Int J Biometeorol (2014) 58:1433–1441
DOI 10.1007/s00484-013-0744-x

ORIGINAL PAPER

The agro-ecological suitability of *Atriplex nummularia* and *A. halimus* for biomass production in Argentine saline drylands

Silvia Liliana Falasca · María José Pizarro · Romina Nahir Mezher

Received: 4 January 2013 / Revised: 9 September 2013 / Accepted: 13 September 2013 / Published online: 15 October 2013

Abstract The choice of the best species to cultivate in semiarid and arid climates is of fundamental importance, and is determined by many factors, including temperature and rainfall, soil type, water availability for irrigation and crop purposes. Soil or water salinity represents one of the major causes of crop stress. Species of the genus *Atriplex* are characterized by high biomass productivity, high tolerance to drought and salinity, and high efficiency in use of solar radiation and water. Based on a search of the international literature, the authors outline an agro-climatic zoning model to determine potential production areas in Argentina for *Atriplex halimus* and *Atriplex numularia*. Using the agroclimatic limits presented in this work, this model may be applied to any part of the world. When superimposed on the saline areas map, the agroclimatic map shows the suitability of agro-ecological zoning for both species for energy purposes on land unsuitable for food production. This innovative study was based on the implementation of a geographic information system that can be updated by further incorporation of complementary information, with consequent improvement of the original database.

Keywords Atriplex sp. · Agroclimatic zoning · Drylands of saline soils · Argentine agro-ecological suitability

S. L. Falasca (✉) · M. J. Pizarro · R. N. Mezher
CONICET, Climate and Water Institute, INTA, Las Cabañas and Los Reseros s/n, Castelar, Province of Buenos Aires, Argentina
e-mail: sfalasca@conicet.gov.ar

S. L. Falasca
e-mail: sfalasca@cnia.inta.gov.ar

M. J. Pizarro
e-mail: mjpizarro@cnia.inta.gov.ar

R. N. Mezher
e-mail: rmezher@cnia.inta.gov.ar

Introduction

Salinity of soil or water is a major cause of agricultural crop stress and can seriously affect production, especially in arid and semiarid regions (Shannon 1998). Desertification processes affect almost 75 % of arid and semiarid regions in the world (Johnston et al. 1996). It is quite difficult to reverse desertification due to the high costs involved and the slow recovery process; therefore, it is necessary to develop integrated vegetation management techniques in these areas (Karlin 1998).

Saline soils exhibit electrical conductivity exceeding 4 dS/m in saturated extracts, or have an excess of Na^+ in soil solution or cation exchange sites (called "sodic soils"). Salinity in soil may be due to natural or anthropogenic causes (derived from activities that produce an elevation of groundwater and / or increase the conductivity of the soil solution, associated with poor drainage, irrigation with poor quality water or excessive fertilization) (Lavado 2008).

Drylands salinity problems in Argentina

According to FAO-UNESCO, Argentina ranks third in the world (after Russia and Australia) in halomorphism processes (salinization, alkalinization and sodicity), which are increasing because of mishandling of irrigated soils (Taboada and Lavado 2009).

In Argentina, halomorphism processes affect arid, semiarid and even humid sectors, with and without irrigation, many of them coinciding with the country's productive areas. An example is the Calchaquíes Valleys' area, in the province of Salta, due mainly to its prevailing climatic and geological conditions. In the semi-arid Chaco—a sub-region of the Chaco Phytogeographic Region—the main limitation to growth is water availability, though soil salinity is also one of the primary constraints of land use (Angueira 1986). Water table dynamic processes in poorly drained soils are also present in the submeridional lowlands of Santiago del Estero and in large parts of the Southern and Eastern Córdoba, with large salinized areas. Other causes of salinization, such as clearings in Chaco and Formosa or drip irrigation in areas of Cuyo (Mendoza, San Juan and San Luis), leading to these phenomena and degradation should also be noted.

The replacement of mountain vegetation under semiarid to arid climates by irrigated crops has contributed to anthropogenic salinity. With supplementary irrigation, the water table rises, together with deep salts. In these areas, evapotranspiration exceeds precipitation, mobilizing water with higher saline concentration that—if evaporated—contributes to soil salinization. Mendoza, located at the Monte Phytogeographical Province, also has a high proportion of lands affected by salinity. Other affected provinces are Tucumán, Catamarca, La Rioja, Rio Negro and Chubut.

It is estimated that, in addition to naturally saline areas, anthropogenic salinity now affects on average 30 % of irrigated land in Argentina (Lavado 2008).

General characteristics of *Atriplex* spp

Atriplex is the largest and most diversified genus of the Chenopodiaceae family. Chenopodiaceae plants are distributed widely in temperate and subtropical saline habitats, particularly in coastal areas of the Mediterranean Sea, Caspian Sea and Red Sea, in the arid steppes of Central and East Asia, in the margins of the Sahara desert, in the alkaline prairies of the United States, in the Karoo of Southern Africa, in Australia, and in the pampas of Argentina. They also grow as weeds in the saline soils of urban areas, especially where water pollution and soil alteration have caused salinity problems (Mulas and Mulas 2004).

Species of the genus *Atriplex* are characterized by high biomass productivity, high tolerance to drought and salinity, and high efficiency in solar radiation use (Múlgura de Romero 1981). Moreover, they can provide a high quantity of leaf biomass during unfavorable periods of the year, being used as forage rich in protein and carotene and as means of combating desertification. Plants of this genus are able to fix CO_2 following the C_4 biosynthetic pathway. They also require good amounts of sodium—an essential element of metabolism. During C_4 photosynthesis in these plants, the conversion of atmospheric carbon gas into plant material uses less oxygen, less water, fewer nutrients, and with minimum destruction of its own living tissue during the process.

Atriplex halimus (common names: saltbush, marisma, orgaza, sea purslane, shrubby orache) is a perennial shrub 2–3 m high. It is highly resistant to drought to the extent that it can survive for some time without rain. The growing season ranges from 60 to 120 days (FAO-Ecocrop 1993–2007). This shrub has a constant high salt content in its leaves, accumulating the salt excess in the plants hairs (Mozafar and Goodin 1970). These plants do not burn well because of their salt content, so their introduction to high risk fire areas could be of interest.

