LAND DEGRADATION & DEVELOPMENT

Land Degrad. Develop. **19**: 429–453 (2008)

Published online 20 June 2008 in Wiley InterScience (www.interscience.wiley.com) **DOI**: 10.1002/ldr.853

PRODUCTIVITY ENHANCEMENT OF SALT-AFFECTED ENVIRONMENTS THROUGH CROP DIVERSIFICATION

M. QADIR[1,2]*, A. TUBEILEH[3], J. AKHTAR[4], A. LARBI[1], P. S. MINHAS[5] AND M. A. KHAN[6]

[1]*International Center for Agricultural Research in the Dry Areas (ICARDA), PO Box 5466, Aleppo, Syria*
[2]*International Water Management Institute (IWMI), PO Box 2075, Colombo, Sri Lanka*
[3]*University of Guelph, Kemptville Campus, PO Box 2003, Kemptville, ON K0G 1J0, Canada*
[4]*Institute of Soil and Environmental Sciences, University of Agriculture, Faisalabad 38040, Pakistan*
[5]*Indian Council of Agricultural Research (ICAR), KAB-II, Pusa, New Delhi-110 012, India*
[6]*Department of Botany, University of Karachi, Karachi-75270, Pakistan*

Received 16 May 2007; Revised 10 December 2007; Accepted 14 December 2007

ABSTRACT

Recent trends and future demographic projections suggest that the need to produce more food and fibre will necessitate effective utilization of salt-affected land and saline water resources. Currently at least 20 per cent of the world's irrigated land is salt affected and/or irrigated with waters containing elevated levels of salts. Several major irrigation schemes have suffered from the problems of salinity and sodicity, reducing their agricultural productivity and sustainability. Productivity enhancement of salt-affected land and saline water resources through crop-based management has the potential to transform them from environmental burdens into economic opportunities. Research efforts have led to the identification of a number of field crops, forage grasses and shrubs, aromatic and medicinal species, bio-fuel crops, and fruit tree and agroforestry systems, which are profitable and suit a variety of salt-affected environments. Several of these species have agricultural significance in terms of their local utilization on the farm. Therefore, crop diversification systems based on salt-tolerant plant species are likely to be the key to future agricultural and economic growth in regions where salt-affected soils exist, saline drainage waters are generated, and/or saline aquifers are pumped for irrigation. However, such systems will need to consider three issues: improving the productivity per unit of salt-affected land and saline water resources, protecting the environment and involving farmers in the most suitable and sustainable crop diversifying systems to mitigate any perceived risks. This review covers different aspects of salt-affected land and saline water resources, synthesizes research knowledge on salinity/sodicity tolerances in different plant species, and highlights promising examples of crop diversification and management to improve and maximize benefits from these resources.

KEY WORDS: salt-affected soils; saline water; saline-sodic water; salt-tolerant crops; forage crops; medicinal and aromatic plants; grasses and shrubs; fruit trees; bio-fuel crops; bio-energy crops; agroforestry systems

INTRODUCTION

Supplies of good-quality water are falling short of demand for intensive irrigated agriculture in many arid and semi-arid countries due to increased pressures to produce more for the growing population as well as competition from urban, industrial and environmental sectors. Therefore, available freshwater supplies need to be used more efficiently. In addition, reliance on saline waters—generated by irrigated agriculture or pumped from aquifers—seems inevitable for irrigation (Minhas, 1996; Bouwer, 2002; Qadir *et al*., 2007a). The same applies to salt-affected soils, which occur on 831×10^6 ha (Beltrán and Manzur, 2005) within the boundaries of at least 75 countries (Szabolcs, 1994). Currently at least 20 per cent of the world's irrigated land is salt affected and/or irrigated with waters containing elevated levels of salts (Ghassemi *et al*., 1995).

* Correspondence to: M. Qadir, International Center for Agricultural Research in the Dry Areas (ICARDA), PO Box 5466, Aleppo, Syria. E-mail: m.qadir@cgiar.org

Salt-affected soils are characterized either by the presence of excess levels of soluble salts (saline soils) and/or high amounts of sodium ions (Na^+) in the soil solution or on the cation exchange sites (sodic soils). Accumulation of salts and/or Na^+ in these soils originates either through the weathering of parent minerals (causing fossil or primary salinity/sodicity) or from anthropogenic activities involving the inappropriate management of land and water resources (contributing to man-made or secondary salinity/sodicity). The adverse effects of salinity on crop growth stem from two aspects: (1) increasing the osmotic pressure and thereby making the water in the soil less available for the plants and (2) specific effects of some elements taken up above critical concentrations. Sodicity causes structural problems in soils created by physical processes such as slaking, swelling and dispersion of clay; as well as conditions that may cause surface crusting and hardsetting (Shainberg and Letey, 1984; Sumner, 1993; Quirk, 2001). Such problems affect water and air movement, plant-available water holding capacity, root penetration, runoff, erosion and tillage and sowing operations. In addition, imbalances in plant-available nutrients in both saline and sodic soils affect plant growth (Naidu and Rengasamy, 1993; Qadir and Schubert, 2002).

