, helping plants withstand harsh or incredibly difficult climatic conditions, and increasing agriculturalsystems' geneticdiversityandgeneticadvantages(Shelef,WeisbergandProvenza,2017).

Limitations for scaling up: Studying crop wild relatives (CWRs) and learning about their genomes can both benefit from the knowledge learned from looking into the domestication process in model species (Kang *et al.*, 2016). It is relatively simple to domesticate monogenic traits, but it is

[3] A plant species adapted to soils containing a concentration of salt that is toxic to most other plant species.

very difficult to domesticate traits that are polygenic and sensitive to abiotic stress (Stitzer and RossIbarra, 2018). Many halophyte species have a great deal of potential as food crops and can help agriculture deal with the issues caused by soil salinization in the future. Due to a lack of information and research, some halophytes with more genetic resources go untapped (Panta *et al.*, 2014).

Box 5.6 | Salt-tolerant crops and halophytes: experience from Pakistan

Halophytes can actually show enhanced growth at elevated salt concentrations, like the river saltbush (*Atriplex amnicola*) which showed a 10 percent rise in growth at salinity levels of 5 dS/m, and while there was a 50 percent reduction in growth at 40 dS/m, the plant is still able to survive at 75 dS/m. However, some salt-tolerant species are not halophytes, such as cotton, sugar beet, barley, and date palm and do not exhibit the same ability. There are almost 1 500 salt-tolerant species globally but <1 percent are being utilized in Pakistan (Qureshi and BarrettLennard, 1998).

Halophytes not only cope with salinity but also improve the physicochemical and biological properties of soil. Some plants are better suited to grow under differing salt levels. Kallar grass *(Leptochloa fusca)* and Sesbania are recommended as the first plants to use for reclamation purposes as these grasses have been shown to not only increase the leaching of salts but also improve the soil's physical properties via their extensive root systems. Some tree species, for example, Tamarix aphylla, Leucaena leucocephala, Eucalyptus camaldulensis, Acacia ampliceps, Albizzia lebbeck, Grewia asiatica and Sesbania sesban are also suitable for reclamation effects in salt-affected soils (Qureshi and BarrettLennard, 1998; Ghafoor, Qadir and Murtaza, 2004; Saqib *et al.*, 2020).

Some other plants that can be grown in salt-affected soils include fruits (wild banana [*Musa acuminata*], coconut [*Cocos nucifera*], date palm [*Phoenix dactilifera*], and wild date palm), woody species (jojoba [*Simmondsia chinensis*], jujube [*Ziziphus jujuba*], wild cherry [*Prunus avium*], drumstick tree [*Molinga oleifera*], guava [*Psidium*], mangrove, mesquite [*Prosopis*], and mustard tree [*Salvadora persica*]), grasses (Bermuda grass [*Cynodon dactylon*], orchard grass [*Dactylis glomerata*], para grass [*Brachiaria mutica*], Rhodes grass [*Chloris gayana*], tall wheat grass [*Thinopyrum ponticum*], Sudan grass [*Sorghum x drummondii*] and perennial ryegrass [*Lolium perenne*]) and other miscellaneous plants (life plant [*Kalanchoe pinnata*], *Aloe vera*, periwinkle [*Vinca minor*], *Dodonaea*, purslane [*Portulaca oleracea*], reed [*Phragmites*], senna [*Cassia acutifolia*], bottle palm [*Hyophorbe lagenicaulis*], and cactus). These plant species are also capable of being grown in recovering salt-affected soils (DAWN, 2006). By following this systematic approach, we can better use salt-affected land and manage our genetic resources by growing salt-tolerant crops, fruits, and grasses with the utilization of saline water. These halophytic species can also be used as a source to preserve our ecosystem, for environmental protection and as a source of flavours, gums, oils, wood, timber and pharmaceuticals (Ladeiro, 2012).

Soil salinity tolerance levels of different crops

Crops	Scientific name	Category	Use	EC threshold (dS/m)
Wheat	*Triticum aestivum*	Tolerant	Grain	6.6
Cotton	*Gossypium hirsutum*	Tolerant	Fibre crop	7.7
Maize	*Zea mays*	Moderately sensitive	Grain	1.7
Soybean	*Glycine max*	Moderately tolerant	Oil seed	5.0
Tomato	*Lycopersicon esculentum*	Moderately sensitive	Vegetable	2.5
Barley	*Hordeum vulgare*	Tolerant	Grain	8.0
Wheatgrass	*Agropyron cristatum*	Tolerant	Forage grass	7.5

Source: **Qureshi, R. & Barrett-Lennard, E.G.** 1998. *Saline agriculture for irrigated land in Pakistan: A handbook*. Canberra, ACIAR.

