Chapter 7
Cash Crop Halophytes: The Ecologically and Economically Sustainable Use of Naturally Salt-Resistant Plants in the Context of Global Changes

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Abbreviations

FAO	Food and Agriculture Organization of the United Nations
IPPC	Intergovernmental Panel on Climate Change
ppm	Parts per million
UNEP	United Nations Environment Programme

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1 Introduction: Population Growth and Climate Change as Challenges for the Future

Feeding the rapidly growing human population is one of the biggest challenges we (will) face on our planet today and in future. During the last 12 years, the world population has increased from 6 to 7 billion (Deutsche Stiftung Weltbevölkerung 2012a). By 2050, 9.3 billion people are expected to live on earth, while the African population will probably double within the next 40 years (Deutsche Stiftung Weltbevölkerung 2012b). Especially in arid and semiarid regions, the increasing population density is collaterally catalysed by the consequences of global climate change which is caused by anthropogenic emissions of trace gases (IPCC 2007). One of the most important greenhouse gases is CO_2, the atmospheric concentration of which has increased from 280 ppm to approximately 380 ppm since the beginning of industrialisation and will continue to rise in future (IPCC 2007). Global climate change manifests itself in extreme weather events such as flooding, storms or drought, as well as in rising global temperatures which have increased by about 1 °C over the course of the last century and will likely rise even more rapidly in coming decades. Scientists predict that temperatures could rise by another 3–9 °C by the end of this century with far-reaching effects (IPCC 2007). Increased drought, desertification, salinisation of arable land and freshwater scarcity are expected to have devastating effects on global croplands and food production (Wang et al. 2003). Abiotic stresses such as drought and salinity are already the primary reason for loss of agricultural productions worldwide, reducing average yields for most major crop plants by more than 50 % (Bray et al. 2000; Wang et al. 2003). Yield losses will soon become even more severe as desertification increases, so the current amount of annual loss of arable land may double by the end of the century because of global warming (Evans 2005; Vinocur and Altman 2005).

One of the major consequences of the increasing freshwater scarcity regarding agriculture in arid climate zones is the frequent use of saline irrigation water in an unprofessional manner, which often leads to further degradation of arable land. If a field is irrigated inaccurately and evapotranspiration exceeds total precipitation, water will rise by capillarity in the soil, and the eluviation of salts will be prevented. Thus the soluble salts present in the soil will be relocated to the upper soil layers together with water and will accumulate there. This process leads to secondary salinisation (Schubert 1999). According to the Food and Agriculture Organization of the United Nations (FAO), more than 30 % of the global irrigated land area (equal to six million km^2 farmland) is already affected by salinity today (Hussin et al. 2013).

Apart from desertification and salinisation, food availability is also limited by the decreasing reserves of fossil resources because energy requirements are partly covered by the energetic exploitation of food plants or the cultivation of energy crops on arable land even today. Food scarcity is further reinforced by ageing societies, especially in western countries (more food has to be provided for a person's lifetime), and by a higher meat consumption. According to the FAO, meat consumption has globally increased by one third since 1980 (industrial countries, from 76 to

82 kg/head; developing countries, from 14 to 30 kg/head), which enhances the need for biomass. Presuming the same energy yield, the acreage needed for animal food is ten times larger than the one needed for vegetable food.

However, there are various approaches to solve the problems mentioned above, including:

- A more equal food distribution and a direct or indirect reduction of water consumption during food production. This is part of the United Nations Millennium Development Goals proclaimed in September 2000.
- An intensified application of pesticides to maintain or (as far as possible) increase agricultural productivity.
- An increased application of genetic engineering to enhance plant stress resistance and productivity.
- The screening of biological resources and the development of new crop plants which consume less water and thrive in very dry habitats. An example is the so-called Groasis system in California, which allows the cultivation of vine with very low water consumption. This system is currently in an experimental phase in the Western Sahara (www.groasis.com).
- The environmentally sustainable and lasting use of alternative water resources such as saline and brackish water.

In order to reclaim degraded land and to prevent the wasting of precious freshwater for agriculture in the future, we need to rethink our use of water, especially the use of alternative water resources, which has a high potential for the extension of arable land. So, many scientists are currently striving to develop salt-resistant plants as crops suitable for agriculture (Rozema and Flowers 2008). The sustainable use of so-called cash crop halophytes is very well suited to ameliorate the negative impacts of global change on agriculture and environment while simultaneously counteracting its cause (due to their ability to sequester CO_2). These and other aspects of cash crop halophytes, and their utilisation will be presented in more detail in the following chapters.

