HALOPHYTES – A PRECIOUS RESOURCE

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ABSTRACT – A review is presented of halophyte potential when grown in saline lands or irrigated with saline waters for the production of forages and other beneficial uses in the various conditions under which salinity may occur. Halophyte use in bioremediation to improve chemical and physical properties of saline-sodic and sodic soils is also illustrated. Conditions for sustainably growing halophytes and salt-tolerant glycophytes as well as for protecting lands endangered by secondary salinization are examined. Halophyte potential in capturing and long-term sequestering atmospheric carbon dioxide is evaluated. Economic and social implications are briefly illustrated.

Keywords: halophytes, bioremediation, salt tolerance, soil salinity

INTRODUCTION

It is well known that the steadily increasing world population puts ever more pressure on land and water resources. In fact, while more and more resources are required, improper irrigation management brings about soil fertility decay in large areas worldwide (secondary salinity): it has been estimated that from 3,8 million (IAEA, 1995) to 7,6 (Douglas, 1994), and up to 10 million (Tanji, 1990) square kilometres are out of production due to primary and secondary salinity, with land losses advancing at a pace spanning from 1,5 million (Ismail *et al*., 2002) to 20 million (Malcolm, 1991) hectares per year, according to the estimates. Ironically, such land losses are mostly due to the mismanagement and wasteful use of scarce water resources.

It becomes therefore imperative to undertake a serious effort not only to train advisers and irrigators to better use available freshwater (which would reduce the rate of land loss) but also to expand agricultural crops in those vast unused areas that are an enormous potential resource. Under those extreme conditions of soil or water salinity where no crop of agricultural interest can be grown it is possible to imagine dedicated halophyte plantations for forage production, soil rehabilitation, bioenergy generation, landscaping, carbon dioxide sequestering, and a number of other useful purposes.

It is the goal of this paper to review the potential of halophytes and salt tolerant glycophytes in taking advantage of those barren and abandoned marginal lands that are commonly believed useless: on the contrary a huge research and demonstration activity in the last decades has demonstrated their unsuspected value.

Mankind today is not in a position to overlook such untapped resources.

HALOPHYTES

Various attempts to classify halophytes have been proposed, however the simplest and clearest definition is probably that of Aronson and Le Floc'h (1996), stating that "halophyte species are those occurring in naturally saline conditions only".

Actually it is difficult to precisely define halophytes, as opposed to glycophytes, due to the variability of plant responses in dependence of a number of factors, including climatic conditions and plant phenophases: for instance a plant may be sensitive during, say, the germination or seedling phase while it is tolerant during the other phases or may suffer salinity under dry conditions while easily overcoming it under a moist climate (an interesting new dynamic salinity stress index linked also to temperature and solar radiation has been worked out by Dalton, Maggio and Piccinni, 1997, 2000 and 2001). In conclusion there is a wide and uncertain frontier between halophytes and tolerant glycophytes.

Those plants growing best under a certain level of salinity are called “euhalophytes”; a further distinction is that between xerohalophytes, thriving under saline, arid conditions, and hydrohalophytes, thriving under saline, moist conditions.

Terrestrial halophytes belong to 550 genera including 1560 species, according to Aronson (1989), but according to a later estimate by Menzel and Lieth (1998) the number of species is considerably higher (almost 2600); the difference is likely due to the different approaches in defining halophytes.

According to Le Houérou (1996) “there are as many as 6000 species of terrestrial and tidal halophytes in the world” and by far the largest proportion is that belonging to Chenopodiaceae, followed by Poaceae; the Mediterranean flora includes about 700 species of halophytes, some 70% perennials and 30% annuals. In China, Kefu *et al*. (2002) identified 430 halophyte species.

Halophytes can tolerate high salinity levels, in some cases even higher than those in seawater (with an EC, electrical conductivity, of about 45-50 dS/m) by enacting several different mechanisms of defence which will not be examined here.

HALOPHYTES AND SALINE LANDS

The wide variety of halophytes and of their characters permits to envision a profitable use of vast barren extensions of saline lands by selecting the appropriate species best fitting local conditions. Possible actions in dependence of peculiar soil and water conditions are synthetically shown in the following table.