Maas, E.V. 1993. Plant growth response to salt stress. In: H. Lieth & A.A. Al Masoom, eds. *Towards The Rational Use Of High Salinity Tolerant Plants*. Tasks for vegetation science, Volume 27. Dordrecht, Germany, Springer.

Salt tolerant trees, grasses and saltbushes

Trees	Grasses	Saltbushes
Eucalyptus camaldulensis	*Leptochloa fusca*	*Atriplex lentiformis*
Albizzia lebbeck	*Elitrigia elongata*	*Atriplex amnicola*
Phoeuix dactylifera	*Cynodon dactylon*	*Atriplex undulata*
Acacia nilotica	*Chloris gayana*	*Maireana amoena*
Prosopis juliflora		Maireana aphylla
Grewia asiatica		
Ziziphus mauritiana		
Leucaena leucocephala		
Pridium guajava		
Acacia ampliceps		

Box sources: **Saqib, M., Akhtar, J., Abbas, G & Wahab H.A.** 2020. Saline agriculture: A climate smart integrated approach for climate change resilience in degraded land areas. In: W.L. Filho, ed. *Handbook of Climate Change Resilience*, pp. 2287–2305. Cham, Switzerland, Springer Nature.

Box sources: **Qureshi, R. & Barrett-Lennard, E.G.** 1998. *Saline agriculture for irrigated land in Pakistan: A handbook*. Canberra, Australian Centre for International Agricultural Research (ACIAR).

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Bioinoculants (application of beneficial microorganisms)

Microbial activities are closely related to plants, and the adsorption enrichment, redox, leaching, mineralization precipitation and synergistic effects of microorganisms can be used to improve saline soils. The application of active microbial fertilizer can not only improve soil properties but also increase crop yield. A bioinoculant is a biological preparation containing living organisms, such as a biofertilizer, used in agriculture for inoculation of seeds, soils or other plant materials.

Trichoderma viride is a fungus and biopesticide in the family Hypocreaceae that can lessen the effects of salt stress. As multifunctional fungi found in various ecosystems, the genus *Trichoderma* exhibits a wide range of abilities among its various strains in the rhizosphere (Lahlali *et al.*, 2022) and its use in microbial inoculants has drawn attention from researchers to other benefits of the fungi (Tamizi *et al.*, 2022). Additionally, by increasing other subcomponents, the interactions of *Trichoderma* spp. with plants effectively control the yield (Cai *et al.*, 2013). Other bioinoculants that interact favourably with plants include *Pseudomonas fluorescence, Glomus mosseae*, and *Gigaspora gigantean* (Ruiz-Lozano, 2003; Adesemoye, Torbert and Kloepper, 2008; Egamberdieva and Lugtenberg, 2014).

In comparison to the control, biological inoculation in plants significantly increases water and nutrient absorption and improves plant growth and development under salinity stress (Zou *et al.*, 2013).

Phytohormones and rhizobacteria that promote plant growth have positive effects on the physiological and metabolic responses of plants to salt stress, improving their tolerance as well as growth and yield (Kamran *et al.*, 2018). Using plant growthpromoting rhizobacteria (PGPR) as inoculums under salt stress is known as an efficient strategy for improving plant growth (Arora, Trivedi and Rao, 2013).

Arbuscular mycorrhizal fungi (AMF) allows plants to explore larger volumes of soil and absorb more water and nutrients (such as phosphorus [P]), provides resistance to soil pathogens and drought, and improves water-use efficiency (Beltrano *et al.*, 2003). Therefore, AMF symbiosis is able to increase root and shoot length and leaf area, delay senescence (Beltrano and Ronco, 2008), and increase salinity resistance in host plants (Al-Karaki, 2000; Cekic, Unyayar and Ortas, 2012).

Limitations for scaling-up. These methods have their limitations due to the bacterial inocula's poor adaptability, short shelf life, improper immunization practices, decreased bioavailability of the pollutants, and higher toxicity toward plants and microbes (Rayu, Karpouzas and Singh, 2012). Environmental constraints when using bioinoculants include soil pH, overapplication of agrochemicals, drought, high temperature, waterlogging conditions, antagonism from other microbes, and incompatibility with other pesticides.

Economic aspects. Biotechnological inputs are inexpensive and efficient, and indirectly increase water and nutrient use efficiency in agriculture.