Several major irrigation schemes throughout the world have suffered from the problems of salinity (Gupta and Abrol, 2000; Herczeg *et al*., 2001; Cai *et al*., 2003; Sarraf, 2004). It is estimated that salinization of irrigated lands causes annual global income loss of about US$ 12 billion (Ghassemi *et al*., 1995), impacting aggregate national incomes in countries affected by degradation of salt-affected land and saline water resources. Generally, the worst salinity impacts occur where farming communities are relatively poor and face economic difficulties. In severe cases, salinization causes occupational or geographic shifting of the affected communities, with the male population seeking alternate off-farm income opportunities (Abdel-Dayem, 2005; Qadir *et al*., 2006).

As the agricultural use of salt-affected land and saline water resources increases, their sustainable use for food and feed production will become a more serious issue (Suarez, 2001; Wichelns and Oster, 2006). In the future, sustainable agricultural systems using these resources should have good crop production with minimized adverse environmental and ecological impacts (Qadir and Oster, 2004). This will require a comprehensive approach to soil, water and crop management. Crop diversification and management are expected to play a key role and are the subject of this review, which aims to: (1) provide insight into different aspects of salt-affected land and saline water resources; (2) synthesize the research-based knowledge on the ability of different crops to withstand salinity and sodicity and (3) highlight emerging examples of crop diversification and management to achieve maximum benefits and sustainability of saline land and water resources. This review does not aim at providing an exhaustive list of the plant species grown under salt-affected environments. Rather, it emphasizes the potential of a range of species groups that can diversify land use patterns to improve the environment and livelihoods of the concerned communities.

SALT-AFFECTED SOIL AND SALINE WATER RESOURCES

Saline Soils

Saline soils account for about 40 per cent of the world's salt-affected area (Tanji, 1990). These soils are non-sodic, containing sufficient soluble salts to adversely affect the growth of most crop plants. The lower limit of saturation extract electrical conductivity (EC_e) of these soils is conventionally set at $4\,dS\,m^{-1}$ (at 25°C). Actually, sensitive plants are affected at half this salinity and highly tolerant ones at about twice this salinity (Soil Science Society of America, 2006). Since EC is a measure of the concentration of total soluble salts (C_{TSS}), C_{TSS} is commonly estimated from EC (Equation 1)

$$C_{TSS} \simeq 10(EC) \tag{1}$$

where C_{TSS} and EC are expressed in terms of $mmol_c\,L^{-1}$ and $dS\,m^{-1}$, respectively. This relationship is considered good up to an EC of $4\,dS\,m^{-1}$ (U.S. Salinity Laboratory Staff, 1954). Other approximate relationships between C_{TSS} and EC are also available (Marion and Babcock, 1976).

Sodic Soils

Sodic soils account for about 60 per cent of the world's salt-affected area (Tanji, 1990). They are non-saline soils containing sufficient exchangeable Na^+ to adversely affect crop production and soil structure under most

DOI: 10.1002/ldr

conditions of soil and plant type. Other terminologies such as black alkali, alkali, solonetz and slick-spot have been used for sodic soils in some countries. Saline-sodic soils, another category of salt-affected soils, are grouped with sodic soils because (1) they share several characteristics and (2) the management approaches required for both soil types are similar.

Sodic and saline-sodic soils are generally described in terms of the relative amounts of Na^+ on the cation exchange complex, or in the soil solution, and the presence of accompanying levels of salinity. Thus, soil sodicity represents the combined effects of (1) soil salinity, as measured by the EC_e or of soil-to-water suspensions of different ratios, and (2) either the soluble Na^+ concentration relative to the soluble divalent cation concentrations in the soil solution (i.e. the sodium adsorption ratio, SAR), or the exchangeable sodium fraction (ESF) expressed as a percentage of the cation exchange capacity (CEC), i.e. the exchangeable sodium percentage (ESP).

