Ecological restoration and productive recovery of saline environments from the Argentine Monte Desert using native plants

Pablo E. Villagra[A,B*], Carlos B. Passera[B], Silvina Greco[B] , Carmen Sartor[B] , Pablo A. Meglioli[A,B], Juan A. Alvarez[A,B], Sofía Dágata[B], Cecilia Vega Riveros[A], Liliana I. Allegretti[B,C], María Emilia Fernández[C], Bárbara Guida-Johnson[A,D], Nerina B. Lana[A,D] & Mariano A. Cony[C]

A- Instituto Argentino de Nivología, Glaciología y Ciencias Ambientales – CONICET Mendoza. CC. 330 – 5500. Mendoza. Argentina.

B- Facultad de Ciencias Agrarias. Universidad Nacional de Cuyo.

C- Instituto Argentino de Investigaciones de la Zonas Áridas (IADIZA) - CONICET Mendoza.

D- Facultad de Ciencias Exactas y Naturales. Universidad Nacional de Cuyo.

* Correspondence: villagra@mendoza-conicet.gob.ar

Abstract

The accumulation of soluble salts in soils is one of the main environmental factors that contribute to the loss the productive capacity of Argentina's arid ecosystems. Salinizacion processes, lead to critical states of degradation and desertification. The challenge to recover and improve the productivity of such degraded areas is complex because it should consider restoration strategies that will be integrated with local economic, cultural and social activities. The integrative use and management of different native species in remediation programs is an attractive restoration tool that could improve the productivity capacity of degraded areas. Native species have developed numerous strategies and adaptations that could ensure their survival in saline environments. Nevertheless, species selection, management and appropriate technologies to be used in afforestation programs may be limited because we do not know in detail both the potential and needs of each native species and the environmental characteristics of each site. In this chapter we analyze not only the problem of soil salinization and the challenge of restoring saline environments in Argentina, but also the characteristics of native species of trees, shrubs and grasses of the Monte region, considering their tolerance to saline stress and the provision of goods and services to local populations, which can be useful in restoration programs.

The problem of salinity in arid lands of Argentina

Drylands represent 41% of the Earth's land surface and 69% of Argentina’s territory (ONDTyD 2010). They are characterized by scarce, infrequent, and irregular rainfall, a large daily and seasonal thermal amplitude, and soils with low organic matter and water content.These features make arid ecosystems inherently fragile. Thus, intense anthropogenic pressures such as deforestation, overgrazing or unsustainable agriculture (UNCCD 1994) can undermine the resilience of the ecosystems triggering degradation processes. Land degradation is defined as the long-term loss of the functioning and productivity of an ecosystem, caused by a disturbance from which it cannot recover to the original state without assistance (Bai et al. 2008). As a consequence, the productivity, biodiversity, and the production of ecosystem services and nature's contribution to people are reduced or lost, affecting the life quality of the local population (Díaz et al. 2018). Therefore, one of the main challenges is to determine which restoration or management strategies result in reversing these degradation trends in different environments.

Environmental heterogeneity at the landscape scale in arid zones is associated with geomorphological and edaphic processes, and their effects on water distribution and availability (Rundel et al. 2007, Bisigato et al. 2009). In the Monte biogeographic province (known as Monte desert), located in the arid West of Argentina, these factors determine typical landscape units, such as rocky slopes, alluvial cones, valley bottoms, and sedimentary plains. Each unit receives different effective precipitation depending on the incident precipitation, and the rates of runoff, infiltration and evaporation, sediment accumulation, and irradiation. Particularly in low-lying areas, with accumulation of fine sediments, a shallow phreatic level, and high evaporation rates, salts tend to accumulate on the surface, becoming the limiting factor for biological communities. In this case, the vegetation is distributed in concentric rings depending on the salinity gradient and the tolerance of different species to salinity.

Agricultural production in drylands depends on systematized irrigation, which generates focis of productivity within the arid ecosystems. In the Monte region, irrigation is performed with water from the snow-melt of the mountain, complemented with groundwater. In this territory, unsustainable agricultural practices determine nutrient loss, salinization, acidification, desiccation, compaction, sealing, or accumulation of toxic substances in the soil (Abraham 2002). Particularly, salt accumulation in the soil profile reduces the productivity of large cultivated areas, decreasing the value of the land. As a consequence, these areas are abandoned due to low or no productivity (Abraham et al. 2014).

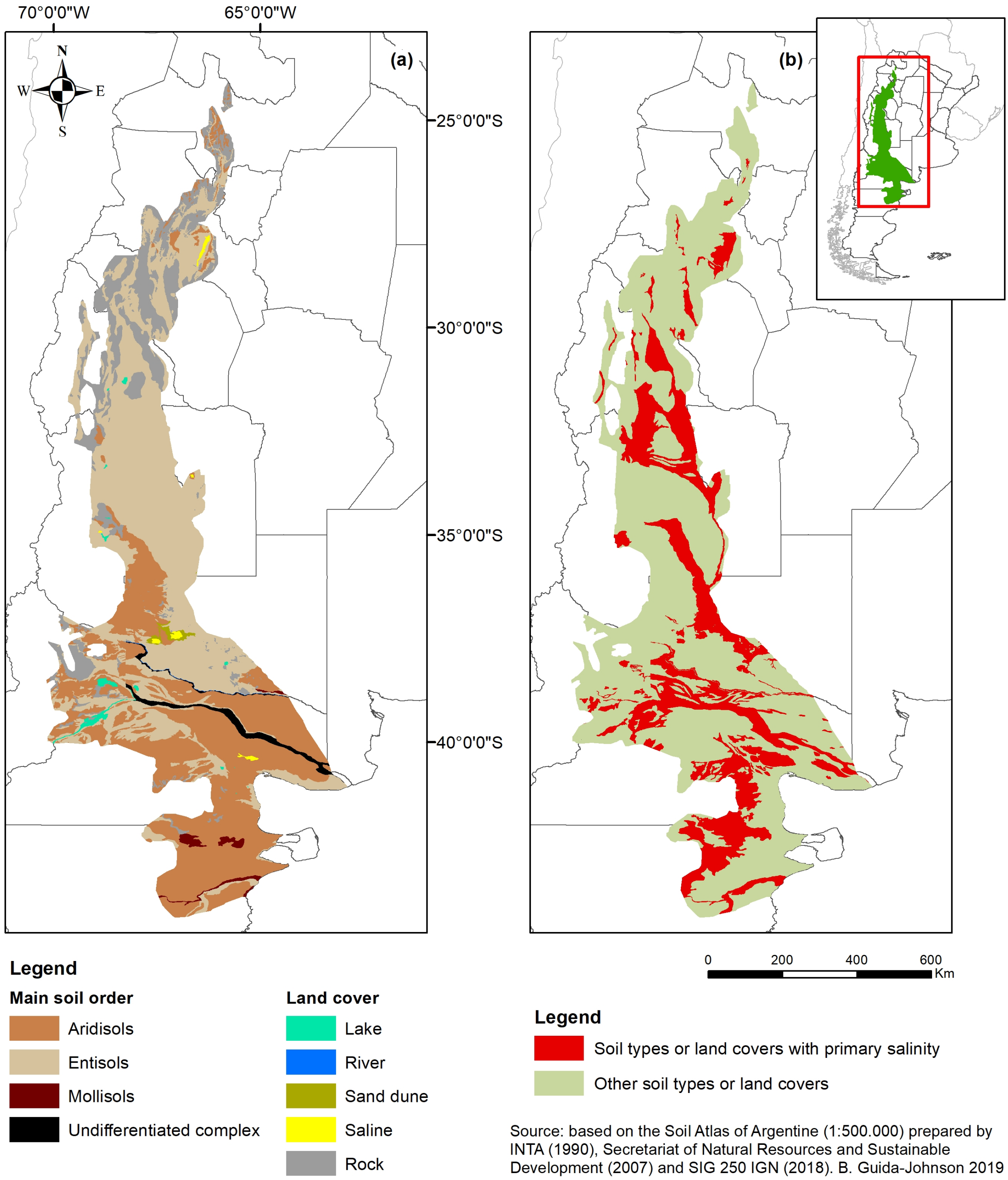
Salinization is a complex problem that leads to critical states of degradation and desertification in drylands. This has negative impacts over natural ecosystems or agroecosystems, from environmental, economic, and social viewpoints. Given this situation, it is necessary to quantify the origin and evolution of soil salinization processes and to evaluate management decisions to revert salinization processes and to restore ecosystem functions and increase land productivity. Ecological restoration is defined as the process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed (SER 2004). It has been recognized as a priority by many global agreements, such as the Aichi Biodiversity Targets 14 and 15 of the Convention on Biological Diversity or the Land Degradation Neutrality Target of the UN Convention to Combat Desertification or the Bonn Challenge on Forest Landscape Restoration (Aronson and Alexander 2013). More recently, in March 2019, the United Nations General Assembly declared 2021-2030 the UN Decade on Ecosystem Restoration, a global call for action that is expected to scale up restoration initiatives. Related to these initiatives, the so-called "restorative" activities are inspired by the values and principles underpinning ecological restoration. They are aimed at increasing ecosystem services and reducing environmental impacts while improving the ecological sustainability and production systems (McDonald et al. 2016). These activities become especially relevant in the search for global sustainability, considering the need to increase the food production rate for a growing population, and to maintain biodiversity (Foley et al. 2011).

