Current Challenges and Future Opportunities for a Sustainable Utilization of Halophytes

Ahmed Debez, Bernhard Huchzermeyer, Chedly Abdelly, and Hans-Werner Koyro

Abstract Increasing salinisation has significant and detrimental impacts on land, water and vegetation quality, wildlife environments, agronomy and ecosystem functioning. This is particularly true for arid and semiarid areas where high evapo-transpiration rates expose plants to further adaptive pressure. Unlike conventional crops, halophytes are plants that survive and are able to reproduce in environments (coasts, wetlands, and inland deserts) with higher salinity levels. These species, which represent about 1% of the world's flora, have evolved complex mechanisms at different levels (whole plant, cellular, and molecular) enabling them to successfully cope with these hostile conditions. There are about a billion ha of salt-affected land world wide, which are unsuitable for agriculture and may therefore provide unique opportunities for "halo-biotechnologies". Taking into account the increasing pressure on fresh water resources and considerable diversity of potentially useful halophytes, such an approach may help in the mid- and long-term to rehabilitate these marginal zones and create sustainable production systems. Agriculture on saline soils is an alternative agriculture under a range of salinity levels in groundwater, and/or soils. A precondition for its use is the economic value added. Yet, fundamental prerequisites have to be considered to ensure that this promising approach would be cost-effective and environmentally safe. It must yield economically viable crops at yields high enough to be accepted by the farmers. This should be concomitant with the development of agronomic techniques relevant for growing saline, water-irrigated crops in a sustainable manner. Most importantly, these practices should be sustainable, ecologically well-tolerated and not lead to further damage of natural environments. If applied successfully, such an approach may lead to domestication of wild, salt-tolerant plants to be used as food, forage, oilseed crops, as well as pharmaceutical or ornamental plants. Soil desalination represents also important tasks for the so called cash crop halophytes. The successful rehabilitation of saline marginal zones by introduction of halophytes largely depends on collecting reliable data on salt-tolerance limits during life cycle of the respective candidate species. In this contribution, we present an overview of new data gained under saline conditions during the last years with respect to halophytes of interest and discuss their likely implications at applied level.

1 Introduction

Growth of the human population by 50%, from 6.1 billion in mid-2001 to 9.3 billion by 2050 (http://www.unfpa.org/swp/2001/), requires a significant and concomitant increase of crop production to ensure food security, especially in the developing countries. Recent estimations of the Food and Agriculture Organization of the United Nations (FAO) indicate that more than 850 million people are suffering from chronic malnutrition. Additionally, this problem becomes enhanced

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by the current climate change. Among the most important challenges are the increase in temperatures, desertification, and salinisation of soil and water resources. Salinity can be either natural or related to human activity (inaccurate irrigation management or fertilizer use) (Galvani 2007; Breckle 2009).

Salinity is actually an ever-present limiting factor to crop yields, notably in countries where agriculture relies on irrigation, which allows farmers to be less dependent on seasonal rainfall and the weather uncertainties (Galvani 2007). Yet, inappropriate irrigation strategies increase salinity of soils and water by depositing ions like sodium, calcium, magnesium, potassium, sulphate and chloride. In arid and semi-arid regions, solutes from irrigation water can highly accumulate, reaching levels that are harmful for the vigour and productivity of crops. According to Szabolcs (1994), 7% (1 billion hectares) of all land area is salt-effected, and about 10 million ha of agriculturally productive soils are being lost annually worldwide because of irrigation-induced salinity. Crop production is restricted by salinity on 40% of the world's irrigated land. In addition, 19.5% of the currently 230 million ha irrigated land, and ca. 5% of 1,500 million ha under dry land agriculture are salt-affected to varying degrees (Munns et al. 1999). It is estimated that salinisation of irrigated lands causes annual global income loss of about US $12 billion, severely impacting aggregate national incomes in countries affected by degradation of salt-affected land and saline water resources (Ghassemi et al. 1995). Generally, the worst salinity impacts occur where farming communities are relatively poor and face economic difficulties. In Australia, the annual expansion rate of dry land salinity is 3–5%, resulting in losses of Australian $270 million. Future projections estimate that 17 million ha of Australia's agricultural land will be significantly affected by salinity by 2050 (http://audit.ea.gov.au). The situation in Australia is even worsened by the extensive secondary salinity caused by substituting superficial rooted annual species for the deep-rooted perennial native vegetation with. As a result, rising water tables are observed that bring salt stored deep in the profiles close to the soil surface (Barrett-Lennard 2002).

Despite considerably varying in their response when salt-challenged, crop species are generally intolerant to one-third of the concentration of salts found in seawater (Flowers 2004). Several attempts to improve salt tolerance of crops through conventional breeding programs have yielded very limited success, mainly because salinity is a multifactorial problem (Koyro et al. 2008). Halophytes are plants that can complete their life cycle in soils with salinity concentrations above 200 mm NaCl (Flowers and Colmer 2008). Halophytes, which represent 1% of the world's flora, thrive in a wide range of habitats, from arid regions to coastal marshes. Several species grow in waterlogged or flooded soils, even withstanding total immersion in seawater (Munns 2008). Some halophytes require fresh water for germination and early establishment but can tolerate higher salt levels during vegetative and reproductive stages, other's may germinate at high salinities but require lower salinity for maximum growth (Debez et al. 2003, 2004; Koyro and Eisa 2008). In extreme cases (obligate or euhalophytes), increased biomass production occurs only under increased salinity. Further, some plants grow well on permanently wet areas; others grow best where the soil dries out in the summer (Galvani 2007). Mechanisms that allow such an extraordinary adaptation are still largely unknown.

Given that oceans contain most of the water on earth, the concept of sustainable agriculture using the so-called "cash crop halophytes" irrigated with saline waters up to seawater salinity is gradually emerging (Lieth et al. 1999). Although economic consideration of halophytes and other salt-tolerant plants is just beginning, they are now receiving increased attention in arid regions where intensive irrigation has led to saline soils or where water shortages are forcing use of marginal resources such as brackish underground water (O'Leary 1987; Öztürk et al. 2006, 2008). According to Yensen (2006) twenty-first century will likely be the century of halophyte agriculture expansion, as diminishing fresh water resources put pressure on civilization to utilize the vast saline soils and aquifers. While much of this land occurs in the Middle East, Central Asia, Northern Africa and Australia it seems that many other countries will face salinity issues" if steps are not taken. More recently, Galvani (2007) claimed: "To meet future agriculture needs, a solution is an environmentally friendly technique which controls salinisation, uses salt removing crops, chooses halophytes crops for direct salt water irrigation, or selects species that have high salt-removing capacity and commercial value. Some plants can be integrated into rotation programs or planted as intercrops for perennial plants to control salinisation". As hypothesized by this author, the unsuitability of sand and saline water for conventional crops may actually be advantageous when considering salt-tolerant plants, owing to the mineral composition of seawater (among the 13 mineral nutrients required by plants, 11 are present in seawater in sufficient amounts) and the texture of sandy soils, which favours the infiltration of water and prevent the harmful salt build up in the zone of root development. If applied carefully, the combination of sand, seawater, sun and salt-tolerant plants constitutes hence a valuable and realistic opportunity for many developing countries.

Several halophytes have been evaluated as potential crops for direct seawater or brackish water irrigation. Their potentialities cover a wide range of applications: the improvement of soil characteristics (desalination, heavy metal extraction), biomass production, food, fuel, fodder, fiber. Although direct consumption of halophytes by humans and animals may be limited, the seeds of many of them are being considered as new sources of grains or vegetable oils (Hinman 1984). Salt-tolerant plants can also be used to produce materials with high economical value, such as essential oils, flavours, fragrances, gums, resins, oils, pharmaceuticals, and fibers (Galvani 2007; Ksouri et al. 2007). They may also be marketed for use for ornamentation for their foliage or flowers (Messedi et al. 2004; Slama et al. 2006). Fuel-wood and building materials may also be manufactured from salt-tolerant species using land and water unsuitable for conventional crops.

The development of successful saline agriculture necessitates a better understanding of the potential of plant species to withstand ambient salinity and sodicity levels in soil and water, and also of the potential uses and markets for the agricultural products. In this contribution, we address the most recent information available with respect to the potential utilizations of halophytes in the context of halo-biotechnology, and present some practical recommendations to be considered for a economically viable and environmentally compatible sustainable biosaline agriculture.