An ESP of 15 (SAR $\sim$ 13) is generally considered the threshold below which soils are classified as non-sodic, and above which soils are dispersive and suffer serious physical problems when water is applied (Soil Science Society of America, 2006). However, considerable data exist on infiltration rates and hydraulic conductivities that show that sodic soil behaviour may occur at ESP values of less than 5 if EC_e is lower than 4 dS m^{-1} (Sumner *et al*., 1998). Therefore, the principal factor determining the extent of the adverse effects of Na^+ on soil properties is the ambient electrolyte concentration in the soil solution, with low concentrations exacerbating the deleterious effects of exchangeable Na^+. The SAR has been widely used as a proxy for ESP within the range 0–40 (the ESP range which is most common in agricultural soils).

Saline and/or Sodic Waters

Saline and/or sodic waters consist of drainage water generated by irrigated agriculture, and groundwater containing different types of salts. Drainage from irrigated lands is necessary for large-scale irrigation to be sustainable (Oster and Grattan, 2002; Wichelns and Oster, 2006). Increases in cropping intensity, excessive use of fertilizers and pesticides, as well as inappropriate irrigation methods and use of salt-affected soils for crop production contribute to increased salt loads in drainage water. Moreover, saline geologic deposits often exist along the flow path of drainage water. As drainage water flows through these deposits, the salt loads in the resulting drainage water can considerably exceed those projected to occur from irrigation alone (Van Schilfgaarde, 1994). In some geological settings, drainage waters may dissolve and displace some minor elements that are potentially toxic (Skaggs and Van Schilfgaarde, 1999).

The exploitation of groundwater resources in different parts of the world reveals that the areas characterized by water scarcity have most often naturally occurring saline aquifers. This is a consequence of reactions with the layers of earth, or strata, through which the water passes on its way to becoming groundwater, as well as reactions within the stratum where groundwater is located. Therefore, the concentration and composition of salts in groundwater are largely dependent upon the geochemical environment that the infiltrating water encounters en route to the groundwater.

The methods of evaluating salinity (EC) and sodicity (SAR) levels in water are the same used for soils as determined from soil paste extracts or from soil-to-water suspensions of different ratios. In addition to SAR, another index reflecting alkalinity and sodicity problems in waters is the residual sodium carbonate (RSC).

EFFECTS OF SALINITY AND SODICITY ON PLANTS

The growth of crops irrigated with saline and/or sodic waters or grown on salt-affected soils is influenced by the osmotic and ion-specific effects, and ionic imbalance leading to deficiency and/or toxicity of some nutrients. Osmotic effects depress the external water potential, making water less available to the plants by two mechanisms: absorption of salts from the growth medium and/or synthesis of organic solutes. Usually both are involved (Läuchli and Epstein, 1990). Halophytes, the salt-tolerant plant species, sequester salts in vacuoles for use as an internal osmoticum (Flowers *et al*., 1977) and synthesize organic compatible solutes that allow osmotic adjustment in the cytoplasm. However, most plants relevant to agricultural production systems are glycophytes or non-halophytes, which are incapable of causing a sharp asymmetrical intracellular compartmentalization of inorganic and organic

DOI: 10.1002/ldr

solutes under highly saline conditions. When exposed to moderate levels of salinity, they tend to exclude salts, thus minimizing the exposure of the leaf cells, and hence the photosynthetic apparatus, to salt (Läuchli and Epstein, 1990). Therefore, glycophytes regulate ion fluxes less efficiently at the cellular level than the salt-accumulating halophytes, but partition ions more effectively at the organ and tissue levels (Epstein, 1985). Since glycophytes tend to exclude Na^+ from the shoots, and, especially the leaves, they have to rely more heavily on the synthesis of organic osmolytes than do halophytes (Läuchli and Epstein, 1990; Zhu, 2001).

Excessive levels of ions such as Na^+ and Cl^- in waters and soils may cause ion-specific effects in plants leading to toxicity or deficiency of certain nutrients. Under salt-affected conditions, concentrations of Na^+ and Cl^- often exceed those of most macronutrients by one or two orders of magnitude, and by even more in the case of micronutrients. Thus, salt-affected soils may have depressed nutrient–ion activities and extreme ratios of Na^+/Ca^{2+}, Na^+/K^+, Mg^{2+}/Ca^{2+} and Cl^-/NO_3^- (Curtin and Naidu, 1998; Grattan and Grieve, 1999). As a result, the salt-stressed plants become susceptible to high osmotic stress, ion-specific toxicity and nutritional disorders. The collective effect of such stresses and disorders impacts crop growth and yield (Grattan and Grieve, 1999), depending upon several edaphic and environmental factors. These include ambient soil salinity and sodicity levels, composition of soil solution and exchange complex, soil pH and redox potential, the particular nutrient in question, salinity/sodicity tolerance level, nutrient requirement of the plant species, as well as several environmental factors.