Table 1. Possible uses of halophytes under various conditions

Soil	Water	Principal possible actions
Coastal lands	Seawater	Fixing dunes, landscaping, growing mangroves, fodder production
Inland saline areas (irrigated)	Brackish/saline water	Various scopes
Inland saline areas (dry)	Rain	Erosion control, fodder production
Salinized agricultural lands	Fresh/brackish water	Soil rehabilitation, agricultural production
Endangered agricultural lands	Fresh/brackish water	Soil protection, agricultural production

All the possible actions listed in the table can be easily undertaken after an accurate plant selection but of course a preliminary analysis assessing their environmental, economic and social feasibility is in all cases required.

In the last decades a valuable mass of experiences has been accumulated worldwide: here emphasis will be put on researches conducted in the Mediterranean region. Among the most active actors here are the UAE-based International Center for Biosaline Agriculture, the Desert Research Center in Egypt, the Ben Gurion University of the Negev in Israel and the Italy-based Mediterranean Agronomic Institute.

The halophyte uses in the various conditions listed in the table are briefly illustrated below.

Coastal Lands

One of the main problems afflicting sandy coastal lands is their vulnerability to wind erosion and dunes shifting, possibly combined with sea eroding action. Under such conditions it is obvious to think of a soil cover with halophytes to be irrigated with seawater, without any risk of damage to the soil and the aquifer, since the soil is typically a-structural, with no colloidal fraction to be protected, and the aquifer is the seawater itself.

Experiences conducted within a European Commission-funded Concerted Action have shown the amazing performance of seawater-irrigated *Sesuvium portulacastrum*, able to rapidly spread to form a thick cover, perfectly tolerant to a wide range of temperatures (- 2°C to 46°C) and drought stresses, apparently free of diseases and natural enemies (Sardo and Merlo, 2002).

Sesuvium grew very well when subsurface irrigated, but tolerated well enough sprinkler irrigation, even when seawater was daily applied in the warmest hours of the day.

The action of sprinkler-applied seawater on the soil was dramatic, since an evident decay was detected in the sprinkled coarse sand, as opposed to subsurface irrigated plot: in the former case, after two years' daily application at the precipitation rate of about 6 mm/h during two hours, a surface crust was formed in the sand which reduced infiltration rate from the initial 1400 mm/h to only 22 mm/h. In the adjacent subsurface-irrigated plot the infiltration rate showed a limited reduction, to 954 mm/h (Belligno and Sardo, unpublished work). After two years' irrigation with seawater, soil mean pH values were increased from 6.46 to 8.14 and the electric conductivity of the saturation extract passed from 42.41 to 144.83 dS/m.

It has been proposed to plant protective strips of Sesuvium along the sandy shorelines, to be automatically irrigated through the use of solar-powered pumps at the cost of about US $ 2 per square meter (Sardo and Merlo, 2002).

In those coastal areas where tourist development is planned it is also possible to select particular halophytes for embellishment and landscaping, thus saving precious freshwater.

Forage production in seawater-irrigated fields (*Salicornia bigelovii, Batis maritima, Suaeda esteroa, Sesuvium portulacastrum, Atriplex barklayana*) has been obtained in Mexico and the Arabian Gulf, and appropriate irrigation systems have been developed (UNEP, 1993; Glenn *et al*., 1996; ICBA, 2003).

Challenges for restoring vegetation on tidal, hypersaline substrates have been recently illustrated by Zedler *et al*. (2003), who point out the importance of the many factors affecting plant mortality upon transplanting.

A typical solution for coastal areas protection in the warmest regions is that of mangrove plantation, which create a rich ecosystem in addition to protecting the coast and supplying fodder and wood.

Inland Saline Areas (Irrigated)

Almost all the beneficial uses listed in the UNEP guidelines (1993) can be applied in the irrigated inland saline areas, primarily including forage production and soil rehabilitation (some other uses will be examined later).

Forage production in saline-sodic or sodic soils, when brackish or saline water is available for irrigation, has been extensively studied, with very encouraging results (e.g. ICBA, 2003; Qadir and Oster, 2004), since water availability permits to simultaneously achieve an appreciable forage yield and a significant action in soil rehabilitation.