2 Soil Bioremediation by Desalination-Efficient Halophytes

In the arid to semi-arid regions, water quality is a major factor limiting crop production (Cantero-Martínez et al. 2007). Interestingly, the natural ecosystems of the Mediterranean-climate areas are characterized by a mixture of rustic perennial shrubs and trees (mainly xerophytes and halophytes) with annual crops or fodder plants (Turner 2004). Growth activity of the annuals is governed by the rainfall regime, the rainy season extending from autumn to spring, while the slowly growing perennials are able to cope with water shortage and soil/water salinity. Variations in biomass and productivity among and within natural ecosystems may be attributed mostly to differences in water and nutrient (especially N) availability and salinity (Sherman et al. 2003). Understanding the functioning of plant saline ecosystems capable of significant productivity under salt stress is of paramount importance in perspective of improvement of soil characteristics using halophytes.

One of the most fascinating natural saline ecosystems are coastal or continental sabkhas, which are typical of the semi-arid and arid areas around the world. Because of the extreme environmental (edaphic and climatic) conditions characterizing these biotopes, they are considered as non productive wastelands. Sabkhas could actually be valorised by implementing agro-ecosystems using “alternative” cash-crop halophytes (Böer and Gliddon 1998). In Tunisia for instance, the annual fodder plant *Hordeum maritimum* (Poaceae) is commonly found in the saline depressions in close association with strict halophytes, such as *Arthrocnemum indicum* and *Halocnemum strobilaceum* (Hafsi et al. 2007). In a 2-year survey, Abdelly et al. (2006) have been monitoring the impact of halophyte-fodder species association on biomass production and soil salinity level in the inland sabkha of Enfidha (100 km south-east from Tunis), a semi-arid bioclimatic zone with moderate winters and mean annual rainfall rarely above 300 mm. The vegetation of studied area was characterized by perennial halophytes tufts in association with fodder annuals, mainly *Medicago* species, highly appreciated for their high fodder value, and ensuring most of to the ecosystem primary production in the absence of water shortage. Parallel field and laboratory investigations revealed that *Medicago* growth was restricted by salt (Abdelly et al. 1995; Abdelly et al. 1996), and nutrient (mainly nitrogen and phosphorus) deficiencies (Abdelly 1997). Halophytes displayed slow growth activity associated with poor accumulation of mineral nutrients (e.g. nitrogen, inorganic Phosphate, and Potassium) and high sodium concentrations in their shoots. On the contrary, annuals were characterized by high growth activity (up to 40% of the plant annual biomass production of the ecosystem), depending on the precipitation and sustained by a high capacity for nutrient acquirement (up to 70% of the total nutrient uptake).

The annuals were almost exclusively clustered under the halophyte tufts, or at their immediate vicinity, where soil nitrogen and inorganic phosphate levels were significantly higher, and salinity significantly lower than between the halophyte tufts. Furthermore, the shoots of the annuals growing in association with halophyte species contained relatively low Na^+ concentrations. These findings indicate that the upper horizon enclosing the halophyte tufts (where sensitive annuals grow) is fertile and contains low salt levels. This was also corroborated by the study of soil samples taken from the upper profile in the tuft centers. However, further studies are needed to support this by following the water movement in different soil horizons in different seasons. Desalination of the upper horizon by the superficial roots of halophytes may be responsible for this micro-gradient of salinity (Caldwell 1974). Further, the litter formed by halophyte fallen organs and by organic debris accumulated by the wind at the vicinity of halophyte tufts, could contribute to localized soil enrichment in N and P. Hence, the upper soil profile, where these plants grew, was fertile and contained (relatively) low salt levels, as corroborated by the results of soil analysis (upper horizon in the tuft centre was always less saline than when taken at the tuft periphery). Soil aeration near the annual glycophytes would be improved by this organic matter and by the higher soil level under the tufts, leading to better drainage capacity. Improved soil aeration is favourable for nitrification and N_2 fixation, which in turn sustains the colonization of the halophytes tufts by the *Medicago* spp. Halophytes may also play an indirect role by developing deep root systems exploiting the more saline horizons, as shown by the presence of halophyte roots at 1 m depth and by the vertical increasing salinity gradient. So, the halophytes directly contributed to maintenance of a relatively low salinity and high fertility in upper horizon, enabling the growth of annuals.

These findings were confirmed using a biological test of soil fertility. Some tufts of *Salicornia arabica* were removed for sampling soil in the upper profile (0–20 cm), where roots of annual plants developed. Other samples were taken between halophytes tufts, in zones devoid of vegetation or weakly populated. Four annual *Medicago* species (*M. ciliaris*, *M. polymorpha*, *M. truncatula* and *M. minima*) were grown on these soil samples, without mineral fertilization, in a greenhouse under controlled conditions. The plants were harvested at flowering stage. In the four species, total biomass production (dry matter per pot) was higher on soils sampled under the halophyte tufts than on soils from nude zones (Fig. 1a). Although these studies revealed that perennial halophytes improve soil characteristics by lowering salt content and by increasing nitrogen and phosphorus concentrations but further studies are needed in this connection by comparing with the salt secreating halophytes.

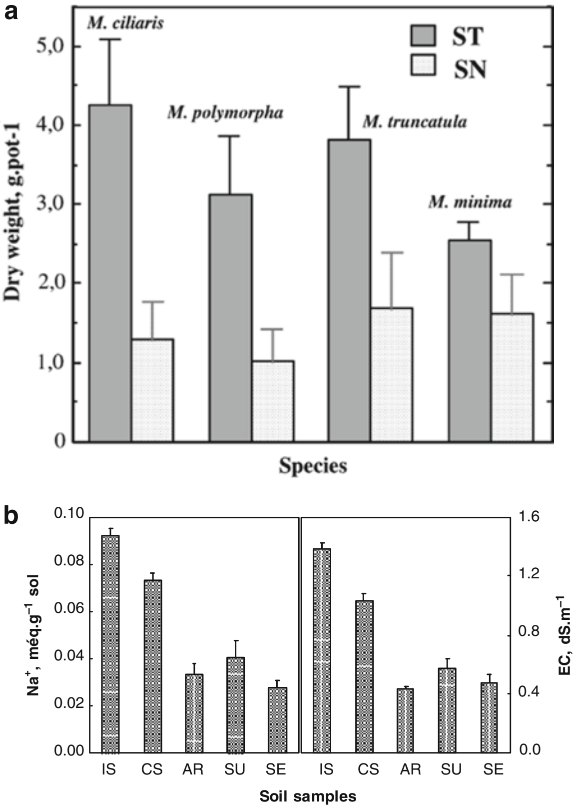

Fig. 1 Capacity of halophyte species for soil desalination. (**a**) Changes in biomass production of *Medicago ciliaris*, *M. polymorpha*, *M. truncatula*, and *M. minima* ($g.pot^{-1}$) depending on the soil origin ($n = 20 \pm$ SE at $p < 0.05$). ST: culture carried out on soil sampled under halophytes tufts, SN: cultures carried out on soil sampled in outside of halophytes tufts. (**b**) Soluble sodium content and electrical conductivity (EC) of 10% (w/w) aqueous extract of soil samples ($n = 6 \pm$ SE at $p < 0.05$) taken from the upper profile (15 cm deep) of pots (8 kg capacity), in which three halophytes: *A. indicum* (AR), *S. fruticosa* (SU), and *S. portulacastrum* L. (SE) were grown for 170 days. Plants were regularly irrigated with tap water. IS and CS stand for the initial and control (irrigated without plantation) soils respectively (adapted from Abdelly et al. 2006)

Involvement of halophytes in creation of micro-habitats favouring development of *Medicago* spp. and their micro-symbionts has been documented by Bekki (1995) who showed that *M. ciliaris* plants growing in combination with *Suaeda fruticosa*, had higher growth rates and better nodulation and nitrogen fixation potentialities than isolated ones. Several studies have highlighted the advantageous role of halophytes in soil desalination processes, especially for the most productive species, such as *Salsola salsa* (20 t · ha^{-1} among which, 3–4 t of salt exported from the soil), *Batis maritima* (3 t · ha^{-1}) (Le Houérou 1993), and the succulent *Sesuvium protulacastrum* (Pasternak and Nerd 1996). Although salt removal from soil is a common feature latter would be particularly interesting because of its high salt tolerance (growth stimulation up to 800 mM NaCl) despite accumulating high salt levels in the shoots (6 mmol · g^{-1} DW, representing ca. 35% of the whole plant biomass) (Messedi et al. 2001). In a 4-year study, Keiffer and Ungar (2002) observed a significant decline in brine-affected soils, following introduction of halophytes (*Atriplex prostrata*, *Spergularia marina*, and *Suaeda calceoliformis*), so that glycophytes could successfully establish. Recent findings of Kiliç et al. (2008) showed that purslane (*Portulaca oleracea*) may be cultivated as an intercrop all year round in one growing season, with a threshold value of salinity at 6.5 dS · m^{-1}. It removed considerable amounts of salt (up to 210 kg · ha^{-1} of Cl$^-$ and 65 kg · ha^{-1} of Na$^+$) from the soil. However,it will better to use it for phytoreclamation if efficiency is enough in comparison with total soil salinity, thus salt balance calculations are needed for this purpose, because it will take 500 years to get rid of the salt if there are 5,000 t of salt in soil per ha in the physiological and ecological sense.