Crops vary not only in the rate at which they absorb a nutrient from a salt-affected soil, but also in the manner by which they distribute that element spatially within their bodies. Glycophytes have developed mechanisms for mineral nutrient absorption, transportation and utilization under non-saline and non-sodic conditions. Consequently, such nutrient-regulating mechanisms may not operate efficiently under saline and sodic conditions (Grattan and Grieve, 1999). Therefore, crop yield or plant biomass may be adversely affected by salinity- and sodicity-induced nutritional disorders. Experimental evidence suggests that addition of nutrients under saline and sodic conditions increased the growth of both glycophytes and halophytes provided the plants were not experiencing salt stress well beyond their respective tolerance levels (Gupta and Abrol, 1990).

An appropriate selection of plant species capable of producing adequate biomass is vital while using saline and/or sodic waters for irrigation or cultivating salt-affected soils. Such selection is generally based on the ability of a crop to withstand ambient levels of soil salinity and sodicity (Maas and Hoffman, 1977) while providing a saleable product or one that can be used on-farm (Qadir and Oster, 2002). The salt tolerance of a crop is not an exact value because it depends on several soil, crop and climatic factors. It reflects the capacity of a crop to endure the effects of excess root zone salinity. Although the capacity of a crop to endure salinity cannot be stated in absolute terms, the relative crop responses to known salinities under certain conditions can be predicted.

Maas and Hoffman (1977) proposed a linear response equation to describe salt tolerance in crops. Two parameters obtained from this model are: (1) the threshold soil salinity (the maximum allowable soil salinity for a crop without yield reduction) and (2) the slope (the percentage yield decrease per unit increase in salinity beyond the threshold salinity level). The data, presented in terms of EC_e at 25°C, serve only as a guideline to relative capacities of the crops to withstand salinity. Considerable variation (almost fivefold) exists among crops in their ability to tolerate saline conditions. The threshold salinity levels and slope values obtained from the Maas–Hoffman equation can be used to calculate relative yield (Y_r) for any given soil salinity exceeding the threshold level by using Equation

$$Y_r = 100 - b(EC_e - EC_{th}) \tag{2}$$

where EC_{th} is the threshold saturated paste extract salinity level expressed in $dS\,m^{-1}$; b the slope expressed in per cent per $dS\,m^{-1}$; EC_e is the average electrical conductivity of the saturated soil paste extract of the root zone expressed in $dS\,m^{-1}$.

The two-piece linear response function (Maas and Hoffman, 1977) is also reasonably accurate when salinity is expressed in terms of osmotic potential of the soil solution at field capacity. In cases where the osmotic potential of the soil solution is known, the crop yield responses can be determined as a function of the osmotic stress that the

DOI: 10.1002/ldr

plants experience (Maas and Grattan, 1999). For osmotic potentials exceeding the threshold of a crop, Y_r can be calculated by using Equation

$$Y_r = 100 - B(OP_{fc} - OP_{th}) \tag{3}$$

where B is the slope expressed in per cent per bar; OP_{fc} the osmotic potential of the soil water extracted from the root zone at field capacity, expressed in bars; OP_{th} is the threshold salinity level expressed in bars.

Equation 3 is a linear equation. Although OP_{fc} is not a linear function of EC_e, the deviation from linearity is negligible. Therefore, the relative yields calculated from Equation 2 remain within 1 to 2 per cent of those calculated from Equation 3 (Maas and Grattan, 1999).

The ability of crops to withstand salinity is described in relative terms and generally divided into four classes: sensitive, moderately sensitive, moderately tolerant and tolerant (Maas and Hoffman, 1977; Francois and Maas, 1999). As a select list from Maas and Grattan (1999), salt tolerance threshold values of some grain, forage and fibre crops as a function of average root zone salinity are given in Table I. The relative tolerances of different plant species to sodicity are presented in Table II (Gupta and Abrol, 1990). The genetic diversity among these crops provides a range of cropping options for salt-affected land and saline water resources. Genotypic variability also occurs in many crops. Considerable inter- and intra-crop diversity in salt tolerance (Shannon, 1997) emphasizes the need to identify crop genotypes that are adaptable to saline conditions.