2 Halophytes: Promising Crop Plants for the Future

More than 80 % of the earth's water resources are sea water. However, only few plants can tolerate sea water conditions—i.e. a salinity of about 3.5 % (sea water salinity, sws)—without serious damage. Though the evolution of plant life started in saline sea water three billions of years ago, this primary adaptation was lost during the development of terrestrial plants about 450 million years ago (Flowers et al. 2010). Today, 99 % of the terrestrial plant species are salt-sensitive meso- and glycophytes which are not able to grow and/or reproduce near coastlines or in saline inlands, including our contemporary crop plants. Their salt resistance is comparatively low, at most 20 % sea water salinity. Therefore, scientists have tried to adapt crop plants such as rice, maize or wheat to adjust to high soil salinity for approximately 20 years. Yet, attempts to increase their salt resistance significantly via plant breeding or molecular genetics has not been very successful up to now (Koyro et al. 2008). This is probably due to the fact that NaCl simultaneously affects several aspects of plant physiology (Koyro et al. 2013a) and to the polygenic inheritance of traits which confer salt resistance (Flowers 2004). Consequently, conventional crop plants are not well suited for production systems using saline irrigation.

Therefore, more focus should be laid on the utilisation potential of plants which can naturally survive in salty environments (Koyro et al. 2013b). They are called halophytes (from ancient Greek halos = salt and phytón = plant) which comprise roughly 2.600 species (Lieth 1999). Halophytes belong to the extremophytes and include annuals and perennials, mono- and dicotyledoneae, herbs, shrubs and trees. Except the polar Arctic and Antarctic regions, halophytes are distributed on all continents. They are found along European seashores as well as in tropical rain forests, arid salt steppes, in alpine regions near saline lakes and salt springs up to 2.500 m above sea level, or in deserts (e.g. Sahara) on sodium-rich sands. Although halophytes are present in all nonpolar climate zones, the tropical and temperate zones are their main distribution range.

Most halophytes prefer a saline environment but can also survive in freshwater habitats while using water very efficiently (Schimper 1898, 1903; Dansereau 1957). They grow preferentially in brackish water which is about half as saline as sea water. However, wide differences in salt resistance can be observed within the group of halophytes. Depending on the level of salt resistance, they can be classified into three categories of halophilia (Koyro and Lieth 1989; Le Houerou 1993): (a) low-salt resistance (up to 7 g NaCl/L), (b) transition zone (up to 25 g NaCl/L) and (c) high salt resistance (up to 65 g NaCl/L) (as a comparison, sea water contains approximately 30 g NaCl/L). Additionally, obligate, facultative or site-indifferent halophytes can be distinguished. Obligate halophytes such as *Sesuvium portulacastrum* and *Tecticornia indica* are salt-loving plants (Rabhi et al. 2011). They grow only in salty habitats and show a clear optimisation of their development through an increased salt supply in experiments (von Sengbusch 2003). Salinity levels of more than 0.5 % lead to growth stimulation and an increased vitality of these plants, whereas salt deficiency causes stunted growth (Künnemann and Gad 1997). Facultative halophytes are able to settle on salty soils, but their optimum lies in a salt-free or at least low-salt milieu (von Sengbusch 2003). They show better growth on salt-free or low-salt soils (physiological optimum) than in saline environments. Site-indifferent halophytes have a big advantage regarding the competition with other plants because on the one hand they can compete with glycophytes in salt-free locations and on the other hand they can grow on saline soils.

The above considerations show that halophytes include a variety of plants that prefer different abiotic conditions. In general, they are very promising future crops because halophytes are already adapted to extreme habitat conditions associated with global change. Additionally, elevated CO_2 can enhance their salt resistance and/or productivity, so that they are likely to thrive in a future with rising atmospheric CO_2 concentration (see sub-title 5 for more details). They are thus well suited to ameliorate the consequences of global change.

3 Utilisation of Halophytes

Halophytes have been considered as almost valueless up to now. At the Danish, German and Dutch coastlines, salt marshes have been destroyed by diking, while in the tropics, mangrove marshes have been reduced by half in order to use this land for agriculture or tourism. In fact halophytes are very valuable because the negative impacts of global change on agriculture and environment in arid regions could be solved or ameliorated by a targeted cultivation of these plants, owing to their diverse options for use. Thereby, we must pursue the goal to grow halophytes in an ecologically and economically sustainable manner. Cultivation should be done at locations which—due to increasing drought and/or improper use of saline irrigation water—are no longer suitable for the production of conventional crops (phytoremediation) or which actually do not host any plants, such as coasts, deserts or regions with saline ground water resources.

The ecologically sustainable use is an important prerequisite for preventing the expansion of salinised areas. It depends on the selection of suitable plant species which should be chosen according to the following principles:

- The species used should tolerate at least 15 g NaCl/L, i.e. 50 % sea water salinity (Miyamoto 1996).
- Their natural distribution area should be along the coastlines of as many arid and semiarid countries as possible.
- The selected species should have a high economic potential, i.e. they should yield good crops (Glenn et al. 1999) and secure sustainable earnings.
- A detailed knowledge about the mechanisms which confer resistance to abiotic stress is necessary. It would also be desirable to gather information about the effects of future atmospheric conditions (e.g. elevated CO_2 or ozone concentrations) or increased temperature on the performance and salt resistance of the species in question.
- It has to be tested if the sustainable use of halophytes is socially compatible, i.e. saline production systems have to fit with the existing agricultural/economic infrastructure (Lieth 2000). If the local population refuses to cultivate certain plants, the project will fail in the end.

