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Management and reclamation of salt-affected soils: general assessment and experiences in the Brazilian semiarid region[1]

Manejo e recuperação de solos afetados por sais: avaliação geral e experiências no semiárido brasileiro

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ABSTRACT - Salt-affected soils occupy extensive areas in arid and semi-arid regions around the world, and impact food production, particularly when salinization processes occur in irrigated areas. In this context, the possibility of using techniques for the reclamation of these soils needs to be considered. However, many of these techniques are inaccessible to most farmers in the Brazilian semi-arid region, given the high costs, mainly when it is necessary to install a subsurface drainage system. Thus, there is a need to evaluate other soil reclamation strategies as well as the possibility of using these areas for other purposes. This review covers topics related to the characterization and impacts of salt-affected soils, the influence of soil microorganisms, and strategies for soil reclamation, such as the use of chemical and organic conditioners, bio-drainage, phytoremediation, and revegetation with tolerant species. The topics addressed in this review indicate new possibilities for the reclamation and management of salt-affected soils in the Brazilian semi-arid region. A case study is also presented, which demonstrates that the use of salt-affected soils is defined by technical, social, and economic aspects.

Key words: Salinity. Sodicity. Soil reclamation. Revegetation. Microbiota.

RESUMO - Os solos afetados por sais ocupam extensas áreas em regiões áridas e semiáridas do mundo, e impactam a produção de alimentos, notadamente quando os processos de salinização ocorrem em áreas irrigadas. Nesse contexto, a possibilidade de uso de técnicas para recuperação desses solos precisa ser considerada. Entretanto, muitas dessas técnicas são inacessíveis para a maioria dos agricultores do semiárido brasileiro, face aos elevados custos, especialmente quando é necessária a instalação de sistema de drenagem subsuperficial. Há, portanto, necessidade de se avaliar outras estratégias de recuperação do solo, bem como a possibilidade de aproveitamento dessas áreas para outros propósitos. Nesta revisão são abordados tópicos relacionados à caracterização e impactos dos solos afetados por sais, a influência dos microrganismos do solo e as estratégias de recuperação, tais como o uso de condicionadores químicos e orgânicos, biodrenagem, fitorremediação e revegetação com espécies tolerantes. Os temas abordados nesta revisão indicam novas possibilidades para a recuperação e manejo dos solos afetados por sais no semiárido brasileiro. Também é apresentado um estudo de caso, que demonstra que o aproveitamento dos solos afetados por sais é definido por aspectos técnicos, sociais e econômicos.

Palavras-chave: Salinidade. Sodicidade. Recuperação do solo. Revegetação. Microbiota.

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INTRODUCTION

Salt-affected soils are formed by natural processes or anthropic actions, which result in salinization, that is, an increase in the concentration of soluble salts (mainly chlorides, sulfates, bicarbonates, sodium, calcium, and magnesium), and in solonization, that is, increase in exchangeable sodium contents (RIBEIRO; RIBEIRO FILHO; JACOMINE, 2016). These soils occupy about 1.0 billion hectares in coastal and continental areas around the world, mainly in arid and semiarid regions of countries in Asia, Oceania (SHARMA; SINGH, 2015; WICKE *et al*., 2011), Europe, North America, and South America (BELTRÁN, 2016; TALEISNIK; LAVADO, 2021). In Brazil, salt-affected soils occupy about 16 Mha, with approximately 70% located in the semiarid region (FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS, 2021; RIBEIRO; RIBEIRO FILHO; JACOMINE, 2016).

The existence of extensive areas of salt-affected soils, including in cultivated areas, creates a challenge for society, as it threatens the sustainability of irrigated agriculture (HOPMANS *et al*., 2021). This concern is even greater when it is known that the natural vegetation, which was in equilibrium with the regional water balance, has been removed and replaced with crops without proper irrigation management and the installation of a drainage system. It is not recommended to continue with the notion of the beginning of the last century, that is, to clear a new area and abandon the one that has been degraded, since the expansion of agricultural borders is faced with environmental issues, which are addressed in various national and international forums. In this context, the possibility of soil restoration and the potential for utilization of these salinized areas need to be considered.

The reclamation of salt-affected soils has been a major challenge for science and the agricultural sector (GOMES; GHEYI; SILVA, 2000; SHARMA; SINGH, 2015). Studies show the high costs of this reclamation process (ARAÚJO *et al*., 2011; COSTA *et al*., 2005a; SOUSA *et al*., 2014), notably when it is necessary to install an underground drainage system, becoming inaccessible to smallholder farmers (COSTA *et al*., 2005a). In view of these difficulties, new strategies for reclamation and utilization of these areas should be envisioned. However, under some situations, soils can be considered economically unreclaimable for the practice of agriculture (BEZERRA, 2006; WICKE *et al*., 2011), especially those affected by excess exchangeable sodium.

The present review study seeks to characterize salt-affected soils and the direct and indirect impacts on plant development and soil microbiota. Reclamation strategies using chemical and organic conditioners, bio-drainage, soil phytoremediation, beneficial effects of microorganisms, and revegetation of salinized areas with halotolerant and/or halophilic native species are also addressed, with emphasis on the edaphoclimatic conditions of the Brazilian semiarid region. Finally, a case study referring to the Morada Nova Irrigated Perimeter is presented, in which the complexity of utilizing these areas for production purposes, which depends on technical, social, and economic aspects, is demonstrated.

CHARACTERIZATION AND IMPACTS OF SALT-AFFECTED SOILS

Salt-affected soils can be chemically characterized by the determination of the electrical conductivity of the soil saturation extract (EC_{se}), exchangeable sodium percentage (ESP), or the sodium adsorption ratio in the saturation extract (SAR_{se}). In addition, the pH value of saturated paste is also considered, especially to indicate the alkaline or even acidic character of these soils. Using these variables, salt-affected soils can be grouped into four (RICHARDS, 1954) or up to 12 categories (RENGASAMY, 2016). On the other hand, for the more complex systems of soil classification, salinity and sodicity attributes are classified into different hierarchical levels, as can be seen in the Brazilian Soil Classification System (SANTOS *et al*., 2018) and in the WRB-World Reference Base for Soil Resources system (FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS, 2015).

The current Brazilian Soil Classification System (SANTOS *et al*., 2018) presents the separation between saline ($4.0 < EC_{se} < 7.0$ dS m^{-1}) and salic ($EC_{se} > 7.0$ dS m^{-1}), and between solodic ($6 < ESP < 15\%$) and sodic ($ESP > 15\%$). However, the classification most used in Brazil derives from that proposed by Richards (1954), which separates salt-affected soils into four categories: Normal ($EC_{se} < 4.0$ dS m^{-1}; ESP < 15% and pH < 8.5); Saline ($EC_{se} > 4.0$ dS m^{-1}; ESP < 15% and pH < 8.5); Saline-sodic ($EC_{se} > 4.0$ dS m^{-1}; ESP > 15% and pH < 8.5); and Sodic ($EC_{se} < 4.0$ dS m^{-1}; ESP > 15% and pH > 8.5). In addition, a category of degraded sodic soil ($EC_{se} < 4.0$ dS m^{-1}; ESP > 15% and pH < 8.5, which may reach 5.5) was also suggested by De Sigmond (1938), which is formed by the solodization process described by Ribeiro, Ribeiro Filho and Jacomine (2016). From the agricultural point of view, however, the salinity limit of 2.0 dS m^{-1} may be more appropriate, since many crops, such as vegetables and fruit trees, are affected between EC_{se} values ranging from 2.0 to 4.0 dS m^{-1} (FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS, 2021; SOIL SCIENCE SOCIETY OF AMERICA, 1976).

The impacts of salt-affected soils on plants can occur directly or indirectly. Salinity, a term associated with excess soluble salts in the soil, directly impacts plant growth and soil microbiota, through osmotic and ionic effects (RENGASAMY, 2016; TAIZ *et al*., 2017). Sodicity, a term associated with excess exchangeable sodium, impacts soil structure and the movement of water in the soil profile. Thus, the effects of sodicity are more indirect (RENGASAMY, 2016), either hindering the growth of roots and/or the aerobic respiration of root cells and microorganisms.

