EIP-AGRI Focus Group

Soil salinisation

MINIPAPER: ***Prevention, mitigation and adaptation strategies for soil salinisation at farm level***

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1. Introduction

This minipaper assesses the strategies that can be used to prevent, reduce or adapt to soil salinity at farm level, identifying their sustainability and innovation potential. We begin with a resume of the available strategies and then present the strategies with high innovation potential discussing their limits and advantages, challenges and opportunities, and the knowledge gaps. Finally, we leave ideas for operational groups to achieve the identified innovation potential.

2. Strategies to lead with soil salinization at farm level

According to the location, soil salinization may be a risk or it may be already a reality. In risk areas it is necessary to take preventive measures, in areas where salinization developed due to poor practices or where the salts equilibrium may be maintained, remediation strategies could be put into place. Adaptation strategies can be used in areas where salinization is recurrent or remediation is not possible, or as a complement to remediation.

Soil salinization problems referred in this minipaper are related to:

- soil salinity, which results from accumulation of dissolved salts in the soil and results in an increase in the osmotic potential of the soil water which limits the plants capacity to absorb water and can cause nutritional imbalances or toxicity due to the presence of specific ions;
- Soil sodicity, which expresses the dominance of Na (sodium) in the soil exchange complex. Sodicity may lead to the destruction of the soil structure through the swelling and dispersion of the clay particles and the formation of low permeability layers that among other drawbacks, restrict root growth, water infiltration through the profile, and enhance soil erosion.

The most used indicators to quantify the salinisation problems are the electrical conductivity of the soil saturation extract (EC_e) for salinity, and the sodium adsorption ratio (SAR) and the exchangeable sodium percentage (ESP) for sodicity. More information on the determination of these indicators can be found in the minipaper *Measuring, mapping and monitoring of soil salinity*.

2.1. Prevention

The identified risk is usually associated with a cause, which can be related to the irrigation water quality, the irrigation management and drainage, seawater intrusion, and to the soil's parent material or groundwater.

Risks related to the irrigation water quality

The irrigation water that can be used without further developing soil salinisation problems depends not only on the quality of the water itself but also on the characteristics of the soil and the leaching and drainage conditions. The irrigation water quality has to be analyzed in terms of water salinity (determining the electrical conductivity of the water, EC_w) and water sodicity (determined by SAR). The following general situations can be identified:

- No salinity-derived cropping problems are expected when using water with $EC_w < 0.7$ dS·m^{-1} (see Table 1);
- No salinity-derived cropping problems are expected when using water with EC_w between 0.7 - 3.0 dS·m^{-1} as long as it is used in a soil with adequate drainage and in sufficient amount to allow the leaching of the excess of salts and to keep the salts concentration under the crops' salinity tolerance threshold. Specific leaching requirements will need to be estimated and applied (see section about "leaching requirements");
- Regions with fresh water scarcity, such as in the south of the Mediterranean area, use saline water for irrigation. This is done by combining strategies described in the section "Irrigation with saline waters" with high-tolerant crops;
- Soil structural degradation and consequent permeability-derived problems are prevented by keeping minimum threshold values for EC_w depending on the SAR of the irrigation water (see Table 1 for those

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threshold values). When EC_w is lower than the threshold value, some prevention strategies can be adopted, such as using chemical amendments (*e.g.* gypsum to prevent soil crusting) to the soil (see details in section about "chemical remediation"), reuse the irrigation effluent water which has higher EC_w, and avoid leaving the soil bare to prevent soil crusting (impermeability of the soil surface). An example of soil structure degradation from using water with low EC_w occurred in several areas of the Middle Ebro River basin (Spain), even in soils with low sodicity levels. They developed physical problems when irrigated with water with low EC_w (i.e. EC_w < 0.4 $dS \cdot m^{-1}$) and when bare soils were exposed to rainwater (typically EC<0.01 $dS \cdot m^{-1}$) (Amezketa et al. 2003, Isidoro et al. 2007).