Numerous halophytes can be utilised for a large variety of economical and ecological purposes which are listed in Fig. 7.1 (see also Fig. 7.2). Only one aspect of ecological utilisation is to be pointed out in more detail at this point because it has a special connection to global climate change: Every new large plant population which is created for long-lasting use can sequester CO_2 (Güth 2001; Arnalds 2004). Salt marshes and halophytes seem to be particularly suited for a long-term CO_2 sequestration (Caçador et al. 2002), and the cultivation of these plants in order to counteract the greenhouse effect was already proposed by the United Nations Environment Programme (UNEP) in 1993 (UNEP 1993).

The above considerations suggest that the sustainable use of cash crop halophytes can probably ameliorate the negative impacts of global change on environment, agriculture and human nutrition, while it can simultaneously counteract one of its

utilisation	examples of species
food: - salad, vegetables - oil (seeds) - fruits	- *Aster tripolium, Plantago maritima* - *Salicornia* ssp., *Critmum maritimum* - *Avicennia marina*
fodder	*Atriplex* ssp., *Sporobulus virginicus, Panicum furgidum*
ornamental plants	*Aster tripolium, Limoniastrum monopatalum, Sesuvium verrucosum, Kosteletzkya virginica*
wood, fibers	mangroves, *Tamarix* ssp., *Juncus maritimus*
chemicals (for chemical and pharmaceutical industry, production of clothes or plastics)	*Beta maritima, Juncus acutus, Critmum maritimum*
renewable resources (e.g. biofuel)	*Spartina alterniflora, Panicum turgidum*
landscaping, combating soil erosion and desertification (planting of streets, residential areas, dune stabilsation, re-greening)	*Sesuvium portulacastrum, Batis maritima*
coast protection	mangroves, *Spartina* ssp.
tertiary treatment of water and soil to reclaim degraded land, soil amelioration (reduction of salinity, oil or heavy metal contamination)	*Suaeda maritima, Salsola kali*
preservation of biodiversity	salt marsh plants, mangroves
marine agro-systems	*Salicornia* ssp., mangroves, algae
CO_2 sequestration	all species

Fig. 7.1 Possibilities for halophyte utilisation. Utilisations of halophytes already existing, utilisation purposes which are investigated and corresponding examples of species. Source of the photo belonging to marine agro-systems: http://www.seawaterfoundation.org/sea_science.html

causes, namely, the rising atmospheric CO_2 concentration. Additionally, the cultivation of halophytes and their manufacturing into foods or industrial products will be cost-effective and economically advantageous. Therefore, this topic is of high sociopolitical relevance.

Fig. 7.2 Utilisable halophytes. (**a**) *Aster tripolium*, (**b**) *Spartina townsendii*, (**c**) *Chenopodium quinoa*, (**d**) *Suaeda maritima*, (**e**) *Salicornia europaea* and (**f**) *Avicennia marina* (mangrove)

4 The Establishment of Saline Production Systems: Necessary Steps

In order to determine the possible contribution of halophytes to the extension of food supplies or to the substitution of conventional crops as renewable resources, detailed studies will be necessary. Some rules and precautions are to be considered while developing saline irrigation systems (Lieth 2000; Lieth and Mochtschenko 2003; for details see Figs. 7.3 and 7.4). First of all, a preselection with the help of existing background information about the foreseeable utilisation potential and environmental demands (climate, soil conditions, water demand) as well as a phytosociological assessment (suitability test) should be conducted. The salt resistance and its threshold as well as the food or fodder quality can be studied by means of a quick check system which can also be used to test the performance of the species under future atmospheric conditions. More details about this system are presented in the following chapter.

In case of positive results, an analysis of yield and sustainability should be carried out in countries which are qualified for cultivation, on local soils, with local saline water resources and suited irrigation systems (for details see Figs. 7.3 and 7.4).