The natural occurrence of salinity in the soil is very common in coastal regions, notably in tidally flooded areas. These areas are also subject to intermittent water excess (SANTOS *et al*., 2020), so in mangrove areas, the vegetation is limited to species that simultaneously have mechanisms of adaptation to salt stress and low oxygen concentration in the soil. For example, the mechanism of ultra-filtration of salts in the membranes of root cortex cells is characteristic of some mangrove species, which reduces the salt concentration in xylem sap and the excessive accumulation of salts in the shoot (PARIDA; JHA, 2010). However, the existence of pneumatophores, roots with negative geotropism, represents a mechanism of adaptation of these plants to coexist with excess water, not salinity (KITAYA *et al*., 2002).

In salinized coastal areas, there is a predominance of sodium ions, originating from seawater, but not necessarily severe problems of sodicity, since the sand fraction prevails in the particle-size composition of soil and most of this cation is in soluble form. However, one cannot rule out increase in soil sodicity problems in coastal areas in the future, considering the possibility of marine intrusion or rising sea level caused by global climate change, or due to tsunamis, which occasionally flood large areas of the continent (HULUGALLE *et al*., 2009).

Excess water is also a problem for plant growth in many continental areas with natural sodicity problems. This occurs mainly in lowlands during the rainy season when these soils remain flooded for a few months. A classic example of this problem is represented by the extensive areas of *Planossolos* (Alfisols), in northeastern Brazil, occupied by carnauba palm trees (*Copernicia prunifera* L.), which were able to establish in these soils and have mechanisms of adaptation to anoxia or hypoxia. It is also possible that these plants keep air pockets around the roots, which remain even after the soil is flooded and meet for some time the respiratory demand, most likely maintained at lower rates than usual.

The formation of salt-affected soils in cultivated areas is defined as secondary salinization (BELTRÁN, 2016; RIBEIRO; RIBEIRO FILHO; JACOMINE, 2016; SHARMA; SINGH, 2015) because it is associated with anthropic activities. This is also true for the salinization process in protected cultivation, where the natural role of seasonal rainfall in the leaching of salts is excluded. However, for most cultivated areas, the risks of salinization, either low or high, are already naturally established according to climatic conditions, terrain location, relief, and soil characteristics.

Indeed, soil salinization problems in irrigated areas in the Brazilian semiarid region occurred in lowlands and where at least part of the area had natural drainage problems (ALBUQUERQUE *et al*., 2018). For example, for the installation of the Morada Nova Irrigated Perimeter (Ceará, Brazil), at the end of the 1960s, vast areas occupied by carnauba palm trees were deforested (SOUSA, 2010), a species that indicates the existence of soils with low natural drainability and, possibly, with natural problems of sodicity. Obviously, this does not exclude the responsibility of man in the salinization of extensive agricultural areas (ALBUQUERQUE *et al*., 2018; BEZERRA, 2006;), since there is evidence that this process occurred due to inadequate irrigation management and lack of conservation and/or maintenance of the drainage system. This also does not exclude the need to adopt adequate irrigation management in other cultivated areas that are currently less subjected to the soil salinization process, such as those observed in areas of tablelands and plateaus of the Brazilian semiarid region.

USE OF CHEMICAL AND ORGANIC CONDITIONERS

The reclamation of salt-affected soils consists of reducing their EC_{se} and/or the ESP, to a level that enhances the growth and development of crops, by adding corrective/conditioner and/or leaching (ARAÚJO *et al*., 2011; D'ODORICO *et al*., 2013; RICHARDS, 1954). Conditioners are grouped as chemical or organic and have characteristics that contribute to the reduction of sodium adsorbed on the exchange complex (that is, reduction of soil sodicity). In the case of saline soils, reclamation is possible only with the leaching of excess soluble salts. However, conditioners are important for all categories of salt-affected soils, because they promote improvements in the soil's physical, chemical, and biological attributes.

Richards (1954) points out that the suitability of correctives is based on the presence or absence of alkaline earth carbonates and soil pH. Based on these criteria, soils can be divided into three groups: I. soils containing alkaline earth carbonates and with pH greater than 7.5; II. soils virtually free of alkaline earth carbonates and with pH greater than 7.5; and III. soils virtually free of alkaline earth carbonates and with a pH lower than 7.5.

Among the chemical correctives used in the reclamation of soils affected by excess exchangeable sodium, the following stand out: a) calcium soluble salts (gypsum and calcium chloride), suitable for soils of any of the three groups mentioned above. Gypsum, although less efficient than calcium chloride, is the most used due to the simplicity of handling, market availability, and low acquisition cost (SOUSA *et al.*, 2014). However, due to its low solubility, on the order of 2.04 g L^{-1}, it is necessary to apply larger water depths, which justifies associating the use of gypsum with the cultivation of flooded rice during the reclamation processes (GOMES; GHEYI; SILVA, 2000), generating an alternative income for the farmer; b) acids or acid-forming agents (sulfuric acid, sulfur, ferrous sulfide, and iron and aluminum sulfate), suitable for soils of group II, which produce gypsum through chemical reactions with alkaline carbonates of the soil. The correctives mentioned in this group can also be used for soils of group I, but with due attention not to cause acidity in the soil (CAVALCANTE *et al.*, 2016). For soils of group III, when the soil pH is lower than 6.0, limestone can be recommended.

Stamford *et al*. (2007) and Silva Júnior *et al*. (2018) report that the use of *Acidithiobacillus* is efficient in combination with gypsum, especially because it promotes a decrease in soil pH, unlike when only gypsum is used. Stamford *et al*. (2007) report that sulfur inoculated with *Acidithiobacillus* applied with gypsum in the proportion of 50:50 on a mass basis promoted the best results in the reduction in the values of exchangeable sodium and electrical conductivity of the soil. Stamford *et al*. (2015) justify inoculation with *Acidithiobacillus*, because these species are relatively less abundant in agricultural soils, even with the presence of sulfur-oxidizing bacteria in soils.

The addition of organic materials (fresh or decomposed plant residues, manure, compost, and food processing residues, among others) in salt-affected soils has become a common practice in recent decades (LEOGRANDE; VITTI, 2018). The use of organic materials contributes to the improvement of soil fertility and reduces the exchangeable sodium percentage through the release of CO_2 and the formation of organic acids (MIRANDA *et al*., 2011; SANTOS *et al*., 2005). The utilization of plant residues, in addition to making the reclamation process sustainable, assists in the process of soil structuring, with a reduction of bulk density and consequent increase in porosity and hydraulic conductivity. There are several types of organic conditioners, such as cattle and sheep manure (MIRANDA *et al*., 2018, 2020), poultry manure (LEOGRANDE; VITTI, 2018), plant residues of coconut shell, rice husk alone or associated with gypsum (SANTOS *et al*., 2019) and industrial residues such as filter cake and vinasse (GOMES; GHEYI; SILVA, 2000; RUIZ *et al*., 1997). Miranda *et al*. (2018) observed that the use of sheep manure, gypsum, and anionic polymer based on polyacrylamide (PAM) increased the saturated soil hydraulic conductivity in the 0-10 cm layer from 4.51 to 16.37 cm day^{-1} (sheep manure), from 11.26 to 23.95 cm day^{-1} (gypsum) and from 7.24 to 22.77 cm day^{-1} (PAM).

A comparative study conducted by Gheyi *et al*. (1995) on the effect of applying chemical amendments (gypsum - 16 Mg ha^{-1}, sulfuric acid - 1.2 Mg ha^{-1}) and organic corrective (bovine manure - 30 Mg ha^{-1}) in saline-sodic soil (EC_{se} between 3.9 and 11 dS m^{-1}, ESP between 26.6 and 39.9%), in the Irrigated Perimeter of Sumé-PB, Brazil, revealed that in the short term (after leaching and rice cultivation) the chemical amendments were more efficient in terms of reducing the EC_{se} and ESP of the soil in the 0-0.30 m layer. However, in succession after 8 cuts of fodder crop (*Pennisetum purpurem*), all treatments, including the control, led to similar values of EC_{se} and ESP of the soil, up to depths of 0-0.60 m. It is worth noting that there was no effect of the treatments on the yield of four rice cultivars (on average 5.8 Mg ha^{-1}) and of the fodder crop after 5 cuttings (on average 30 Mg ha^{-1}).