The reuse of drainage water for irrigation is useful to conveniently dispose of an otherwise dangerous salt load, provided that long-term sustainability is secured. It is recommended to prepare seedbeds ripping the soil to the depth of some 50 cm in case of an existing hardpan, following with a shallow cultivation.

Forage production is frequently obtained by adopting appropriate intercroppings or rotations; among the most used species are Kallar grass (*Leptochloa fusca*) and old man saltbush (*Atriplex nummularia*). Kallar grass is a perennial extensively used in Pakistan with excellent results both in forage production and soil reclamation, but it dries up during the winter season (Aslam *et al*.,1991); for this reason it has been suggested to substitute it with saltbush which is more salt tolerant and produces green forage throughout the year (Hanjra and Rasool, 1991). It has also been suggested to integrate it with *Aster tripolium* which is cold-tolerant and able to vegetate during the winter. It has been also suggested. *Aster tripolium* is also marketed as an edible delicacy in the Netherlands (Lieth, 1999).

In Australia, saltbush (five species of *Atriplex*) when irrigated with water containing up to 10.000 ppm dissolved solids averaged a fresh biomass yield of over 20 tons per hectare in the second year of saline irrigation as opposed to a production of 17,4 tons when freshwater-irrigated (Schulz and West, 1994).

Saline Drylands

Problems with halophytes growing in saline rainfed areas refer mainly to the germination phase; to the scope special techniques have been devised, including the formation of "niches" where rainfall water is collected and seeds are protected with a mulch to reduce evaporation (Malcolm, 1981; Malcolm *et al*., 2003).

A very simple mechanical equipment permitting a fast soil preparation (from 2 to 14 ha /day) at the cost of US$ 20 to 60 per hectare has been developed and used on a relatively large scale (over 100.000 ha) by Vallerani (Vallerani, 2002), which combines pit digging to seeding in a single passage. Such a system is particularly useful in rainfed areas during the crop cycle and not only in the establishment phase since it has the advantage of harvesting rainwater conveying it to the plants.

In rainfed areas the soil rehabilitation action is typically slower than in the irrigated ones due to the lower amount of incoming water and fodder production is less, however it can reach appreciable levels provided that the right species are selected. For instance Greig (1994) reported the results of an interesting trial with 72 different halophytic species in an area in Australia receiving an average of 425 mm rainfall and rated their performance according to salt tolerance, palatability, productivity, persistence and ability to spread.

Although it is often assumed that drought and salinity tolerance follow the same pathways, observations conducted in Sicily by the authors on plants of *Pancratium* and *Nicotiana,* highly tolerant to drought, showed that they are relatively salt-sensitive, which gives support to the claim that plant response is not only determined by osmotic potential values but also by the specific cations and anions. In conclusion it is suggested that it is not sufficient to report solution EC values, but also salt components should be specified.

Of a particular interest in arid saline soils is the "old man saltbush" (*Atriplex nummularia)*, reportedly able to grow with only 150-200 mm of rainfall per year, and able to survive for a year with only 50 mm (Aganga *et al*., 2003).

Moselhy and El-Hakeem (2002) report the results of an interesting experiment conducted in Egypt during three years, combining in an "alley cropping system" rows of *Atriplex nummularia* with barley; in a loamy sand under a yearly average precipitation of about 144 mm they obtained the best results when barley was grown in alleys 10 metres wide (i.e. saltbush rows were spaced 10 metres) and saltbush was planted at the distance of 3 metres along the row. Results were less positive when rows were 15 and 20 metres apart: the authors explain this with a less effective wind protection.

An overlooked crop, certainly deserving more attention, is quinoa (*Chenopodium quinoa* Willd). Quinoa*,* a pseudocereal*,* is one of the three big staple crops existing in South America at the time of Spanish invasion (the other two being potato and maize), but its use was discouraged by Spaniards who saw it linked to pagan practices and later by middle classes who considered it a food for the poor. Nowadays it is being explored with ever increasing interest due to its vast nourishing potential (Oelke *et al*., 1992) and its unbelievable ability to adapt to extreme conditions (it is tolerant to drought, salinity, frost, submersion: Jacobsen and Mujica, 2001) provided that the right cultivar is selected. For instance, from a research conducted in Peru by CIP, it resulted that the highest yield was obtained with an EC of 15 dS/m in the irrigation water (Jacobsen *et al*., 2000).