Spatial characterization of natural and anthropogenic salinity in the Monte

Salinization is the ionic accumulation process in the soil profile, with two main types being differentiated according to their origin as primary and secondary salinization (Amezketa 2006, Zhou et al. 2013). The first is the result of natural processes that take place in areas where the parental material is rich in salts, and the evapotranspiration rate is higher than the precipitation rate. Other factors that may induce primary salinization are natural drainage patterns or topographic features, the geological structure, or the distance to the sea.

Secondary salinization occurs when salt accumulation is a consequence of unsustainable anthropogenic activities. There are two different triggers, according to whether it occurs in irrigated or non-irrigated drylands (Thomas et al. 1993, Rengasamy 2006, Zhou et al. 2013). On the one hand, the salinization of non-irrigated drylands occurs when the perennial native vegetation (with deep roots) is replaced by annual crops or grasslands with shallow roots systems. Reduced evapotranspiration alters the natural water balance and causes the phreatic level to rise. The accumulation of salts from the groundwater will depend on both climatic conditions and soil hydraulic properties. On the other hand, the salinization of irrigated drylands occurs as a consequence of excessive irrigation and lack of adequate drainage. This process can be accelerated by poor irrigation water quality, low hydraulic conductivity, and high evaporation conditions (Abraham et al. 2002, Jobbágy et al. 2008).

Argentina ranks third in the world regarding its extent of salt-affected soils (Marinoni 2019), with approximately 35 million hectares (12.6% of the total area) being affected by primary salinity (INTA 1990). The Monte Biogeographical Province, which comprises approximately 460,000 km^2 from the province of Salta to the Atlantic coast in Chubut, displays regional differences related to predominant types of soil (Fig. 1). The Northern Monte is occupied mostly by rock outcrops (49%) and Entisols (42%), and the Central Monte is dominated by Entisols (77%), whereas in the Southern Monte, Aridisols (60%) are the prevalent soil type. According to data produced by INTA (1990), Central and Southern Monte are affected by primary salinity in extensions that cover 28% and 29% of each region, respectively. In general, a quarter of the Monte soils (25%) are affected by the presence of natural salinity in the first 50 cm of the soil profile (Fig.1).



Source: based on the Soil Atlas of Argentine (1:500.000) prepared by INTA (1990), Secretariat of Natural Resources and Sustainable Development (2007) and SIG 250 IGN (2018). B. Guida-Johnson 2019

Figure 1. *Main soil orders* ***(a)*** *and zones affected by primary salinity* ***(b)*** *in the Monte region.*

Only 5% of the total productive area in Argentina corresponds to irrigated areas (2.1 million ha), and it is estimated that 24% of this area is affected by salinization or sodicity processes (Sánchez and Guerra 2017). In the Monte region, 25% of the irrigated land is affected by secondary salinization, with a wide range of variation that goes from 8% in Salta to 68% in Chubut (Table 1).

Table 1: Irrigated areas and areas affected by salinity or sodicity in Argentine provinces located in the Monte region (Sánchez and Guerra 2017).

	[illegible]	[illegible]	[illegible]

Within the great territorial extension of the Monte, different natural conditions and processes give rise to high spatial heterogeneity in terms of quality and quantity of ions present in the soil. This variability is observed even at fine scales, so it is necessary to know the superficial and deep distribution of salts when implementing projects for the recovery of degraded areas. In semiarid degraded ecosystems, besides the effect of postplanting drought, the small-scale heterogeneity of abiotic factors plays an important role in the survival of transplanted seedlings (Maestre et al. 2003). For example, microtopography, soil texture, vegetation cover, and water table can generate microsites that favor salt accumulation. The combination of these environmental variables and the biological characteristics (salinity tolerance, growth rate, root development) of the plant species used can generate synergistic effects that threaten the viability of restoration projects. The quali/quantitative study of these variables allows the development of conceptual tools tending to recover soils affected by salinization processes.

In this context, soil and water factors that affect the spatial heterogeneity of soil salinity were analyzed in the locality of Media Agua (San Juan). In 16 plots, soil and groundwater evaluations were carried out, based on topsoil (<0.25 m deep) sample and deep soil profiles (up to 4.5 m deep). High spatial heterogeneity of salinity was found within plots and with increasing variability at the superficial layer (Meglioli et al. 2018). Consequently, this fine-scale variability in salinity should be considered and represents a challenge for the planning of restoration projects (Figure 2).