More recently, it has been demonstrated that the use of biochar, obtained from different organic sources, applied alone or in association, results in the improvement of physical and chemical attributes of sodium-affected soils (SAIFULLAH *et al*., 2018; SANTOS *et al*., 2021; ZHANG *et al*., 2020). A study conducted in the Northeast region of Brazil showed that the biochars from sugarcane bagasse and corncob applied alone or in combination with gypsum, significantly reduced the EC_{se}, ESP, and SAR_{se}, due to the influence on pore-size distribution, water flow, and reduction of exchangeable sodium (SANTOS *et al*., 2021). Also according to this study, all treatments with biochar improved seed germination, reduced germination time and promoted the growth of maize plants.

Saifullah *et al*. (2018) presented an important literature review that analyzes and discusses recent studies investigating the role of biochar in improving the properties of salt-affected soils and plant growth. These authors pointed out important topics that should be considered when evaluating the use of biochar, such as residual effects of biochar with the continuous use of brackish water in irrigation; increased availability of nutrients; mechanism of sorption of Na salts by the biochar, and improvement in plant growth even maintaining Na in the soil; and testing and selecting raw materials with low Na content and high Ca content to obtain biochar.

The beneficial effects of using organic conditioners in salt-affected soils, especially on their physical, chemical, and biological attributes, are undeniable. However, some points must be considered before use, as highlighted by Leogrande and Vitti (2018): I. importance of choosing the appropriate strategy for the application of organic conditioners, such as origin of organic material and application rate and time; II. need for processing some organic residues before application, so that biological transformation and stabilization occur to reduce the risks of contamination.

Also according to Leogrande and Vitti (2018), the adoption of composting is efficient in this process, especially due to the phytotoxicity of animal manure and immature or non-stabilized composts, since a variety of chemicals such as heavy metals, phenolic compounds, ethylene and ammonia, excess of salts and organic acids may be released. This can slow seed germination, reduce plant growth, and affect microbial activity. Associated with these aspects, these authors highlight that it is of fundamental importance to pay attention to the use of organic conditioners in sandy soils, characterized by high permeability and low cation exchange capacity (CEC), where the salts and other organic compounds can be easily leached and, consequently, contaminate the subsoil and/or groundwater.

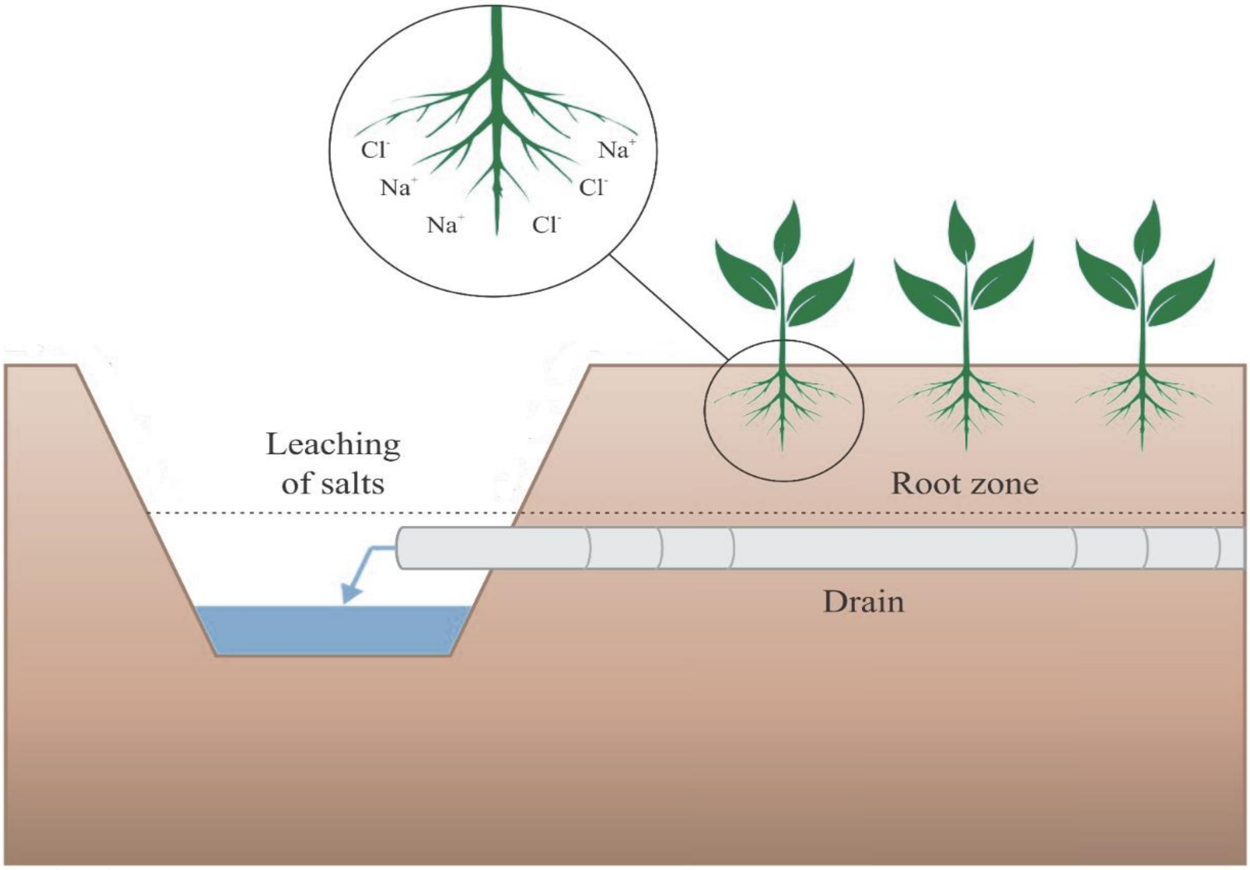
It is worth highlighting the importance of efficient drainage in the remediation process of saline and sodic soils since the effectiveness of reclamation depend essentially on the removal of salts from the system. The next topic will present several drainage strategies, with the theoretical foundation and applications.

DRAINAGE STRATEGIES FOR LEACHING SALTS FROM THE SOIL

The need to remove excess water for the development of crops has always been a concern, since the ancient civilizations, and many areas have been degraded by the accumulation of salts, caused by successive irrigations in excess for millennia (VALIPOUR *et al.*, 2020). Currently, several techniques are being used to remove the salts in agriculture, particularly agricultural drainage, leaching of salts and bio-drainage.

In view of the increase of salinity in irrigated areas, monitoring and diagnosis of areas with salt problems and agricultural drainage become paramount to the reclamation of saline and sodic soils. With the use of leaching depths, soluble salts are removed from the root zone of the plants to the drainage system (AYERS; WESTCOTT, 1999), which is artificially installed, below the root zone of the plants to control the groundwater table (SOUSA *et al*., 2011) and remove excess salts (Figure 1). Tiwari and Goel (2017), in studies on agricultural drainage in India and Pakistan, observed heterogeneity of criteria for deciding on the use of drainage systems, and the installation of drains for the development of the region is essential. However, when soil conditions are favorable, such as high values of saturated soil hydraulic conductivity (Ko) and the absence of impediment layers, natural drainage can reduce the concentration of salts from the root zone only with the precipitation events that occur during the year.