Halopriming

A simple and effective method for improving the stress tolerance of plants that does not involve creating a geneticallyaltered organism is halopriming (Moreno *et al.*, 2018). Halopriming is a seed priming technology that is used before a seed has completed germination. Seeds are soaked in aerated inorganic salt solutions, controlling temperature and seed moisture content in the early stages of germination. It harmonizes the metabolic processes required for improving seed quality and further promotes the seeds emergence rate for healthy seedling vigour (Gour *et al.*, 2022). In general, halopriming is a simple and inexpensive adaptation method recommended for farmers (Rong *et al.*, 2017).

There are several priming methods, classified as hydropriming, osmopriming, halopriming, hormone priming, hardening, solid matrix priming, humidification and stratification, or thermal shock, depending on the priming agents. The first four techniques – hydropriming, osmopriming, halopriming, and hormone priming – involve soaking seeds in water or a solution containing inorganic salt, sugar, or hormones, followed by air drying before sowing, and are the ones that are most frequently used (Hidayah *et al.*, 2022).

An evaluation of the effectiveness of seed priming treatments of *Chenopodium quinoa* and *Amaranthus caudatus* in improving germination under salt stress showed that hydropriming and osmopriming of seeds resulted in significant improvements in seed speed and uniformity of germination, and led to high final germination percentages, high germination indices and shorter average germination times. During seed germination, *C. quinoa* had a higher tolerance for salt than *A. caudatus* (Moreno, Seal and Papenbrock, 2018).

5.3.3 | Saline agriculture as an integrated approach

Saline agriculture is an integrated approach that assimilates the adaptation and mitigation strategies mentioned previously in this chapter. There is no single definition of saline agriculture as it is a relatively new concept. It integrates the use of saline irrigation water and saline soils involving salt-tolerant crops and halophytes while avoiding expensive soil reclamation measures (Ladeiro, 2012). Saline agriculture requires approaches that integrate crop, soil, water and climate to ensure the sustainable use of saline resources (Box 5.7). It is a longterm measure that should be included in the national plans of the countries that experience soil salinity and water scarcity as it provides a costeffective solution from an environmental, food security and economic perspective (Qadir *et al.*, 2014; Negacz *et al.*, 2021).

Box 5.7 | Reclamation and management of a saline sodic Vertisol in India with saline agriculture

Salinity and sodicity have a great impact in Vertisols which are widespread across Gujarat, Madhya Pradesh, Karnataka, Tamil Nadu, and Maharashtra states of India. These soils have a heavy texture and a higherthanaverage percentage of clay. The groundwater under such soils is saline or brackish. Due to the high amount of clay, they are prone to recurrent cycles of drying and wetting which causes deep cracks to form. Such soils are difficult to reclaim once salinity has developed, as the exchangeable sodium percentage (ESP) in such soils has a more adverse effect on crops and the physicochemical parameters of soil. Vertisol management and reclamation opportunities through biosaline agriculture are enormous.

For sustainable management, plants with economic potential that can withstand salt under Vertisols have been identified. As a salt-tolerant facultative halophyte, *Salvadora persica* L. (Meswak) is recognised as a possible nonedible oil source. It can withstand salinity up to 50 dS/m and reacts well to watering with saline water (Rao *et al.*, 2004). It is possible to grow *Salvadora* seedlings with the application of 15 dS/m of saline water (Gururaja Rao, Arora and Chinchmalatpure, 2016). The seeds of *Salvadora* are an excellent source of non-edible seed oil with high fatty acids (C-12 and C-14) and is used extensively in the soap and detergent industries. Its cost for field cultivation – including nursery growing – is INR 2 760 (about USD 70) during the first year (Rao *et al.*, 2004). After five years, oil is produced at a rate of 1 800 kg/ha, resulting in a net annual return of INR 8 400 (about USD 210). Another crop suited to growing in black, moderately saline soils is dill (*Anethum graveolens*). In such an environment, this nontraditional seed spice crop can produce a respectable yield of 4 to 6 dS/m (Rao, Nayak, and Chinchmalatpure, 2000).

Crop yields can be increased by irrigating with saline groundwater mixed with good quality surface water that is readily accessible. Surface water should be used for one irrigation if it is available, and saline water for the vegetative and flowering periods. It costs around INR 6 000 (USD 150) per ha to cultivate dill in moderately salinized soils, and the crop generates INR 16 500 (USD 413) per ha as net returns with a benefit cost ratio of 2.75 (Rao, Nayak, and Chinchmalatpure, 2000; Vineeth *et al.*, 2023). Additionally, this crop gives farmers the chance to successfully cultivate a crop in the Rabi season (November to March) on salty soils that had previously been left fallow due to salinity and water restrictions. Wheat and safflower (*Carthamus tinctorius*) can also be grown by alternately using both high and low quality groundwater.