Table I. Yield potential of some grain, forage, vegetable and fibre crops as a function of average root zone salinity. Based on the salt tolerance data of different crops and percentage decrease in yield per unit increase in root zone salinity in terms of dS m^{-1} as reported by Maas and Grattan (1999) [a]

Crop		Average root zone salinity (dS m^{-1}) at specified yield potentials		
Common name	Botanical name	50 per cent	80 per cent	100 per cent
Triticale (grain)	× *Triticosecale*	26	14	6
Kallar grass[b]	*Leptochloa fusca* (L.) Kunth	22	14	9
Durum wheat	*Triticum durum* Desf.	19	11	6
Tall wheat grass	*Agropyron elongatum* (Hort) Beauv.	19	12	8
Barley	*Hordeum vulgare* L.	18	12	8
Cotton	*Gossypium hirsutum* L.	17	12	8
Rye	*Secale cereale* L.	16	13	11
Sugar beet	*Beta vulgaris* L.	16	10	7
Bermuda grass	*Cynodon dactylon* L.	15	10	7
Sudan grass	*Sorghum sudanese* (Piper) Stapf	14	8	3
Sesbania	*Sesbania bispinosa* (Jacq.) W. Wight	13	9	6
Wheat	*Triticum aestivum* L.	13	9	6
Purslane	*Portulaca oleracea* L.	11	8	6
Sorghum	*Sorghum bicolor* (L.) Moench	10	8	7
Alfalfa	*Medicago sativa* L.	9	5	2
Spinach	*Spinacia oleracea* L.	9	5	2
Broccoli	*Brassica oleracea* L. (Botrytis Group)	8	5	3
Egg plant	*Solanum melongena* L.	8	4	1
Rice	*Oryza sativa* L.	7	5	3
Potato	*Solanum tuberosum* L.	7	4	2
Maize	*Zea mays* L.	6	3	2

[a]These data serve only as a guideline to relative resistances among crops. Absolute resistances vary and depend on climate, soil conditions and cultural practices.
[b]Yield potential calculated from Malik *et al.* (1986).

DOI: 10.1002/ldr

Table II. Relative tolerance of crops to soil sodicity expressed as exchangeable sodium percentage, ESP (Adapted from Gupta and Abrol, 1990)[a]

	Crop	
ESP range	Common name	Botanical name
10–15	Safflower	*Carthamus tinctorius* L.
	Mash	*Vigna mungo* (L.) Hepper.
	Pea	*Pisum sativum* L.
	Lentil	*Lens culinaris* Medik.
	Pigeon pea	*Cajanus cajan* (L.) Millsp.
	Urd-bean	*Phaseolus mungo* (L.)
16–20	Bengal gram	*Cicer arietinum* L.
	Soybean	*Glycine max* (L.) Merr.
20–25	Groundnut	*Apios americana* Medik.
	Cowpea	*Vigna unguiculata* (L.) Walp.
	Onion	*Allium cepa* L.
	Pearl millet	*Pennisetum glaucum* (L.) R. Br.
25–30	Linseed	*Linum usitatissimum* L.
	Garlic	*Allium sativum* L.
	Guar	*Cyamopsis tetragonoloba* (L.) Taub.
30–50	Indian mustard	*Brassica juncea* (L.) Czern.
	Wheat	*Triticum aestivum* L.
	Sunflower	*Helianthus annuus* L.
	Guinea grass	*Panicum maximum* Jacq.
50–60	Barley	*Hordeum vulgare* L.
	Sesbania	*Sesbania bispinosa* (Jacq.) W. Wight
60–70	Rice	*Oryza sativa* L.
	Para grass	*Brachiaria mutica* (Forssk.) Stapf
70+	Bermuda grass	*Cynodon dactylon* (L.) Pers
	Kallar/Karnal grass	*Leptochloa fusca* (L.) Kunth
	Rhodes grass	*C. gayana* Kunth

[a]Yields are about 50 per cent of the potential yields in the respective sodicity (ESP) ranges.

CROP DIVERSIFICATION AND MANAGEMENT OPTIONS

Based on salt tolerance of plant species, there are emerging examples of crop diversification and management for optimal utilization of salt-affected soils and saline-sodic waters. This section highlights the role of cropping as a major contribution to the management of salt-affected environments. The plant species that have shown potential under such environments are divided into five groups: (1) fibre, grain and special crops; (2) forage grass and shrub species; (3) medicinal and aromatic plant species; (4) bio-fuel crops; (5) fruit trees and (6) agroforestry systems.

Fibre, Grain and Special Crops

The most important fibre and grain crops commonly grown on salt-affected soils or irrigated with saline water are rice (*Oryza sativa* L.), wheat (*Triticum aestivum* L.), barley (*Hordeum vulgare* L.) and cotton (*Gossypium hirsutum* L.). There are several other crops—such as sorghum [*Sorghum bicolor* (L.) Moench], mustard (*Brassica juncea* L.), canola (*Brassica napus* L.) and sugar beet (*Beta vulgaris* L.)—that are grown under salt-affected environments to a variable extent. The overall yield response of these crops and their varieties is evaluated by comparing their performance under saline and non-saline conditions. Various approaches have been taken to improve the salt tolerance of these crops by introducing genes for salt tolerance into adapted cultivars, including screening of large international collections, extensive testing of selected cultivars under field conditions, conventional breeding methods and unconventional crosses with the crop-specific relatives. The aim has been to exploit variation in salt

DOI: 10.1002/ldr

tolerance within a particular crop and its progenitors or close relatives to produce new cultivars with more tolerance than the existing cultivars.