Figure 1 - Underground drainage system installed below the root zone of plants



Source: the authors

The effects of drainage in reducing salinity have been observed in several parts of the world. According to Bahçeci and Nacar (2009), in studies in southeastern Turkey, the use of drainage promoted an 80% reduction in salinity in the 0-20 cm layer of the soil. Davoodi, Darzi-Naftchali and Aghajani-Mazandarani (2019), in studies in northern Iran, observed the removal of up to 586 kg ha^{-1} of salts in subsurface drainage systems. A study conducted in the Curu-Pentecoste Irrigated Perimeter, Ceará, associating the installation of subsurface drainage with management practices (subsoiling and use of soil conditioners), demonstrated the reclamation of a saline-sodic soil, reduction of waterlogging problems, and the improvement in the growth of coconut trees (SOUSA *et al.*, 2011, 2014) (Figure 2). In this study, in the first two years, annual species (cowpea and sunflower) were cultivated between the coconut rows (intercropping) and showed good development after 9 months of starting the reclamation process (Figure 2).

Several factors should be considered in the design of an adequate drainage project, such as the climatic factors, which consider the project recharges and rainfall characteristics, the magnitude of the necessary surface runoff, and impediment layers in the soil profile (DUARTE *et al.*, 2015), among others. In irrigated areas of arid and semiarid regions, subsurface drainage has been essential to control soil salinity and minimize risks of crop yield losses, and for most cases, a discharge capacity of 2 to 4 mm day^{-1} is sufficient for leaching salts (FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS, 2007).

According to Duarte *et al*. (2015), the costs of a drainage project vary greatly depending on the drainage sizing required. In general, the costs of excavation of emitters, main drains, and collectors, installation of drains in the field, regularization of the terrain, management of the facilities, and maintenance, in addition to

Figure 2 - Evolution of coconut tree development during the reclamation process (1, 9, and 21 months after the installation of the subsurface drainage system and soil management practices) of a saline-sodic soil in the Curu-Pentecoste Irrigated Perimeter, Ceará

Source: Sousa *et al*. (2011, 2014)

the regularization of watercourses are considered. Therefore, the decision to execute a drainage project, in addition to the technical criterion of great relevance, must take into account the economic aspect, considering the benefit/cost ratio. The economic and financial benefits of agricultural drainage projects mainly refer to increments and opportunities in crop diversification and improvement of food security, compared to the condition without agricultural drainage projects (FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS, 2007). According to Duarte *et al*. (2002), the economic viability for the installation of drains at spacings that allow reaching satisfactory yields of the crops should consider physical attributes of the soil, such as hydraulic conductivity (Ko).

In the Brazilian semi-arid region and with perennial crops, however, the strategy of designing underground drains for non-permanent flow conditions has been used. In these cases, a project rain (recharge) can make the investment economically viable. This drainage criterion ensures greater drainage intensity, which results in high salt leaching capacity (COSTA *et al*., 2019).

Although the drainage strategy requires the installation of drains at greater depths in many situations, this is not always possible in practice due to limitations in the outlet height and the presence of physical impediments. Nevertheless, even with drains installed at a lower depth, it is possible to reduce problems related to the excess of salts, as verified in a subsurface drainage system installed at 0.80 m depth in a 4.0 ha area cultivated with grape in Jaguaruana - CE (SALES *et al*., 2004).

Although the factors mentioned are of great importance, the analysis of irrigation water quality cannot be forgotten or ignored, as it is a preponderant factor to allow the quantification of the accumulation and balance of salts and, consequently, calculation of the leaching depth necessary for the salt balance in the soil and their removal by the drainage system (BAHÇECI; NACAR, 2009).

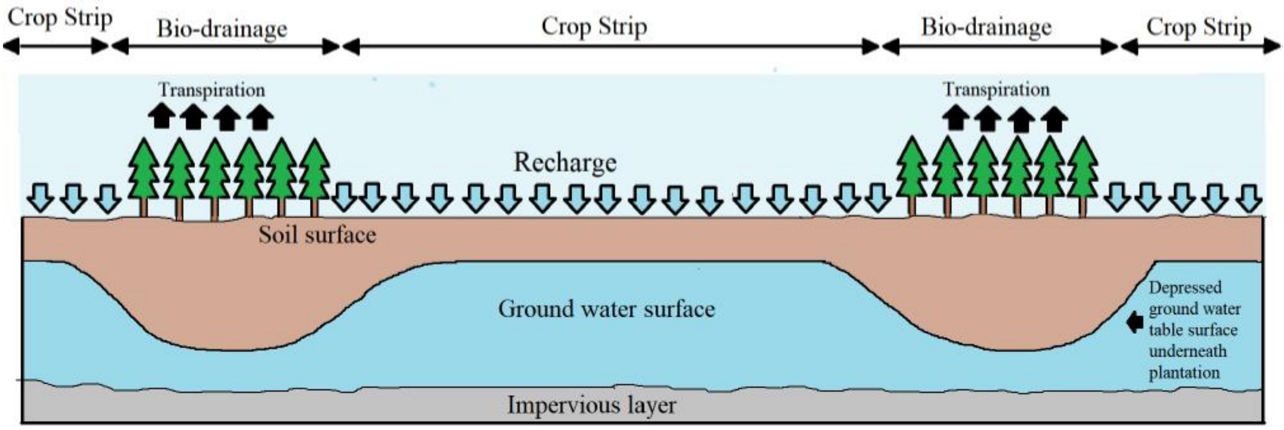
Also known as hydrotechnics, the process of applying water required for leaching the salts below the root system of plants can be classified into leaching methods (surface, continuous, and intermittent washing) and washing estimates (DUARTE *et al.*, 2015). All classifications consist of the removal of salts by means of leaching depths, either by empirical estimates or by practical processes. Silva *et al*. (2019) observed that the leaching process in irrigated areas is of vital importance for soil reclamation, while Resende *et al*. (2014) explained that the process of leaching the salts in irrigated perimeters located in the Brazilian semiarid region can be intense in the rainy season. Another alternative to assist in the subsequent leaching may be the addition of organic residues, considered as an auxiliary technique for the reclamation of saline and sodic soils, since the addition of organic matter increases the permeability of soils, thus facilitating the removal of salts through hydrotechnics (DUARTE *et al.*, 2015).

A strategy for controlling soil salinization would be through subsoiling and mole drains, which can promote improvement in internal drainage. This type of alternative has a lower fixed cost than the conventional drainage system but needs to be periodically implemented in the area (LARANJEIRA *et al.*, 2006). A study conducted in the Açu Valley - RN showed that subsoiling alone had a positive effect in reducing the exchangeable sodium percentage (ESP) and pH in a saline-sodic alluvial soil (HOLANDA *et al.*, 1998).

Another strategy used efficiently and with low cost to remove salts and lower the groundwater table is bio-drainage. According to Zhao *et al*. (2004) and Medeiros *et al.* (2016), this technique consists of using vegetation to dry soil profiles and lower the groundwater table to a depth tolerable by commercial crops (Figure 3). Among the crops used in bio-drainage, different eucalyptus species such as *Eucalyptus camaldulensis* and plants with high evapotranspiration such as *Tamarix troupii* and *Acacia nilotica* stand out (MEDEIROS *et al*., 2016). This technique has been shown to be effective in several regions of the world to reduce salinity in irrigated areas. However, Akram, Kashkouli and Pazira (2008), in studies on the use of bio-drainage in the control of salinity and groundwater, observed that the maximum salinity of water in the soil that can be controlled by bio-drainage under the cultivation conditions and soils studied was 3.0 dS m^{-1}.

According to Han *et al.* (2015), bio-drainage involves the cultivation of plants with a high rate of evapotranspiration and should be done along the drainage channels to reduce the possibility of groundwater elevation. For Magliano *et al.* (2009), in studies on the use of bio-drainage to control water excess in Argentina, plantations of some forest species such as *Pinus taeda* and *Eucalyptus viminalis*, in addition to reducing groundwater levels and soil salinity, represented a viable financial alternative in silvopastoral systems. In bio-drainage studies in Northwest China, Zhao *et al.* (2004) observed that the species *Lycium barbarum* and *Puccinellia chinamponsis* consumed large amounts of water and were not affected by soil salinity, increasing the extraction of salts according to their growth. Thus, both species are viable agricultural options for wood production and can also contribute to phytoremediation and revegetation processes, which will be discussed in the next topic.