Safflower flowering and branching stages are sensitive to irrigation with saline water. If there is just enough surface water for one irrigation, the vegetative and flowering stages should be watered with saline solution and the branching stage with surface water. Further, if surface water is available for two irrigations, saline water should be used for the vegetative stage and surface water for the growth stages of branching and flowering.

Halophytic grasses like *Aeluropus lagopoides* and *Eragrostis* have been proven to be appropriate for biosaline agriculture in highlysalinized black soils that are underlain by highlysalinized groundwater. Saline water with an electrical conductivity (EC) of 30 to 40 dS/m can be used to cultivate these grasses (Dagar, 2018). It was discovered that *Dichanthium annulatum* could be grown in salty soils with salinities up to 12 dS/m. Similarly, medicinal crops like *Matricaria chemomilla* and *Plantago ovata* may also be grown in soils with a pH of up to 9.5 and salinity between 6 and 8 dS/m (Dagar, Kumar and Tomar, 2006).

Saline waterlogged Vertisol

Saline Vertisol with cotton after reclamation

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Chapter 6 | Conclusions and way forward

With almost 1.4 billion hectares of land already affected by salinity and over a billion hectares at risk, urgent action is required to address soil salinization and sodification globally. In the following lines FAO´s Global Soil Partnership and its International Network of Salt-affected Soils propose a series of recommendations intended to facilitate decision-making and actions by all stakeholders including policy makers, the private sector, academia and civil society to address this major challenge to food security and land degradation:

1. Upscale sustainable management practices

Soil salinity and sodicity pose significant challenges to production of conventional crops, land availability for cultivation, and environmental sustainability. As the global population continues to rise, there is an urgent need to enhance food production. Given that salt-affected soils cover approximately 10 percent of arable land, their sustainable management is crucial to meet food demand and increase agricultural productivity. Mitigation and adaptation strategies are essential for sustainable soil management, focusing on reducing salinity levels in the root zone and coping with existing salinity levels, respectively. There is a big variety of the practices that help to improve the state of salt-affected soils including improved drainage techniques, optimization of leaching requirements, mulching, organic matter and calcium-containing amendments, improved crop rotations and diversification, biofertilization and halopriming.

The upscaling of sustainable management practices should be prioritized for the areas affected by salinity and sodicity through targeted agricultural incentives, subsidies and farmers training.

2. Promote sustainable saline agriculture, wider adoption of salt-tolerant varieties and the use of halophytes

Given the necessity for farmers in salt-affected areas to adapt to changing conditions, policy focus should shift towards promoting saline agriculture as a viable solution to sustain livelihoods amidst climate change and water scarcity. Saline agriculture is an integrated approach that assimilates the adaptation and mitigation strategies integrating the use of adapted crops with saline soil and water. The sustainability of this practice should be ensured by the proper management of saline soil and water that minimizes the risks of secondary salinization and sodification.

The underutilized potential of halophytes and salt-tolerant plants in agriculture should be leveraged through policy interventions combined with investment by the private sector and farmers, awareness and capacity raising as they can provide valuable resources such as grain, biofuels, and fodder. Their applicability in bioremediation of degraded lands has also been documented. Policies should encourage the cultivation of halophytes on marginal lands unsuitable for conventional agriculture, as this practice can enhance soil quality, water retention, and biodiversity. Additionally, fostering research and innovation in crop breeding and cultivation techniques tailored to salt-affected environments will enhance the viability and productivity of these crops.

3. Promotion of market for crops grown on salt-affected soils, including non-conventional crops such as halophytes

In tandem with efforts to promote saline agriculture among farmers, it is imperative to facilitate the development of markets for these crops, encompassing both conventional and non-conventional varieties like halophytes. This entails implementing supportive policies and incentives to facilitate the commercialization of these crops and developing strong communication campaigns targeting consumers, thereby creating economic opportunities for farmers in regions affected by soil salinity and sodicity. By promoting market access and consumer awareness of the nutritional benefits and environmental resilience of crops grown on salt-affected soils, countries can stimulate demand and investment in this sector, ultimately contributing to food security, economic diversification, and sustainable land use practices.

4. Improve salinity and sodicity assessment

Comprehensive data on the extent of salt-affected soils and soils at risk of salinization and sodification are lacking worldwide. Many countries lack official data or face controversy on existing data. Insufficient data currently hampers the ability to distinguish between human-induced and natural salinization, underscoring the need for enhanced assessment methods and targeted data collection to enable accurate differentiation of these causes. Improving mapping techniques, adopting regular soil surveys, and transitioning to digital tools are essential steps to enhance monitoring and management efforts. Moreover, harmonizing data collection methods and developing conversion equations (pedotransfer functions) are crucial for accurate assessment of soil salinity and sodicity. The international community and academia should focus on developing and promoting standardized measurement techniques to facilitate data comparability and analysis, with a focus on advance technologies that can reduce costs and time.