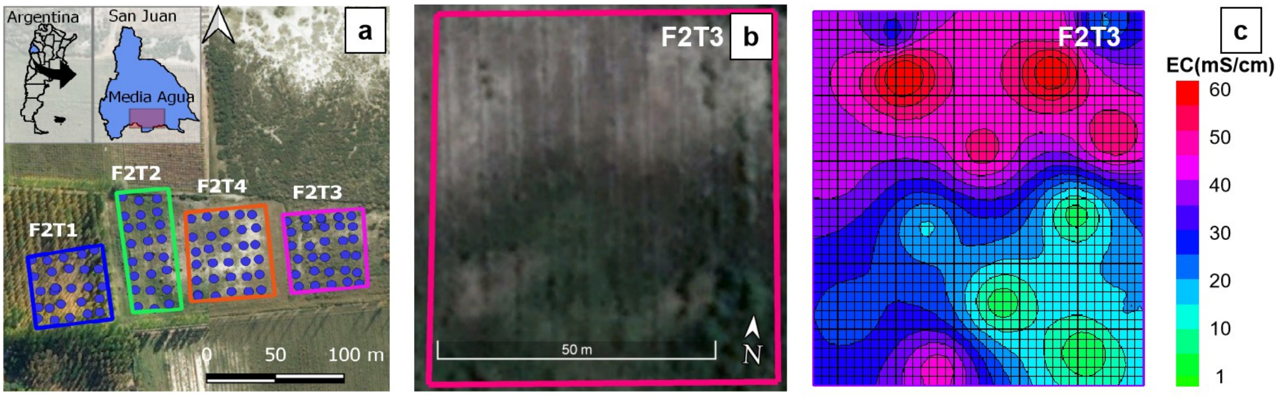


Figure 2. Evaluation of spatial variability of saline condition in a irrigated farmland (poplar farm) of Media Agua (San Juan). a) Examples of plot stablishment in a site of the study area. The four plots represent diferent salinity conditions within a farmland. Each blue point represent a superficial soil sample. b. Detailed image of the plot F2T3 c. Analysis of spatial interpolation of salinity levels for F2T3 (GMS 6.5 software) (Meglioli et al. 2018)

The different edaphic profiles showed similar patterns, with levels of electrical conductivity decreasing with increasing depth. However, high salt concentrations (>20 $mS.cm^{-1}$) were also observed even in deep soil samples, especially in fine texture soils (silty clay loam and silty loam). These results highlight that soil salinization is a problem that affects both surface and deep layers. In turn, the depth and quality of the water table are relevant to the development of revegetation programs. In this study case, the phreatic level is relatively shallow (between 1 and 4 m deep), which may increase the chances of survival if the implanted species reach this water reservoir. However, measurements of the electrical conductivity of the phreatic for the different analyzed plots indicate that the quality of this water resource is variable spatially and temporally (Meglioli et al. 2018).

Restoration of salinized environments using native species

The ecosystem restoration approach as a practice to reverse salinization processes has allowed diminishing the economic and logistical difficulties associated with some management strategies related to a more engineering approach (Chhabra and Thakur 1998, Hamidov et al. 2007, Ram et al. 2007). Actions that can be used to restore soils affected by secondary salinization should result in the reduction of groundwater table level, the promotion of infiltration and the improvement of the physicochemical conditions of the soil (Taleisnik and López Launestein 2011). In this sense, different strategies have been tested in arid zones: reforestation to promote a decrease in the water table, an effect known as "biodrainage" (Hbirkou et al. 2011); or revegetation to improve the soil structure, that favors drainage and therefore salt leaching. Revegetation could be performed either with halophyte species (Basavaraja et al. 2007) or with non-halophyte species inoculated with microorganisms. In this case, arbuscular mycorrhizal fungi (Zhang et al. 2011) or rhizosphere bacteria (Nabti et al. 2010) are commonly used for this purpose. Another alternative is phytoremediation, which, in general terms, involves the removal of contaminants from the environment. In this case, the intention is to remove salts from the soil using halophyte plant species due to their bioaccumulatory capacity (Ravindran et al. 2007, Hasanuzzaman et al. 2014). This ability can be confirmed by detecting a decrease in the concentration of salts in the soil, along with its increase in plant tissues. This could be corroborated for different species, both native and exotic, either under controlled greenhouse conditions (Rabhi et al. 2009) or in field experiments (Hamidov et al. 2007).

The selection of suitable species in restoration projects is a key factor that can greatly determine the efficiency and success of the process. The species to be introduced in degraded ecosystems should preferably be selected from those existing in nearby non-degraded environments, in order to guarantee their adaptation to the adverse conditions in which they will be established (Cortina et al 2004). In addition, they must also be able to endure in the context of Climate Change according to the concept of prestoration (Butterfield et al. 2017). The use of native species in restoration programs requires knowledge of propagule collection sites and times, seed quality and germination requirements, as well as preconditioning techniques to overcome transplant shock and improve seedling survival (Fernández et al. 2016, Fernández et al. 2019). Besides, degraded arid lands are associated with significantly altered soil conditions, therefore knowing the different physiological adaptations of native species also allowed to evaluate their suitability to restore a particular site or microsite. The availability of information and appropriate techniques to achieve germination and subsequent production of seedlings of some native species, is a limiting factor in their selection.

Physiological adaptations of native species to be used in saline environments from the Monte desert

The use of native plants is an especially appropriate tool in restoration projects as they can ensure their adaptation to stressful environmental conditions. High salinity affects plants both by salt toxicity and by dehydration caused by low water potential. Native species exhibit physiological, morphological and anatomical mechanisms that allow them to live in saline environments. These include the elimination of salts from specialized organs, ion compartmentation, ion selectivity, osmotic adjustment, partitioning of assimilates, specialized conduction systems, reduced leaves, modification of stomatal density, presence of aquifer parenchyma, thickened cuticle, and deposition of waxes (Villagra et al. 2010, Taleisnik and López Launestein 2011, Hasanuzzaman et al. 2014, Villagra et al. 2017).

Germination is a critical stage in the plant life cycle, particularly in fluctuating and stressful environments such as those affected by salinity. The success of germination and seedling establishment is conditioned by the existence of adaptive mechanisms at these stages. The presence of dormant states in seeds is widespread in most of the native halophytes shrubs (Flowers and Colmer 2015, Tug and Yaptrak 2019). The production of heteromorphic seeds is another adaptive strategy, in which the response of each type of seed depends on different environmental factors and dormancy mechanisms. Several species of the family Asteraceae and Amarantaceae show such adaptation (Liu et al. 2018). However, the production of heteromorphic seeds for woody shrub species native from the Monte has not been described.

The propagules of many halophytes may remain viable in the soil seed bank at high salinity levels and germinate when stress decreases. Field germination for many species of saline environments usually occurs after the rainy season, when salinity levels decrease, improving the chances of seedlings surviving (Piovan 2016). On the other hand, it has been found that some species present higher germination percentages after preconditioning of the seeds with moderate salinity concentrations (<250Mm NaCl). Rapid germination (<4 days), when environmental conditions are favorable, is another adaptive strategy found in species from saline environments (Tug and Yaptrak 2019).

In the Monte region there are several species adapted to saline environments or with potential for use in the ecological restoration of degraded environments (Villagra et al. 2017, Villagra and Alvarez 2019). They can be used by diverse human populations because they provide forage, firewood, charcoal, medicinal and aromatic substances, and elements for the construction of housing in these extreme areas with low vegetation cover (Alvarez and Villagra 2009, Montani et al. 2010, Taleisnik and López Launestein 2011).