Figure 3 - Representation of a bio-drainage system for groundwater control and removal of soil salts



Source: the authors

PHYTOREMEDIATION AND REVEGETATION OF DEGRADED AREAS

The most visible impact of soil degradation caused by the accumulation of salt is the loss of vegetation cover. When this happens, the process is already well advanced, compromising the development of cultivated plants and even spontaneous species adapted to the environment and tolerant to salts (DIAS *et al*., 2020). Then, there arises the need to use some techniques that promote improvement in plant survival conditions so that the areas degraded by salinity can be revegetated.

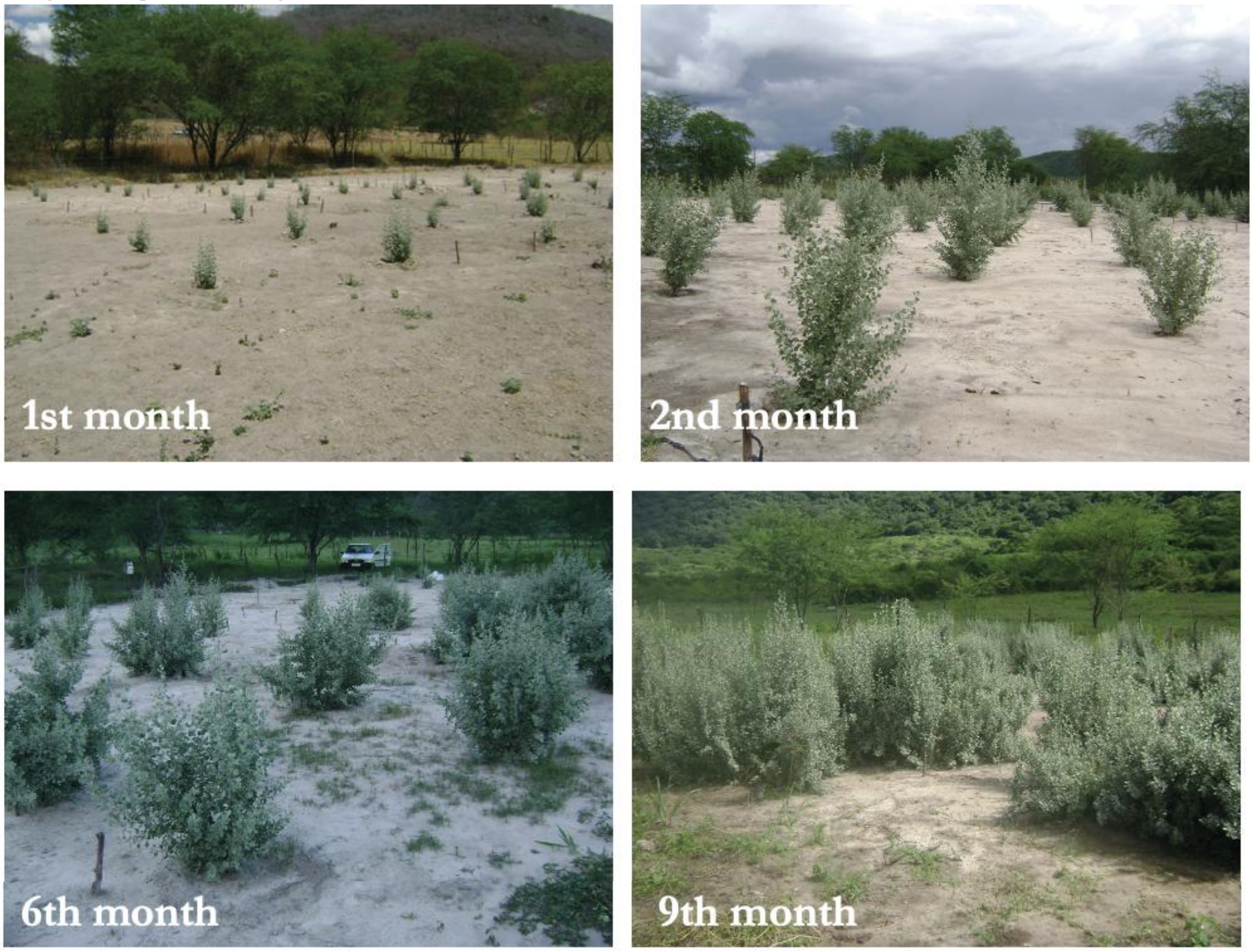
Initially, species adapted to the local climate and tolerant to salinity, including halophytes, which can establish in the area without requiring intensive care, should be selected (HASANUZZAMAN *et al.*, 2014). For the process to succeed, plants that survive and can extract salts from the soils are indicated, improving their properties to facilitate the future introduction of other less tolerant species (SANTOS *et al*., 2011). In this context, some studies have already been conducted in the semiarid region of Brazil, especially with the halophyte *Atriplex nummularia* Lindl (AZEVEDO *et al*., 2005; LEITE *et al*., 2020; SILVA *et al*., 2016b; SOUZA *et al*., 2014). It is a species of the Chenopodiaceae family, and the genus *Atriplex* has more than 400 species distributed worldwide (AGANGA; MTHETHO; TSHWENYANE, 2003).

Due to their ability to survive in saline environments and accumulate salts in their biomass, some species of *Atriplex* have been studied for aspects related to water use, productivity, and forage quality in arid areas of the United States of America (GLENN *et al*., 1998), optimization of establishment in the field by seed germination in Australia (STEVENS; BARRET-LENNARD; DIXON, 2006), and nutritional composition of leaves in Saudi Arabia (KHALIL; SAWAYA; HYDER, 1986). In Brazil, there are also reports of productivity and nutritive value of parts of shoots of *A. nummularia* plants irrigated with effluents from tilapia farming (BARROSO *et al*., 2006), extraction of salts from soils irrigated with desalting wastewater (AZEVEDO *et al.*, 2005; PORTO *et al.*, 2006), use in animal feed (ALVES *et al*., 2007), among others.

Over time, the focus has shifted to the use of *A. nummularia* in the reclamation of areas degraded by salinity, through the phytoremediation technique. One example is the study conducted by Souza *et al.* (2014), evaluating biomass production and salt extraction by *A. nummularia* with and without periodic shoot pruning, with plants grown under rainfed conditions in the semiarid region of Pernambuco. The authors recommended pruning as a way to remove the salts from the area and stimulate the regrowth of plants and production of plant material that is more tender and palatable to the animals.

A study conducted by Souza *et al.* (2014) demonstrated that pruning at 6, 12, and 16 months after transplanting of *A. nummularia* seedlings resulted in the final production of fresh matter and dry matter of leaves, thin branches, thick branches and total production of 11.29, 4.49, 5.89, and 21.67 Mg ha^{-1} and 2.19, 2.65, 3.80, and 8.64 Mg ha^{-1}, respectively. This material can be used in animal diets, especially in drought periods with low availability of biomass for feed. The authors also reported total salt extractions of 785.9 and 604.3 kg ha^{-1} in plants with and without pruning, respectively. There was higher extraction of Na and Cl compared to the other elements (Ca, Mg, and K), a positive factor when the goal is to reduce Na and Cl contents in salt-affected soils, without making them poor in the other cationic nutrients. It was also possible to observe the influence of the soil reclamation process by the appearance of spontaneous vegetation over time, as demonstrated at six and nine months after transplanting of *Atriplex nummularia* seedlings in saline-sodic soil (EC_{se} ~23 dS m^{-1} and ESP ~30%) in the semiarid region of Pernambuco (Figure 4).