Table 1. Irrigation water-quality guidelines based on EC_w and SAR of the irrigation water. Adapted from Ayers and Westcot (1985).

Potential problems		No restriction	Slight to moderate restriction	Severe restriction
Salinity		$EC_w < 0.7$	$EC_w = 0.7 - 3$	$EC_w \geq 3$
Degradation of the soil structure	SAR = 0 - 3	$EC_w > 0.7$	$EC_w = 0.7 – 0.2$	$EC_w \leq 0.2$
	SAR = 3 - 6	$EC_w > 1.2$	$EC_w = 1.2 - 0.3$	$EC_w \leq 0.3$
	SAR = 6 - 12	$EC_w > 1.9$	$EC_w = 1.9 - 0.5$	$EC_w \leq 0.5$
	SAR = 12 - 20	$EC_w > 2.9$	$EC_w = 2.9 - 1.3$	$EC_w < 1.3$
	SAR = 20 - 40	$EC_w > 5.0$	$EC_w = 5.0 – 2.9$	$EC_w < 2.9$

Risks related to the irrigation management and drainage

Appropriate irrigation and drainage management for salinisation prevention at the field scale include the selection of irrigation method, adjusting irrigation scheduling, meeting the leaching requirements, and the use of multi-salinity waters.

Irrigation methods and systems

The selection of the irrigation method should consider irrigation water quality and the detrimental effects that both water and method of application can have on crop growth and yields. The most relevant considerations when selecting the irrigation method are (Pereira et al. 2014): (i) soil salinity hazards due to the accumulation of salts in the root zone; (ii) toxic hazards caused by direct contact of the salty water with plant leaves and fruits; (iii) soil permeability changes caused by modifications of soil properties; and (iv) yield reductions when the irrigation system does not allow defining appropriate irrigation management practices (i.e. frequency and volume). For example, **surface systems (flood irrigation)** are well adapted for leaching due to the higher volumes and more uniform application of water, but are less appropriate for irrigation of less tolerant crops due to the increased water and salinity stresses that may rise in-between irrigation events. On the other hand, **drip irrigation** is appropriate for salt sensitive crops because small and frequent irrigation depths are used, but salts need to be prevented from returning into the wetted bulb.

Irrigation scheduling

Even low salinity water will add salts to the soil which may accumulate over time, especially in arid climates. The irrigation scheduling should be able to fulfil crop water requirements and to help promoting salt leaching from the root zone. For surface irrigation, the large volumes and reduced number of irrigation events can eliminate salinity-build-up in the root zone and assure optimal crop production conditions, if the fields are properly levelled and water and salt distribution are uniform. For drip irrigation, small and frequent events can maintain maximum leaching in the root zone. However, on-farm management should be specific for each field conditions as small irrigation intervals can induce water uptake from shallow soil layers, increasing evaporation losses from soil surface and increasing salt load of soils. On the other hand, large irrigation intervals can enhance salt transport upwards from deeper layers or from saline groundwater.

Leaching requirements

Under conditions of salinisation risk, leaching requirements should complement crop water needs in order to control the salt balance in the root zone. The traditional salinity management approach considers the following equation to calculate the leaching fraction (LR) (Richards, 1954):

$$LR = \frac{EC_w}{5\ EC_e - EC_w}$$

The EC_e value should be the average soil salinity tolerable by the crops for attaining an acceptable yield of 70-90%. The equation is known to overestimate leaching requirements, but there is no general alternative. Therefore, leaching strategies should always be case specific, taking into account the soil, climate, and crops to be grown.