In the following sections, we review eco-physiological and morphological aspects and possible uses of species that present themselves as potential tools in the restoration of saline environments in the Monte desert; whereas they can be added to future eco-technological packages to be implemented.

Woody species

Native woody species with tolerance to salinity are a group of species belonging to several taxonomic families, which have different mechanisms of adaptation to environments that impose conditions of high salt toxicity and strong water stress (Taleisnik and López

Launestein 2011, Villagra et al. 2011, Villagra et al. 2017). The studies of physiological aspects of native species of the Monte have focused particularly on the species of the genus *Prosopis* and *Atriplex.* For some species of these genera, there are already technological packages that allow their multiplication and establishment in different field situations such as for *P. flexuosa*, *P. chilensis, A. lampa* and *A. cordobensis* (Passera and Borsetto 1989, Aiazzi et al. 2005, Villagra et al. 2010, Passera 2017). While for many species of saline environments, endemic and native, key aspects for their use in restoration tasks are still unknown, such as *Ehretia cortesia, Allenrolfea vaginata, Lycium tenuispinosum* and *Suaeda divaricata*, among others. Currently, research is being carried out by our working group in search of the productive recovery of degraded environments and/or the current demand for eco-technological packages to restore mining environmental liabilities.

Trees and shrubs of Fabaceae family

Afforestation with species of the genus *Prosopis* has been suggested as having a high potential for the productive restoration of saline environments in the Monte, taking into account their tolerance to salinity and their potential uses (Guida-Johnson et al. 2017, Villagra et al. 2017).

Prosopis shows a high inter and intraspecific variability in tolerance to salt and other environmental stresses. Moreover, salt tolerance varies during ontogeny and is associated to different physiological processes. The tolerance is lower during the initial stages of the life cycle, which seem to be critical for their persistence in saline environments (Cony 1998, Villagra et al. 2010). Salinity tolerance mechanisms observed in the genus include both the ability to regulate the absorption and transport of ions and thus to avoid the toxic effect of salinity, as well as the ability to counteract the effects of low osmotic potentials through osmotic adjustment, regulation of stomatal opening and induction of anatomical changes in roots, stems and leaves (Zhao and Harris 1992, Villagra and Cavagnaro 2005, Villagra et al. 2011).

The inter and intraspecific variability in *Prosopis* species from the Monte has been studied in different trials. From these studies, it is possible to identify a gradient of salinity tolerance among the species of the genus, from glycophytes to euhalophytes. This gradient appears to be related to the distribution of the species. Among trees, the germination capacity of *P. flexuosa* seeds is greater than that of *P. chilensis* in -0.3 M NaCl solutions (Cony and Trione 1998) and the survival of *P. flexuosa* seedlings is greater than that of *P. chilensis* in 0.5 M NaCl solutions (Rhodes and Felker 1987). In shrubs, *P. alpataco,* a dominant species in clayey and saline soils, shows a higher germination capacity and a lower reduction on its growth in saline conditions than *P. argentina*, which comes from sandy soils with very low saline content (Villagra 1997, Villagra and Cavagnaro 2005). In contrast, *P. alpataco* is more affected by water stress than *P. argentina*, which has shown to be very tolerant of low water potential but not of the toxic effect of salinity. Similarly, *P. chilensis* is more tolerant to water stress than to saline toxicity (Zhao and Harris 1992). These evidences suggest that the tolerance to salinity in some species of the genus is the result of their ability to avoid ion toxicity. In this sense, *P. alpataco* is capable of regulating the absorption and transport of ions, since it maintains low Na^+ contents and high K^+ and Ca^{++} contents in its leaves when it growths in saline conditions (Villagra and Cavagnaro 2005, Vega Riveros et al. 2011). In *P. strombulifera*, a species found in highly saline areas, it has been found that low NaCl concentrations stimulate growth indicating that this species is an euhalophyte with respect to NaCl; however, SO_4Na_2 concentrations determine growth inhibition and severe toxicity (Sosa et al. 2005). This species has been studied as a model of salinity tolerant species and presents numerous anatomical and physiological adaptations (Luna et al. 2017)

For the study of intraspecific variability of different species of *Prosopis*, seeds from randomly selected mother plants have been collected in different areas within the Monte. In total, seeds of approximately 240 origin plants of different native species of the Monte are conserved in a germplasm bank in Mendoza (Cony 1993). Besides, these seeds have been used to establish 12 hectares of progeny-procedure trials for *P. flexuosa* and *P. chilensis* in the town of Bermejo (Mendoza). The comparison of the growth characters, bioform and physiology among different origin enabled the identification of rapid growth provenances in both species (e.g. Bolsón de Fiambalá, Catamarca) (Cony 1996, Cony and Trione 1998, Mantován 2002, Mantován 2005). The observed differences among provenances are consistent with the structural differences among woodlands in their natural distribution (Villagra et al. 2005, Alvarez et al. 2015). Genetic studies in *P. flexuosa* suggest that these morphological and physiological differences have a significant genetic basis and may be explained by local adaptation (Bessega et al. 2019). However, the potential of these provenances for afforestation of areas with water or salt stress has not been extensively evaluated for Monte species; while initial studies have been conducted on species in Chaco and other sites (Velarde et al 2003, Felker et al. 2008). In this sense, differences have been observed among *P. flexuosa* provenances at germination stages in saline conditions, with some of them emerging as potential provenances to select for salinity tolerant (Cony and Trione 1998).

The high genetic variability observed (Bessega et al. 2019) and the differences between the provenances in salinity tolerance at germination stage in *P. flexuosa* and *P. chilensis* (Westphal et al. 2015, Cony and Trione 1998), leads us to think about the possibility of selecting suitable provenances of these species for the implantation of areas with environmental stress. To test this idea, we performed greenhouse and field experiments to evaluate the effects of salinity on growth performances of four provenances of *P. flexuosa* and five provenances of *P. chilensis*.

In the greenhouse trial, a split-plot design was arranged, containing the combination of species and provenances, and three treatments of sodium chloride solutions (T1 = 0.02 M; T2 = 0.10 M; T3 = 0.25 M) were applied to blocks, during the summer 2015. Results showed that all species and provenances decreased their growth and ecophysiological parameters (such as water potential) under increased salinity stress. Plant growth indicators of salinity tolerance showed that aerial biomass per plant was reduced between 41% and 48% for T2 and between 55% and 65% for T3 in relation to T1 (control) (Figure 3).