Some populations able to survive to salinity levels higher than those of sea water (up to EC: 60 mS/cm) have been the subject of several studies (Zid 1970; Franclet and Le Houérou 1971; Malcom and Pol 1986; Le Houérou 1986, 1993). When excreting salt through its leaves, *Atriplex* becomes a potential desalination plant, provided the material is removed periodically to prevent the salt from returning to the ground, which makes it ideal as a biomass producer. *A. halimus* is also able to grow and produce normally in non-saline soils (Mulas and Mulas 2004).

In Australia, many studies have focused on soil salinity combat using native species (Malcom 2000). *Atriplex nummularia* (common name: old man saltbush; http://www.florabank.org.au/lucid/key/species%20navigator/media/html/Atriplex_nummularia.htm) is an evergreen shrub, dioecious, erect, branched, evergreen, ashen colored, which reaches 1–3 m tall, is columnar in appearance and is originally from Australia (Enríquez-Carrillo et al. 2011). Its root system may develop over 3 m in depth and up to 10 m in width (Jones 1970). Thornburg (1982) reported that *Atriplex nummularia* grows where rainfall is at least 180 mm/year. Positive characteristics of this species are: good forage yields, strong resistance to extreme drought, resistance to grazing with fast resprouting, resistance to disease, and easy propagation. Moreover, its fuel wood has good energy content.

In the arid IV Region of Chile, *A. nummularia* is currently the most important species in reforestation and desertification control projects (Mulas and Mulas 2004). In these environmental conditions, forage shrub plantations can provide a supplement to cattle feed, which is based mainly on pasture, when forage availability from herbaceous cover is low due to drought.

Belkheiri and Mulas (2013a) compared both species after having subjected them to water stress. *A. nummularia* showed a greater osmotic adjustment and a positive net solute accumulation than *A. halimus*, suggesting that water stress resistance in *A. halimus* is linked to higher water use efficiency rather than a greater osmotic adjustment.

Uses and productivity

The benefits of *Atriplex* species are: long-term survival and biomass production on moderate-to-strong saline and waterlogged soils; drought tolerant; they can be used as plant-based “water pumps” to maintain saline water tables below critical depths; best used in conjunction with other feeds because they have: high protein concentration, adequate metabolizable energy, high salt concentrations, limited edible dry matter and moderate oxalate concentrations. Species of this genus also have a high ability to absorb nitrogen from the soil and can benefit from the action of nitrogen-fixing microorganisms (Ismaili et al. 2000).

A. halimus presents high bromatological values. The crude protein content is equivalent or superior to that of legumes and its digestibility is very high (Barroso et al. 2005). The literature suggests values of crude protein of 15–20 % and of 60 % digestibility (Correal 1993). It is tolerant to both intense and brief grazing, with full recovery the year after being grazed (Valderrábano et al. 1996). Salt content of edible parts of *Atriplex* plants, such as leaves and young shoots, is high. For this reason, sheep fed with *Atriplex* need to drink frequently and, in this case, the amount of ingested water may reach 11 L head^{-1} day^{-1} (Le Houérou 1991; Mirreh et al. 2000).

In the South of Spain, *A. halimus* produces edible biomass yields of 450–500 g/plant per year, in spite of its low nutritive value, due to its high content of non-proteic nitrogen (Correal et al. 1990).

At a research trial, Belkheiri and Mulas (2013b) observed that the leaves and roots of both species responded positively to increasing NaCl concentrations up to 600 mM NaCl for *A. halimus*, whereas the optimal growth of *A. nummularia* was recorded at 300 mM NaCl. *A. halimus* is a better ion accumulator and it may be used for phytoremediation.

The best yields, of about 15–20 ton ha^{-1} year^{-1}, can be obtained with salt concentrations below 300 mM/L of NaCl equivalents (Le Houérou 1986). Trials performed at drylands with saltbush plantations are much modest than those with irrigated trials.

In some areas of Southern Coquimbo (Chile), with rainfall ranging from 100 to 220 mm/ year, yields of *A. nummularia* plantations have varied from 50 to 900 kg DM ha^{-1} year^{-1}, depending on age, field management and plant density. In areas with 143 mm/year rainfall, average yields of 1,806 g/plant have been observed (Soto 1996). Planting density directly affects yield. So, as *A. nummularia* planting densities increase from 625 to 10,000 plants/ha, yields also experience an increase. However, leaf production decreases at planting densities over 2,500 plants/ha (Soto 1996).

A. nummularia has become commonly cultivated as a source of stock fodder and its potential to also address dryland salinity in southern Australia is under investigation (Hobbs et al. 2006). It has good production of biomass when irrigated with saline water (EC: 15–20 mS/cm) and yields may exceed 30 tons DM ha^{-1} year^{-1} (Le Houérou 1992); it also withstands long periods under soil flooded conditions: in North Africa, plants survived 3 months of flooding; they present fast and abundant regrowth after grazing and overgrazing resistance, which is the main limitation to the use of forage species. After elimination of the leaves, the plant needs a rest period of about 8–10 months to recover. On the other hand, if the plant is not grazed, its life is no longer than 12–15 years. Every 5 years, renewal pruning is recommended at 20–40 cm above the ground (El Mzouri et al. 2000).

Pruned woody branches are an important energy resource. For instance, the energy content of *A. nummularia* wood is about 4,538 kcal /kg (Garcia 1993). Yields of fuel wood obtained from *Atriplex* plants can also be considerable (Rivera 1996).

Atriplex can be utilized for biotechnical conversion in the production of gaseous or liquid fuels. Growing on saline land in Pacca Ana (Pakistan), the calorific value is 4,331 kcal /kg dried matter (El Basam 2010).

Carbon sequestration is a function of the biogeochemical exchange between plants and the atmosphere, and depends on land use and climate. According to Sochacki et al. (2012), *A. nummularia* produces a mean total biomass of 3.8 tons ha^{-1} year^{-1}, that is to say 6.9 tons CO_2-e ha^{-1} year^{-1} averaged over 4 years in Australia.

Ecological requirements

Selection of the best cultivation species is fundamental in semi-arid and arid climates and is determined by many factors, such as temperature and rainfall, soil type, water availability for irrigation and crop purposes.