Irrigation practices with saline waters

As fresh water supplies are not always available to fulfil crop water requirements, saline waters are often seen as a valuable alternative resource. Saline irrigation waters can be applied either separately, in a cyclic way, or mixed together with fresh waters. When cyclic strategies are considered, fresh waters are applied to the most sensitive crop growth stages (germination and seedling) while saline waters can be allocated when the crop can tolerate higher salinity levels. When blending strategies are adopted, two or more waters sources are mixed together to reach a targeted salinity for a particular crop, and depend on the crop salt tolerance, the soil type and climate, and the long-term management plan for irrigation and crop production. Blending also requires additional infrastructures (dilution network, storage reservoirs) to allow the control mixing of two (or more) water sources. Cyclic strategies are known to lead to higher yields than blending but all are associated to a risk of crop failure that needs to be properly managed.

Drainage

Drainage systems have to be carefully planned. For instance the distance and depth of drains have to be determined according to each specific condition. Insufficient drainage may cause salts accumulation in the rootzone. However, high drainage may also become problematic as the excessive removal of irrigation water and rainfall from surface layers may favour the rise of existing deeper saline water, particularly in dry months, when evapotranspiration increases.

Risks related to seawater intrusion

In coastal and estuarine areas, sea water intrusion can result from storm surge, droughts, sea-level rise, and human activities associated to the over-exploitation of groundwater resources, land use changes, river damming, and dredging of navigation corridors. Most agricultural areas located close to river estuaries need to be protected from sea water intrusion. Prevention measurements are normally associated with flow regulation from upstream reservoirs when these exist. Yet, some more radical measures may be needed. For example, in a high-productive irrigated agricultural peninsula located by the estuaries of the Tejo River and the smaller Sorraia River in Portugal, and where the irrigation water is captured from the rivers, an earth wall has been temporary built in drought seasons to prevent the sea tide from going up the Sorraia River and increase the salinity of the irrigation water. These strategies can have impacts in the area, as they disrupt the previous hydrology and have therefore to be carefully analyzed. Due to their large size and impacts, they are multi-farm/regional level strategies.

Risks related to parent material and groundwater

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

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

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

2.2. Mitigation

When the soil salinisation has already occurred, several strategies can be considered to mitigate or reduce it. The possibilities include the use of chemical treatments, phyto- and bioremediation, leaching and drainage of excess salts and some agronomical practices.

Chemical remediation of sodic and saline-sodic soils

In sodic and saline-sodic soils, the sodicity can be reduced through chemical amendments. In the case of saline-sodic soils, the sodicity levels have to be reduced first, adopting strategies for leaching the excess salts in a second step (see section about “Leaching and drainage of saline soils”). In the chemical reclamation of sodicity, Ca (calcium) is released by the chemicals amendments and is exchanged with the Na in the soil’s exchange complex, the soluble Na can then be leached from the soil profile. Chemical amendments also increase the soil salinity level, mitigating or even preventing soil crusting. The most widely used chemical amendments are **gypsum** and gypsum-like by products such as **phosphogypsum** (a by-product of the manufacture of phosphoric acid), **coalgypsum** (a by-product obtained from coal power plants), **lactogypsum** (a by-product from the manufacture of lactic acid and lactates), among others (Amezketa *et al.*, 2005). In general, these products are applied on the soil surface for soil crusting prevention or incorporated into the soil for sodic soil remediation. The doses depend on the soil and amendment characteristics. As general rule, the theoretical amount of gypsum required per hectare to replace 1 $cmol_c$ of exchangeable Na per kg of dry soil in a layer of 30 cm and with a mean soil bulk density of 1.3 $g{\cdot}cm^{-3}$, is 3.4 $t{\cdot}ha^{-1}$ (Weil and Bradley, 2017). Enough amount of water is also needed for gypsum dissolution. As a general rule, 1 m^3 of water is needed to dissolve 7 $t{\cdot}ha^{-1}$ of gypsum. Other amendments that can be useful in soils with calcite are acids or acid formers. Compounds such as **sulphur**, **sulphuric acid**, and **calcium polysulfide** dissolve the calcite releasing Ca. Other amendments such as calcium chloride and calcium nitrate, which are highly soluble, are possible, but they are usually more expensive solutions.