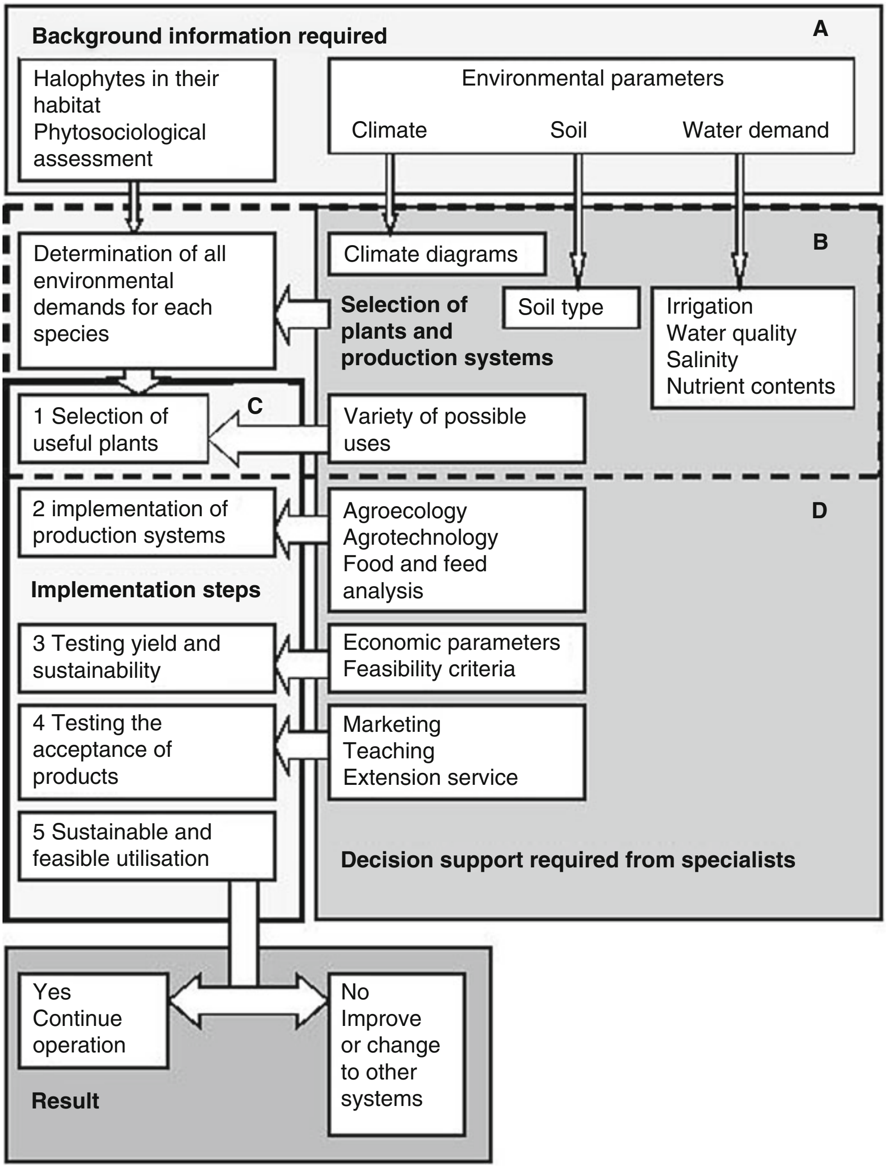

Fig. 7.3 Flowchart of work steps for the implementation of saline production systems (after Lieth, in Lieth and Lohmann 2000)

In doing so, also economic criteria should be considered, including yield and its longevity and the practicability of the culture. The final step will be testing the marketing, i.e. the acceptance and the profitability, of the new product.

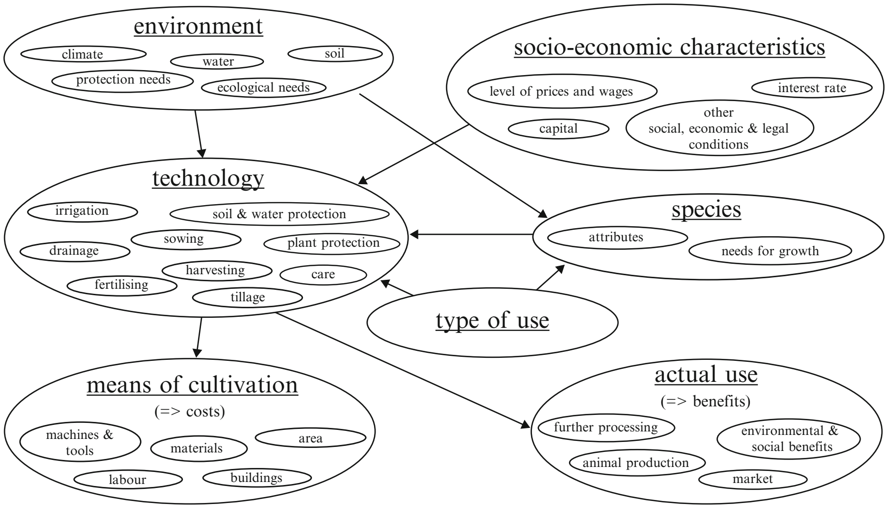

Fig. 7.4 The interdependencies between parameters which have to be considered when establishing saline production systems (after Lieth, in Lieth and Lohmann 2000)