Agricultural Salinized Lands and Their Rehabilitation

This is the case of those barren lands affected by secondary salinization mostly dependent on irrigation mismanagement; the case, recurrent in Australia, of problems due to a shallow saline water table is rather rare in the Mediterranean region (one example in Spain is given by Moreno *et al.*, 2001; more examples in Egypt by Ghaffer *et al*., 2004 and Kotb *et al*., 2000). Compared to Australian conditions the task of reclaiming soils in the absence of a shallow water table is relatively easier since it is possible to rely on the natural drainage to leach excess salts down, if sufficient rainfall or irrigation water is available for leaching.

One additional difference between Mediterranean and Australian conditions (where problems were originated by forest clearing) is that in the Mediterranean there is a limited interest to explore the potential of tree plants such as Eucalyptus or Casuarina in soil reclamation since there is no need of applying such "biopumps", which are useful in lowering the water table but certainly do not offer an appreciable income nor permit an intercropping.

The potential of halophytes in bioremediation is well illustrated by Qadir and Oster (2004) who compared the results from 14 experiments with gypsum application versus vegetative reclamation in sodic soils. Results were slightly in favour of chemical treatments (62% sodicity decrease versus 52%) but in the bioremediation treatments sodicity was reduced throughout the whole root zone whereas gypsum was effective only in the layer where it was applied and furthermore the plant action improved soil structure and formed macropores enhancing air and water infiltration. In an earlier work Qadir and Oster (2002) listed advantages and disadvantages of bioremediation as follows:

- advantages: low initial capital input; promotion of soil aggregate stability and creation of macropores, better plant nutrient availability; more uniform and greater zone of reclamation; financial or other benefits from crops grown during reclamation.
- disadvantages: action slower than chemical methods; limited plant tolerance to highly saline-sodic and sodic soils; essential presence of adequate $CaCO_3$ in the soil.

Qadir *et al*. (2001) compared bioremediation (or phytoremediation) to chemical soil or water treatment, concluding that similar results can be achieved at a lower cost with bioremediation; they attributed its action to CO_2 emission from roots, encouraging Ca^{2+} ions release from the calcareous soil.

Several authors (e.g. Barrett-Lennard, 2002; Marui *et al*., 2003) however caution against excessive optimism about bioremediation, showing that plant action can be very slow, particularly in low-producing rainfed areas; however vetivergrass (*Vetiveria zizanioides)* with adequate leaching has proved useful in promptly reducing saline load in lysimeter-contained sandy soils (Hamdy *et al*., 2004).

Yunusa and Newton (2003) remark that salt damage depends not only on chemical degradation but on soil structure degradation as well and suggest the use of plants (which they call "primer plants") capable of drilling "biopores" in the soil thus helping to restore its structure, conditioning it for the following agricultural crops.

SELECTING CROPS FOR SALINE ENVIRONMENTS

Frequently in the case of secondary salinization salinity levels do not reach those extreme values which impose the adoption of highly salt-tolerant plants and as a consequence two courses of action can be planned, namely either selecting or "domesticating" halophytes to be used as an agricultural crop or "training" agricultural crops to thrive in the saline environment.

In all cases the first step is the formation of an extended gene pool, which is a crucial starting point due to the variability of edaphic conditions and the consequent multiplicity of plant traits required to best fit them.

Selection, hybridisation and breeding, to be conducted in the field, under specific pedo-climatic conditions, "hold tremendous promise for domesticating wild species and developing economically useful crops with higher salinity thresholds" (Biosalinity Awareness Project, 2004). The International

Center for Biosaline Agriculture is conducting a very fine work in constituting a germplasm bank of halophytes and salt-tolerant species, in selecting the most promising varieties and in trying to fill the gap in the large scale halophyte use existing between Australia and the more conservative Mediterranean region (ICBA, 2003).