Figure 4 - Evolution of *Atriplex nummularia* growth in saline-sodic soil in the semiarid region of Pernambuco, highlighting the emergence of spontaneous vegetation at 6 and 9 months



Additional data on soil characterization can be found in Souza *et al.* (2014)

Spacings were also tested for field cultivation of *A. nummularia* by Silva *et al.* (2016b). Two planting spacings were evaluated, 1.0 x 1.0 m and 2.0 x 2.0 m, with all plants being pruned at 6, 12, and 18 months after transplanting. Na and Cl contents extracted per plant were higher at 2.0 x 2.0 m spacing; however, the extraction per area was higher with plants grown at the smaller spacing (1.0 x 1.0 m). Extractions of 396.0 and 324.6 kg ha^{-1} of Na and 322.2 and 234.3 kg ha^{-1} of Cl by the shoots were observed at the spacings of 1.0 x 1.0 m and 2.0 x 2.0 m, respectively. The authors suggest that more densely spaced plantations be adopted, which allow greater extraction of salts from the soil. However, if the objective is to obtain better-developed plants, which explore the soil in the subsurface, larger spacings should be adopted, of 2.0 x 2.0 m or up to 3.0 x 3.0 m. In the case of intercropping with other species, this should also be reviewed and assessed, observing the requirements of spacing between the plants used.

In a study on revegetation of saline-sodic soil in the Sertão region of Pernambuco, Leite *et al.* (2020) evaluated the monoculture of *A. nummularia*, *Mimosa caesalpiniifolia*, *Azadirachta indica*, and *Leucaena leucocephala* plants and intercropping of *A. nummularia* with each of the other three species. The revegetation process resulted in higher contents of microbial biomass carbon, lower soil basal respiration rates, and higher densities of arbuscular mycorrhizal fungi spores, only 30 months after transplanting. The authors also confirmed a mycorrhizal association in *A. nummularia*, although it is a plant of the Chenopodiaceae family, which contains species that do not form this type of association. It is worth noting that the seedlings were transplanted without extra inoculation, being naturally mycorrhized.

Other species should be considered in the revegetation of areas degraded by salinity, especially due to the low acceptance of *A. nummularia* by rural communities due to the lack of knowledge of its potentialities. In the case of northeastern Brazil, the ideal would be the use of native plants of the Caatinga. However, there are still no consistent results of these species with the capacity to survive in a saline environment. In field revegetation experiment conducted since August 2016, with six native species: Aroeira-do-Sertão (*Myracrodruon urundeuva* Allemão), Catingueira (*Caesalpinia pyramidalis Tul.*), Jatobá (*Hymenaea courbaril*), Mulungu (*Erythrina mulungu*), Pau-Ferro (*Caesalpinia leiostachya*), and Umbuzeiro (*Spondias tuberosa* Arruda), there are no defined results so far. At 54 months after transplanting, the survival of Jatobá was 5% and the survival of Mulungu was 36%, while out of the *Atriplex* and Aroeira-do-Sertão plants initially planted, 99% remain alive in the field (Personal information provided by M. B. G. S. Freire at 2021).

The low survival of some native species suggests the need to use additional techniques, such as the application of chemical and organic conditioners, which improve soil characteristics and favor the establishment of plants in the field, as demonstrated for *A. nummularia* in the Brazilian semiarid region (MIRANDA *et al*., 2020). Thus, phytoremediation and revegetation can be favored by the use of organic products available in the area, making management more ecologically and economically sustainable. However, the use of organic products should be constant, since decomposition rates are very high in regions under tropical climates and longer-lasting effects will only occur with successive applications.

INFLUENCE OF THE MICROBIOTA ON SALT-AFFECTED SOILS

Microorganisms are indispensable agents in the soil ecosystem, being responsible for organic matter decomposition, nutrient cycling, and promotion/ suppression of plant growth (JACOBY *et al*., 2017; SACCÁ *et al*., 2017; ZHENG *et al*., 2019). Because they have a high cell surface/volume ratio, in addition to permeable cell membranes and high renewal rates, microorganisms respond quickly to variations in salinity (MORRISSEY *et al*., 2014). Therefore, any effect of salts on microbial processes will have major implications for soil organic matter content and nutrient cycling.

Salinity has a direct effect on soil microbial composition and, on a global scale, is the most important factor affecting microbial distribution in soils compared to any other chemical factor, such as acidity and nutrient availability (AUGUET; BARBERAN; CASAMAYOR, 2010; LOZUPONE; KNIGHT, 2007; SILVA *et al*., 2016a). In general, salinity has a negative effect on soil microbial community (RATH; ROUSK, 2015), mainly due to osmotic stress, which can cause desiccation and lysis of the cells (LEOGRANDE; VITTI, 2018). Microbial biomass, soil basal respiration and microbial enzyme activity decrease as salinity increases (BEZERRA *et al.*, 2010; GHOLLARATA; RAIESI, 2007; MIN *et al*., 2016; YAN; MARSCHNER, 2012; YUAN *et al*., 2007). However, some studies have demonstrated different responses of microbial biomass and activity to salinity, probably due to the different groups of microorganisms present in different locations of the experiments and their differences in terms of salinity tolerance (BAUMANN; MARSCHNER, 2013; MORRISSEY *et al*., 2014; SILVA *et al*., 2016a).

With the development of next-generation sequencing technologies, it has been possible to understand how changes in the structure and composition of the microbial community occur in salt-affected soils. A molecular ecological network analysis study found that the diversity of prokaryotes decreased with salinity and that this change was primarily influenced by the salinity levels in agricultural soils (ZHENG *et al*., 2017). However, high salinity increased the abundance of some taxa, such as Proteobacteria, Bacteroidetes, and Firmicutes, and increased microbial interactions. This demonstrates that microorganisms in naturally saline habitats develop multiple adaptations to survive under high concentrations of salts, including changes in interactions between microorganisms (ZHENG *et al*., 2017).

Soil microorganisms associated with plants can be used as an efficient strategy to improve plant growth under salt stress. There is considerable evidence that arbuscular mycorrhizal fungi (AMF) cause variations in soil-water-plant relationships and the improvement of tolerance to biotic and abiotic stresses (LÓPEZ-RÁEZ, 2016). Arbuscular mycorrhiza (AM) symbiosis is among the most widespread beneficial associations between plants and microorganisms. It is more than 450 million years old and is considered a fundamental step in the evolution of terrestrial plants (SMITH; READ, 2008). Most terrestrial plants, including agricultural and horticultural species, are able to establish this type of association with fungi of the phylum Glomeromycota (ANDREO-JIMÉNEZ *et al*., 2015; BAREA *et al*., 2005; SMITH; READ, 2008).

The formation of AM symbiosis improves nutrient acquisition and maintains ionic homeostasis; improves water absorption and maintains osmotic balance in plants; induces the antioxidant system to prevent damage by reactive oxygen species; protects the photosynthetic apparatus and increases photosynthetic efficiency; and modulates the phytohormone profile to minimize the effects of salts on growth and development (EVELIN *et al*., 2019). In addition, AM symbiosis alters stomatal morphology, increasing stomatal density and the size of guard cells, thereby improving stomatal conductance and water relations of wheat leaves under salt stress (ZHU *et al*., 2018).

Indeed, numerous studies have shown that AM symbiosis can alleviate the harmful effects of salt stress (DASTOGEER *et al*., 2020; EROĞLU *et al*., 2020; EVELIN *et al*., 2019; KAVROULAKIS *et al*., 2020; LÚCIO *et al*., 2013; PORCEL; AROCA; RUIZ-LOZANO, 2012). For example, mycorrhized wheat plants under salt stress conditions produced more shoot and root biomass, had higher N uptake and N concentration in the shoots, and showed greater stability of plasma membranes compared to non-mycorrhized plants. In addition, the expression of genes related to water stress was markedly lower in mycorrhized plants, indicating that AM symbiosis reduces the plant's need to activate mechanisms of response to salt stress (FILECCIA *et al*., 2017). AM symbiosis can increase the tolerance to salt stress of plants that are already resistant to abiotic stresses. Chang *et al*. (2018) observed that *Elaeagnus angustifolia* L. plants under salt stress produced more biomass of roots, stems, and leaves, in addition to higher activities of superoxide dismutase, catalase, and ascorbate peroxidase, when they were mycorrhized. These plants, compared with non-mycorrhized plants also under salt stress, had higher capacity to acquire K^+, Ca^{2+}, and Mg^{2+}, and maintained higher K^+:Na^+ ratios in leaves and lower Ca^{2+}:Mg^{2+} ratios. Leite *et al.* (2020) demonstrated that the halophyte plant *Atriplex nummularia* Lindl established a mycorrhizal association in a saline soil of an area in the semiarid region of Brazil, promoting revegetation and changes in the microbiological properties of the soil.