5. Adopt water quality monitoring and management

Given the already high levels of saline groundwater, the rapidly deterioration of existing water reserves, and the widespread use of brackish water for irrigation, urgent measures are needed to prevent further salinization caused by droughts and excessive aquifer exploitation. Establishing robust irrigation water quality monitoring systems is essential to ensure the sustainable utilization of water resources and mitigate salinity-related challenges. Additionally, efforts to enhance water quality monitoring must be intensified, considering the significant proportion of poor-quality water bodies globally. Monitoring of irrigation water quality, especially in arid regions where salinity and sodicity pose significant threats to agricultural productivity, is crucial for sustainable soil and water management.

6. Quantify yield losses and gains

National assessments of yield losses due to soil salinity and potential gains from reclamation efforts and saline agriculture are essential for understanding the magnitude of the challenge and devising effective strategies. Policy frameworks should encourage countries at the national and local levels to quantify these aspects to inform sustainable agricultural development plans.

7. Ensure conservation and sustainable use of natural salt-affected ecosystems

Prioritize the conservation of natural salt-affected ecosystems holding valuable or unique soils and species, recognizing their vital role in providing essential ecosystem services for human well-being. These services encompass provisioning, regulating, cultural, and supporting functions, ranging from food and water provision to flood control, cultural benefits, and nutrient cycling. Despite being integral components of ecosystems, the ecological function of saline and sodic soils is often underestimated or disregarded. It is imperative to conduct further research and raise awareness about the significant ecological contributions of natural salt-affected soils to ensure their protection and sustainable management for the benefit of present and future generations.

8. Strengthen cross sectoral communication and engagement within and between governments at all levels to form an efficient management model

Given the multidisciplinarity required for addressing salt-affected soil management, involving water conservancy, agriculture, finance, environment, and other relevant ministries and departments, seamless cooperation among all stakeholders is imperative.

Inadequate communication and collaboration between relevant stakeholders can lead to fragmented funding and diminished efficiency of actions. Therefore, the establishment of a coordinating mechanism or institution is essential to designate and involve responsible parties, optimize governance effectiveness, foster interdepartmental cooperation, and establish a monitoring mechanism to ensure streamlined operations in salt-affected soil.

9. Strengthen the capacities of relevant scientific and technological talents and promote academic platforms and technology development

Improving salt-affected soils requires the strengthening of multidisciplinary research and enhancing the cooperation between academia and the private sector involved in technology development. In addition, strengthening the present platforms is needed to attract and gather talents. Particularly, the focus should be on developing local scientific and technological talents, as they would be able to serve the local community for a longer period and be more familiar with the local conditions. By using these platforms to vigorously introduce high-level talents and projects, a wide range of cooperation channels between industry, academia, and research institutions can be catalyzed. Research platforms can provide new technologies, such as biomediated methods, which can offer technical support and reserves for the high-quality development of large-scale industries that can help manage salt-affected soils.

10. Develop training programmes for farmers and university curricula in the countries affected by soil and water salinity and sodicity

In addition to strengthening the training of scientific and technological talents and promoting the function of academic and research platforms, there is a pressing need to prioritize the development of comprehensive training programmes for farmers and expand university curricula in countries grappling with soil and water salinity and sodicity. These programmes should be tailored to address the specific challenges and needs of these regions, equipping students and professionals with the knowledge and skills required to effectively manage salt-affected soils and water resources. Incorporating interdisciplinary approaches and practical training modules into university curricula and farmers field schools and extension centers will ensure that all stakeholders are well-prepared to tackle the complexities of soil and water salinity, contribute to innovative solutions, and drive sustainable development in affected areas. By investing in education and capacity-building initiatives, countries can build a skilled workforce capable of addressing the multifaceted challenges posed by soil and water salinity and sodicity, thereby fostering resilience and promoting long-term sustainability.