The capacity of desalination of saline soil by halophytes was also evaluated in strictly controlled conditions, using *Arthrocnemum indicum, Suaeda fruticosa*, and *Sesuvium portulacastrum* (Rabhi et al. 2008). The plants, also originating from the edge of a sabkha, were cultivated for 6 months on saline soil and irrigated with tap water without losses by drainage. Salt export by plants was assessed by the difference between the amounts of Na$^+$ and Cl$^-$ initially measured in the culture substrate, and those found at the end of the experiment in the soil. After 170 days, the soil electric conductivity (EC) in the pots used for the culture of the three halophytes decreased by more than 50% in average (0.6 dS · m^{-1} vs. 1.4 dS · m^{-1}) (Fig. 1b). Among the three studied species, *S. portulacastrum* was most productive and showed highest capacity of sodium extraction. It accumulated up to 26% of the original Na$^+$ content of the soil after 170 days, while both, *A. indicum* and *S. fruticosa* plants, accumulated 8% (Fig. 1b). Based on these findings, the calculated Na$^+$ export rates per ha were 2.50, 0.80 and 0.71, respectively, for *S. portulacastrum*, *A. indicum*, and *S. fruticosa* (Table 1). This study demonstrates once again that the halophyte traits displayed by *S. portulacastrum*, namely high growth rate and high capacity for salt accumulation, contribute efficiently to the soil desalination, even in short-term cultures. Hence, this species would be promising for rehabilitation of saline lands, especially those located in arid and semi-arid regions. Ravindran et al. (2007) evaluated the desalination capacity of six halophytes (*Suaeda maritima*, *S. portulacastrum*, *Clerodendron inerma*, *Ipomoea pes-caprae*, *Heliotropium curassavicum*, and the tree *Excoecaria agallocha*), in terms of fast growth rate associated with high salt accumulation. All tested species decreased the EC of the saline soil used, in concomitance with an increase of the EC of plant samples. Salt removal capacity calculated over in 4 months of time was 504, 473.9, 396.3, 359.5, 325.2 and 301.5 kg · ha^{-1} of NaCl in *Suaeda*, *Sesuvium*, *Excoecaria*, *Clerodendron*, *Ipomoea* and *Heliotropium*, respectively.

Table 1 Estimation of the capacity of soil desalination by three perennial halophytes grown during 170 days on a soil originating from a sabkha, and constantly irrigated with tap water

Species	*S. portulacastrum*	*S. fruticosa*	*A. indicum*
DW per pot (g)	30.00	9.25	10.50
Quantity of Na$^+$ exported per pot (g)	11.32	3.63	3.22
Quantity of Na$^+$ exported (t · ha^{-1})	2.50	0.80	0.71

Source: Adapted from Rabhi et al. (2008)

3 Heavy Metal Phytoextraction

Saline depressions, which are less populated, often constitute sites of accumulation of industrial and urban effluents contaminated by heavy metals. The plants from saline habitats can be evaluted to some extent in their phytoextraction potential as an environmental friendly alternative for the remediation of such contaminated areas (Cunningham and Berti 1993; Brooks 1998; Djebali et al. 2002). The first step in this direction will be to assess the potential interest in a plant species for phytoextraction and quantify, under fully-controlled conditions, the optimal level of toxic metal accumulation in relation to the growth rate (Lutts et al. 2004). Hyperaccumulators (plants able to concentrate high levels of heavy metals in their aerial parts without showing any symptom of injury) have to be identified. Plants are usually considered as hyperaccumulators if they contain more than 10,000 mg · kg^{-1} Zn or 100 mg · kg^{-1} Cd (Brooks 1998). Several studies demonstrated different tolerance mechanisms operating at the whole-plant level. For instance, salt excluding mechanisms are not always specific to sodium, so that other toxic elements such as copper, zinc, or cadmium may accumulate in salt glands, as in *Armeria maritima* and *Avicennia marina* (Lutts et al. 2004), or in trichomes, as found in *Tamarix aphylla* (Hagemeyer and Waisel 1988). Several halophyte species of the genus *Atriplex*, which are naturally salt- and drought-tolerant and mostly typical "includers" (Reimann and Breckle 1993), have been suggested as potential candidates for a phytoremediation approach (Salo et al. 1996; Glenn et al. 2001). A recent study reported that *Atriplex halimus* displayed high resistance to heavy-metals (Cd and Zn) in contaminated mining sites and that it has a strong potential for the rehabilitation of heavy metal-polluted lands (Lutts et al. 2004). This was strongly correlated to the over-accumulation of phytochelatins in combination with the induction of detoxification mechanisms, such as the co-precipitation of Cd and/or Zn with Ca in oxalate structures (oxalic acid is commonly produced in *Atriplex* species) within the stems, to prevent their toxic accumulation in the photosynthetic tissues (Karimi and Ungar 1986). Given that this species is able to produce 4–5 t of dry matter.ha^{-1} · $year^{-1}$ (Ben Ahmed et al. 1996) and that it may accumulate up to 0.083% Cd and 0.044% Zn on a dry weight basis in the shoots, the amounts expected to be removed could reach 4.15 kg · ha^{-1} Cd and 2.2 kg · ha^{-1} Zn (Lutts et al. 2004).

Halimione portulacoides was also suggested as a suitable species for the phytoremediation owing to the high translocation rates of Cd and Cu towards the aboveground tissues (Reboreda and Caçador 2007). Ghnaya et al. (2005) compared growth, cadmium accumulation and mineral nutrition in two halophytes from Aizoaceae: *S. portulacastrum* (perennial) and *Mesembryanthemum crystallinum* (annual) under the combination of mild salinity (100 mM NaCl) and Cd-stress (up to 300 µM $CdCl_2$). Cd-exposure had no impact on the growth of *S. portulacastrum*, while that of *M. crystallinum* was significantly decreased at the lowest Cd level (50 µM $CdCl_2$) (Fig. 2a). The better behavior of *S. portulacastrum* was partly ascribed to its

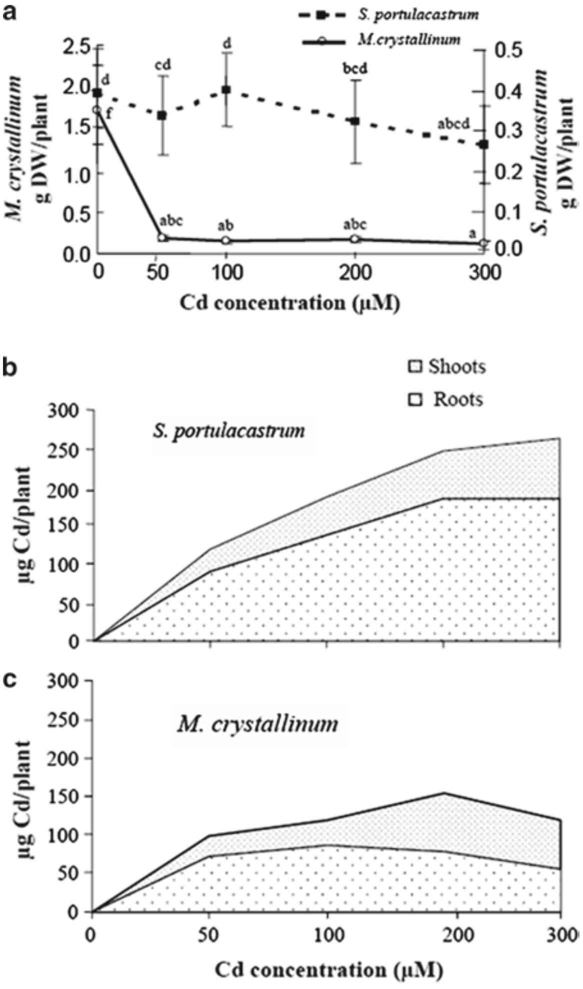

Fig. 2 Comparative heavy metal extraction capacity of the halophytes *M. crystallinum* and *S. portulacastrum*. (**a**) Changes in whole plant dry matter (g · $plant^{-1}$) produced by *M. crystallinum* and *S. portulacastrum* treated by various Cd concentrations. Means ($n = 8 \pm$ SE at $p < 0.05$) marked with same letter are not significantly different at $p < 0.05$. (**b**) Distribution of the cadmium absorbed by the whole plant (mg · $plant^{-1}$) between roots and shoots of *S. portulacastrum* and *M. crystallinum*. (adapted from Ghnaya et al. 2005)