Breeding techniques applied to conventional crops include not only screening, selection and hybridisation, but also the more recently developed bioengineering solutions. As Flowers puts it ”attempts to enhance tolerance have involved conventional breeding programmes, the use of *in vitro* selection, pooling physiological traits, interspecific hybridisation, using halophytes as alternative crops, the use of marker-aided selection and the development of transgenic plants. After ten years of research, the value of using transgenic plants to alter salt tolerance has yet to be tested in the field. The use of physiological traits in breeding programmes and the domestication of halophytes currently offer viable alternatives to the development of tolerance through the use of transgenic technologies” (Flowers, 2003). Such cautious statements substantiate the early sceptical previsions of Malcolm (Malcolm, 1991).

Contrary to that, an optimistic view is shared by Sharma *et al*. (2002) who presented in an interesting review the prospects of biotechnology for crop improvement and Wei *et al*. (2001) who illustrated their (only partly successful) efforts to transfer salt tolerance from a halophyte, *Aeleuropus littoralis,* to wheat via asymmetric somatic hybridisation. Suiyun *et al*. (2004) report some promising results obtained applying asymmetric somatic hybridisation to *Triticum aestivum* and *Thinopyrum ponticum (Agropyron elongatum).*

Also López-Bucio *et al*. (2000) are optimistic about the possibility of obtaining transgenic varieties able to elaborate and excrete organic acids permitting plants to thrive in “extreme soils”.

Munns *et al*. (2002) illustrate the " avenues " for increasing crop salt tolerance, highlighting the potential of molecular markers to solve the problem of the society rejection of genetic engineering and concluding that “possibly a combination of all approaches, old and new, will be the most productive”.

ENDANGERED AGRICULTURAL LANDS – SUSTAINABLE SALINE IRRIGATION

An integrated approach to soil, water and crop management is required to achieve irrigation sustainability in the long term (rainfed crops are unlikely to give origin to secondary salinization) and to forestall that the often quoted sentence “in irrigated arid areas salinity build up is not a question of if but of when” turns true.

Thorough reviews of irrigation management under saline conditions aimed at averting the risk of soil salinization are given by Hamdy (1996, 2001), who examines in detail the various practices for a sustainable land and water use, stating that “there is usually no single way to control salinity in irrigated land. Several practices can be combined into systems that function satisfactorily depending upon the economic, climatic, social and hydrogeological situation. Thus, management measures should not be considered in isolation but should be developed in an integrated manner to optimise water use, minimize drainage and increase crop yields within limits of the physical and social environment.”

When embarking in an action of soil rehabilitation it is crucial to take into account the water and salt balance, securing an adequate drainage of salts; a decisive support in the planning stage can be obtained from the adoption of simulation models, permitting to explore various contrasting scenarios and to have “a glimpse into the future”; one of the best known is WATSUIT (Oster and Rhodes, 1990).

A quite useful tool in predicting the evolution of salinity in the soil as affected by soil and water quality, climate, drainage and irrigation management is the recently developed simulation model SALTMED (Flowers *et al*., 2003). It is in fact imperative to monitor salt balance in the soil, controlling rainfall and irrigation water action in order to maintain fertility in the long term (Hamdy and Ragab, 2003) and it is imperative to adopt a holistic strategy considering simultaneously in-farm and off-farm impact of irrigation and drainage, including drainage water reuse (Oster and Wichelns, 2003).

While a major support to the maintenance of a favourable salt and water balance can be achieved through the adoption of water harvesting technologies, introducing halophytes or salt tolerant crops in the rotation can significantly help in keeping a low salt level in endangered areas.

Vetivergrass hedgerows can be quite useful to reduce overland flow and solid transport (to about 25 - 30% compared to unprotected lands: Hamdy and Sardo, unpublished data), thus encouraging water infiltration and salt leaching. Additionally, vetivergrass can thrive in highly saline soils and contribute to their bioremediation (Hamdy *et al*., 2004).

Mitchell *et al*. (1999) give a very interesting report on the results obtained with 125 winter-growing potential cover crops in the Mediterranean environment of California, on moderately saline soils: the best results in terms of biomass production were achieved with some *Brassica* species, while with the N-fixing plants outstanding results were given by some species of *Hedysarum, Trifolium, Medicago* and *Vicia*.