Most often, the high pH values of sodic soils are decreased by the sodicity remediation. As the soil becomes saturated with Ca, this cation precipitates with the carbonate and biocarbonate anions, lowering the soil’s pH. This process is enhanced by the biological activity in the soil (Weil and Brady, 2017).

Phyto and bioremediation of sodic and saline-sodic soils

Phytoremediation can be used for Na removal through a similar mechanism to that of chemical amelioration, by making Ca available to replace Na in the soil’s exchange complex. Other mechanisms, such as the bioaccumulation of salts in the aboveground biomass by halophytes have been shown to not be effective in reducing the soil salinity (Qadir et al. 2007). The mechanism of sodium removal by phytorremediation requires therefore a source of Ca, which typically is the calcite existing in soils. The role of the plants in this process is to increase the CO_2 in the root zone, which enhances the dissolution of calcite. The increase of CO_2 in the root zone can be further helped by the activity of bacteria. Phytorremediation can be used in cases of low to medium sodicity. Studies have shown that phytorremediation can have similar and improved results compared to chemical remediation, but it requires specific and more complex planning of the amelioration process (crop rotation, irrigation timings, etc). Phytoremediation can be a cheaper mitigation method for farmers. It is also more environmentally sustainable by avoiding the use of synthetic products and improving carbon sequestration. Studies have also shown that it can also improve the overall nutrient availability to plants as result of root exudates and calcite dissolution. An exceptional advantage is that Na removal occurs more uniformly and in-depth when compared to chemical remediation, as it occurs along the root depth, for instance, alfafa roots can reach 1.2 m deep (Qadir et al., 2007).

Leaching and drainage of saline soils

Besides its use as a preventive strategy, the leaching of soluble salts is necessary to remediate saline soils. This is also the second part in the reclamation of saline-sodic soils, after the Na is solubilised in the soil solution either through chemical or bioremediation. This process is usually accompanied by the leaching of nutrients such as nitrates, therefore measures to restore soil fertility may be necessary. The monitoring and control of the irrigation effluent is also necessary to minimize harmful effects to downstream users and habitats. While in the arid regions leaching requires the use of irrigation, in the semi-arid regions rain usually provides leaching of the soil. Ensure a correct drainage can also be a determinant mitigation strategy. See details about the leaching requirements and drainage in section about “leaching requirements”.

Soil management practices

Incorporation of organic matter

Maintaining good infiltration levels and permeability helps the remediation processes. This can be done by incorporation of organic matter into the soil, by leaving harvest residues on the surface, by maximizing soil surface cover/mulching and by adopting minimum tillage approaches. It is well-known in fact that the maintenance of increase of organic matter into the soil plays a direct role in the capacity of soil to hold water, and indirectly contribute to favouring infiltration and circulation of water within the soil (BIO Intelligence Service, 2014).

Physical operations

Subsoiling (deep plowing and deep ripping) can be useful to improve remediation of subsurface sodic layers. This operation has to be well-planned in order to prevent creating other problems such as water saturation in the rhizosphere during the crop growth. Mixing sand with heavy textured soil, although an expensive practice, could improve soil physical properties in order to increase drainage capacity and infiltration rate. This leads to an enhanced soil reclamation process and results in improved leaching of salts. This has to be carefully planned to prevent a negative impact over soil structure and fertility of the soil. Physical removal of the surface salt crust can be suitable for small areas. The salts which appear at the soil surface through capillary rise and subsequent evaporation, can be removed manually or mechanically, although this is an economically ineffective way to remove salt and it could have short temporary effect.

2.3. Adaptation

In this section we consider strategies that are not directly targeted at reducing the salinisation problems, but that are aimed at adapting to the existing problems.

Agronomical practices

Plant selection

Some crops have high tolerance to salinity levels, with a productivity reduction of only 10% at EC_e above 8 $dS \cdot m^{-1}$ or higher. Such is the case of olive, rapeseed, among others (Weil and Bradley, 2017). New varieties are being developed that are able to successfully cope with high salinity values. Also the plantation of halophytes is becoming an agronomical niche in some very high salinity areas. The Minipaper *Examples of salt tolerant crops as an alternative for farmers* presents a summary of crops and varieties that can be used as adaptation to saline soils.