In addition to mycorrhizae, there is a group of fungi that are root endophytic, known as dark septate endophytic (DSE), which are involved with host resistance to environmental stress. DSE are characterized by intense dark pigmentation and the formation of melanized septate hyphae and, occasionally, microsclerotia (KNAPP *et al*., 2015; YUAN; SU; ZHANG, 2016). In contrast to the vast information about AMF in the alleviation of salt stress in plants, information on the role of DSE fungi in the ecosystem is limited (GUPTA *et al*., 2020). However, some studies have shown that DSE have the potential to promote plant growth in saline environments, as demonstrated by Santos *et al*. (2017), who observed that inoculation with DSE promoted growth and reduced oxidative stress in two varieties of rice under salt stress. Inoculation in cowpea plants with the DSE Sordariomycetes sp1-B'2 and *Melanconiella elegans-21W2* improved nutrition with N and P under salt stress, favoring plant growth and net photosynthetic rate (FARIAS *et al*., 2020). In general, studies show that the beneficial effects of DSE vary according to fungal species and are more evident at moderate salinity levels.

Like AM symbiosis, plant growth-promoting bacteria (PGPB) are increasingly being studied and used to alleviate stress in plants (KUMAR *et al*., 2020; NUMAN *et al*., 2018). PGPB are found mainly in rhizospheric soil, besides inhabiting plant tissues (endosphere) and aerial surfaces of leaves or stems (phyllosphere). PGPB have numerous mechanisms, such as indole acetic acid (IAA) production, phosphate solubilization, and biological nitrogen fixation (COHEN *et al*., 2015; PATHAK; KUMAR; RANI, 2017). In addition, some mechanisms may induce salinity tolerance through the induced systemic tolerance process, which involves several biochemical and physiological changes in the plant (YANG; KLOEPPER; RYU, 2009). Among these mechanisms, the formation of biofilm (TIMMUSK *et al*., 2014), the production of exopolysaccharides (ROLLI *et al*., 2015) and osmotic adjustment (SARMA; SAIKIA, 2014) stand out.

One mechanism that has been widely studied is the production of ACC deaminase by PGPB to combat salt stress in plants (OROZCO-MOSQUEDA; GLICK; SANTOYO, 2020). Plants under salt stress accumulate ethylene in their tissues, causing damage to cell elongation and division and activation of the plant defense system (FRACETTO *et al*., 2013). The limiting step of ethylene biosynthesis is the conversion of AdoMet (S-adenosylmethionine) into ACC (1-aminocyclopropane-1-carboxylic acid), which is catalyzed by the ACC synthase enzyme (LIN; ZHONG; GRIERSON, 2009). The enzymatic activity of ACC deaminase results in the production of α-ketobutyrate and ammonia, which, by reducing ACC levels, avoid excessive increases in ethylene synthesis under stress conditions and constitute one of the most efficient mechanisms to induce plant tolerance to stress (BHARTI; BARNAWAL, 2019; GUPTA; PANDEY, 2019).

Most studies using bioinoculants are conducted using PGPB or AMF, neglecting the synergistic effects of joint inoculation. Synergistic interactions between the two types of microorganisms can improve plant growth and tolerance in saline environments (KRISHNAMOORTHY *et al*., 2016; MOREIRA *et al*., 2020; PEREIRA *et al*., 2016). Studies of tripartite interactions, involving AMF, PGPB, and plant, with the objective of alleviating the adverse effects caused by salt stress, which affect soils of the tropical semiarid region, are scarce and need to be explored.

CASE STUDY: AGRICULTURAL PRODUCTION IN SALT-AFFECTED SOILS OF THE MORADA NOVA IRRIGATED PERIMETER, CEARÁ

Although there are many techniques for the reclamation of salt-affected soils, they have not been widely used due to socio-economic aspects. This is quite evident in the Brazilian semiarid region, where no large-scale credit program has been implemented for the reclamation of salt-affected soils in the Irrigated

Perimeters, which is largely due to the long payback period (time required to recover the invested capital), as demonstrated in studies conducted in the State of Ceará (ARAÚJO *et al.*, 2011; COSTA *et al*., 2005a, 2016). On the other hand, salinity problems vary naturally over time, even without application of reclamation techniques. This occurs due to soil drainage conditions, precipitation in the area, and groundwater level. Changes in the production organization of the rural community is another aspect that impacts the levels of soil salinization, besides directing the use of these degraded areas. This case study, related to the Morada Nova Irrigated Perimeter (MNIP), is presented within this complexity, often unknown by the Academy community.

In the oldest irrigated perimeters of the Brazilian semiarid region, which began operating in the 1970s, as is the case with MNIP, the occurrence of salt-affected soils has been noticeable since 1975, due to inadequate soil and water management, poor drainage due to low water transmission in the soil profile, lack of maintenance of the drains, unfavorable topographic conditions, and the constant agricultural exploitation of the land (ALBUQUERQUE *et al*., 2018; LEITE *et al.*, 2007).

The MNIP is located in the municipalities of Morada Nova and Limoeiro do Norte, Ceará, and its activities are carried out based on the use of surface irrigation systems, on alluvial soils, with a predominance of fine and medium textures (BRASIL, 1992). The General Dossier based on the physical attributes of soils recommended occupation of 28% of its useful agricultural area (3,737 ha) for rice crop (BRASIL, 1969), totaling an area of approximately 1050 ha, corresponding to clayey textured soils, more suitable for the crop and for continuous flood irrigation.

Studies conducted by the Israel Mission in the mid-1970s indicated that 57.2% of the total MNIP area was already salinized or in the process of salinization, which corresponded to an area of 2502 ha. Of this degraded area, 40% was economically unfeasible to reclaim (BEZERRA, 2006). Also according to the author, studies conducted in 2002 by the Department of Irrigated Agriculture of the State of Ceará in partnership with the National Water Agency, confirmed a total of almost 60% of halomorphic soils in the MNIP.

The rice crop is classified by Ayers and Westcot (1999) as sensitive to salinity, but moderately tolerant to sodicity, and can be cultivated with ranges of exchangeable sodium percentage between 15 and 40% depending on the cultivar. Due to its tolerance to sodicity and the possibility of being cultivated under flooded conditions, rice is one of the most recommended species worldwide in the planning of use or during the reclamation of salt-degraded soils. In addition, the osmotic effects of salinity are partially reduced by the dilution of salts after inundation of cultivated area, which favors the development of the crop.

From 1980 to 1996, MNIP occupation varied between 50 and 70% with rice crops. In the early 2000s, with the marked scarcity of water, the Government of the Ceará state implemented the “Plano Águas do Vale”, which, among other measures, proposed payment as compensation to farmers not to grow rice, in view of the low level of water stored in the Banabuiú Reservoir that supplied water to the irrigated perimeter. In subsequent years, however, with the replenishment of the reservoir, the rice area expanded considerably (COSTA *et al.*, 2005b), a situation that lasted until 2014. As a result of the drought from 2012 to 2017 (MARENGO; TORRES; ALVES, 2017), which resulted in the reduction of the surface water supply, the water source supplying the perimeter became shallow wells (< 20.0 m).

The reduction in water supply resulted in drastic changes in production systems and crops exploited in the perimeter, with the area cultivated with rice decreasing to 365 ha in 2018, which represents less than 10% of the useful agricultural area. The irrigation water productivity for rice crop, which was 0.20 kg m^{-3} with surface water and continuous flooding (COSTA *et al*., 2005b), increased to 0.87 kg m^{-3} with groundwater and intermittent flooding (UNIVERSIDADE FEDERAL DO CEARÁ, 2019). However, the low generation of direct employment, of only 0.2 jobs generated per hectare, associated with the low profitability of rice for the cultivation conditions in MNIP, indicated that the continuity of its exploitation would only be justified by the aversion to the risk inherent to the size of the family farmer of that irrigated perimeter.