A. halimus fits better in Mediterranean climates; however, it is a rustic species that tolerates harsh environmental conditions. It adapts to wet tropical and dry tropical climate (Aw), desert or arid climate (BW), or semi-arid steppe climate (BS) and subtropical dry summer (Cs) (FAO-Ecocrop 1993–2007).

Atriplex is a short-day plant (less than 12 h) (FAO-Ecocrop 1993–2007). It grows up to 1,500 m above sea level (Iglesias and Taha 2010).

Usually, the genus *Atriplex* can grow and reproduce under rainfall conditions ranging between 100 and 400 mm/year, with yields varying from 1 to 3 tons DM ha^{-1} year^{-1} (Sankary 1986).

The plant survives with precipitation ranging from 100 to 250 mm; however, better production is obtained with mean annual rainfall from 250 to 650 mm (Nefzaoui and El Mourid 2008). No problems are observed with precipitation of 50 mm per year and—in some cases—it survived one or more years without rainfall.

Atriplex has high water-use efficiency (Belkheiri and Mulas 2013a). In fact, *A. nummularia, A. halimus*, and *A. canescens* produce 10–20 kg DM ha^{-1} year^{-1}, per millimeter of rain (Forti 1986; Correal et al. 1990; Le Houérou 1992). In spite of the high water-use efficiency of *Atriplex* plants (Silva and Lailhacar 2000) when planted in regions with an average rainfall of 200–300 mm/year, it is convenient to irrigate the crop with at least 200–250 mm water/year (Le Houérou 1992).

At irrigation levels ranging from 100 to 400 mm of water ha^{-1} year^{-1}, some *Atriplex* species—*A. halimus* included—showed water-use efficiency values of 5–10 kg DM ha^{-1} year^{-1}, per millimeter of water and yields of 2 to 4 tons DM ha^{-1} year^{-1}. Therefore, these forage shrubs showed water-use efficiency high enough to produce a DM quantity twice higher than that of wheat and barley, and 4–5 times higher than that of Lucerne (Le Houérou 1992). In Western Australia, plantations of *Atriplex* irrigated with 500 mm/year yielded more than 5 tons DM ha^{-1} year^{-1} (Malcom and Pol 1986).

A. nummularia lives naturally in areas with rainfall between 150 and 400 mm (Enríquez-Carrillo et al. 2011). Winter temperatures decrease growth, e.g., saltbush presents very little or no growth at all when the average ambient temperature is lower than 11 °C. According to Florabank of Australia (http://www.florabank.org.au/…/Atriplex_nummularia), it inhabits sites where the mean annual temperature fluctuates from 13 to 24 °C, with the mean maximum temperature of the warmest month ranging from 32 to 37 °C and the mean minimum temperature of the coldest month ranging from 3 to 7 °C. Seeds usually germinate in 1–3 weeks at 13 °C (Rice 1988). Optimum temperatures fluctuate between 16 and 28 °C (FAO-Ecocrop 1993–2007) and they need an average solar radiation of 766 cal cm^{-2} day^{-1} (Iglesias and Taha 2010).

Regarding minimum temperatures that these species can withstand, we may say that they can resist frost intensity between −8 °C (*A. nummularia*) and −12 °C (*A. halimus*) (Huxley 1992). Plants can be damaged by severe frosts but they soon recover (Bean 1981).

In terms of soil requirements, they survive quite well in heavy textured thin soils, poor and sandy soils, but their best development and productivity can be found in deep medium textured soils with good drainage. They tolerate well a pH range of 6.8 to 8.2 (Iglesias and Taha 2010), with an optimum of 7.2 to 7.8 (FAO, Ecocrop 1993–2007).

This aim of this work consisted in defining the agro-ecological suitability of Argentine drylands saline soils to produce lignocellulosic biomass from *A. halimus* and *A. nummularia*.

Materials and methods

We used mean annual rainfall and temperature data available for the period 1981–2010, from meteorological and agrometeorological stations located within the geographical area under analysis.

In a first step and in order to analyze the bioclimatic requirements of *Atriplex* spp, we focused on the moisture factor, analyzing the average annual isohyets of 250, 400 and 650 mm. Those areas receiving from 100 to 250 mm annually (Nefzaoui and El Mourid 2008), were described as marginal areas; although the situation could be improved by implementing complementary irrigation. In the range of 250–400 mm (Sankary 1986) the area qualifies as suitable, and from 400 to 650 mm: optimal. However, rainfall higher than 650 mm to 1,200 mm also determined suitable areas (FAO-Ecocrop 1993–2007).

In order to consider the thermal factor, we took into account the isotherm corresponding to the average annual temperature of 13 °C.

The country's geographic areas that do not meet this condition qualify as non-suitable areas. In addition, we considered that the coldest month's average minimum temperature should exceed 3 °C and the warmest month's average maximum temperature should not exceed 34 °C (average 32–37 °C).

Once satisfied that the mean minimum temperature of the coldest month was over 3 °C and the average maximum temperature of the warmest month was below 34 °C, we outlined the optimal area from the thermal point of view. When the average maximum temperature of the warmest month exceeds 34 °C, the area qualifies as a marginal area. Similarly, when the average temperature is over 13 °C and the