With large differences among cultivars, rice is rated as a sodicity-tolerant crop as it can withstand ESP levels as high as 70. The mortality of seedlings can be substantially reduced by using 35–40-day-old seedlings instead of relatively young seedlings. In addition, the crop stand can be improved by increasing the number of seedlings from two (normal practice in non-saline soils) to four per hill (Aslam *et al*., 1993). Rice grows well under flooded conditions and needs more water during its vegetative stage than other crops. It benefits from the dilution of salts in the root zone. As most micronutrients, particularly zinc, are usually available at low concentrations in salt-affected soils, rice is sensitive to zinc deficiency, which may appear during early growth stages causing stunted growth, reduced number of productive tillers, and rusty-brown spots on mature leaves. Studies have shown that the application of zinc sulphate at 40–50 kg ha^{-1} along with gypsum can ensure good crop yields from salt-affected soils (Singh *et al*., 1987).

Although wheat is rated as a moderately salt-tolerant crop (Maas and Hoffman, 1977), there is a large variation within the species in response to salinity (Munns *et al*., 2006). The choice of planting method for wheat under saline conditions depends on soil texture and permeability of the soil to water. For soils with good drainage, the land should be prepared well and seed should be sown into almost dry soil (dry sowing), which should be subsequently irrigated with excess water to leach the salts from the root zone. The next irrigation should be scheduled 3–4 week after seeding. In poorly drained soils where water applied as irrigation stays longer, the land should be prepared as raised beds, which may be 0·7–1·0 m wide, 0·2–0·3 m high and separated by irrigation channels. The crop should be sown in rows at a distance of 0·15 m. In the field, where the salinity rises to about 10 dS m^{-1}, wheat survives but produces a reduced yield (Qureshi and Barrett-Lennard, 1998). The work on breeding wheat genotypes for salt tolerance reveals the most successful cases have been the KRL1-4 and KRL19, released by the Central Soil Salinity Research Institute (CSSRI) at Karnal, India; Sakha 8, released by the Agricultural Research Center (ARC) at Giza, Egypt and LU26S and SARC-1, SARC-2, SARC-3 and SARC-5 released by the Saline Agriculture Research Center (SARC) at Faisalabad, Pakistan. In field trials evaluating SARC varieties with a commonly grown recommended variety (Inqulab-91), the 3-year average grain yield of SARC varieties was greater than Inqulab-91 when cultivated on moderately (8–15 dS m^{-1}) and highly saline soils (>15 dS m^{-1}). Under slightly saline conditions (<8 dS m^{-1}), Inqulab performed better than SARC varieties (Figure 1).

Akhtar *et al.* (1994) found large differences among different wheat accessions and amphiploids in their ability to tolerate flooding and salinity both in terms of vegetative growth and reproductive yield. Taeb *et al.* (1993) reported

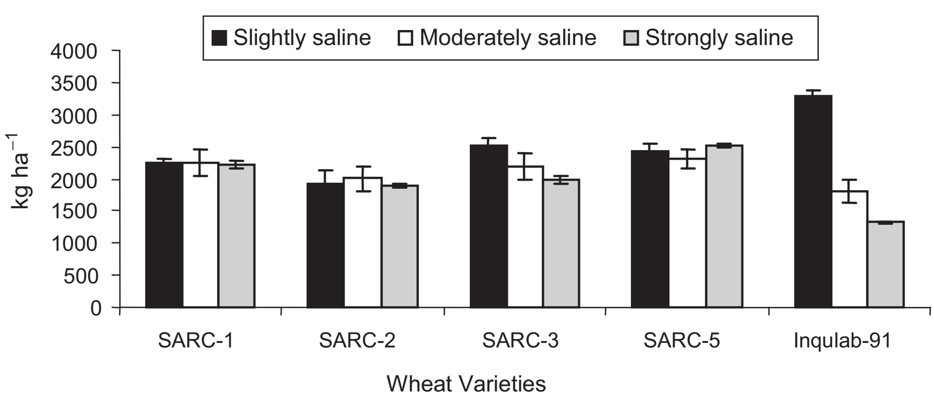

Figure 1. Field-scale evaluation of salt-tolerant wheat varieties (SARC-1, SARC-2, SARC-3 and SARC-5) and a recommended wheat variety (Inqulab 91) commonly grown in Pakistan. The varieties were grown on soils with different salinity levels; slightly saline (<8 dS m^{-1}), moderately saline (8–15 dS m^{-1}), and highly saline (>15 dS m^{-1}). Salt-tolerant varieties were released by the Saline Agriculture Research Center (SARC) Faisalabad, Pakistan. Bars represent 3-year average grain yield values along with standard error (Akhtar *et al*., 2007; unpublished data).