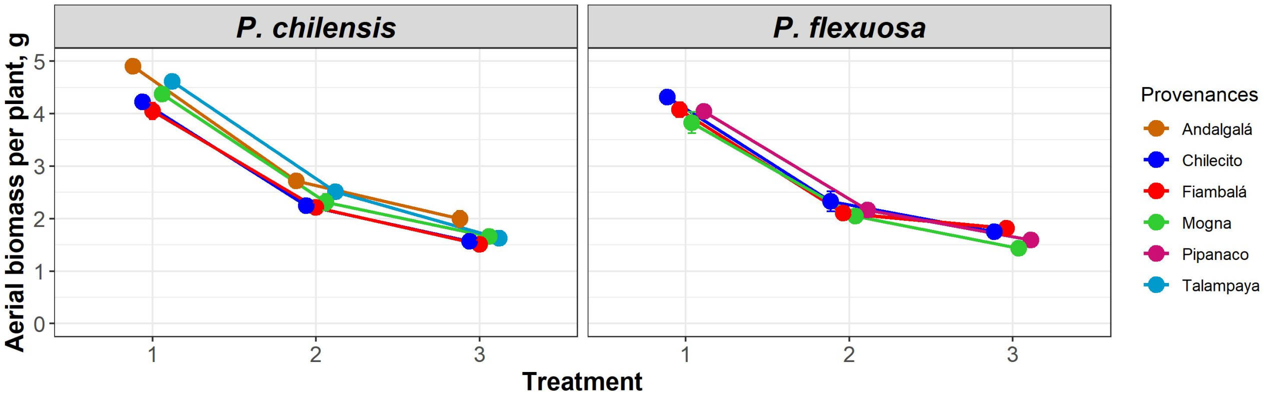


Figure 3. Aerial biomass of different provenances of *P. chilensis* and *P. flexuosa* growing under three saline treatments (T1=0.0; T2=0.10; T3=0.25 M NaCl) in a greenhouse trial.

The field trial was performed in salinized soils of irrigated areas of Media Agua (San Juan Province). These sites were chosen because there is a large proportion of land with salinized soils and/or irrigation problems. In areas with non-saline soils are developed poplar, olive, vine and fruit plantations, whereas salinized areas are excluided of the local productive system. In this trial, a factorial experimental design was used according to the following detail: a) two species: *P. flexuosa* and *P. chilensis*; b) three provenances of each species: local origin, from highly saline environments, and origin with high growth rate according to previous trials (Cony and Trione 1998); and c) four site qualities: site with high soil salinity, site with medium salinity, site with low salinity but not suitable for poplar production and site suitable for poplar production (as a control to evaluate potentiality of *Prosopis* species in high-quality sites). The first results suggest that both species present some tolerance to salinity, *P. flexuosa* appears to be less affected by salinity than *P. chilensis*. Both species show a 50% of survival under medium to high salinity conditions (about 40 mS cm^{-1}) and a decrease in growth was observed as salinity increase. The establishment is a critical stage for restoration of salinized areas, and *P. flexuosa* from Fiambalá shows advantages during this period with respect to other origins. The spatial heterogeneity of the soil is a determinant of the restoration. In very saline treatments (>50 mS.cm^{-1}), the mortality of the seedlings occurs in a spatially heterogeneous way in response to the spatial distribution of soil salinity (Villagra et al. 2019). The detailed analysis of this data will be interesting since it would allow the establishment of a tolerance limit for each species and to plan with more precision the implantation strategy.

Shrubs of Chenopodiaceae family

Many native species of the genus *Atriplex* are appreciated for their nutritional quality and fodder potential. In addition, some species of this genus have been used extensively in revegetation tasks of degraded environments (Passera 1990, Fernández et al. 2016, Piovan 2019). Under laboratory-controlled trials, seeds of some native species can germinate in high proportions under water potentials of -1.5 MPa. Some species such as *A. undulata* are sensitive to saline stress, but seeds that do not germinate at high salt concentrations maintain their viability and are able to germinate when transferred to distilled water (Piovan 2014). On the other hand, seeds of *A. lampa* have the capacity to germinate in oil drill cuttings which contain alkaline salts and heavy metals and petroleum hydrocarbons (Pentreath et al. 2015, Dalmasso et al. 2018).

Seedlings of *A. lampa* and *A. cordubensis* perform an osmotic adjustment, allowing them to maintain turgidity in leaves with low water potential and to continue absorbing water from the soil both in saline and water stress conditions (Passera and Allegretti 1996, Aiazzi et al. 2005, Fernández et al. 2018b). As in species of the genus *Prosopis*, there is great intra- and interspecific variability in response to different types of stress in the genus *Atriplex* (Ungar 1987; Piovan 2014). For instance, Aiazzi et al. (2005) found that seedlings of *A. cordubensis* respond differently to salinity according to their provenance.

Atriplex lampa shows low water potentials and reduced growth as a response to increasing soil salt concentrations (Caraciolo et al. 2002). The ability to achieve such negative water potentials may be due to the high protein contents associated with compatible osmolites, such as proline and betaine found after plants have been subjected to water deficit (Trione and Passera 1993). *A. lampa* can reach water potentials of -5.47 MPa under conditions of severe water stress (Fernández et al. 2018b). In addition, a lower shoot/root ratio has been observed for this species under salt and water stress (Passera and Allegretti 1996, Caraciolo et al. 2002, Villagra et al. 2011). This mechanism can be advantageous since the maintainance of root growth in saline soils allows plants to explore a larger volume of soil in search for water or less saline soil strata, and thus mitigate the effect of salinity. In field trials *A. lampa* has shown high levels of survival (>90%) in different environments and soil stress conditions (Dalmasso 2018, Fernández et al. 2018a, CB Passera, personal communication).

Another adaptive character to saline environments of some species of the genus *Atriplex* is the presence of salt-secreting glandular trichomes, which avoid ions accumulating in other tissues (Pérez Cuadra 2012).

Two endemic shrub species of the genus *Allenrolfea*, *A. vaginata* and *A. patagonica*, are present in Argentina and both are found in saline and alkaline soils. They present adaptations in the morphology of their leaves and the anatomy of their vascular system. Both species have reduced and stem welded leaves, and aquifer parenchyma that gives succulence and allows osmotic regulation. The stem of *A. patagonica* presents anomalous secondary growth that probably gives the phloem greater resistance to cavitation (Pérez Cuadra and Cambi 2010). *A. vaginata* has a highly specialized water conduction system. This species presents very numerous, small, short, multiple and grouped vessels. The fibrotracheids and tracheids collaborate in the conduction of water (Giménez et al. 2008). In *A. vaginata,* the utricles are dispersed with perianth remains. Both structures restrict but do not inhibit seed imbibition, constituting an adaptive mechanism to prevent germination under unfavorable conditions (Dágata, unpublished data). In *A. patagonica,* the seeds must be scarified to eliminate physical dormancy (Piovan 2014). The germination of *A. patagonica* is more affected under conditions of alkaline than saline stress and can germinate in concentrations of 0.4 M of NaCl (Piovan et al. 2019).

Shrubs of other families

Atamisquea emarginata (Capparaceae) is a foraging, melliferous and medicinal shrub. This species is a facultative phreatophyte (Jobbágy 2011) moderately tolerant to salinity. It can be easily propagated by seeds or asexually (Eynard et al. 2017). Seeds may have endogenous dormancy. However, without pre-germination treatments, 50% of seeds can germinate at 25°C (Fernández et al. 2016). Seedlings of this species reduce foliar area and stomatal conductance but maintain good growth rates under moderate water stress. Besides, under severe water stress (4-5% soil water content), it can reach water potentials of -8.2 MPa and have a high survival rate (>80%). The manipulation of irrigation, as a pre-conditioning treatment to drought, could favor a greater survival of the seedlings transplanted to the field, becoming an interesting technique for revegetation purposes (Fernández et al. 2016).