better ability to avoid oxidative stress, when challenged with Cd (Nouairi et al. 2006). Indeed, leaves of *S. portulacastrum* showed lower decrease in their lipid content as compared to *M. crystallinum*, and cadmium treatment did not induce changes in the fatty acid composition of the total membrane lipids. Both halophytes accumulated more Cd in the roots than in the shoots. Yet, values of Cd concentrations in shoots (350–700 μg · g^{-1} DM) were characteristic of Cd hyperaccumulator plants (Fig. 2b). Hence, *S. portulacastrum* could extract up to 5950 g Cd · ha^{-1} · year^{-1}, this performance being even improved in the calcareous soils (Ghnaya et al. 2007).

4 Halophytes for Livestock Production

The amount of edible biomass produced is an essential aspect with respect to livestock production in biosaline agriculture. Even at high salinities a range of halophytic grasses and shrubs with appreciable crude protein and digestible fibber contents are still able to produce 0.5–5 t of edible dry matter per year. Valuable species include *Leptochloa fusca* (Ahmad et al. 1990), *Brachiaria mutica* (Kumar and Abrol 1984), *Sesbania bispinosa* (Ahmad et al. 1990), *Cynodon dactylon* (Oster et al. 1999), *Kochia scoparia* (Garduno 1993), *Echinochloa crusgalli* (Aslam et al. 1987), and *P. oleracea* (Grieve and Suarez 1997). Among the most used halophytes for grazing and forage production under both saline and non-saline conditions are the shrubs from the Chenopodiaceae family, including the saltbushes, small-leafed bluebush (*Maireana brevifolia*), *Kochia* spp., *Tamarix* spp., glassworts (*Salicornia* spp.), and *Suaeda* spp. (Le Houérou 1994; Masters et al. 2001). All these species are well known to be drought and salt tolerant. According to Le Houérou (1992), 5–10 kg · DM ha^{-1} · year^{-1} of edible forage production from a range of saltbush species could be produced for each mm of rainfall in areas with low salinity. Under favorable conditions in terms of soil structure and rainfall (between 200 and 400 mm), yields of 2–4 t DM ha^{-1} · year^{-1} could be reasonably attained. Regular cutting practices associated with heavy grazing of woody shrubs such as saltbush favors the regeneration of less woody and more digestible shoots. Significant attention should also be paid to the appropriate cutting height, a critical point to avoid die-off of the existing plant material. *Atriplex lentiformis*, *Batis maritima*, *Atriplex canescens*, *Salicornia bigelovii* and *Distichlis palmeri* yielded over 10 t · ha^{-1} · year^{-1} following successful establishment (Glenn and O'Leary 1985), whereas *Atriplex* spp. irrigated with saline drainage water were able to yield 2.2–5.3 t DM · ha^{-1} · year^{-1} of forage (Watson and O'Leary 1993). Recent studies reported that highly saline groundwater (30 dS · m^{-1}) allowed to produce much larger amounts of hay from irrigated and intensively managed inland salt grass (*Distichlis spicata*) and marine couch (*Sporobolus virginicus*) (International Center for Biosaline Agriculture 2004). Abdelly et al. (2006) investigated the salt-response of two Poaceae halophytes native to Tunisia, with fodder potential: *Aeluropus littoralis* (perennial) and *Catapodium rigidum* (annual). The latter was slightly more productive than *A. littoralis* in the absence of salt. Increasing salinity decreased the growth activity of both species, but *A. littoralis* was more tolerant than *C. rigidum* (Fig. 3a). In the salinity range not exceeding 400 mM NaCl, the relative growth rate (RGR) of both species remained between 0.04–0.06 day^{-1}. Under non saline conditions, the following data were found for other plant species: *Medicago* spp. (0.08–0.09 day^{-1}) (Abdelly 1997), *Suaeda fruticosa* (0.07–0.09 day^{-1}) (Sleimi and Abdelly 2002), *Spartina alterniflora* (0.03 day^{-1}) (Sleimi and Abdelly 2002), *Spartina anglica* and *Puccinellia maritima* (0.02–0.05 day^{-1}) (Rozema and Van Diggelen 1991).

Barhoumi et al. (2007) reported that *A. littoralis* was able to survive up to 800 mM NaCl, with only a 50% reduction in leaf water content. Salt glands were observed on both leaf sides at high density in salt-treated plants. Interestingly, these morphological structures showed to be selective for Na^{+} and Cl^{-}, and owing to their high density, enabled the elimination of about 50% of absorbed NaCl (Fig. 3b). If the results on production, yield, and reproduction are significantly high the species can be evaluted properly. In a recent survey, Laudadio et al. (2009) assessed the nutritional value of fourteen halophytes (*Aeluropus littoralis*, *Artemisia campestris*, *Atriplex halimus*, *Frankenia thymifolia*, *Imperata cylindrica*, *Limoniastrum guyonianum*, *Nitraria retusa*, *Reaumuria vermiculata*, *Salicornia Arabica*, *Salsola tetragona*, *Salsola tetrandra*, *Suaeda mollis*, *Tamarix gallica*, and *Zygophyllum album*) naturally growing in the arid regions of Tunisia. The contents of ash, crude protein, crude lipid, structural carbohydrate and nitrogen-free extract indicated nutritional

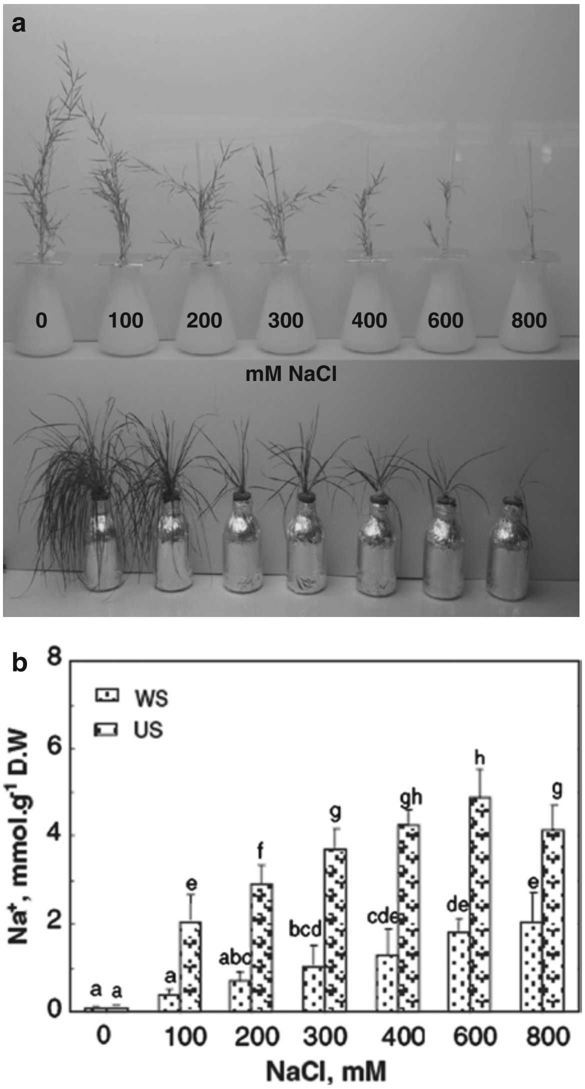

Fig. 3 (**a**) Comparative salt response of two fodder halophytes: *Aeluropus littoralis* (*above*) and *Catapodium rigidum* (below) to increasing salinity. (**b**) Importance of salt glands in salt excretion for *A. littoralis*: Na^+ contents ($mmol \cdot g^{-1}$ DW) mainly in washed (WS) and unwashed shoots (US) of plants exposed for 2 months to 0–800 mM NaCl NaCl. Values ($n = 7 \pm$ SE at $p < 0.05$) followed by the same letter are not significantly different at $p < 0.05$ (adapted from Barhoumi et al. 2007)

characteristics close to those found in the essence of the typical pastures of the Mediterranean region and compatible with the digestive physiology of the ruminant species.