An important aspect to be considered is that groundwater represents a higher risk of soil salinization than surface water, so the change in water source observed in the MNIP could increase the area of salt-affected soils. A study conducted by Nunes, Costa and Paiva (2019), with 20 wells distributed in the MNIP, showed that 55% of the wells evaluated had increasing problems of sodicity, but only a few wells showed moderate salinity problems. Among the wells evaluated, the highest electrical conductivity (ECw) was 1.49 dS m^{-1} and the overall mean was below 1.0 dS m^{-1}. However, in the same study, the authors demonstrated that the static levels in the wells in 2018 varied between 8 and 10 m deep, resulting from the lower water volumes applied to the crops when irrigation began to be performed with groundwater source, in addition to the long period of low rainfall recharges, thus resulting in a higher static level in the wells. This lowering of the groundwater implies a lower risk of soil salinization in areas of alluviums of the Brazilian semiarid region. In fact, drainage problems and groundwater elevation were determinant for the salinization of soils in the MNIP (COSTA *et al*., 2016; MOREIRA *et al*., 2015).

Table 1 - Net income per cycle in the shrimp farming activity in Morada Nova (Year: 2018)

Shrimp farmer	Production cost (R$ ha^{-1})	Yield (kg ha^{-1})	Selling price (R$ kg^{-1})	GVP* (R$ ha^{-1})	Net income (R$ ha^{-1})
01	26,167.05	3,500.00	15.00	52,500.00	26,332.95
02	22,001.82	2,461.54	16.00	39,384.64	17,382.82
03	25,615.53	2,833.33	16.00	45,333.28	19,717.75

Source: Universidade Federal do Ceará (2019); *GVP: gross value of production

The droughts from 2012 to 2017 resulted in a clear change in the soil exploitation profile in the MNIP. From a historical profile of annual occupation with more than 50% with rice crop, the MNIP gradually advanced towards livestock farming, based on dairy cattle, having incorporated the guidelines of the Leite Ceará Project (CEARÁ, 2009). Currently, around 90% of the total area of MNIP is occupied with plant species used as forage support, including sorghum, Bermuda grass, elephant grass, Buffel grass, and native pasture (BRASIL, 2018). It is worth mentioning that many forage crops, such as sorghum, have moderate tolerance to salinity (AYERS; WESTCOT, 1999), with good potential for cultivation in salt-affected soils.

In addition to some varieties of forage sorghum, other tropical forage grasses such as elephant grass (Napier), sugarcane and buffel grass have the potential for cultivation in the northeastern semiarid region in salt-degraded soils under irrigated regime (NUNES FILHO *et al.*, 2008). Simões *et al.* (2016) evaluated the effect of salinity on the growth of ten sugarcane varieties and found that they showed similar responses of growth reduction as soil salinity increased, being considered moderately sensitive to salinity. In addition, Simões *et al.* (2021) analyzed 19 accessions of the *Saccharum* complex subjected to irrigation with salinized water (6.0 dS m^{-1}) and verified that the accessions of *E. arundinaceus* (BGCN 120 and BGCN 123) had the highest photosynthetic rate, transpiration rate, plant height, and leaf length, indicating greater adaptability to salt stress, so they can be promising in breeding programs.

Another activity that has expanded in the MNIP is inland shrimp farming, as already expected in the early 2010s for the Baixo Jaguaribe region, where the MNIP is located (MIRANDA *et al*., 2010). The area of tanks with *Litopenaeus vannamei* shrimp cultivation has increased exponentially in recent years, from 6.5 to 227.0 ha between 2017 and 2020. The existence of sodic soils of clayey texture and low permeability, favors the construction of tanks for this activity in theMNIP. Obviously, the availability of low-salinity water from the alluvial aquifer with excellent capacity of the exploitable reserve, and the economic attractions for farmers are decisive factors for the expansion of this activity and the increase in the value of the land.

Table 1 shows net income data (R$ ha^{-1}) obtained during a shrimp production cycle in the MNIP in 2018, excluding the fixed cost associated with infrastructure, whose amortization has been occurring on average with one and a half years, given the possibility of three cycles of shrimp production per year. The shrimp farming activity has had average values of direct employment generation, the main social indicator, almost twice that of irrigated agriculture, and it should be noted that many of these jobs are formal, unlike temporary jobs generated in irrigated agriculture under the conditions of the MNIP (UNIVERSIDADE FEDERAL DO CEARÁ, 2019). It is common to observe variations in production costs and yield among producers, resulting from several factors, including differentiated management.

There are environmental issues related to inland shrimp farming, particularly the possibility of contamination of water bodies by untreated effluents, something that can cause damage to the entire community. Nevertheless, these effluents can be used in the irrigation of crops such as rice (MIRANDA *et al*., 2008) or in the irrigation of grasses such as Tanzania and Guinea grass, promoting yields similar to those obtained with river water (MIRANDA *et al*., 2010). The coating, practiced by some shrimp farmers, despite the cost, besides minimizing the risks of groundwater contamination, promotes significant savings water and energy cost. Thus, it is possible to develop a production model that allows the economic and environmental sustainability of MNIP, with greater integration between irrigated agriculture, dairy farming, and shrimp farming.

FINAL REMARKS

1. The themes addressed in this review indicate new possibilities for the reclamation and management of salt-affected soils in the Brazilian semiarid region. Literature data indicate that there is a need for the integrated use of strategies, including drainage techniques (e.g. bio-drainage) and soil management practices (e.g. application of conditioners), as a way to obtain long-lasting results, reduce costs and create new opportunities. Such cost reduction is extremely necessary, considering the need to use degraded areas to ensure food production under climate change conditions;

2. There is a pressing need for technologies that enable the use of biochars, as soil conditioners, and the inoculation of microorganisms that can mitigate the effects of salinity on plants and promote improvements in soil quality in the reclamation process. In the processes of revegetation, it is important to conduct long-term studies with species native to the semiarid region and with economic potential. In this context, the use of these plants, associated with the application of soil conditioners and inoculants, allows the revegetation of salt-affected areas, with the restoration of soils and the entire ecosystem;
3. The existence of soils of difficult reclamation is also a reality observed in salt-affected areas in the Brazilian semiarid region. This is evident for sodic soils of clayey texture, which have very low values of hydraulic conductivity. For these areas, sustainable plant production is practically unfeasible, except with adapted plants, such as carnauba palms. This paves the way for using these areas for other production purposes;
4. The expansion of shrimp farming in the Morada Nova Irrigated Perimeter (MNIP) in recent years is partly justified by the existence of salt-affected soils with low natural drainability. In this perimeter, the increase in the production of forage species, intended for dairy farming, to the detriment of grain production, has also been observed. The occupation plan of this Irrigated Perimeter demonstrates that it is possible to enable the economic exploitation of salt-degraded soils with adequate agricultural and livestock farming activities, without the need for a time-consuming and costly process of soil reclamation;
5. A final aspect to be considered is the worldwide decrease in the use of surface irrigation, which makes it possible to infer a reduction of salt-degraded soils, especially by the process of secondary salinization. In Brazil, the perimeters under surface irrigation in the Brazilian semiarid region managed by the National Department of Works Against Droughts (*Departamento Nacional de Obras Contra as Secas* - DNOCS) are an example, because after the long period of scarcity of water resources in the last decade of 2010 and the advance in the deterioration of the infrastructure of common use, there is strong evidence that they will not operate again with furrow or flood irrigation system. This change reduces the water volume applied throughout the perimeter, with consequent lowering of the groundwater and lower risks of soil salinization. For soils that remain with high levels of salinity and/or sodicity, there are opportunities for revegetation projects and obtaining of carbon credits, which can also promote improvements in physical, chemical, and biological attributes, ensuring improvements in the soil resource for future generations of farmers.

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