Annex 1 | Criteria used for the identification of different classes of salt-affected soils in the GSASmap

Table A1.1 | Criteria used for the identification of different classes of salt-affected soils in the GSASmap

Soil property	Major category of salt-affected soils			Subcategories by intensity (of salinity or sodicity)					
	Saline	Sodic	Saline sodic	None	Slight	Moder-ate	Strong	Very strong	Extreme
EC (dS/m)	>0.75	<4	>4	<0.75	0.75–2	2–4	4–8	8–15	>15
pH (water)	<8.2	>8.2	<8.2						
ESP (%)	<15	>15	>15	<15	15–30	30–50	50–70	>70	

Annex 2 | Areas of salt-affected soils (EC>2 dS/m or ESP>15 percent) in the GSASmap at the country level

Table A2 1 | Areas of salt-affected soils (EC>2 dS/m or ESP>15 percent) in the GSASmap at the country level

Country	Region*	Area of salt-affect-ed soils at 0–30 cm depth (km²)	Area of salt-affect-ed soils at 0–30 cm depth (%)	Area of salt-affect-ed soils at 30–100 cm depth (km²)	Area of salt-affect-ed soils at 30–100 cm depth (%)
Afghanistan	Asia	118 064.8	18.1	382 449.9	58.6
Andorra	Europe and Eurasia	0.0	0.0	–	–
Angola	Africa	32 484.6	2.6	61 967.4	5.0
Argentina	Latin America and the Caribbean (LAC)	352 442.3	12.9	1 531 252.6	56.0
Austria	Europe and Eurasia	1.8	0.0	–	–
Azerbaijan	Europe and Eurasia	25 291.2	30.6	–	–
Bangladesh	Asia	19 609.8	15.1	25 101.2	19.3
Belgium	Europe and Eurasia	0.0	0.0	–	–
Benin	Africa	1 220.6	1.1	7.5	0.0
Bhutan	Asia	0.8	0.0	–	–
Bolivia (Plurinational State of)	LAC	10 376.4	1.0	9 984.9	0.9
Botswana	Africa	26 927.2	4.8	37 073.4	6.5
Brazil	LAC	3 076.2	0.0	5 609.6	0.1
Bulgaria	Europe and Eurasia	0.0	0.0	–	–
Burkina Faso	Africa	45.2	0.0	38.6	0.0
Cambodia	Asia	10.9	0.0	185.2	0.1
Cameroon	Africa	1 025.6	0.2	16 420.7	3.5

Country	Region*	Area of salt-affected soils at 0–30 cm depth (km²)	Area of salt-affected soils at 0–30 cm depth (%)	Area of salt-affected soils at 30–100 cm depth (km²)	Area of salt-affected soils at 30–100 cm depth (%)
Canada	North America	9 422.4	0.1	45 854.5	0.5
Central African Republic	Africa	174.1	0.0	423.4	0.1
Chad	Africa	18.4	0.0	2 128.6	0.2
Colombia	LAC	26 572.6	2.4	39 579.6	3.6
Costa Rica	LAC	0.0	0.0	0.0	0.0
Croatia	Europe and Eurasia	0.0	0.0	–	–
Cuba	LAC	2.4	0.0	11 477.2	11.1
Cyprus	Europe and Eurasia	370.1	4.0	–	–
Czechia	Europe and Eurasia	0.0	0.0	–	–
Democratic Republic of the Congo	Africa	114.4	0.0	80.7	0.0
Denmark	Europe and Eurasia	0.0	0.0	–	–
Djibouti	Africa	44.4	0.2	72.8	0.3
Ecuador	LAC	88 696.8	35.7	80 544.8	32.4
Eritrea	Africa	36 659.5	30.3	48 577.6	40.1
Estonia	Europe and Eurasia	0.0	0.0	–	–
Ethiopia	Africa	13 091.3	1.2	–	–
Finland	Europe and Eurasia	0.0	0.0	–	–
France	Europe and Eurasia	0.0	0.0	–	–
Gambia	Africa	728.8	7.2	–	–
Georgia	Europe and Eurasia	89.6	0.1	1 289.5	1.9
Germany	Europe and Eurasia	0.0	0.0	–	–
Ghana	Africa	1 323.0	0.6	1 0179.6	4.5
Guinea	Africa	166.8	0.1	1 582.8	0.6
Guinea-Bissau	Africa	696.4	2.5	–	–
Guyana	LAC	0.0	0.0	3.4	0.0
Hungary	Europe and Eurasia	14 157.9	15.5	15 545.5	17.0
India	Asia	285 023.0	9.6	280 248.9	9.4
Iraq	Near East and North Africa (NENA)	120 872.1	27.8	305 936.3	70.5
Israel	Europe and Eurasia	171.2	0.8	–	–
Italy	Europe and Eurasia	1 126.9	0.4	–	–
Jamaica	LAC	541.7	5.0	2 334.3	21.6
Jordan	NENA	17 042.8	19.2	80 445.3	90.6