Despite varying in both palatability and nutritive value, most halophytes contain sufficient levels of crude proteins and essential nutrients, covering the nutritional requirements of animals, particularly during the wet season (El Shaer 2006). In summer and autumn (dry season), they need to be supplemented with other feed ingredients, particularly with energy feed resources (El Shaer 1997). On the field, the mineral composition of the plants may be considerably affected by both the concentration and type of salts in the soil and/or water. For instance, sodium, potassium, chloride, calcium and magnesium may accumulate above the maximum tolerable levels for livestock (Masters et al. 2007). The high concentrations of sodium chloride in particular may decrease feed intake and under some conditions even threaten animal health. Furthermore, plants growing in saline environments often accumulate secondary compounds, which can have either beneficial (e.g., vitamin E and betaine) or toxic (oxalates, coumarins, saponines, and nitrites) impact on grazing livestock. Therefore, further investigations are essentially needed to ensure the well-tolerated application of halophytes as fodder plants.

Several treatments have been applied in order to improve the palatability and nutritive values of halophytic forage species (El Shaer and Kandil 1990). Chopping is an effective process to increase the palatability of succulent species and hence enable a more efficient utilization of whole shrubs. Appropriate conservation such as hay making and ensiling of halophytes could improve their utilization as good quality fodder and their acceptability by sheep and goats (El Shaer and Kandil 1990). This was ascribed to the effect of anaerobic fermentation during the ensiling process on some anti-nutritional factors such as tannins and other phenolic compounds. Additionally, the ash content and fibber materials are lowered. Feeding these silages to animals represents an economic alternative, feed costs being 30–50% lower in comparison with conventional diets such as berseem hay, which is of high importance in developing countries (El Shaer and Kandil 1990). The problem of preparing proper feed supply from halophytes is far from being solved. There are several reports showing mineral imbalances and shortage of essential mineral intake by animals in arid areas. It was found, for instance, that additional supply of the essential trace element Selenium may overcome nutritional constraints limiting animal productivity (see Khan et al. 2005 and citations therein).

Further combinations with other feed ingredients such as broiler litter, crushed date seeds, fodder beet and other forages could be also considered. In this way, voluntary feed intake was shown to increase by ensiling a mixture of some halophytic species, *A. halimus*, *H. strobilaceum*, *Tamarix mannifera* and *Zygophyllum album* with some agro-industrial byproducts such as ground date seeds and olive pulp (El Shaer 1997).

5 Halophytes for Oil Production

Seeds of several halophytes may contain appreciable quantities of edible oil (Weber et al. 2001). Oil extracted from the seeds (Up to 30% of seed DW) of *Salicornia bigelovii*, a highly salt tolerant annual halophyte, was found to be of good quality with unsaturation degree comparable to oils from conventional oil seeds (Glenn et al. 1991). Interestingly, *S. bigelovii* (Glenn et al. 1991) and several accessions (Mexico, Egypt, and United Arab Emirates) of the stem succulent *Salicornia europaea* appear to be highly productive, with a biomass production of 20 t · ha^{-1} among which 2 t are seeds (Goodin, et al. 1990). According to Yajun et al. (2003), *Descurainaia sophia* collected from saline soil (0.4% NaCl) contained higher amounts of linolenic acid in their seeds as compared to plants originating from non-saline soil (<0.1% salt) (53.7% and 36% linolenic acid, respectively). Weber et al. (2007) analysed the seeds of *Arthrocnemum indicum*, *Alhaji maurorum*, *Cressa cretica*, *Halopyrum mucronatum*, *Haloxylon stocksii* and *Suaeda fruticosa* to assess their potential as source of edible oil. Seed-oil content was 22–25%, and amounts of unsaturated fatty acids were high (65–74%) excepting *Alhaji maurorum*. In addition, seed lipids contained 12 unsaturated and four saturated fatty acids.

Zarrouk et al. (2003) retained *Zygophyllum album* (Zygophyllaceae), *Crithmum maritimum* (Apiaceae), and *Cakile maritima* (Brassicaceae) as potential oilseed halophytes. The dry weight of 100 seeds ranging from 133 mg in *Z. album* to 774 mg in *C. maritima*. Interestingly, the value for the latter species is nearly two times higher than that for rape (*Brassica napus*) seeds, a conventional oleaginous plant. Seeds of *C. maritima* and *C. maritimum* were rich in oil, (up to 42% and 30% of the seed FW, respectively), whereas seed-oil content was much lower in *Z. album* (ca. 6%). As for olive oil, fatty acid composition of *C. maritimum* seeds was characterised by a high level of oleic acid (81%), whereas that of *Z. album* seeds showed a high percentage of linoleic acid (64%), similar to sunflower seed-oil composition. Therefore, both species contained oil of good quality which may be used without any further modification. Erucic acid (22:1) was prominent in fatty acid spectrum (over 25% of total fatty acids) of *C. maritima* seeds, suggesting the possibility of its utilisation for industrial purposes (nylon, emollients, lubricants etc.) (Bhardwaj and Hamama 2003).

In more recent papers, the natural variability of fruit and seed oil characteristics was investigated in twelve local accessions of *C. maritima*, harvested along the Tunisian coasts, and covering different bioclimatic stages (humid to arid) (Ghars et al. 2006). Seed-oil amount was highly variable among accessions (25–39%) (Fig. 4a) and triacylglycerols (TAG) represented 80–97% of the lipid categories. Erucic acid (22:1), found only in TAG, represented 25–35% of total fatty acids. Such a variability was consistent with previous studies on Australian and Moroccan ecotypes of *C. maritima*, whose seed-oil content ranged from ca. 35–48%, respectively (Hocking 1982; Kumar and Tsunoda 1978). This intra-specific variability in the amount and the quality of the extracted oil could be ascribed to environmental factors, such as precipitation (Rana and Ahmed 1981; Pannelli et al. 1994), temperature (Champolivier and Merrien 1996), and salinity (Zarrouk and Cherif 1983). Fruit morphology and NaCl accumulation also were accession-dependent. Furthermore, the repartition pattern of Na^+ and Cl^- between the plant tissues (stems, siliques, and seeds) suggested that some protective mechanisms prevent excessive salt accumulation in reproductive organs, which is essential for the establishment and survival of *C. maritima* in saline biotopes. The successful rehabilitation of saline marginal zones by introduction of halophytes for the creation of sustainable production systems largely depends on the germination capacity at each site as stressed by Debez et al. (2004, 2006a, 2008) (Fig. 4b) and Ben Amor et al.(2006) and Ksouri et al.(2007).

At fructification stage, the number of seeds per plant was also significantly augmented at salt concentrations optimal for plant growth (50–100 mM) (Debez et al. 2004). Concentrations exceeding 200 mM NaCl strongly reduced both seed mass and seed viability, likely owing to salt-induced restriction of seed nutrition and filling. While seed-oil content was only slightly increased at the extreme salt levels (25%), qualitative changes of seed-oil were more obvious: erucic acid (C22:1) was the major fatty acid (29%) in seed-oil of plants grown at NaCl above 200 mM to the detriment