5 Quick Check System: The Basic Step to Select Suited Cash Crop Halophytes

In a so-called quick check system, plants are grown under different salinity levels, but otherwise under identical growth conditions. Several types of cultivation can be used, such as soil cultures, gravel hydroponics with drip irrigation (Fig. 7.5a) or pure hydroponics (Fig. 7.5b). The quick check system is used to analyse the individual (species specific) salt resistance mechanisms and the salt resistance threshold. It can also serve to test the performance of the plants under elevated CO_2 concentration. In this case two identical quick check systems are run in two open-top chambers where the plants are supplied with ambient (just under 400 ppm) and elevated CO_2 concentration (e.g. 540 ppm, simulating the future atmospheric concentration in 40–80 years time; IPCC 2007) (Fig. 7.5b). Owing to these qualities, the quick check system is essential for the selection of promising cash crop halophytes (Flowers and Colmer 2008; Koyro and Lieth 2008). These plants exhibit a broad bandwidth of morphological, physiological and biochemical adaptive mechanisms (Koyro et al. 2006; Huchzermeyer 2011; Debez et al. 2012) and also differ in their response to elevated CO_2. The quick check is well suited to investigate the reaction of plants to the growth constraints of saline habitats (osmotic stress and restriction of CO_2 uptake; ion toxicity and nutrient imbalance; Geissler et al. 2013) and to the influence of elevated CO_2 on salt resistance.

Growth depression under saline conditions can be explained at least for glycophytes such as barley and wheat by a two-phase model (Munns 1993, 2002)

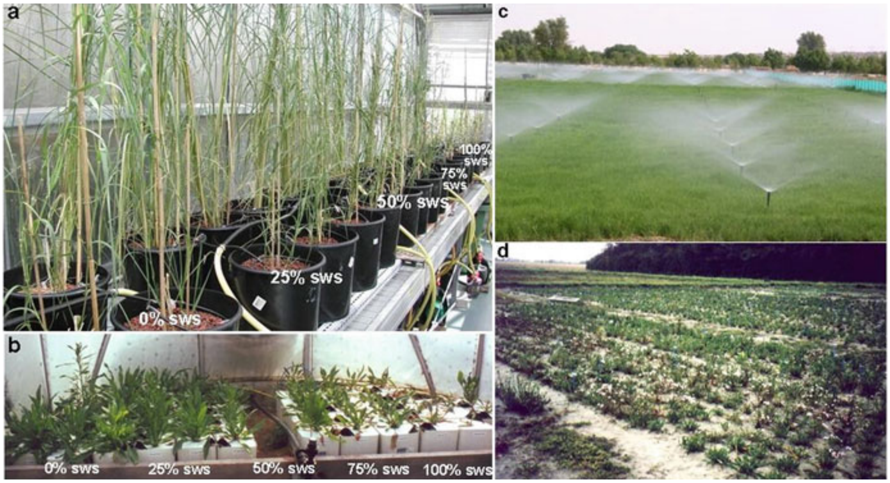

Fig. 7.5 (**a**, **b**) Quick check systems to determine species-specific salt resistance mechanisms and salt resistance threshold. (**a**) *Sporobolus virginicus* (*left/back row*) and *Leptochloa fusca* (*right/front row*), gravel hydroponics with drip irrigation; (**b**) *Aster tripolium*, pure hydroponics culture, permanently aerated, in open-top chamber. (**c**, **d**) Examples of saline production systems. (**a**) *Sporobolus virginicus* cultivated for fodder using sprinkler irrigation in the United Arab Emirates; (**b**) *Aster tripolium* cultivated for food in the Tejo estuary, Portugal (photo: Lieth 2000)

distinguishing between osmotic and ionic stress. It is not proved that halophytes experience these constraints within the same time frame, but they need to react to both of them in any case. Osmotic stress is caused by the reduced osmotic potential of the external medium (physiological drought). Osmotic stress has negative effects on the water balance of plants and causes detrimental changes in cellular components because the biologically active conformation of proteins and biomembranes depends on an intact hydration shell (Schulze et al. 2002). Water loss can be minimised, e.g. by stomatal closure. As a consequence, gas exchange and thus the assimilation rate are inhibited, which in turn may lead to the formation of reactive oxygen species (ROS) which are highly destructive to lipids, nucleic acids, and proteins (Geissler et al. 2010; Ozgur et al. 2013). Compared to salinity, elevated CO_2 concentration often has contrary effects on plants, especially C_3 plants. It leads to a higher CO_2 concentration gradient between the outside air and the intercellular spaces of the leaves, so that the diffusion of CO_2 into the leaves and the pCO_2/pO_2 ratio at the sites of photoreduction are increased (Robredo et al. 2007). Therefore, usually photorespiration and the rates of oxygen activation and ROS formation are reduced due to an increased NADPH utilisation, whereas the net photosynthetic rate and thus the carbon supply are enhanced (Kirschbaum 2004; Long et al. 2004; Ignatova et al. 2005; Pérez-López et al. 2012; Wang et al. 2012). Furthermore, we often find a lower stomatal resistance (Li et al. 2003; Rogers et al. 2004), which, together with higher net assimilation, also leads to a better water use efficiency of photosynthesis (Morgan et al. 2001; Urban 2003). As a consequence of these effects, on the one hand, there might be less need for antioxidants as elevated CO_2 ameliorates oxidative stress (Schwanz et al. 1996). On the other hand, more energy can be provided for energy-dependent stress resistance mechanisms such as the synthesis of osmolytes and antioxidants. Due to both effects mentioned above, elevated CO_2 can increase plant survival under abiotic stress conditions, especially in C_3 plants (Ball and Munns 1992; Rozema 1993; Wullschleger et al. 2002; Geissler et al. 2010).