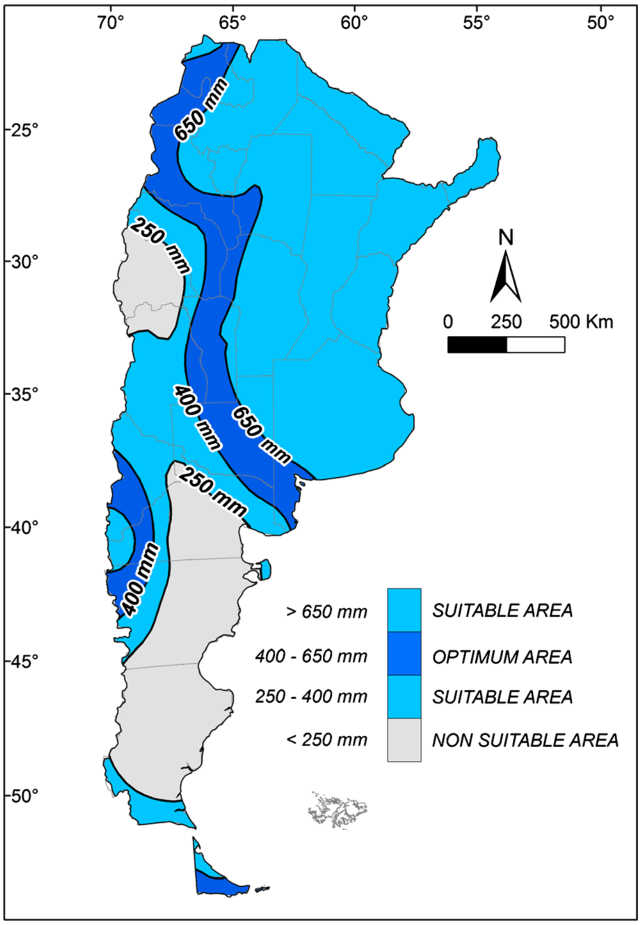

Fig. 1 Moisture regimes in Argentina: annual rainfall

average minimum temperature of the coldest month is higher than 3 °C, the area qualifies as suitable.

Furthermore, winter frosts intensity should be below −8 °C; otherwise, it would have a lethal effect on *A. nummularia* and −12 °C on *A. halimus* (Huxley 1992).

An agro-climatic zone map was then obtained by overlaying the previous maps. With the available database, we used the geographical limits for the different variables as five aptitude classes: optimal zone, very suitable, suitable with irrigation, suitable with constraints and non suitable were defined and mapped.

To obtain the maps, we used a series of previously interpolated bioclimatic variables, which were then processed with the Geographic Information System (GIS) tool of the Arc-GIS 9.3 program. These five bioclimatic variables, obtained from interpolation from data from 125 meteorological stations of the National Meteorology Service, and which cover all the Argentine Republic, were: (1) average annual temperature >13 °C, (2) mean minimum temperature of the coldest month (July) >3 °C, (3) average maximum temperature of the warmest month (January) <34 °C, (4) absolute minimum temperature −8 °C (*A. nummularia*) and −12 °C (*A. halimus*), and (5) average annual rainfall (240, 400 and 650 mm).

Climatic interpolations were made using the "Interpolate to Raster" tool, within the "3D Analyst" extension of the Geographic Information System (GIS) of the Arc-GIS 9.3. Program, following the Ordinary Kriging interpolation method.

Agroclimatic suitability and agro-ecological suitability mapped variables were obtained from multivariable integration geoprocessing, using the "Raster Calculator" tool of the "Spatial Analyst" extension of the same program.

Based on FAO (2008) salinity classification, drylands saline soils were plotted in Argentina, considering "moderately saline phase" when soil electrical conductivity ranges from 8–16 mmhos/cm and "strongly saline" when it exceeds that value, as possible sites for *Atriplex* spp. implantation, since both species tolerate values of 12.4 to 22.1 dS/m of high to extremely high salinity.

The overlap of the agroclimatic suitability map with the drylands saline soils map shows the agro-ecological zoning and defines the potential growing areas for *Atriplex*

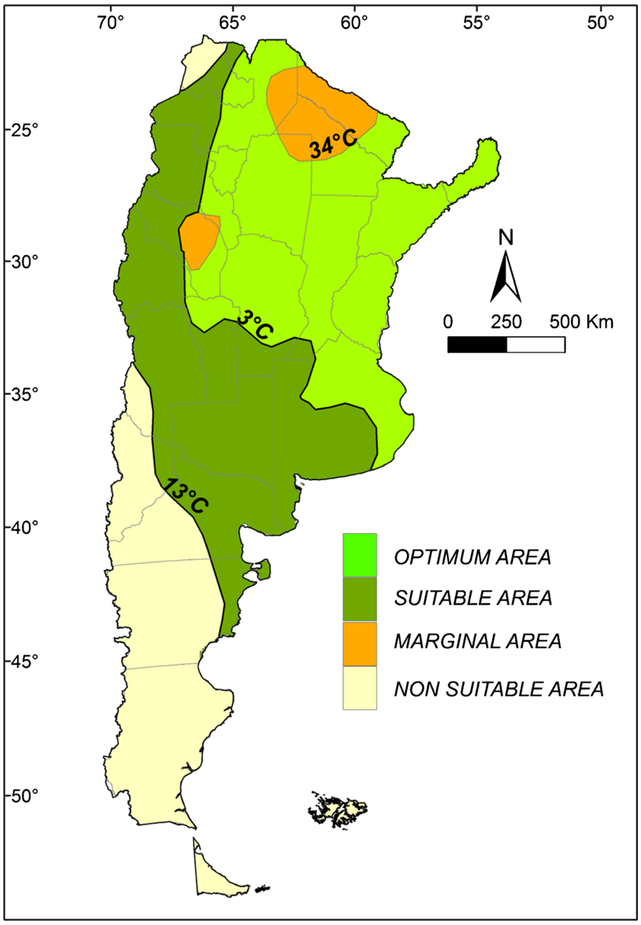

Fig. 2 Thermal regime: 13 °C is the mean annual temperature, 3 °C represents the mean minimum temperature of the coldest month and 34 °C represents the mean maximum temperature of the warmest month