DOI: 10.1002/ldr

that increased waterlogging tolerance of the Chinese Spring × *Thinopyrum elongatum* amphiploid could be attributed to two additional chromosomes, 2E and 4E. The effect of the latter was a non-specific dosage effect which was also observed in tetrasomic 4B and 4D wheats, whereas the effect of 2E was specific to the alien chromosome and was not observed in tetrasomic group 2 wheats. Although the amphiploids were not fully fertile under control conditions, and have some undesirable qualities (brittle rachis and difficulty in threshing), they were found to be more salt tolerant than the wheat varieties (Gorham *et al*., 1986). The amphiploid derived from wheat cultivar Chinese Spring and *Thinopyrum elongatum* had the highest grain yield at 100 mol m^{-3} NaC1. The imposition of waterlogging in addition to NaCl significantly reduced salt tolerance in all the wheat varieties. Also, increasing salinity of the growth medium and decreasing oxygen concentration simultaneously caused a significantly greater reduction in wheat growth, but not of the amphiploid. Although vernalization resulted in the flowering time of the amphiploid being closer to that of the wheat, seed maturation still occurred considerably later than wheat (Akhtar *et al*., 1994).

Cotton is a relatively salt-tolerant crop with 50 per cent yield reduction estimated at salinity levels of EC_e around 17 dS m^{-1} (Francois and Maas, 1999; Table I). However, under sodic conditions where surface crusting is typical, there can be problems with seedling emergence of cotton, resulting in a reduced number of plants per unit area. In addition, growth may be affected as water movement into and through sodic soils is restricted, which may cause inundation in post-irrigation soil. The crop should be planted on ridges or raised beds about 0·3 m high, 0·75 m wide and separated by 0·75 m wide irrigation furrows. Use of gypsum may improve germination under these conditions.

Barley is a salt-tolerant crop with large cultivar differences, which have been shown in several studies under both glasshouse and field conditions (Gill and Qadar, 1998). Barley plants subject to salinity stress retain more Na^+ in roots compared with wheat. In addition, higher yield in barley is attributed to effective grain filling under salt stress. At salinity (EC_e) levels around 12 dS m^{-1}, it can produce 80 per cent of the yield potential anticipated from non-saline conditions. Its 50 per cent yield reduction is estimated at salinity levels around 18 dS m^{-1} (Maas and Grattan, 1999). Barley can also tolerate ESP levels up to 60. Its greater salt tolerance in the field may derive partly from its rapid growth and phenological development, leading to an early maturity date (Munns *et al*., 2006).

Sugar beet is one of the most salt-tolerant crops. However, it is reported to be less tolerant of salinity during germination, emergence and at the seedling stage (Maas and Grattan, 1999). Because of this, there may be difficulties in establishing adequate numbers of sugar beet plants under saline conditions. The crop can tolerate moderate levels of salinity in irrigation water (4–8 dS m^{-1}). Once established adequately under saline conditions, the sugar content in the crop increases compared to non-saline conditions (Moreno *et al*., 2001). It is a deep-rooted crop that can use water stored in the soil profile missed by other crops.

Soil amelioration programs have used relative performance and adaptability to select suitable crops and cropping sequences. For example, rice is used as a preferred crop during high-rainfall monsoon season to ameliorate highly sodic soils. Rice is followed by wheat in winter during the initial 3 years of the amelioration process. In the post-amelioration phase, moderately tolerant crops such as sorghum, pearl-millet, oilseed crops and sugarcane may be used. Salt- and sodium-sensitive crops can only be introduced after complete amelioration of the soil. Under resource-constrained conditions, sodium-tolerant varieties of rice, for example CSR-10 and CSR-31, can be grown on sodic soils after the application of limited quantities of gypsum (10–25 per cent of the actual needs).

Forage Crops

High-quality forages for cattle and sheep are in short supply in many parts of the world, particularly South and Central Asia. In addition, there is a decreasing access to grazing locations. Therefore, searching for, evaluating and using salt-tolerant forage grass and shrub species in a forage-livestock system developed through saline water irrigation or on salt-affected soils could increase the availability of quality feed, and thus meat and milk outputs. Salt-tolerant herbaceous grasses and legumes could be grown as pure or mixed stands in feed gardens, in fodder banks and on fallow lands to improve feed resources in smallholder crop-livestock systems. Farmers can cut and carry the forage to penned or tethered animals and/or graze pure stands *in situ*. Forages produced by irrigation with saline water provide additional income sources for farmers in marginal lands (Stenhouse and Kijne, 2006).