Ion-specific stress is caused by the accumulation of high amounts of Na^+ and Cl^- ions in the cell wall and in the cytosol, leading to toxic effects on the structure and function of biomembranes and proteins. Moreover, the increased Na^+ uptake can inhibit the uptake of other nutrients and/or disturb their internal distribution within the plant (ion homeostasis). Such an ion imbalance leads to Na^+-induced nutrient deficiencies, particularly to deficiencies of the macronutrients K^+, Mg^{2+} or Ca^{2+} in the plant (Marschner 1995). During this phase of salt stress, one can differentiate between salt-sensitive, less sensitive and salt-resistant species. In general, plants have the ability to prevent high ion concentrations either by ion compartmentalisation (includers) or by ion exclusion (excluders) (Schachtman and Munns 1992). While halophytes often take up high amounts of Na^+ and accumulate them in the leaf vacuoles (inclusion) (Läuchli and Epstein 1984), glycophytes pursue mainly the exclusion strategy (Läuchli 1984). However, this popular classification into includers and excluders is somewhat simplified and undifferentiated because most plants show an individual combination of both inclusion and exclusion mechanisms.

The determination of individual regulation of the growth constraints (which mainly limit the salt resistance of the species in question) is an essential preliminary stage for a successful sustainable use of halophytes. Preferably, the influence of future atmospheric conditions such as elevated CO_2 on salt resistance mechanisms should also be tested in order to get more detailed information about the future potential of the plants as crops. Species which exhibit an enhanced salt resistance under elevated CO_2 may be especially suited for sustainable use.

The above considerations show that the investigations carried out within the frame of the quick check system have to be tightly related to the main constraints of salinity on plant growth (Marschner 1995). Basic parameters characterising plant responses to salinity are determined via this system. If the effect of elevated CO_2 on salt resistance is to be studied, these parameters are measured in plants grown under ambient and elevated CO_2 concentration under otherwise identical conditions. The most important basic parameters to be determined are listed below:

- Life cycle (annual, biennial, perennial), form of asexual reproduction (vegetative multiplication) or sexual reproduction
- Growth parameters of various parts of the plants (e.g. dry weight, ratios leaf area/plant biomass (LAR) and shoot/root)
- Yield parameters (biomass, grain yield, food or fodder quality, etc.)
- Morphological and anatomical adaptations
- Photosynthesis (such as correspondence between electron transport rate and CO_2 fixation), stomatal resistance, chlorophyll content and ratios and antioxidant defence

Table 7.1 Examples of data obtained from quick check systems of different halophytes under varying salinity levels

NaCl (mM)	*A* (μmol/m^2/s)	R_s (s/cm)	*E* (mol/m^2/s^2)	WUE *A*/*E*	ψ (MPa)	FW (g)
Panicum turgidum						
0	10.8±0.15	6.44±0.19	1.55±0.05	6.53±0.32	−0.59±0.05	468.34±30.70
125	14.85±0.17	5.80±0.17	1.95±0.06	7.64±0.24	−0.93±0.05	517.99±41.49
250	8.90±0.05	3.39±0.06	1.38±0.05	6.50±0.19	−1.60±0.04	121.22±6.24
375	6.25±0.06	7.96±0.13	1.38±0.03	4.55±0.11	−1.82±0.01	80.22±3.12
500	5.47±0.03	9.31±0.27	1.20±0.07	4.60±0.27	−3.13±0.02	23.74±0.60
Atriplex nummularia						
0	18.25±0.38	2.08±0.34	5.61±0.14	3.26±0.15	−0.18±0.03	64.10±7.69
125	13.95±1.23	4.04±0.65	2.98±0.24	4.69±0.09	−0.33±0.06	358.97±26.30
250	12.65±0.74	5.62±1.01	2.74±0.31	4.70±0.31	−0.81±0.12	383.97±16.03
500	8.94±0.46	8.03±0.42	1.72±0.19	5.24±0.34	−1.58±0.27	319.23±7.05
750	5.01±0.51	15.95±0.68	0.75±0.10	6.75±0.86	−2.58±0.20	135.90±10.90
Chenopodium quinoa						
0	27.37±5.97	1.10±0.06	6.75±0.44	4.05±0.45	−0.18±0.09	105.81±3.08
125	21.15±1.49	2.70±0.23	2.83±0.22	7.47±2.34	−0.36±0.02	121.20±2.56
375	15.23±1.65	5.48±0.66	0.98±0.26	15.54±1.31	−1.28±0.07	37.26±2.07
500	9.42±1.26	6.55±0.65	0.64±0.11	14.72±1.92	−1.80±0.13	19.32±1.71
Aster tripolium						
0	21.55±6.10	1.65±0.75	4.32±0.87	5.09±1.55	−0.67±0.14	76.87±12.52
125					−1.23±0.22	49.66±4.68
250	11.39±5.96	4.51±2.15	2.84±1.48	4.27±0.87	−1.90±0.54	37.24±3.04
375					−3.50±1.11	28.55±2.26
500	7.57±4.60	9.69±5.42	2.30±1.57	3.50±0.43	−4.95±1.15	17.21±6.00
Aster tripolium, under elevated atmospheric CO_2 concentration (520 ppm)						
0	33.63±6.25	1.15±0.72	6.11±1.45	5.79±1.53	−0.57±0.13	79.37±19.65
125					−1.12±0.37	53.06±12.90
250	20.79±7.79	3.08±2.06	4.00±1.91	5.39±1.06	−1.90±0.50	38.20±4.11
375					−2.48±0.58	28.95±5.46
500	12.96±4.78	6.89±4.90	2.52±1.26	5.62±0.30	−4.09±1.10	19.47±6.33