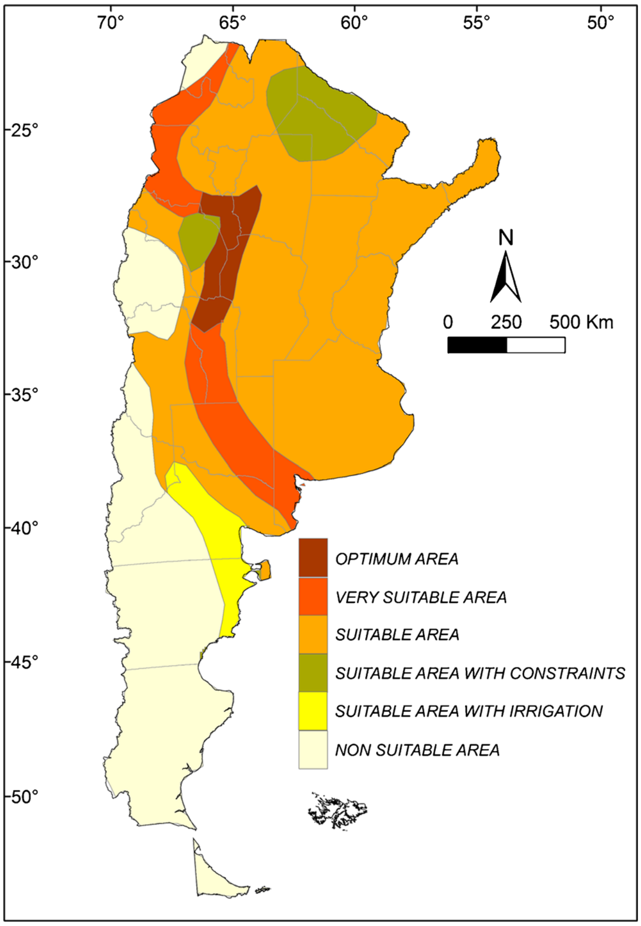

Fig. 3 Agroclimatic suitability for the cultivation of *Atriplex halimus* and *Atriplex nummularia*

nummularia and *A. halimus* in Argentina for bioenergy on marginal soils.

According to Sochacki et al. (2012), *A. nummularia* produces a mean total biomass of 3.8 tons ha^{-1} year^{-1}, that is to say, 6.9 tons CO2-e ha^{-1} year^{-1} averaged over 4 years in Australia. On the basis of this data, we calculated the potential carbon sequestration for each of the agro-ecological zoning aptitude classes. The obtained results provide an approximate idea of the ton CO_2e that could be "sequestrated" in Argentina, by the implementation of *Atriplex nummularia* at each delimited zones.

Results and discussion

Figure 1 shows the delimitation of moisture regions. For this purpose, mean annual isohyets of 250, 400 and 650 mm were included. If an area receives from 100 to 250 mm rain annually (Nefzaoui and El Mourid 2008), it determines a marginal area and requires the application of complementary irrigation to obtain good yields of biomass; the range 250 to 400 mm (Sankary 1986) results in a suitable area; while 400–650 mm describes an optimal area. Annual rainfall of over 650 mm to 1,200 mm determines suitable areas (FAO-Ecocrop 1993–2007). Optimal areas comprise two sub-regions: one covers a strip running down the center of the country and extending to the province of Jujuy in Northern Argentina; and the other is located in the Patagonian mountain skirts, covering the provinces of Neuquén, Rio Negro and Chubut. Suitable areas extend on both sides of the optimal areas.

Figure 2 shows thermal regions. Thus, the isotherm corresponding to the average annual temperature of 13 °C determines non suitable areas to the south and to the west. Suitable areas are circumscribed to conditions of 13 °C isotherm and 3 °C, corresponding to the average temperature of the coldest month. Optimal areas are determined by conditions of 3 °C isotherm and 34 °C isotherm, corresponding to the average temperature of the warmest month. When such a temperature range is exceeded, the area qualifies as marginal. The optimum area covers most of northern and central Argentina. This area is interrupted by two marginal sectors: one located in the province of La Rioja, which covers part of southern Catamarca, and the other located in the province of

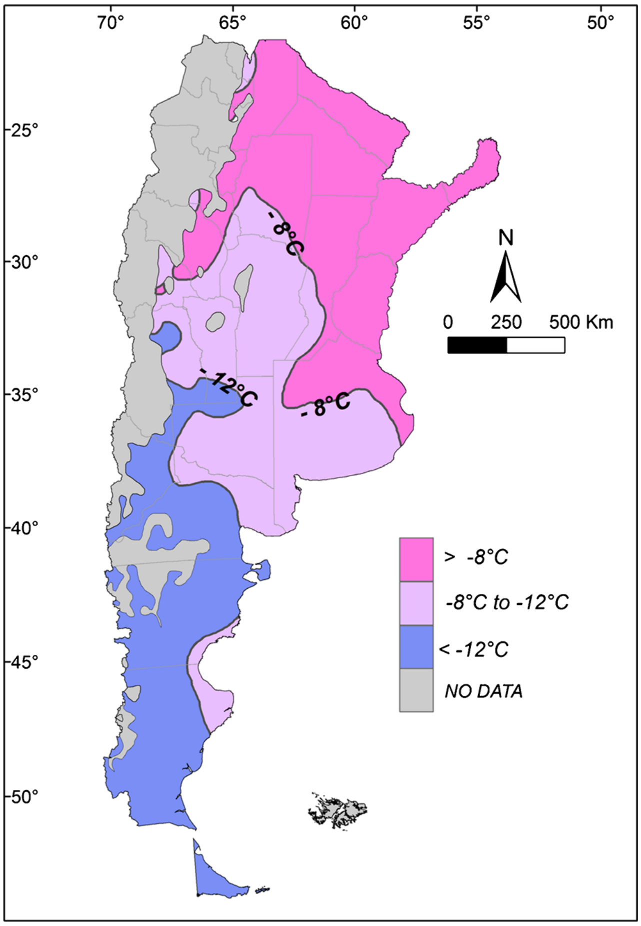

Fig. 4 Absolute minimum temperature: −8 °C (*A. nummularia*) and −12 °C (*A. halimus*)