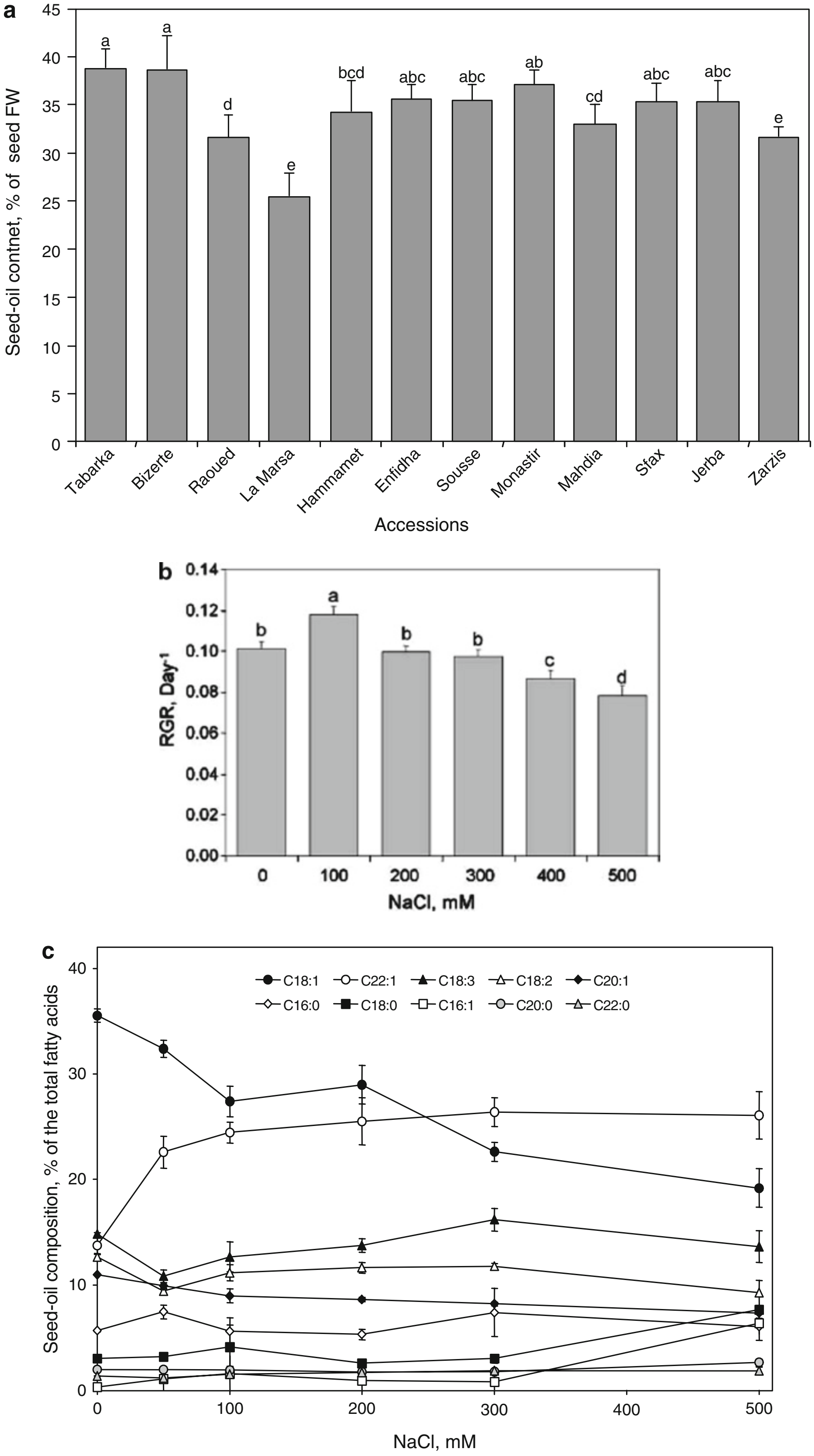

Fig. 4 Seed-oil characteristics and salt-responses of the halophyte *C. maritima* (**a**) Variability of seed-oil content in seeds of *C. maritima* Tunisian accessions. Means ($n = 3 \pm$ SE at $p < 0.05$) followed by at least one same letter are not significantly different between the accessions at $p < 0.05$ (adapted from Ghars et al. 2006). (**b**) Changes in relative growth rate (RGR) of plants exposed for 6 weeks to 0–500 mM NaCl salinities ($n = 10 \pm$ SE at $p < 0.05$) (adapted from Debez et al. 2006). (**c**) Effect of increasing NaCl on the seed-oil composition ($n = 3 \pm$ SE at $p < 0.05$)

of oleic acid (C18:1), which was prominent in the control (36%) (Debez et al. 2006b). Such a trend likely mediated elongases, which are known to catalyze the formation of long fatty acids (such as erucic acid), using oleic acid as initial substrate (Katavic et al. 2002). The search for accessions with a better match between salt concentrations optimal for seed production, seed oil content, and erucic acid concentration, is therefore of high interest. Seed-oil content seemed also to be unaffected by salinity in the oleaginous halophyte *Lesquerella fendleri* (Dierig et al. 2003).

Another promising oilseed halophyte is *Kosteletzkya virginica*, native to the American salt marsh. This species was introduced into China as a candidate species to improve tideland and develop ecologically sound saline agriculture Ruan et al. (2008). A 10 year-long field study revealed that *K. virginica* was flooding-tolerant, displaying multiple eco-benefits, such as landscape beautification, revegetation, and representing a food source for migratory birds. Besides, seed yields of unselected mixed and bred lines were 621 kg · ha^{-1} and 957 kg · ha^{-1}, respectively. Oil contents in the seeds of the unselected mixed and bred lines were 18% and 21%, respectively. Gallagher (1985) reported that seed yield of *K. virginica* in the USA was 800–1,500 kg · ha^{-1} with a seed-oil content of 20–30%. Unsaturated fatty acids (70%) in the seed oil predominated over saturated ones (30%). Oil content in the seeds of *K. virginica* was equivalent to the soybean, whose oil content was about 5%–20% (Yang et al. 2000). The content of unsaturated fatty acids was slightly less than soybean (85%), peanut (82%) and gingili (86%). All these indicated that seed of *K. virginica* has a high potential to become a oil resource at saline sites.

6 Halophytes with Medicinal Potential and for Cosmetics

The use of medicinal plants is common in many developing countries. In addition, there is a renewed interest in developed countries in using medicinal plants to treat humans, pets and livestock. In the late 1990s, the world market for herbal remedies was estimated at US $19.4 billion (Qadir et al. 2008). Environmental stresses (salinity, drought, heat/cold, luminosity and other hostile conditions) often trigger in plants a significant oxidative stress, generating the formation of ROS, leading to cellular damage, metabolic disorders, and senescence processes (Wang et al. 2004). Increasing ROS concentrations eventually affect biological molecules, such as DNA, proteins, or lipids, resulting in mutations and membrane damage, and finally lead to cell and tissue injuries (Abdil and Ali 1999). Enhanced synthesis of protective secondary metabolites under stressful conditions is believed to save the cellular structures from oxidative effects (Buchanan et al. 2000). Halophyte ability to withstand salt-triggered oxidative stress is governed by multiple biochemical mechanisms that facilitate retention and/or acquisition of water, protect chloroplast functioning, and maintain ion homeostasis. Most essential ones include the synthesis of osmotically active metabolites, specific proteins, and antioxidant compounds (Ksouri et al. 2008). This might explain (i) the utilization of some halophytes as traditional medicinal plants and (ii) the increasing interest for their potential for industrial applications (e.g. agro-food, cosmetic and medicine). Natural antioxidants occur in all plant parts, and the typical compounds that exhibit antioxidant activities include phenols, carotenoids and vitamins (Chanwitheesuk et al. 2005). Among various kinds of natural antioxidants, polyphenols constitute the main powerful compound. Accordingly they are widely applied in food industry, cosmetic, pharmaceutical and medicinal materials (Maisuthisakul et al. 2007). In plants, polyphenol synthesis and accumulation is generally stimulated in response to biotic/abiotic stresses (Naczk and Shahidi 2004), such as salinity (Navarro et al. 2006). In addition to their role as antioxidant, these compounds exhibit a wide spectrum of physiological properties, such as anti-allergic, anti-arthero-genic, anti-inflammatory, anti-microbial, anti-thrombotic, cardio-protective and vasodilatory effects (Balasundram et al. 2006).