In case of *A. tripolium*, ambient (380 ppm) and elevated (520 ppm) CO_2 concentration was applied for each salt treatment. Values represent mean±SD values of ≥3 measurements per treatment

A net photosynthetic rate, R_s stomatal resistance, *WUE* water use efficiency of photosynthesis, ψ shoot water potential, *FW* fresh weight

- Water use efficiency (WUE), leaf water potential, osmotic potential and water saturation deficit (WSD)
- Mineral content (indicator of ion deficiency or ion excess), ion selectivity, ion compartmentation and compatible solutes

Some examples of such data obtained from quick check systems of different halophytes (*Panicum turgidum*, *Atriplex nummularia*, *Chenopodium quinoa*, *Aster tripolium*) are presented in Table 7.1. The results show that under ambient CO_2 concentration, all mentioned plant species adjust osmotically to salinity by decreasing their water potential. Under salt stress, the net photosynthetic rates decrease due to a higher stomatal resistance and thus a lower transpiration rate (in case of *P. turgidum*, this trend is transient). However, there are marked differences in the water use efficiencies of photosynthesis (WUE), the most crucial parameter regarding gas exchange. While *A. nummularia* and *C. quinoa* are able to enhance WUE with rising salinity, the WUE in *P. turgidum* shows an optimal value at 125 mM NaCl and decreases at higher salinities, and in *A. tripolium* it continually decreases. These results are in accordance with the data for plant growth which show that *A. nummularia* is the most resistant species (optimal growth at 250 mM NaCl), followed by *C. quinoa*, *P. turgidum* (optimal growth of both species at 125 mM NaCl, but more growth reduction at high salinity in *P. turgidum*) and *A. tripolium* (continual growth depression with increasing salinity). Consequently, *A. nummularia* is probably the most profitable cash crop halophyte among the mentioned species. However, in a CO_2-rich future, the salt resistance of C_3 plants such as *C. quinoa* and *A. tripolium* is likely to be more enhanced than the one of C_4 species, with positive effects on the utilisation potential of C_3 plants. In case of *A. tripolium*, we could show that elevated CO_2 increases water relations (water potential), photosynthesis and WUE in salt-treated plants (Table 7.1). The enhanced energy supply was not employed for producing more biomass (Table 7.1), but for increasing the investment in salt resistance mechanisms, leading to a higher survival rate under saline conditions (Geissler et al. 2009a, b, 2010). Investigations on other plants about the interaction of salinity and elevated CO_2 would be very desirable to assess the future potential of halophytes as crop plants more accurately.

Apart from revealing the most promising future cash crop halophytes, the results of the quick check system often influence and support the selection of suited production or irrigation systems (drip irrigation, ditch irrigation or sprinkler system) and of the type of cultivation (monoculture or mixed cultures) (Khan et al. 2009a).

6 Conclusions and Future Perspective

Due to global climate change which exacerbates freshwater scarcity and salinisation, the last decade has witnessed marked losses of arable land, especially in arid and semiarid regions. At least until the breeding of salt-resistant crops will succeed and be accepted, we need to acquire and test candidate halophyte species, screen germplasm under highly saline conditions and develop management techniques for the productive use of halophytes. The further use of these plants is the only available way for a sustainable utilisation and can ameliorate the water crisis.