Crop rotation

The choice of a suitable crop rotation can be an adaptation measure to soil salinisation. In the rotation, the less tolerant species can be used during the rainy season, while more tolerant crops can be grown during the dry period. There would be a set-aside period in the beginning of the rainy season, when the rain washes the salts and brings salinity to levels tolerable by the crops. Additionally, in more severe cases, irrigation could be

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used on alternate years. The cycling strategies presented in the prevention section about irrigation with saline waters, can also be used as adaptation strategies. Examples of this strategy where tested under the OTIRIS and IN.TE.R.R.A projects in southern Italian regions. In these projects, rotations of spring-summer crops irrigated with saline waters and winter crops were tested. The results show that in dry winters the rain might not always be sufficient to wash the salts added during the irrigation season. Therefore, the salinity of the soil in the root zone must be periodically monitored in order to avoid further salinisation.

Nutrient management

Root zone salinity reduces the absorption of water by roots due to the high osmotic pressure in the soil solution, decreasing the plant growth and development due to adverse effects on physiological processes such as photosynthesis. Foliar applied **salicylic acid** has been shown to enhanced vegetative growth of several crops under salinity stress. This may be due to the protective role of salicylic acid on membranes that might be responsible for increasing plant salt tolerance (Saraf et al., 2018).

Microbial management

Naturally salt-affected soils show a potential in their microbial communities, which represents a source of beneficial microorganisms and a gene reserve for future biotechnological applications. From the genetic point of view, these species display an under- or over-expression of peculiar genes and metabolites, which confer them the capability of coping with osmotic stress. Different kinds of *saline-related* microorganisms, belonging to several taxa of bacteria (*Baciullus*, *halobacillus*, cyanobacterial filaments), archaea and fungi, can be utilized for the formulation of bio-inocula to promote and enhance the salt tolerance in plants. They can be used also in reclamation or prevention of soils with salinisation problems. Several studies suggested the beneficial effects and the success of the microbial amelioration of salt stress, which included the inoculation with specific bacteria strains of the crop seeds, the soil, and farmyard manure applied to soil (Kayasth et al. 2014, Bhambure et al 2017, Sharma et al 2017, Numan et al. 2015, Naz et al. 2007, Arora et al, 2016).

Synthetic conditioners for maintaining the soil structure

Compounds such as polyacrylamides (PAM) and polysaccharides act as cementing agents binding soil particles and increasing soil structural stability, due to their large size, which allows them to be adsorbed simultaneously by several soil particles (Barvenik, 1994; Chenu, 1993). They require low doses, for example, in furrow and sprinkler irrigation, about 10-20 $kg \cdot ha^{-1}$ of PAM is enough to reduce soil crusting and erosion. There are several commercial brands in the market, although in general, the economic cost makes them only attractive in the case of very high added value crops.

Land-use changes

The successful of the previously presented adaptation strategies depends on several factors, and in some cases they may not be able to counter the problem. As an alternative, the adaptation to local salinisation problems can be to consider a change in the land-use. This can offer opportunities to implement soil ecosystem services beyond food production because, in fact, soil plays a crucial role in ecosystem functioning, providing and regulating environmental, health, climate, and cultural services. In this manner, it is crucial to evaluate the best use for a given soil. Such analysis is often based on georeferenced soil survey and field work observations integrated in a GIS system, which allows identifying the main limiting factors for the agricultural production and enables decision makers to develop an environmentally-sound range of strategies. Alternative soil uses can consist on the conversion of agricultural areas to recreation and ecotourism, cultural heritage, biodiversity and landscape protection. An example of such measure is the natural park “Salto di Fondi”, created in 2008 in the Lazio region in Italy, in an area which had initially been recovered for agricultural purposes in 1930. Another example is the “Soto de Los Tetones” (Navarre, Spain), a riparian area that exhibited strong soil salinization problems under improper irrigated agricultural management, and few years ago underwent a conversion to be “Enclave Natural” (“Natural Enclave”), a legal form of environmental protection in Navarre (Amezketa and del Valle de Lersundi, 2008).