Lycium tenuispinosum (Solanaceae) is a xero-halophyte shrub widely distributed in the Monte. This species has been used for the restoration of degraded slopes (Dalmasso 2015). *L. tenuispinosum* is sensitive to hydric stress during its germinative stage, decreasing significantly the percentage of germinated seeds at water potential lower than -0.28 MPa and being inhibited the germination at -2. 24 MPa. It can germinate at pH of 5 to 9 (Dágata, 2018). However, adult specimens have been found in saline sodic soils. Branches that touch the ground can originate new plants by asexual multiplication, and its propagation by layering is feasible. In conditions of water stress, it loses the foliage and it can recover quickly after new precipitations.

Baccharis spartioides (Asteraceae) occurs in open environments with high salinity (20 dS/m). It is an endemic perennial, aromatic and medicinal shrub. In addition, it is used by local people for the manufacture of brooms. It has rhizomes and gemiferous roots that allow it to sprout (Dalmasso et al. 2016). It presents small leaves, a common characteristic in species of xeric environments. Its stomata are not protected, being elevated or at the level of other epidermal cells. It tolerates salinity but does not tolerate severe hydric stress (Pérez Cuadra 2012).

Cyclolepis genistiodes (Asteraceae) inhabits saline and alkaline soils. It is forage and medicinal shrub. In the leaves and stems of this species, the stomata are pseudo-sunken. The vascular bundles in the leaves are immersed in aquifer parenchyma (Pérez Cuadra 2012). The seeds of this species are dormant, but the rupture mechanism has not been clarified. There are problems due to fungal infection of the seeds under laboratory conditions (Peter et al. 2014). Piovan (2014) found that the threshold at which germination does not occur is -1.5 MPa. *C. genistiodes* is sensitive to saline stress in its germinative stage. However, seeds remain viable under such conditions and can germinate when transferred to distilled water; this is an important adaptive feature for species in saline environments (Piovan 2019).

Grasses

Native forage grasses of the Monte are able to resist conditions of water stress and saline toxicity (Céccoli et al. 2015) and allow livestock production in marginal areas. Besides, they enhace other associated environmental benefits such as: soil fixation, the addition of organic matter and benefits to soil microorganisms.

Pappophorum phillippianum and *Leptochloa crinita* are important forage species of the Monte owing to their presence and coverage, they even grow in saltpeter beds (Candia and Guevara 1973, Ragonese and Piccinini 1978, Pérez Cuadra and Cambi 2010). *L. crinita* was indicated as tolerant to salinity by Zabala et al. (2011). The leaves of *L. crinita* and leaves and stems of *P. phillippianum* have salt glands that excrete salts from metabolically active tissues (Taleisnik and Anton 1988, Pérez Cuadra and Cambi 2010). According to that fact it may be probable that *Pappophorum caespitosum, Chloris castilloniana, Cottea pappophoroides, Sporobolus cryptandrus* and *Panicum urvilleanum* are resistant to saline soils, since they also have cogeneric species that have glands or salt hairs (Céccoli et al. 2015).

Moreover, intra-specific variability has been found within these species, and for this reason, the selection of specific genotypes more adapted to saline soils could allow reducing the risks of mortality during the plant establishment. In this context, *L. crinita* is a promising species because it grows in a wide variety of environments with fast establishment and colonization. The fact that it is an autogamous species allows us to maintain relatively pure lines of genotypes throughout time (Kozub et al. 2017). Cavagnaro et al. (2006) classified 20 accessions of *L. crinita* from different environments of the Monte into three groups, based on the forage production per plant: high productivity (>110g dry matter plant^{-1} year^{-1}), medium productivity (between 110 and 75 g dry matter plant^{-1} year^{-1}) and low productivity (<75g dry matter plant^{-1} year^{-1}). Seeds of high productivity genotypes were collected from plants that grow in saline soils (apparent electrical conductivity >2 dS m^{-1}) thus they could be used in restoration programs for saline soils.

In germination trials, the proportion of *Digitaria californica* and *A. mendocina* seeds that germinated under a saline solution of NaCl 0.1M at 30°C was reduced by half than those incubated under distilled water. On the other hand, *Leptochloa crinita* and *Pappophorum caespitosum* maintained the same proportion of germinated seeds as the control treatment. When the seeds were placed in more concentrated saline solutions, 0.3M and 0.5M, only *P. caespitosum* seeds germinated (20% and 50% of the control, respectively) while the other species did not germinate or did so in very low proportion (Greco and Cavagnaro 2004). Therefore, *L. crinita* and *P. caespitosum* have shown to be promising species for revegetation programs of saline soils by the incorporation of seeds to the soil (Fig. 4a).

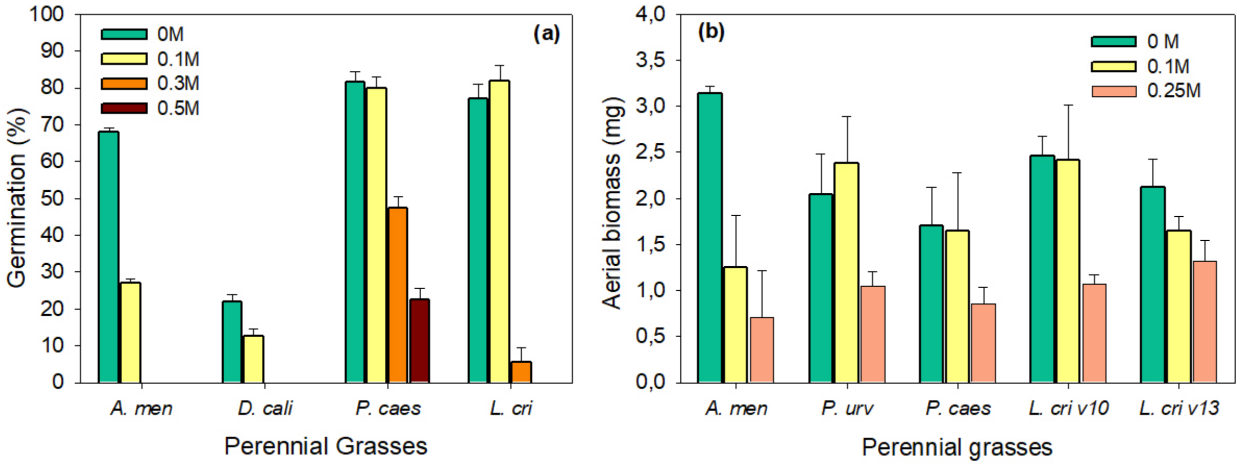


Figure 4. Germination (a) and biomass (b) of perennial grasses under different NaCl solutions. References: ***A. men***: *Aristida mendocina,* ***D. cali***: *Digitaria californica,* ***P. caes***: *Pappophorum caespitosum;* ***L. cri***: *Leptochloa crinita,* ***P. urv***: *Panicum urvilleanum,* ***L. cri v10***: *Leptochloa crinita v10,* ***L. cri v13***: *Leptochloa crinita v13.*