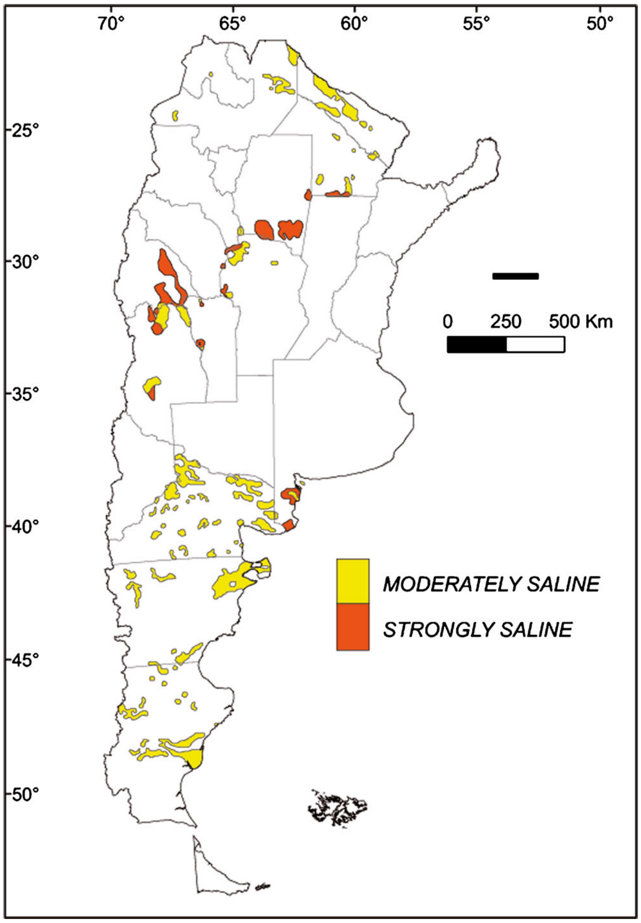

Fig. 5 Drylands salinity map (reference: FAO 2008)

Formosa. Suitable areas include part of the Patagonian sector, most of the western part of the country and the rest of the pampas.

The overlay of both maps (Figs. 1 and 2) allows an Agroclimatic suitability map to be generated (Fig. 3), which determined five suitability classes. The optimal area comprises Southwestern Santiago del Estero, Northwestern Cordoba, Northern San Luis, Western La Rioja and Catamarca. The area comprises two very suitable sub-regions: the Northwestern Region (Salta, Jujuy, Northern La Rioja and Western Catamarca) and another center sub-region covering Central San Luis, Western Mendoza, Central La Pampa, Southern Buenos Aires and a small sector of Rio Negro. To the South, it was possible to define a zone classified as suitable area with irrigation, which covers a small area of Neuquén, a small area of Rio Negro and Chubut, which could be irrigated with seawater at coastal areas. There were two areas suitable with constraints: one covers part of Chaco, Santiago del Estero, Formosa and Salta, and the other part of La Rioja and Catamarca.

Figure 4 shows the lowest temperature that represents the minimum lethal temperature for each species, which is −8 °C for *A. nummularia* and −12 °C for *A. halimus*. While these low temperatures have a recurrence of one occurrence every 30 years, this must be weighed against a possible loss of biomass, because both species recover easily after frost.

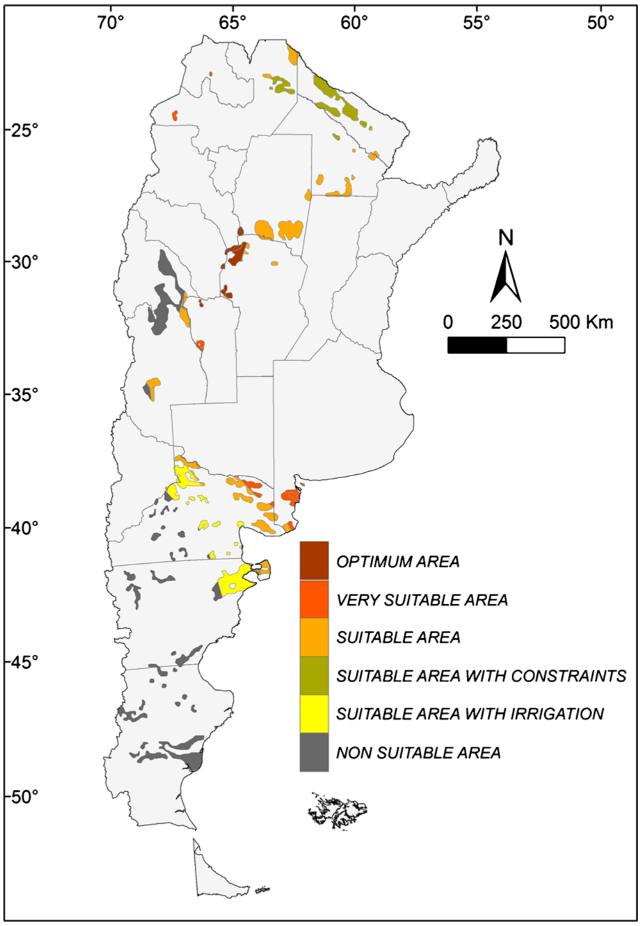

Fig. 6 Agro-ecological suitability map for the cultivation of *Atriplex halimus* and *A. nummularia*

Table 1 Potential carbon sequestration in the potential growing areas for *A. nummularia and A. halimus*

Area	Potential agricultural land (ha)	Carbon sequestration CO$_2$-e ha^{-1} year^{-1}
Optimal	771,779	5,325,275.1
Very suitable	967,885	6,678,406.9
Suitable	4,494,218	31,010,104.0
Suitable with constraints	1,676,886	11,570,513.0
Suitable with irrigation	2,352,033	16,537,161.0
Total carbon sequestration		71,121,460.0

Figure 5 shows the Drylands saline soils in Argentina (FAO 2008).

Finally, Fig. 6 shows the agroecological suitability map resulting from the overlap of the agroclimatic suitability map with the drylands salinity map (Fig. 5). The same six fitness classes delimited at the agroclimatic suitability map were observed. Lands classified with different degrees of fitness should be allocated to the cultivation of *A. nummularia* and *A. halimus* for energy purposes, knowing that such lands are not intended to compete with those designated for food.

Furthermore, *Atriplex* species planted in soil with moderate to severe salinity problems can produce additional fodder for livestock, while stabilizing severely disturbed lands, meaning that these shrubs may be used for the rehabilitation of saltland.

Besides, *A. nummularia* is one of the plants that have been identified by the United Nations' Carbon Emission Trading Scheme to assist with the battle against global greenhouse warming and the sequestration of atmospheric carbon back into the soil. Potential carbon sequestration was calculated according to Sochacki et al. (2012) considering that *A. nummularia* produced 6.9 tons CO$_2$-e ha^{-1} year^{-1} averaged over 4 years. Table 1 presents potential carbon sequestration in Argentina for the different classes defined at the agro-ecological zonation.

The implementation of *A. nummularia* and *A. halimus* culture will provide feedstock for bioenergy or second generation biofuels and produce salt-tolerant forage for livestock. These crops do not compete for lands with those destined for food production.

