Proceedings

Salt-affected soils at the farm scale: successful experiences and innovation needs†

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Abstract: Climate change, land use and management malpractices are increasing the areas of salt-affected soils, threatening soil health and economical sustainability of farms. The causes and processes are manifold and variable in space and time. There is the need to continuously update strategies to tackle salt-affected soils, finding solutions tailored at different scales. The aim of this article is to present a selection of case studies with high innovation potential and covering a range of farming systems and approaches. These include cases studies within irrigation scheduling, chemical and phytoremediation of sodic soils, agronomical and microbial management, and land-use changes. The reviewed cases cannot constitute a complete overview of techniques to counter salinisation, but they show the successful application of innovative practices and delineate further research and innovation projects to counter salt-affected soils.

Keywords: soil salinisation; salinity; sodicity; farm-scale; irrigation; chemical remediation; phytoremediation; management; land-use changes

1. Introduction

Salt-affected soils are mainly characterized by an excess of soluble salts, in which case they are classified as saline, by an excess of sodium ions, sodic soils, or a combination of these conditions (saline-sodic soils). Salinisation of agricultural soils is mainly caused by evapotranspiration rates higher than precipitation rates and soil characteristics that impede water drainage and cause salt accumulation in the upper layers. The accumulation of salt can affect soils in coastal areas, because of seawater intrusion, as well as internal and continental lands, especially on salt-rich parent materials where saline layers can occur in the soil profile, also because of man-made earthworks. Besides the lands which are naturally affected by salinisation (primary salinisation), there are many more where soil salinisation is due to human activities (secondary salinisation). The adoption of improper agricultural practices, especially irrigation with poor quality water, overpumping and consequent drawing of saltwater have induced or exacerbated soil salinisation, and their frequency appears to be increasing [1]. The rise of the mean temperatures observed in the last decades and the consequent increase in evapotranspiration have also boosted the risk of soil salinisation in many parts of the world. The projections for future climatic conditions and their consequences on soils are alarming. Thus, soil salinisation is expected to further increase in the future as a consequence of the current climate, land use and management changes [2].

As a whole, soil salinity has a significant negative effect on food production and several other soil ecosystem services: provision of freshwater for livestock, wild animals and plants, regulation of groundwater quantity and quality, soil water and wind erosion, supporting habitats and also on recreational areas and the aesthetic value of the landscape [1]. Soil salinity has a marked effect on farmers' income, reducing yields and rising costs of agricultural management. For this reason, affected lands have been included by the EU in the delineation of the agricultural areas with natural handicaps (Reg. EC 1698/05).

In the framework of a Focus Group of the European Innovation Partnership on Agriculture (EIP-AGRI), we reviewed different case studies at the farm-level, in order to be able to identify strategies and define a framework to deal with soil salinisation in Europe. In this work we report a selection of innovations that successfully countered soil salinisation. The case studies show good agricultural practices related to irrigation scheduling, chemical and phytoremediation, crop selection and crop rotation, microbial management, and land-use changes.