While reviewing the cultivation of halophytes in detail relating to NaCl salinity and global change/elevated CO_2 concentration for the first time, the following major conclusions can be drawn: A precondition for the sustainable use of halophytes is a detailed knowledge of individual resistance mechanisms, the food or fodder quality and the performance under new climate change scenarios. Such information has already been obtained for some species by growing them in a so-called quick check system. The results show that many halophytes are high-productive and high-quality crops and that they often exhibit an enhanced salt resistance and/or productivity under elevated CO_2, so they are very promising future crop plants. As their cultivation can sequester CO_2, it can also counteract the causes of global change. However, especially regarding the interaction of salinity with other abiotic factors associated with global change such as elevated CO_2, more knowledge is required to assess the potential of halophytes as future crops. Additionally, saline agriculture needs to be much further developed although several promising pilot projects regarding the sustainable use of halophytes are already in progress worldwide:

- The combination of terrestrial saline cultures with aquacultures of fish or shrimps. This includes the establishment of plantations of food crop halophytes in tropical countries such as Eritrea (Manzanar Project, a combination of fish farming and mangrove cultivation, and Seawater Farms, a combination of fish and shrimp farming, *Salicornia* and mangrove cultivation).
- The cultivation of *Sporobolus virginicus* or *Distichlis spicata* as fodder plants under saline sprinkler irrigation in the United Arab Emirates (Fig. 7.5c).
- The use of halophytes in order to detoxify wastewater (e.g. to decrease heavy metal pollution, Tejo River, Portugal).
- The cultivation of *Aster tripolium* in the Tejo Estuary (Portugal) as food plant (salad or vegetable) (Fig. 7.5d).
- The cultivation of *Salicornia bigelovii* in Jubail (Saudi Arabia) to obtain oil seeds. 12.7–24.6 t of biomass/ha (on average 18.0 t/ha) and 1.39–2.46 t of seeds/ha (on average 2 t/ha), respectively, are produced every year (Glenn et al. 1991).
- The culture of *Spartina alterniflora* (which is flooded regularly) near Dubai (United Arab Emirates). *Spartina* is used as fodder and produces up to 40 t biomass/ha (Odum 1974).
- The cultivation of *Salicornia* for food or of *Tamarix aphylla* for wood production within the frame of the Colorado Delta Project carried out by OASE (Organisation for Agriculture in Saline Environments).
- The cultivation of *Panicum turgidum* for fodder, in mixed cultures with *Suaeda maritima* which is used for wood production (Karachi, Pakistan).
- The cultivation of *Crambe maritima* as food plant on saline soils on the island of Texel (Netherlands).

The current projects were at least ambitious ventures because of the risk of a death spiral in consequence of continuously increasing soil salinity. However, the different combination of salt-resistant plants with controlled flux of salt import (and export), salt accumulators, well-matched composition of species and periodically or permanently flooded areas under cultivation led to sustainable and partially cost-effective systems in nearly all cases (at least for the years of trial period). However, these projects were carried out exclusively with wild plants, so their domestication is given priority (Stanton et al. 1992; Flowers 2004). The domestication of these wild plants enables us to develop halophytic crop plants which will be as competitive and productive as traditional crops like maize or barley. The first step of such a process is the selection of productive genotypes. However, while developing new crop plants, various risks and imponderabilities have to be overcome, such as the optimisation of culture systems, vulnerability to diseases or economic profitability. An example of how such difficulties can be successfully overcome is the cultivation of *Panicum turgidum* in conjunction with *Suaeda fruticosa* at the Sindh/Balochistan coast of Pakistan (Khan et al. 2009b).

Although the utilisation of saline production systems is still in its infancy, the advantages cannot be ignored. Sea water and brackish water are abundant and contain not only Na^+ and Cl^- but many essential macro- and micronutrients. Especially, the irrigation with brackish water would enlarge the application range and the number of suited halophytes and their potential yield, while reducing ecological risks.

Apart from the soil cultures described above, aquacultures, e.g. of seaweeds or microalgae, do also have a high potential for utilisation. Algae contain up to 70 % valuable proteins and minerals in their dry mass and can be used instead of wheat or soya.

Existing potentials should therefore be fully exploited before extending herbicide applications or genetic engineering. Additionally, more research should be done regarding the suitability of salt-resistant plants as crops in a CO_2-rich future. This topic has been very much neglected so far. Only one potential cash crop halophyte (*Aster tripolium*) has been investigated in detail (Geissler et al. 2009a, b, 2010), with promising results, namely, a higher survival rate of salt-treated plants under elevated CO_2. Species such as *A. tripolium*, which seem to be promising crop plants in general, and the salt resistance of which is enhanced under elevated CO_2 concentration, should be given priority for advanced local field studies and the application in saline production systems because they are probably best suited for both counteracting the cause of global climate change and mitigating its consequences.

Considering all the points mentioned above, it has to be emphasised that time is running fast, so if we do not react quickly by carrying out more basic research as well as applied field studies, there will soon be no further necessity to investigate salt resistance because soil salinity will reach levels where not even halophytes can grow.

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