These perennial forage grasses also show different performance when growing with saline watering. *A. mendocina, P. urvilleanum, P. caespitosum,* and *L. crinita* were submitted to a trial in pots. Irrigation was applied with two saline solutions of NaCl: low salinity (0.1 M) and high salinity (0.25 M), and a control irrigated with running water (Próspero et al. 2018). Most of the *A. mendocina* plants died for saline treatment at 0.25M. With the 0.1M treatment, plants decreased in crown diameter, number of tillers and total aerial dry matter compared to the control treatment plants (Fig 4b). *P. urvilleanum* plants survived the 0.1M and 0.25M watering treatments, with very little reduction in crown diameter in the 0.1M treatment compared to the control and a significant decrease for the 0.25M treatment. Salinity did not affect the number of tillers. Total aerial biomass was not affected by an irrigation of 0.1M and it was reduced by half with the treatment of 0.25M (Fig 4). In the case of *P. caespitosum* plants, both, crown diameter and number of tillers were not affected by the 0.1 M treatment but were significantly reduced with the 0.25M treatment compared to the control. Aerial biomass was not affected by 0.1 M treatment compared to control and was half reduced with 0.25 M watering (Fig 4). Two accessions of *L. crinita* were evaluated, one of high productivity (*L. crinita* v13) and the other of low productivity (*L. crinita* v10). *L. crinita* v10 plant crown diameter was not affected by 0.1M and 0.25 M treatments. The number of tillers was slightly lower with saline treatments. The total aerial biomass of the 0.1 M treatment was similar to the control and with 0.25 M treatment it was reduced by half (Fig 4b). *L. crinita* v13 plants had similar crown diameters between treatments and the number of tillers was slightly reduced with 0.1 M and 0.25 M saline treatments. The total aerial biomass in 0.1 M treatment was reduced by 30% compared to the control and by 40% in 0.25M treatment (Fig 4b).

Summarizing, all the four species of native grasses showed tolerance to watering with saline water, although differences between species were observed. In the case of *A. mendocina*, it was the only species that did not survive with watering of 0.25M, while it did so at 0.1M. The rest of the species grew in both 0.1M and 0.25M treatments. When salinity is low (0.1M), *P. urvilleanum, P. caespitosum* and *L. crinita* v10 show little variation in their total aerial biomass compared to control. With higher salinity, the aerial biomass of all species was affected, decreasing by half. *L. crinita* v13 is a promising variety to produce fodder biomass under saline conditions because it has high productivity and it only showed a 40 % decrease in the aerial biomass with salinity.

Another promising species could be *Distichlis spicata*, named "saltgrass", which is common in drainages, salty and humid soils, mainly in the floody valleys of the southern Mendoza. It is considered a species of regular preference for livestock (Passera and Borsetto 1989) being consumed by goats and to a minor degree by horses (CB Passera, personal communication). In addition, it has been indicated as a component of the livestock diet in 8% to 24% in the summer season in humid areas (Brizuela et al. 1990).

Objectives of the restoration of saline environments

Livestock management in saline areas

The most important livestock activities in the central Monte desert, Mendoza, are goat husbandry in the northeast, and cow–calf operations in the southeast, which are managed using extensive production systems (Guevara et al. 2009). Shrublands and open woodlands play an important role because they provide forage for grazing animals throughout the year. Continuous grazing is the dominant strategy employed. In the other hand, semi-intensive or intensive livestock production, mainly cattle production, takes place in irrigated oases. In both areas we can find areas with soils with high salinity or salinized by anthropic action, characteristic that constitutes one of the main restrictions for agricultural and livestock production (Taleisnik et al. 2008).

The possibility of establishing pastoral systems in saline or salinized areas should be evaluated according to the environmental conditions, the carrying capacity of agrosystems, the objectives of livestock production and the possibilities of capital investment. In some cases, grazing management can be a tool to improve these environments. The rotation of grazing sectors, depending on the availability of fodder and times of the year, together with the use of a moderate animal load adjusted to carrying capacity, would allow the maintenance of plant cover and diversity and thus the improvement of these environments. In other cases, it is necessary to resort to techniques such as the introduction of forage species, especially native species tolerant or moderately tolerant to salinity. In Mendoza, Martínez Carretero (2001) indicates for saline, warm and cold temperate deserts, the presence of species such as *Suaeda divaricata, Lycium chilense* and *Atriplex lampa*; mentioned in this work as possible species to be used for restoration. Other species also described here, both woody and herbaceous, that could be used in this type of soil are *P. flexuosa*, *A. lampa*, *T. usillo*, *L. crinita* and *P. urvilleanum*, which, are native fodder species selected by goats and cattle in different proportions, according to their diet (Allegretti et al. 2012a; 2012b, Egea et al. 2014).

The establishment of forage species in irrigated areas affected by salinity was studied in Mendoza at the INTA (National Institute for Agricultural Technology) with promising results. Besides, Ochoa (2011) evaluated the implementation and production of dry matter of introduced fodder species, such as tall wheatgrass (*Thinopyrum elongatum*), white clover (*Melilotus albus*) and yellow clover (*Melilotus officinalis*). The results obtained in these studies indicate that it is feasible to implant these species in saline areas, becoming potential material to revegetate these areas.

Forestry

In the salinized fields of the irrigated oases from the Monte, traditional forest crops are not successful. The occupation of these fields with other forest species that are less demanding in terms of soil quality and resistant to various stress conditions is a productive alternative, as has been suggested for other irrigated areas of the world (Ridley and Pannell 2005). According with the results showed in previous section of this chapter, native trees such as *P. flexuosa* and *P. chilensis* appear to be promising species given their multiple uses (production of poles, charcoal and firewood and in some cases, wood for timber) and environmental benefits, such as nitrogen fixation, nutrient cycling and generation of microhabitats for other species, among others (Fig. 5a y 5b). Although these are perhaps the species in which studies for their use are most advanced, the lack of proven technologies for their establishment and management in these extreme environments still makes it difficult for producers to consider this alternative species and their use for productive purposes. In plantations with both *Prosopis* species under saline soils we observed great variability in plant growth, even within the same provenances, which is an aspect to be improved in order to achieve a homogeneous plantation for productive purposes. Further study is still needed on the selection of adequate germplasm, transplanting methods, irrigation requirements, the control of weed competition, the use of fertilisers and manures, and pruning management. Additionally, it is important to evaluate the costs related to the different stages of production and planting of the seedlings, as well as the management and monitoring of the forested plots.

Both *Prosopis* species are also proposed for the afforestation of non-irrigated saline environments of the Monte desert. *P. flexuosa* grows in saline areas of the Monte. However, the distribution of this species woodlands in saline environments gives us an idea of the importance of considering the spatial heterogeneity of salinity when setting the implementation strategy in afforestation tasks.

Figure 5. a) Afforestation with *Prosopis* spp. in moderately saline irrigated lands in Media Agua, San Juan (Photograph: P.E. Villagra. b) Restoration of highly salinized irrigated

lands in Media Agua, San Juan. c) Ecological restoration in an oil well location in Tupungato, Mendoza (Photograph: M.E. Fernández). d) Restoration of areas degraded by mining activities, Catamarca (Photograph: C.B. Passera).