This alternative approach to cultivating abandoned farmland affected by anthropogenic or natural salinization also serves the purpose of mitigating carbon emissions.

Native species of the genus Atriplex in Argentina should be investigated in production systems to exploit the country's natural resources and preserve the biodiversity of the ecosystem.

Conclusions

Based on a search of the international literature, the authors outline an agro-climatic zoning model to determine potential production areas in Argentina for *Atriplex halimus* and *A. numularia*. This model may be applied to any part of the world, using the agroclimatic limits presented in this work.

Lands classified with different degrees of aptitude on the agroecological suitability map could be used for cultivation of *A. nummularia* and *A. halimus* for energy purposes, knowing that such lands are not intended to compete with those designated for food. These crops provide lignocellulosic biomass for solid fuel or for second-generation biofuels, at the same time providing food for livestock in times of scarcity and contributing to CO_2 sequestration and thus mitigating climatic change. Besides, the use of saline lands—as long as they do not compete with those destined for food production—becomes of great importance for our growing global population.

References

Angueira MC (1986) Geomorfología de la provincia de Santiago del Estero. Curso Taller Internacional "Desmonte y habilitación de tierras en zonas semiáridas". Santiago del Estero. Red de Cooperación Técnica en uso de Recursos Naturales - FAO 1:32–54

Barroso FG, Pedreño A, Martínez T, Robles AB, González-Rebollar JL (2005) Potencialidad de las especies C_4 como alimento para el ganado en repoblaciones de zonas semiáridas. In: Osoro K, Argamentería A, Larraceleta A (eds) Producciones agroganaderas: gestión eficiente y conservación del medio natural. Serida, Gijón, pp 351–357

Bean W (1981) Trees and Shrubs Hardy in Great Britain. Vol 1–4 and Supplement. Murray, Clapham, UK

Belkheiri O, Mulas M (2013a) Effect of water stress on growth, water use efficiency and gas exchange as related to osmotic adjustment of two halophytes Atriplex spp. Funct Plant Biol. doi:10.1071/FP12245

Belkheiri O, Mulas M (2013b) The effects of salt stress on growth, water relations and ion accumulation in two halophyte Atriplex species. Environ Exp Bot 86:17–28. doi:10.1016/j.envexpbot.2011.07.001

Correal E (1993) Grazing use of fodder shrub plantations. In: Papanastasis V (ed) Agrimed Research Programme - Fodder trees and shrubs in the Mediterranean production systems: objectives and expected results of the EC research contract. Commission of the European Communities, Luxemburg, pp 99–118

Correal E, Otal J, Sotomayor JA (1990) Effects of grazing frequency and cutting height on the production of browsing biomass of old man saltbush (*Atriplex nummularia* L.) in southeast Spain. In: Development and preservation of low input Mediterranean pastures and fodder systems. 6th Meeting of the FAO European Sub-network on Mediterranean Pastures and Fodder Crops, Bari, Italy, pp 153–156

El Basam N (2010) Handbook of bioenergy crops. A complete reference to species. Development and applications. Earthscan, London

El Mzouri E, Chiriyaa A, El Mourid M, Laamari A (2000) Improving feed resource and quality in the dryland areas of Morocco by introducing the strip-alley cropping system. In: Gintzburger G, Bounejmate M, Nefzaoui A (eds) Fodder Shrub Development in Arid and Semi-arid Zones. Proceedings of the Workshop on Native and Exotic Fodder Shrubs in Arid and Semi-arid Zones, Hammamet, Tunisia. ICARDA, Aleppo (Syria). Vol. II, pp 340–347

Enríquez-Carrillo E, Parra-Galindo MA, Ramírez-Moreno F (2011) Producción y valor nutritivo de forraje de Atriplex en un suelo salino. Revista de Ciencias Biológicas y de la Salud 2011;13(2): 29-34 Available from: http://www.9biotecnia.uson.mx/revistas/articulos/16-BIO-11-IN-AGRI-05.pdf

F.A.O. (2008) Principales Órdenes, Subórdenes y Grandes Grupos de Suelos Presentes en las Regiones Secas de la República Argentina (Soil Taxonomy, 1979). Available from: http://www.fao.org/ag/agl/agll/lada/arg/Archivos/04%20-%20Recursos/suelo.htm

F.A.O. - Food and Agriculture Organization of the UN. Ecocrop (1993-2007) The crop environmental requirements database. Roma. Available from: http://ecocrop.fao.org/ecocrop/srv/en/home

Forti M (1986) Salt-tolerant and halophytic plants in Israel. Reclam Revegetation Res 5(1–3):38–96

Franclet A, Le Houérou HN (1971) Les Atriplex en Tunisie et en Afrique du Nord. SF/TUN 11, Rapp. Techn. No 7. FAO, Rome

Garcia P (1993) Efecto del corte en la producción y calidad forrajera del rebrote de *Atriplex nummularia* Lindl. Memoria Ingeniero Forestal. Facultad de Ciencias Agrarias y Forestales. Universidad de Chile, Santiago

Hobbs TJ, Bennell M, Huxtable D, Bartle J, Neumann C, George N, O'Sullivan W (2006) Flora Search Agroforestry Species and Regional Industries: Low rainfall farm forestry options for southern Australia. A report for the Joint Venture Agroforestry Program and CRC for Plant-based Management of Dryland Salinity. RIRDC Publication No 06/2006

Huxley A (1992) The New RHS Dictionary of Gardening. Royal Horticultural Society. MacMillan, London

Iglesias R, Taha E (2010) Monografías de especies anuales, arbustivas y acuícolas con potencial energético en Chile. Oficina de Estudios y Políticas Agrarias del Ministerio de Agricultura, Santiago

Ismaili M, Saloua B, Salema MP (2000) Biological nitrogen fixation and ^{15}N-labeled mineral nitrogen uptake by *Acacia cyanophylla, Acacia cyclops* and *Atriplex* spp. In: Gintzburger G, Bounejmate M, Nefzaoui A (eds) Fodder Shrub Development in Arid and Semi-arid Zones. Proceedings of the Workshop on Native and Exotic Fodder Shrubs in Arid and Semi-arid Zones. Hammamet, Tunisia. ICARDA, Aleppo, Syria. Vol. II, pp 390–394