HALOPHYTES AND CO_2 EMISSION MITIGATION

The rapid increase in atmospheric CO_2 content in the last decades has aroused concern about its impact on the greenhouse effect. In principle, agriculture could help to contrast CO_2 increase in two ways: by reducing its emissions from fossil fuels through the production of renewable biofuels and/or by sequestering it in the biomass; however, although repeatedly demonstrated technically feasible, such solutions have not been adopted due to economical reasons.

It has been suggested (UNEP, 1993; Glenn *et al*., 1993) to use halophytes for capturing and long-term sequestering atmospheric CO_2, to alleviate the greenhouse effect. UNEP (1993) has estimated in fact that in world dry lands 0.5 to 1.0 gigatons of carbon per year over 100 years can be sequestered at a cost of 10-20 US $/ton of carbon: a significant part of the desert land needed for sequestration could be irrigated with seawater to enhance biomass production.

Mean carbon storage in forest biomass (including above ground and below ground parts) in dry areas of low latitudes has been estimated in the range of 33 to 124 tons/ha (Winjum and Schroeder, 1997) but such figures are quite distant from those given by Douglas for seawater- irrigated halophytes in Mexico, of about 4 to 8 metric tons per hectare (Douglas, 1994).

One interesting feature of halophytic biomass behaviour in drylands is its slow decomposition rate, a sort of “salami effect”, favouring the long term sequestration of the captured carbon; however such effect has been questioned, at least for specific environmental conditions (Goodfriend *et al*., 1998).

It has also been proposed (e.g. Douglas, 1994) to use halophytes to produce bioenergy, since annual dry biomass yields in the range of 17 to 34 metric tons per hectare have been reported for seawater irrigated plants in an experimental Mexican farm (from researches conducted in Sicily a biomass yield in the order of 10 to 15 metric tons appears more probable, however). The solution is certainly attractive, since no fossil fuel would be used to add CO_2 to the already overburdened atmosphere, but the problem has been overlooked of the high ash and salt content in such biomass, which can be detrimental in the process of bioelectricity production with the current technologies.

ECONOMIC AND SOCIAL CONSIDERATIONS

Until today the possible agricultural utilization of saline lands has been overlooked, in the belief that it would be un-economic.

But if worthless, saline lands and waters are used to grow dedicated halophytes, able to produce some useful yield, albeit at a lower level than in good arable lands, then the economic framework can be totally different, particularly if externalities are taken into account.

Externalities can include social benefits depending on soil protection against water or wind erosion (and hence reductions in-site and off-site damages), biodiversity enhancement, the creation of shelters for wildlife, the protection of atmosphere quality through the production of biofuels, the mitigation of the greenhouse effect through the capture of CO_2.

The attribution of a monetary value to such items (their “internalisation”) would give to the biosaline agriculture the right to claim a financial support to integrate the limited direct farm income.

Furthermore growing crops and achieving significant productions without putting any more pressure on limited good quality land and water resources would contribute to mitigate social strains and litigations, inside and outside national boundaries.

Through such possible pathways agriculture can abandon its present uncomfortable position of environmental polluter to assume instead that of the environment defender.

CONCLUSIONS

“The development of mankind has reached the point that a variety of new resources need to be tapped in order to fill our basic needs for food, feed and freshwater”: in this statement of Lieth (1999) lies the basic reason for the interest in halophyte research.

A vast, very promising field is now facing the research on halophytes, where only part of the “conventional” knowledge of those previously engaged in research with saline water and soils can be used. Paradoxically, it can be argued that those approaching such researches without the support of the classic background are under some respects in a position of privilege: evidence is in fact accumulating of the need of new agronomic approaches and to revise currently accepted guidelines for water quality evaluation and recommendations for irrigation with saline waters.

Undeniably the problems to be overcome for an environmentally safe and economically convenient use of saline lands and waters are still formidable and their solution requires a coordinated effort of a vast number of experts in various domains. However, though challenging the task may appear, it is exciting and stimulating to participate in an undertaking which can lead to enormous strides towards mankind’s well being and environmental protection.

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