2. Case studies at the farm level

2.1. Irrigation scheduling

Even low salinity water will add salts to the soil which may accumulate over time, especially in arid climates. As a result, adequate irrigation and drainage management is determinant to prevent salt unbalances in the soil at the farm scale. The irrigation scheduling should be able to fulfill crop water requirements and to promote salt leaching from the root zone, but can face further demands such as to control the ground water level or to deal with limited water availability. The irrigation management is specific to each type of irrigation system, being the irrigation frequency its most flexible variable. In the case of surface irrigation, Pereira *et al.* [3] used simulation models for improving irrigation scheduling, showing how larger volumes of water and less irrigation events helped to prevent salinization arising from rise of water tables, while meeting the crop water requirements and leaching from the root zone, as well as providing water savings. The adjustment of the applied water volume is of major importance, as water availability is often limited, and the use of excess irrigation can cause leaching of nutrients and soluble organic compounds, especially in soils with low bulk density and low water holding capacity, such as in Arenosols, which can potentially accelerate the soil's degradation processes [4]. In the case of drip irrigation, Dudley *et al.* [5] showed a careful adaptation of the system to local soil and plant conditions. They adopted small volumes and more frequent irrigation events, in order to both ensure maximum leaching in the root zone while reducing salt load in drainage water, as salts were stored in upper soil layers, but beyond the root's zone of active uptake. However, irrigation scheduling to prevent salt unbalances is complex and highly dependent of the specific pedo-climatic, crop, and farm conditions. Some counteracting processes can be identified: on one hand, frequent irrigation events help ensure matric and osmotic potentials are optimal for the crop, but promote the concentration of roots in the shallower soil layers, can increase evaporation losses from soil surface, and the salt load to the soil, due to the larger overall applied volume. On the other hand, larger irrigation intervals promote root growth and water use from larger soil volume, but can enhance salt transport from deeper layers or from saline groundwater. According to Minhas *et al.* [6], this issue demands further experimentation, but modeling can provide indicative solutions, combining adequate water volume and irrigation frequency to obtain optimal results.

2.2. Chemical amendments

Soil sodicity can be reduced by using chemical amendments. In the case of saline-sodic soils, the sodicity levels have to be firstly reduced, followed by the leaching of the soluble salts in a second step. The remediation process involves the release of calcium (Ca) by the chemical amendments, which is exchanged with the sodium (Na) in the soil's exchange complex. Once in the soil solution, Na can then be leached from the soil profile. 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. The most widely used chemical amendments are gypsum and gypsum-like by-products. Other amendments such as calcium chloride and calcium nitrate, which are highly soluble, are possible, but they are usually more expensive solutions. Chemical amendments also increase the soil salinity level, mitigating or even preventing soil crusting. Amezketa et al. **[7]** tested four amendments in crusting prevention of two calcareous soils (non-sodic and sodic) and remediation of a sodic soil. The four chemical amendments: mined-gypsum, coalgypsum (a by-product obtained from coal power plants), lactogypsum (a by-product from the manufacture of lactic acid and lactates), and sulfuric acid, were effective in crusting prevention and sodic remediation, but sulfuric acid was the most efficient, leading to quicker reduction of soluble salts and Na in the soil leachates. The three gypsum-materials were equally effective in the sodic remediation process and in the crusting-prevention of the non-sodic soil, whereas lacto-gypsum was less efficient in the crusting-prevention of the sodic soils.

2.3. Phytoremediation of sodic and saline-sodic soils

Phytoremediation can be used for Na removal through a similar mechanism to that of chemical remediation, i.e. 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 be not so effective in reducing soil salinity **[8]**. The mechanism of Na removal by phytoremediation 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, as shown in Figure 1. The increase of CO_2 in the root zone can be further helped by the activity of bacteria. Phytoremediation can be used in cases of low to medium sodicity and it can constitute a cheaper and more sustainable method than chemical remediation, because of avoiding the use of synthetic products and improving carbon sequestration in the soil. Qadir et al. **[8]** reviewed seventeen phytoremediation studies and showed that it can have similar or improved results compared to chemical remediation, but it requires specific and more complex planning of the amelioration process (crop rotation, irrigation timings, etc). The review also showed an improvement of the overall nutrient availability, as a result of root exudates and calcite dissolution. An advantage is that Na removal occurs more uniformly and in-depth when compared to chemical remediation, as it occurs along with the root depth, for instance, alfalfa roots can reach 1.2 m deep.

2.4. Plant selection and crop rotation

Some crops and varities have a moderate or high tolerance to salinity levels, with a productivity reduction of only 10% at ECe above 4 $dS{\cdot}m^{-1}$ or higher **[9]**. New varieties are being developed that can successfully cope with high salinity values. In addition, the plantation of halophytes is becoming an agronomical niche in some very high salinity areas. Grafting can also constitute an approach to grow less tolerant crops in soils susceptible to salinization. Gioia et al. **[10]** showed that grafting of a salt-sensitive tomato variety into a more resistant tomato rootstocks can improve the salinity tolerance of the salt-sensitive cultivar and maintain its organoleptic properties. Vine rootstock have also been produced to cope with salinity and drought **[11]**.