The nonhalophytic species like medicinally important *Catharanthus roseus* can perform successfully at 10 dS · m^{-1} salinity without showing substantial decline in biomass production (Anwar et al. 1988). *Lycium barbarum* (Solanaceae) is a perennial halophytic species, which is important in traditional medicine in arid and semi-arid areas of China. It has been widely used as health-giving food for about 2,300 years (Cui and Xing 1999). Furthermore, *L. barbarum* fruits are used owing to their nourishing virtues for the kidney, liver, and for brightening eyes (Peng and Tian 2001). Wei et al. (2006) reported that moderate salinity (100 mM NaCl) was optimal for the plant biomass production (+30% as compared to the plants cultivated in non-saline conditions). This was associated with higher shoot succulence, significant accumulation of osmotically active compounds (i.e., betaine and sugar) and the absence of depressive effect on chlorophyll content, gas exchanges (CO_2 assimilation rate and stomatal conductance) and maximum quantum efficiency of photosystem II. Recent findings of Meot-Duros et al. (2008) confirmed the multiple potential of halophytes as natural food (or cosmetic) preservatives. The authors assessed both antioxidant and antimicrobial activities (against 12 bacterial and yeast strains) of three halophytes (*Eryngium maritimum*, *C. maritimum*, and *C. maritima*) collected from the Brittany (France) shoreline. The chloroformic and methanolic extracts were tested for their antimicrobial activities. Interestingly, all bacterial strains were inhibited by plant extracts with exception of *Listeria monocytogenes*. Both phenol content and the antioxidant activity were variable among the tested extracts, *E. maritimum* showing the lowest phenolic level as well as the lowest radical scavenging activity. On the contrary, *C. maritimum* exhibited the highest total phenol content and ABTS (2,2'-azinobis (3-ethylbenzothiazoline-6-sulfonic acid)) radical scavenging activity. Total antioxidant capacity was strong and ranged from 32 mg · g^{-1} DW in *E. maritimum* to 48 mg · g^{-1} DW in *C. maritima*. Antimicrobial activity of the apolar fraction was appreciable in the three investigated species, as most of the extracts showed a MIC (minimum inhibitory concentrations) of 100 µg · ml^{-1}, being even active at 1 µg · ml^{-1} in some cases. Polar fraction was effective as well. *E. maritimum* showed a strong antibacterial activity against *Pseudomonas aeruginosa* and *P. fluorescens*, while *C. maritima* was very effective against *Salmonella arizonae*. A good antimicrobial activity was found in *C. maritimum* against *Pseudomonas aeruginosa* and *Candida albicans*.

Besides its potential as oilseed, *C. maritima* could be of interest for production of secondary metabolites and antioxidant compounds. A comparative survey of two Tunisian accessions (Jerba and Tabarka, respectively, sampled from arid and humid bioclimatic stages) of this halophyte highlighted the presence of an accession-dependent capacity to induce antioxidant mechanisms in response to salt (up to 400 mM NaCl). This may result in a corresponding variability for growth sustainability (Ksouri et al. 2007). Indeed, Tabarka growth (shoot biomass, leaf expansion) was significantly restricted by increasing salinity whereas Jerba growth increased at 100 mM NaCl before declining at 400 mM NaCl. The better behaviour of Jerba was closely related to higher polyphenol content (+56% and 30% of the control values at 100 and 400 mM NaCl, respectively) and better antioxidant activity (lower IC_{50} values for both 1,1-diphenyl-2-picrylhydrazyl and superoxide scavenging), associated with lower leaf MDA (malonyldialdehyde) accumulation (*ca.* –66% of the control at 100 mM NaCl) (Table 2). The parallel stimulations of shoot biomass and polyphenol concentration in tissues in Jerba at 100 mM NaCl hence support the assumption that stress-tolerant plants (such as halophytes) are potentially interesting systems for production of secondary metabolites useful for food and medicinal applications. A similar trend was documented by Falleh et al. (2008) in *Cynara cardunculus*, (Asteraceae). Moderate salinity (25–50 mM NaCl) had no significant impact on leaf growth (biomass, length and number), but these parameters showed a severe reduction at 150 mM NaCl (–30% to –90% as compared to the control). Leaf phenolic content was significantly higher at 25–50 mM NaCl, before declining at 150 mM NaCl. The superoxide anion scavenging capacity of leaf extracts was proportional to the external NaCl concentration. *C. cardunculus* occurs mainly in Mediterranean arid regions, characterized by high

Table 2 MDA and total polyphenol and contents and antioxidant activities (IC_{50} values) in leaves of two *C. maritima* accessions irrigated for 28 days with a nutrient solution containing 0, 100, or 400 mM NaCl

NaCl (mM)	MDA (nmol · g^{-1} FW)		Total polyphenol (mg of GAE · g^{-1} DW)		DPPH· scavenging activity IC_{50} (µg · ml^{-1})		Superoxide scavenging activity IC_{50} (µg · ml^{-1})	
	Jerba	Tabarka	Jerba	Tabarka	Jerba	Tabarka	Jerba	Tabarka
0	4.30 ± 0.2e	4.64 ± 0d	43.02 ± 4c	42.84 ± 8c	0.67 ± 0.1c	0.62 ± 0.2c	3.10 ± 0.1bc	3.57 ± 0.9bc
100	1.48 ± 0.2f	7.48 ± 0.2b	66.93 ± 4a	37.73 ± 8c	0.76 ± 0.0c	1.34 ± 0.2b	1.70 ± 0.3c	5.10 ± 1.1b
400	5.61 ± 0.1c	12.03 ± 0.0a	56.04 ± 1b	31.58 ± 8c	0.89 ± 0.5c	1.95 ± 0.1a	3.90 ± 0.1bc	14.90 ± 3.0a

Source: Adapted from Ksouri et al. (2007)

Values ($n = 8$ ± SE at $p < 0.05$) of each parameter followed by at least one same letter are not significantly different at $p < 0.05$

temperature, elevated salinity and drought in summer (Gominho et al. 2000). It is noteworthy that *C. cardunculus* flowers are used for cheese preparation (Valentao et al. 2002), while leaves are traditionally known for their therapeutic virtues as diuretic, antidiabetic, and antimicrobial agent (Fratianni et al. 2007).

Saïdana et al. (2008) focused on the chemical composition of the essential oil and the antibacterial and antifungal activities from the flowering parts of *Suaeda fruticosa* (Chenopodiaceae) and *Limonium echioides* (Plumbaginaceae) sampled from the Sahel region in Tunisia, where semi-arid Mediterranean climate prevails. The first species is known for its hypoglycaemic action, while *Limonium* spp. is known as an antioxidant medicinal herb. 65 compounds were identified in *L. echioides* among which 48 were common with *S. fruticosa*. The main components in *L. echioides* were hexacosane (10.7%), palmitic acid (9.8%), nonacosane (8.4%), (E,E)-farnesyl acetate (7.0%) and vanillin (6.5%). Palmitic acid (15.2%) was also prominent in *S. fruticosa*, followed by methyl linoleate (10.8%), phytyl acetate (8.8%), hexacosane (7.4%) and methyl decanoate (7.0%). Oil of both species was effective against bacteria such as *Staphylococcus aureus*, *S. epidermidis*, *Micrococcus luteus*, *Escherichia coli*, and *Salmonella typhimurium*, but no antifungal activity was detected, presumably because of the low concentrations used in this study.

Recently, more exhaustive studies revealed large variability in total polyphenol contents and antioxidant activities (DPPH and superoxide radicals scavenging activities, and iron chelating and reducing powers) of several halophytes (*C. maritima*, *Limoniastrum monopetalum*, *Mesembryanthemum crystallinum*, *M. edule*, *Salsola kali*, and *Tamarix gallica*), depending on biological (species, organ and developmental stage), environmental (original habitat), and technical (extraction solvent) factors (Ksouri et al. 2008; Ksouri et al. 2009; Falleh et al. 2009). Such a variability might be of great importance in the perspective of valorising these halophytes as a source of naturally secondary metabolites.

7 Agroforestry Ecwosystems and Carbon Sequestration

Implementing salt-tolerant tree plantations while utilising saline drainage or groundwater represents a promising alternative of using abandoned lands. Of the most promising species are *Prosopis juliflora*, *Acacia nilotica*, *Casuarina equisetifolia*, and *Eucalyptus camaldulensis* (Qadir et al. 2008). Widely used *Acacia* species in agroforestry on saline soils include *A. stenophylla*, *A. nilotica*, *A. ampliceps*, *A. tortilis*, *A. maconochieana*, and *A. cyclops*. Although most *Acacia* species are not halophytes but some are highly salt-tolerant and at the same time sensitive to waterlogging (Craig et al. 1990). *Casuarina*, a fast-growing evergreen tree native to Asia and Australia, was successfully used in the coastal regions of Africa due to its ability to cope with extreme environmental conditions. Marcar et al. (2000) reported a 77% survival rate in *C. cunninghamiana* growing in soils with 11.5 dS · m^{-1} EC for 30 months and 55% for more than 7 years. The evergreen tree *E. camaldulensis* is a medium to tall (20–45 m) tree native to Australia with several uses, such as essential oil and paper production, landscaping, sand dune stabilization, and to lower high water tables of saline environments. In a mid-term (4-year) field study, Oster et al. (1999) found significant restriction of both growth rate and water use of *Eucalyptus* when irrigated with saline-sodic waters (20–22 dS · m^{-1} salinities in the root zone). Whereas a long-term (9 year-long) investigation with 31 tree species challenged with saline water at 8.5–10.0 dS · m^{-1} EC showed that *Tamarix articulata*, *A. nilotica*, *P. juliflora*, *E. tereticornis*, *A. tortilis* and *Cassia siamea* were performing best (Tomar et al. 2002).