Restoration of areas degraded by mining activities

Mining can severely affect natural ecosystems in aridlands. The observed environmental changes by mining activities depend on the type of techniques used and the exploited field. The main types of environmental modifications are loss of the vegetation cover, complete loss of surface soil, erosive processes, environmental liabilities, soil compaction, changes in the landform, salinity, and sodicity problems, and drainage changes (Ciano et al. 2005, Arce et al. 2015). To restore these environments, it is first necessary to improve soil conditions through modifications of the topography, soil scarification, application of new soil covers, soil amendments, and water-retention polymers (Fig. 5c y 5d) (Ciano et al. 2005, Cony et al. 2013, Cony 2016, Busso and Pérez 2018).

Due to the harsh environmental conditions, the main technique to restore the native vegetation of these areas is the transplanting of nursery-grown seedlings. This allows higher survival rates than seed-based restoration (Cony et al. 2013, Pérez et al. 2019). Many of the species mentioned in this chapter have been successfully used to restore areas degraded by the mining industry. Some of them are *P. flexuosa*, *A. lampa, A. sagittifolia,* and *P. caespitosum*. Survival percentages of transplanted seedlings are highly variable, around 40-90% (Ciano et al. 2005, Cony et al. 2013, Dalmasso et al. 2015, Cony 2016), and the main causes of mortality are soil heterogeneity, water availability and herbivory.

Biomass production for energy

An alternative to be evaluated is the implantation of species with energy potential, whose objective is the carbon fixation and the subsequent transformation into energy from biomass. This is an underdeveloped line of study in the Argentine Monte region, but it is beginning to develop in other arid areas of the world (Paneque 2013). Possible products include firewood, thermal power generation, biofuel and biogas production. Of these alternatives, firewood production is traditional for local people, where there are native species of excellent quality and calorific value, such as *P. flexuosa* and *P. chilensis* (Alvarez y Villagra 2009). There are no major advances in the rest of the products although it is interesting to start exploring the heating power of species from highly saline environments, such as *Allenrolfea vaginata, Suaeda divaricata* and *Atriplex crenatifolia*. Some observations in these species suggest that they have relatively high productivity in these environments. The productivity of other *Atriplex* species has been evaluated in the coastal desert of Chile, finding under-irrigation yields of 5200 kg ha^{-1} year^{-1} and a calorific value between 3500 and 4500 kcal kg^{-1} (Paneque 2013).

Final considerations and general conclusions

The restoration of soils affected by salinization is, therefore, a challenge that requires interdisciplinary studies that broaden the knowledge not only of native species and origins to be used, the appropriate implantation practices and technologies but also of environmental factors and management practices that generate the saline conditions (Meglioli et al. 2018). The diversity of ecosystems and agroecosystems in the Monte region, with their different states of degradation of their environments, and the range of economic and cultural activities, imprints on us particular dynamics of resource use and management, wich should be integrated into any restoration project (Fig. 6).

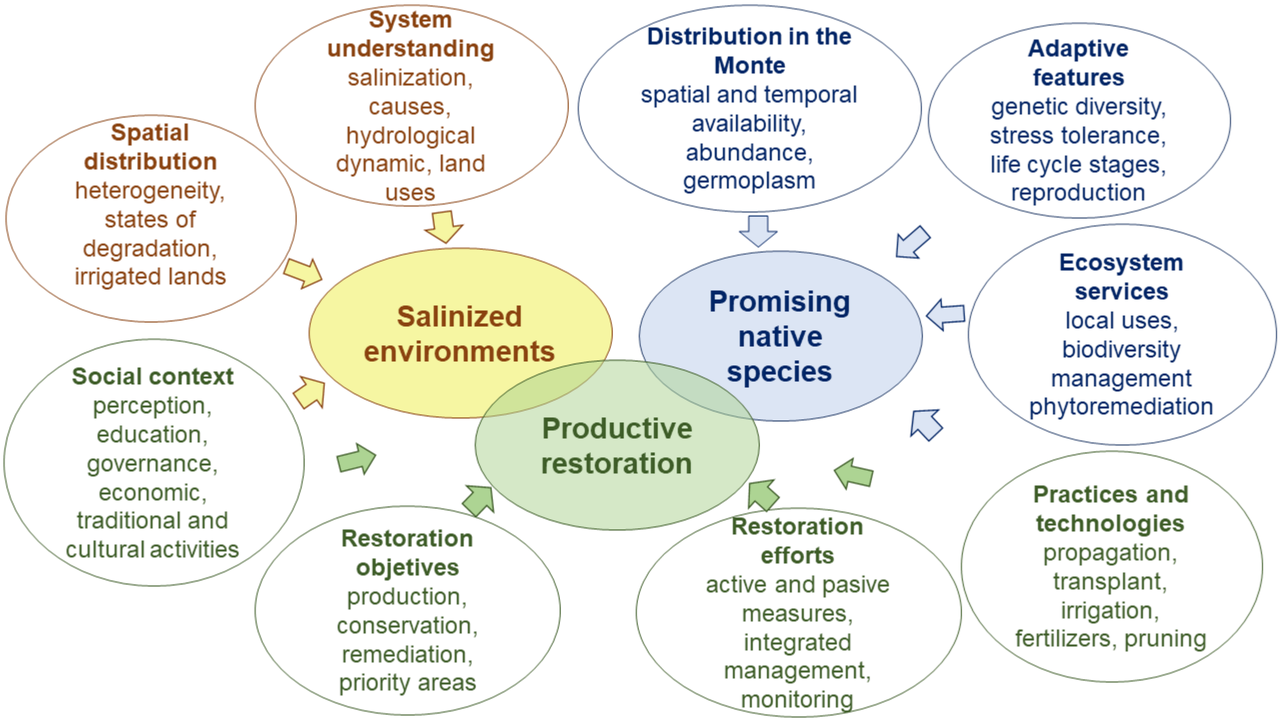


Figure 6. Some aspects of native plant species, salinized environments and productive restoration that would be relevant to consider for improving the success of ecological restoration programs.

The selection of native species mixtures and plant functional groups to be applied in restoration programs, still requires detailed information about the biology and ecophysiology of the species, their interactions with biotic (included herbibory) and abiotic stress, which coexist with those imposed by salinization (Fig. 6). The restoration and productive recovery of saline environments in the Argentine Monte region presents different development according to the objective and the species to be considered for restoration. While a few species have been studied for a long time and are in stages of evaluation and selection of germplasm to take in cultivation, others are practically unknown on their physiology and behavior in different environmental conditions. The species of the genera *Prosopis* and *Atriplex*, and the grasses *L. crinita* and *P. caespitosum* appear initially as the most promising. It is important to advance with the studies of other species, in order to determine productive potential and degree of tolerance to saline stress. The high variability on their adaptations to salinity found in native species implies a high potentiality for germplasm selection.

The restoration and productive recovery of saline environment can improved the provision of ecosystem services and benefits, including traditional activities in the region as livestock management and forestry, and non-traditional as energy production.

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