Adapted crop rotation can be an efficient measure to counter the soil salinization effects. Gabriel et al. **[12]** incorporated cover crops into a cropping system, so to prevent or reverse salinization. The authors showed that the inclusion of barley (Hordeum vulgare L.) and vetch (Vicia villosa Roth) in a cropping system with irrigated maize in a

Mediterranean area is able to maintain or reduce the salinity of the topsoil, as well as to decrease the nitrate leaching, compared to the option of a having a fallow period. A different approach in the case of rainfed cropping systems is the use of the less tolerant species during the rainy season, while more tolerant crops can be grown during the dry period. There would be a set-aside period at the beginning of the rainy season, when the rain washes the salts and brings salinity to levels tolerable by the crops.

2.5. 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 [13]. Different kinds of saline-related microorganisms, belonging to several taxa of bacteria, archaea and fungi, can be utilized for the formulation of bioinoculants to promote and enhance the salt tolerance in plants [14]. 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 [15–17]. However, the selection of microorganisms promoting plant resistance under stressful salinity conditions still needs further research in order to be applied as beneficial bioinoculants for crops [18].

2.6. Land-use changes

The success of the previously presented adaptation strategies depends on several factors, and in some cases, they may not be able to counter the problem. As an alternative, 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, such as providing and regulating environmental, health, climate, and cultural services. For a land use change, it is crucial to evaluate the best use for a given soil. Innovative methods include georeferenced soil survey and field work observations integrated in a GIS system, which allows identifying the main limiting factors for the agricultural production and enable decision makers to develop an environmentally-sound range of strategies. A recent example of successful application of this approach was made in a coastal area of about 3,500 ha in Italy, for determination of land suitability and degradation susceptibility [19].

In cases that agricultural uses can lead to severe soil degradation, alternative soil uses can be a solution, as for example converting them into recreation and ecotourism areas, cultural heritage, or natural protection areas. An example of such alternative measure is the “Soto de Los Tetones” (Navarre, Spain), a riparian area that exhibited strong soil salinization problems under improper irrigated agricultural management and underwent a conversion to a natural protection area [20].

3. Conclusions

The reviewed case studies constitute a set of very different approaches that can be taken to deal with salt-affected soils at the farm level. Although the studies present successful approaches, they also help to identify knowledge gaps and innovation needs. Such is the case of nutrient and microbial management for improving the crop’s tolerance to saline soils, which shows high potential but demands further research and experience in order to be more widely implemented. The presented case studies will also set the bases for identifying strategies to deal with salt-affected soils in Europe, according to the types of production system and the level of exposure to salt unbalance.

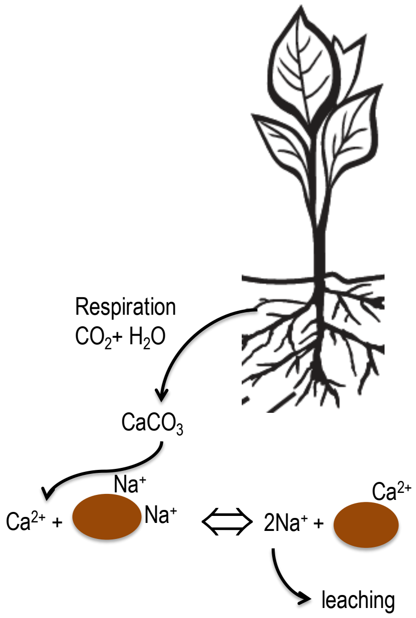

Figure 1. Mechanism of phytoremediation of sodic soils: plant (and microbial) respiration enhance Table 3. making Ca available for replacing the Na in the soil's exchange complex. Once in the soil solution, Na can then be leached from the soil profile.

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