Country	Region*	Area of salt-affected soils at 0–30 cm depth (km²)	Area of salt-affected soils at 0–30 cm depth (%)	Area of salt-affected soils at 30–100 cm depth (km²)	Area of salt-affected soils at 30–100 cm depth (%)
Kenya	Africa	79 269.9	13.9	19 362.4	3.4
Kuwait	NENA	10 550.1	59.2	15 815.4	88.8
Lao People’s Democratic Republic	Asia	317.2	0.1	37 234.5	16.1
Latvia	Europe and Eurasia	0.0	0.0	–	–
Lebanon	NENA	1 531.6	15.0	–	–
Lesotho	Africa	0.0	0.0	–	–
Lithuania	Europe and Eurasia	2.0	0.0	–	–
Luxembourg	Europe and Eurasia	0.0	0.0	–	–
Madagascar	Africa	3.3	0.0	–	–
Malawi	Africa	24 564.9	26.1	7 031.9	7.5
Mali	Africa	16 588.3	1.4	135.6	0.0
Mauritania	Africa	193.9	0.0	235.8	0.0
Mexico	LAC	154 789.5	8.0	334 132.7	17.2
Morocco	NENA	134 555.7	30.1	164 363.9	36.8
Mozambique	Africa	1 221.3	0.2	510.6	0.1
Myanmar	Asia	12 139.4	1.9	15 068.5	2.3
Namibia	Africa	288 916.3	35.1	310 517.6	37.7
Nepal	Asia	0.0	0.0	467.8	0.3
Netherlands (Kingdom of the)	Europe and Eurasia	0.0	0.0	–	–
Nicaragua	LAC	456.6	0.4	80.1	0.1
Niger	Africa	1 112.5	0.1	1 418.8	0.1
Nigeria	Africa	5.9	0.0	542.6	0.1
North Macedonia	Europe and Eurasia	2.6	0.0	381.6	1.5
Oman	NENA	81 718.1	26.4	289 489.9	93.5
Pakistan	Asia	80 436.3	10.4	113 424.6	14.7
Papua New Guinea	Pacific	0.0	0.0	–	–
Paraguay	LAC	9 767.7	2.5	127 476.8	32.1
Peru	LAC	81 480.5	6.4	86 021.4	6.7
Philippines	Asia	759.6	0.3	–	–
Poland	Europe and Eurasia	214.9	0.1	–	–
Portugal	Europe and Eurasia	1 430.7	1.6	–	–
Republic of Moldova	Europe and Eurasia	20.4	0.1	–	–
Romania	Europe and Eurasia	13.2	0.0	–	–
Russian Federation	Europe and Eurasia	527 784.9	3.2	769 639.9	4.7

Country	Region*	Area of salt-affected soils at 0–30 cm depth (km²)	Area of salt-affected soils at 0–30 cm depth (%)	Area of salt-affected soils at 30–100 cm depth (km²)	Area of salt-affected soils at 30–100 cm depth (%)
Rwanda	Africa	110.2	0.4	1 429.2	5.8
San Marino	Europe and Eurasia	0.0	0.0	–	–
Senegal	Africa	51 471.8	26.7	12.4	0.0
Serbia	Europe and Eurasia	1.8	0.0	–	–
Sierra Leone	Africa			114.9	0.2
Slovakia	Europe and Eurasia	1.7	0.0	–	–
Slovenia	Europe and Eurasia	0.0	0.0	–	–
Somalia	Africa	204.8	0.0	2 332.1	0.4
South Africa	Africa	59 187.0	4.9	25 943.5	2.1
South Sudan	Africa	18 351.0	2.9	5 578.4	0.9
Spain	Europe and Eurasia	1 042.1	0.2	–	–
Sudan	NENA	393 453.0	21.1	435 720.2	23.3
Sweden	Europe and Eurasia	0.0	0.0	–	–
Syrian Arab Republic	NENA	30 903.9	16.8	50 128.6	27.3
Thailand	Asia	71 082.9	13.9	110 493.7	21.6
Togo	Africa	227.8	0.4	7.6	0.0
Tunisia	NENA	25 010.9	16.1	49 910.7	32.1
Türkiye	Europe and Eurasia	1 224.8	0.2	–	–
Ukraine	Europe and Eurasia	53 615.9	9.3	52 670.4	9.1
United Arab Emirates	NENA	25 139.7	35.4	42 986.2	60.5
United Kingdom	Europe and Eurasia	9.1	0.0	–	–
United Republic of Tanzania	Africa	3 574.7	0.4	114 012.9	12.9
United States	North America	202 957.3	2.2	734 057.6	8.0
Uzbekistan	Europe and Eurasia	338 448.8	76.8	409 281.6	92.9
Venezuela (Bolivarian Republic of)	LAC	14 048.2	1.6	29 019.6	3.3
Yemen	NENA	59 475.1	11.3	205 313.1	38.9
Zambia	Africa	4.9	0.0	119.5	0.0
Zimbabwe	Africa	1 339.7	0.3	7 863.3	2.0
Total		**4 068 418.1**		**7 566 743.8**	