The process of carbon sequestration, or flux of carbon, into soils forms part of the global carbon cycle. Movement of carbon between the soil and the above ground environment is bidirectional and consequently carbon storage in soils reflects the balance between the opposing processes of accumulation and loss. Carbon in soils comes from CO_2 in the atmosphere, which is captured by plants *via* photosynthesis, and ultimately stored to soil by direct decomposition of plant material. Halophytic plants adapted to saline dry lands offer potential for sequestering carbon in this hostile ecosystems. Investment in anti-desertification measures in the world's drylands appears to be an economical method to offset CO_2 build-up in the atmosphere while accomplishing a major international objective of re-vegetating drylands. This alternative relies on the assumption that salinity of a halophyte agro-ecosystem may slow the processes of residue decay, and thereby increases the potential for sequestering halophyte carbon. According to Glenn et al. (1993), 0.6–1.2 Gt C · year^{-1} could be assimilated by halophytes, among which 50% of C might enter long-term storage in soil (Glenn et al.

1993). Taking into account the irrigation requirements (based on the irrigation demand which is related to the plant biomass production), the authors consider the rate of 22.5–30% as realistic. Yet, this assumption needs to be corroborated by further field surveys, as the potential for storing organic carbon in agronomic soils depends on the type of organic material in the system. Goodfriend et al. (1998) addressed the decomposition of three promising halophytic crops (*S. bigelovii*, *Suaeda* sp., and *B. maritima*) in order to assess their potential for carbon storage in a coastal desert agro-ecosystem, near Sonora (Mexico). Several parameters including decay rates, incorporation of residues into the soil, microbial decomposition activity, the abundance of bacteria, fungi were determined. Results showed that after 1 year, the rate of halophyte residue decay and the number of microbial decomposers associated with the residues are similar to those of fresh water systems. There appears to be no advantage in storing carbon as plant residue in this saline agricultural system.

Mangroves are woody tress or shrubs located at the interface between land and sea, presently occupying ca. 181,000 km^2 of tropical and subtropical coastline. Over the past 50 years, approximately one-third of the world's mangrove forests have been lost, mostly because of urban development, aquaculture, mining and overexploitation for timber, fish, crustaceans and shellfish (Alongi 2002). Mangroves grow in sheltered shores, penetrating into the estuaries of rivers, tidal creeks, backwaters, salt marshes and coastal mudflats. They are open systems since they are constantly subject to tidal flow and seasonal flooding. As halophytes, mangroves thrive well in saline waters but require fresh water to a certain extent in order to maintain an optimum salinity balance and to get nutrients. Mangrove ecosystems contribute to stabilize sediments and may augment local sediment accumulation and enrich soil with nitrogen, phosphorus and sulphur (Hussain and Badola 2008). They not only create a living buffer between neighbouring river, marine and terrestrial communities, but also play an important role in supporting the productivity of the coastal environments. Among the most common species there are *Avicennia officinalis*, *A. alba*, *Aegiceras majus*, *Aegialitis rotundifolia*, *Acanthus ilicifolius*, *Kandelia rheedii*, *Bruguiera caryophylloides*, *Sonneratia griffithii*, *Laguncularia racemosa* and *Carapa obovata*. Ecophysiological (salt-tolerant, highly efficient nutrient retention) and morphological features (respiratory aerial roots, viviparous embryos, absence of growth rings, wood with narrow densely distributed vessels rings) make mangroves structurally and functionally unique (Alongi 2002).

Because mangroves fix and store significant amounts of carbon, their loss may drastically affect global carbon budgets. Cebrian (2002) calculated that a loss of about 35% of the world's mangroves led to a net loss of $3.8 \cdot 10^{14}$ g · C stored as mangrove biomass. The ecological significance of mangroves in protecting the coastal areas was recently highlighted by Danielsen et al. (2005) who showed that mangroves and *Casuarina* plantations attenuated the tsunami-induced waves and protected shorelines against damage: indeed, villages located within the *Casuarina* plantations remained undamaged except for rows of 5–10 trees nearest to the shore, which were uprooted. In addition, based on analytical models, mangrove plantations at 30 trees per 100 m^2 in a 100-m wide belt may reduce the maximum tsunami flow pressure by more than 90%. Measurement of wave forces and modeling of fluid dynamics suggested that tree vegetation may protect coastlines from tsunami damage by reducing wave amplitude and energy.

8 Conclusions and Perspectives

Crop diversification and production systems based on halophytes are likely to be the key to both socially and economically rehabilitate, and thereby valorise, the salt-affected-regions. Such an approach will be particularly relevant for developing arid and semi-arid countries, where most farmers exploiting these marginal lands are resource-limited and communities face severe unemployment, poverty, and population migration (Qadir et al. 2008). Revolutions in agriculture rely on empirical approaches. Looking towards the future, sometimes means taking a step to the past, in order to discover guided by an open mind thousands of possibilities hidden by nature, and enlarged by cultural evolution (Galvani 2007). Historical evidence suggests that farmers always shift from more sensitive to more tolerant crops as salinity in their fields rises (Flowers 2004). Ending this infernal series could be achieved by the sustainable use of the wide range of halophytes available, whose large potential as crops is still under-explored (Koyro and Huchzermeyer 2004). The use of salt-affected land and saline water resources by crop diversification could also be an alternative to move from subsistence farming to higher income-generating ventures.

The emerging data supporting the feasibility of successfully cultivating salt-tolerant plants in saline agro-ecosystems offer unexpected opportunities for researchers, farm advisors, and farmers to identify the most appropriate cash crop halophytes and their combinations to optimize the input/output ratios. Besides, since salt-affected soils and ground waters cross national boundaries, co-operation and coordination at regional and global levels is of high importance to elaborate and apply effective salinity strategies. With this respect, it is crucial to initially involve politicians, institutions, select farmers, water user associations, and other potential beneficiaries, so that (when the critical time for expansion comes) all parties will be familiar with their role. (Yensen 2006). This means changing the general opinion of the affected farming communities and policy makers about the questionability of using salt-affected soils.

Preliminary assessments suggest that there are 26 salt-tolerant plant species capable of producing 13 products (or services) of value to agriculture in Australia (Barrett-Lennard 2002). As suggested by Koyro et al. (2006), once the selection of halophytic species suitable for a particular climate and for a particular utilization has been achieved, a progressive realization of the following steps may bring to establish useful cash-crop halophytes:

(a) Performing greenhouse experiments at the local substrates (and climatic conditions) to select and propagate promising sites (Fig. 5)
(b) Using Lysimeters on the field to gather reliable and long-term data about the water consumption and ion movements
(c) Developing a sustainable production system in plantations at coastal areas or at inland sites (for example for economical use)
(d) Assessing the plant yield and the financial outcome for the farmers
(e) Evaluating the economic acceptance of the product The development of successful industries for salt-land will require pertinent information regarding the capabilities of land and water, plants and animals, and markets
(f) Protecting the environment by using appropriate culture and irrigation practices and finally
(g) A major task is the need to change perception in the community of biosaline agriculture

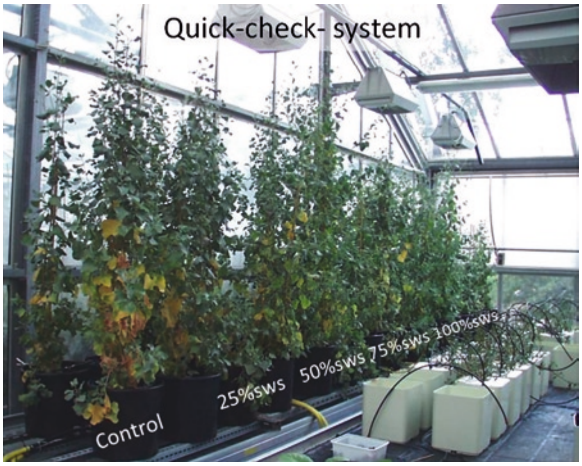

Fig. 5 On the left side gravel/hydroponic quick check system (QCS) with automatic drip irrigation under photoperiodic conditions in a growth cabinet (plant species: *Atriplex nummularia*) and on the right side hydroponic culture of *Sesuvium portulacastrum*. Controls are visible in the foreground, the sea water salinisation treatment (100% sws ≅ 500 mol * m^{-3} NaCl) in the background

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