Johnston M, Fernández G, Olivares A, Silva H (1996) Métodos de propagación biotecnológicos y convencionales de especies herbáceas forrajeras para zonas áridas. In: Izquierdo F, Palominos G (eds) Técnicas convencionales y biotecnológicas para la propagación de plantas de zonas áridas. Serie: Zonas Áridas y Semiáridas (FAO/PNUMA), Nº 9 / FAO. Oficina Regional para América Latina y el Caribe, Santiago

Jones R (1970) The biology of *Atriplex*. Division of Plant Industry, Commonwealth Scientific and Industrial Research Organization, Camberra, Australia

Karlin UO (1998) Conocimientos y Tecnologías tradicionales en el marco de la Convención de Lucha contra la Desertificación: América del Sur

Lavado R (2008) Visión sintética de la distribución y magnitud de los suelos afectados por salinidad en la Argentina. In: Taleisnik E, Grunberg K, y Santa María G (eds) La salinización de suelos en la Argentina: su impacto en la producción agropecuaria. EDUCC, Córdoba, pp 11–16

Le Houérou HN (1986) Salt-tolerant plants of economic value in the Mediterranean Basin. Reclam Revegetation Res 5:319–341

Le Houérou HN (1991) Feeding shrubs to sheep in the Mediterranean arid zone zone: intake performance and feed value. In: CIRAD (eds) Actes Du Quatrième Congrès International Des Terres de Parcours, Montpellier, pp 623–628

Le Houérou HN (1992) The role of salt bushes (Atriplex spp.) in arid land rehabilitation in the Mediterranean basin: a review. Agrofor Syst 18: 107–148

Le Houérou HN (1993) Land degradation in Mediterranean Europe: can agroforestry be a part of the solution? Agrofor Syst 21:43–61

Malcom CV (2000) Management of forage shrub plantations in Australia. In: Gintzburger G, Bounejmate M, Nefzaoui A (eds) Fodder Shrub Development in Arid and Semi-arid Zones. Proceedings of the Workshop on Native and Exotic Fodder Shrubs in Arid and Semi-arid Zones, 27 October-2 November 1996, Hammamet, Tunisia. ICARDA, Aleppo (Syria). Vol I, pp 67–76

Malcom CV, Pol JE (1986) Grazing management of saltland shrubs. J Agric W Aust 27(2):59–63

Mirreh MM, Osman AA, Ismail MD, Al Daraan MS, Al Rowaili MM (2000) Evaluation of six halophytic shrubs under centre-pivot sprinkler irrigation. In: Gintzburger G, Bounejmate M, Nefzaoui A (eds) Fodder Shrub Development in Arid and Semi-arid Zones. Proceedings of the Workshop on Native and Exotic Fodder Shrubs in Arid and Semi-arid Zones, Hammamet, Tunisia. ICARDA, Aleppo, Syria. Vol II, pp 293–308

Mozafar A, Goodin JR (1970) Vesiculated hairs: a mechanism for salt tolerance in *Atriplex halimus* L. Plant Physiol 45:62–65

Mulas M, Mulas G (2004) The strategic use of Atriplex and Opuntia to combat desertification. Sassari: Desertification Research Group. University of Sassari. Sasari 101 p

Múlgura de Romero ME (1981) Contributions to study of the genus Atriplex (Chenopodiaceae) in Argentina. Darwiniana 23(1):119–150

Nefzaoui A, El Mourid M (2008) Rangeland Improvement and Management in Arid and Semi-Arid Environments of West Asia and North Africa. Cairo: International Center for Agricultural Research in the Dry Areas. 2008. KARIANET/IDRCICARDA-IFAD booklet. IDRC Cairo

Rice G (ed) (1988) Growing from Seed, vol 2. Thompson and Morgan, United Kingdom

Rivera H (1996) Rendimiento y poder calorífico de la leña de diferentes especies y procedencias del género *Atriplex* L. Memoria Ingeniero Forestal. Facultad de Ciencias Agrarias y Forestales. Universidad de Chile, Santiago

Sankary MN (1986) Species distribution and growth in salt effected land of Syria. Reclam Revegetation Res 5:125–143

Shannon MC (1998) Adaptation of plants to salinity. Adv Agron 60:75–119

Silva RY, Lailhacar S (2000) Efficacité transpirationelle au niveau des échanges gazeux chez des espèces du genre *Atriplex* installées dans la zone aride Méditerranéenne du Chili. In: Gintzburger G, Bounejmate M, Nefzaoui A (eds) Fodder Shrub Development in Arid and Semi-arid Zones. Proceedings of the Workshop on Native and Exotic Fodder Shrubs in Arid and Semi-arid Zones.1996, Hammamet, Tunisia. ICARDA. Aleppo, Syria. Vol. II: 422-425

Sochacki SJ, Harper RJ, Smettem KR (2012) Bio-mitigation of carbon following afforestation of abandoned salinized farmland. GCB Bioenergy 4(2):193–201

Soto G (1996) *Atriplex nummularia Lindl.* Una especie pionera para las zonas áridas de Chile. La Serena, Chile, Organización de las Naciones Unidas para la Agricultura y la Alimentación. In: Estudios de caso de especies vegetales para las zonas áridas y semiáridas de Chile y México. Serie: Zonas áridas y semiáridas No 10. Santiago, Chile, pp 113–135

Taboada MA, Lavado RS (2009) Alteraciones de la fertilidad de los Suelos. El halomorfismo, la acidez, el hidromorfismo y las inundaciones. Ed. FAUBA. Buenos Aires

Thornburg AA (1982) Plant materials for use on surface-mined lands in arid and semiarid regions. Tech. Rep. SCS–TP–157 EPA –600/7–79–134: Washington DC: Soil Conservation Service, Superintendent of Documents Government Printing Office

Valderrábano J, Muñoz F, Delgado I (1996) Browsing ability and utilization by sheep and goats of *Atriplex halimus* L. shrubs. Small Rumin Res 19:131–136

Zid E (1970) Influence du chlorure de sodium sur la croissance et la nutricion minérale d'*Atriplex halimus*. Labo. de Physoil. Végét., Fac. des Sces, Tunis