Note: *Regions are given according to **FAO**. 2023. Global Soil Partnership. Regional Soil Partnerships. In: FAO. Rome. [Cited 2023]. https://www.fao.org/global-soil-partnership/regional-partnerships/en/

Source: FAO. 2021. Global Map of Salt-affected Soils (GSASmap) v1.0. In: **FAO**. Rome. [Cited 2023]. https://www.fao.org/soils-portal/data-hub/soil-maps-and-databases/global-map-of-salt-affected-soils/en/

Annex 3 | Areas of salt-affected soils of different intensity in the GSASmap at the country level

Table A3. 1 | Areas of salt-affected soils of different intensity in the GSASmap at the country level

The table is available at: https://www.fao.org/3/CD3044EN/Annex3.xlsx

Annex 4 | Areas of salt-affected soils in the countries not represented in the GSASmap according to miscellaneous sources

Table A4. 1 | Areas of salt-affected soils in the countries not represented in the GSASmap according to miscellaneous sources

Country	Region	Area of salt-affected soils (km²)	Source	Area of saline soils (km²)	Source	Area of sodic soils (km²)	Source	Area of salt affected soils (%)
Australia	Pacific	3 570 000	Northcote and Skene (1972)	–	–	–	–	46.4
Chile	LAC	86 420	Massoud (1977)	50 000	Massoud (1977)	36 420	Massoud (1977)	11.6
China	Asia	360 000	National Soil Survey Office (1998)	–	–	–	–	3.8
Algeria	NENA	32 000	Szabolcs (1989)	–	–	–	–	1.3
Egypt	NENA	13 800	Sum of saline and sodic	11 200	Gehad (2003)	2 600	Hassan (2012)	1.4
Indonesia	Asia	132 130	Massoud (1977)	132 130	Massoud (1977)	–	–	7.0
Iran (Islamic Republic of)	NENA	556 000	Banaei *et al.* (2004)	–	–	–	–	34.3
Kazakhstan	Europe and Eurasia	939 823	Ministry of Agriculture of the Republic of Kazakhstan (2021)	358 174	Ministry of Agriculture of the Republic of Kazakhstan (2021)	581 649	Ministry of Agriculture of the Republic of Kazakhstan (2021)	34.8
Kyrgyzstan	Europe and Eurasia	16 710	State Agency for Environmental Protection and Forestry under the Government of the Kyrgyz Republic (2020)	11 908	State Agency for Environmental Protection and Forestry under the Government of the Kyrgyz Republic (2020)	4 802	State Agency for Environmental Protection and Forestry under the Government of the Kyrgyz Republic (2020)	8.7
Mongolia	Asia	40 700	Massoud (1977)	40 700	Massoud (1977)	–	–	2.6
Malaysia	Asia	30 400	Massoud (1977)	30 400	Massoud (1977)	–	–	9.3
Saudi Arabia	NENA	60 020	Massoud (1977)	60 020	Massoud (1977)	–	–	2.8
Turkmeni-stan	Europe and Eurasia	141 000	Pankova (1992)	–	–	–	–	30.0
Viet Nam	Asia	9830	Massoud (1977)	9 830	Massoud (1977)	–	–	3.1

Sources: **Northcote, K.H. & Skene, J.K.M.** 1972. Australian Soils with Saline and Sodic Properties. Soil Publication No 27, Melbourne, Australia, Commonwealth Scientific and Industrial Research Organisation (CSIRO).

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Annex 5 | The responses to the INSAS survey "Status of salt-affected soils measurement, monitoring and management"

Table A5. 1 | The responses to the INSAS survey "Status of salt-affected soils measurement, monitoring and management" [4]

The table is available at: https://www.fao.org/3/CD3044EN/Annex5.xlsx

Annex 6 | Relative potential yield loss due to salinity stress

Table A6. 1 | Relative potential yield loss due to salinity stress

The table is available at: https://www.fao.org/3/CD3044EN/Annex6.xlsx

4 We acknowledge the intern of the Global Soil Partnership, Alena Pochtennaia, for preparing the excel spreadsheets for Annex 5.

GLOBAL SOIL PARTNERSHIP

The Global Soil Partnership (GSP) is a globally recognized mechanism established in 2012. Our mission is to position soils in the Global Agenda through collective action. Our key objectives are to promote Sustainable Soil Management (SSM) and improve soil governance to guarantee healthy and productive soils, and support the provision of essential ecosystem services towards food security and improved nutrition, climate change adaptation and mitigation, and sustainable development.

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