3. Innovative and sustainable strategies

In this section we present and discuss the strategies with higher innovation potential for tackling soil salinization.

Strategy type	Specific strategy	Potential innovation	Limitations/ challenges	Advantages/ Opportunities	Knowledge gaps/Needs from practice
Prevention	Irrigation practices including leaching requirements	Development of adequate water quality guidelines and leaching requirements for specific pedoclimatic regions; Development of guidelines for successful use of more saline waters	Specific to pedoclimatic regions, crops used and quality of the available water	Potential for use of saline waters; Preservation of soil ecosystem services	More case studies in EU pedoclimatic regions.
Mitigation of sodicity	Phyto and bioremediation	Guidelines and case studies of phytorremediation systems	Only possible in soils with a source of calcium (eg. calcite); Only possible in low to medium sodicity.	No residues left in the soil; More uniform and in-depth reclamation could be possible; Improvement of soil health and ecosystem services compared to chemical reclamation.	Case studies to understand specific relations between the remediation practices for each pedoclimate and plants used.
Adaptation	Salt-tolerant varieties and halophytes	Introduction of varieties that are more tolerant; introduction of new commercial halophyte crops	Sets limits to the crops to be produced; Halophytes might now have a viable market.	Potential for cultivation in saline soils; New markets to be developed.	More case studies; See minipaper “Examples of salt tolerant crops as an alternative for farmers”
Mitigation/ Adaptation	Soil management and agronomic practices (organic matter; crop rotations; nutrient management)	Guidelines for practices that favour plant tolerance to salinity	Can be successful in low to medium salinity;	Potential to improve soil health and soil ecosystem services.	More practical case studies with combinations of practices in different pedoclimatic regions.
Adaptation	Microbial management	Introduction of microbes that are beneficial for soils and plant tolerance	Specific to each soil-plant system	Potential for low environmental impact and improvement of soil health	More knowledge of the *in situ* role of soil biodiversity on plants tolerance; More practical case studies on the environmental impact caused by use of ne microorganisms.

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4. Ideas for innovative projects/Operational Groups

Operational groups are practical projects intended to gather different actors in the solution of a specific question, to advance innovation in the area. In the next table are gathered some ideas for innovative projects/operational groups from the previous identified innovative strategies.

TITLE	DESCRIPTION	STAKEHOLDERS	EXPECTED RESULTS/IMPACT
Mapping of soil salinity and relationship with irrigation and farming practices performed by farmers	Surveillance of soil salinity at pre-irrigation and after irrigation and explain the changes with the field management performed by farmers, weather characteristics, etc. (*Note: this idea can be extrapolated to other areas with pre-irrigation salinity maps, or post-irrigation salinity maps at two different moments, etc.*)	Researchers, agronomists, farmers, irrigation districts, Department of Agriculture/Soils, among others	Irrigation/farming practices responsible for successful and failure cases; identification of best practices for farmers; improve salinity management; establishment of surveillance programs of soil salinity in irrigated agriculture.
Leaching requirements for salinity prevention	Test leaching schemes in different EU pedoclimatic regions	Researchers, farmers, advisory companies	Successful schemes for different pedoclimatic regions.
Phytorremediation of sodic soils	Test different crops, eventually including microbial inoculation for enhanced respiration rate and different leaching schemes for sodium removal in different pedoclimatic regions.	Researchers, farmers, advisory companies	Successful schemes for phytorremediation in different pedoclimatic regions.
Microbial use for plant tolerance in salt-affected soils	*In situ* test microbia already known to be helpful in improving plant tolerance to salinity	Researchers, farmers, phytosanity companies	Microbial products that could be used to improve plants tolerance to salinization.

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