DOI: 10.1002/ldr

Table III. Biomass produced by different grass and forage species on salt-affected soils

Plant species	Biomass ($t\,ha^{-1}$)	EC_e ($dS\,m^{-1}$)	SAR/ESP[a]	Reference
Para grass	4·8	2·7	94	Kumar and Abrol (1984)
Karnal grass	19·9	2·7	94	Kumar and Abrol (1984)
Kallar grass	7·4	7·4	17	Chaudhry and Abaidullah (1988)
Karnal grass	18·8	2·5	94	Kumar (1988)
Land grass	2·5	2·5	94	Kumar (1988)
Blue panic grass	3·8	2·5	94	Kumar (1988)
Rhodes grass	12·5	2·5	94	Kumar (1988)
Coastal bermuda	4·0	2·5	94	Kumar (1988)
Karnal grass	22·3	4·6	94	Singh and Singh (1989)
Sesbania	33·9	7·8	62	Ahmad *et al.* (1990)
Kallar grass	29·5	7·9	66	Ahmad *et al.* (1990)
Sordan	9·7	7·8	65	Ahmad *et al.* (1990)
Karnal grass	20·6	2·1	95	Kumar *et al.* (1994)
Sesbania	32·3	10·1	59	Qadir *et al.* (1996a)
Kallar grass	24·6	9·7	60	Qadir *et al.* (1996a)
Millet rice	22·6	11·0	62	Qadir *et al.* (1996a)
Finger millet	5·4	9·6	64	Qadir *et al.* (1996a)

[a]Ahmad *et al.* (1990) and Qadir *et al.* (1996a) determined SAR while others determined ESP of the soil.

Compared to most field crops, forage grasses in general are more salt-tolerant, making it possible to economically rehabilitate large areas of salt-affected soils. A select list of promising species as reported by different researchers includes Kallar grass [*Leptochloa fusca* (L.) Kunth] (Malik *et al*., 1986; Ahmad *et al*., 1990), para grass (*Brachiaria mutica* Forsk.) (Kumar and Abrol, 1984), sesbania [*Sesbania bispinosa* (Jacq.) W. Wight] (Ahmad *et al*., 1990), alfalfa (*Medicago sativa* L.) (Ilyas *et al*., 1993), Bermuda grass (*Cynodon dactylon* L.) (Oster *et al*., 1999), Kochia (*Kochia scoparia* L. or *Bassia prostrata* L.) (Garduno, 1993), barnyard grass [*Echinochloa crusgalli* (L.) P. Beauv] (Aslam *et al*., 1987), purslane (*Portulaca oleracea* L.) (Grieve and Suarez, 1997), and shrub species from the genera *Atriplex* and *Maireana* (Malcolm, 1993; Barrett-Lennard, 2002), among others. Le Houérou (1993) provided information on salt-tolerant plants of the arid regions of the Mediterranean zone. Biomass produced by different forage species on salt-affected soils is given in Table III.

Among forage and grass species, sesbania has shown promise for biomass production on moderately saline-sodic soils as well as for phytoremediation of sodic soils (Ahmad *et al*., 1990; Qadir *et al*., 1996a; Qadir *et al*., 2007b). Sesbania is an annual species which belongs to the family Fabaceae, and has been rated as moderately tolerant against salinity (Maas and Grattan, 1999). As a nitrogen (N) fixing crop, it improves soil's N content, which is an important growth-limiting factor in salt-affected soils. Ghai *et al.* (1988) reported that sesbania, grown for 45 days and green-manured, enriched sodic soils by making up to 122 $kg\,N\,ha^{-1}$ available to the rice crop which followed it. It has also been shown that soil's N levels can be increased by up to 80 $kg\,ha^{-1}$ solely through the action of sesbania roots alone (i.e. without green manuring) during the amelioration of calcareous saline-sodic soils (Qadir *et al*., 1997).

Kallar grass—also known as Karnal grass or Australian grass—is a salt-tolerant perennial forage species, which is grown on salt-affected soils (Malik *et al*., 1986). The grass is widespread in tropical and southern Africa, the Middle East, and Southeast Asia. The species is rated as a potential biotic material for soil amelioration (Kumar and Abrol, 1984; Sandhu and Qureshi, 1986; Qadir *et al*., 1996b). In addition, it grows well under waterlogged conditions because of the development of aerenchyma in the roots. The grass can be established by root slips pressed into the flooded fields. Its above-ground part (forage) contains salt content in the range of 40–80 $g\,kg^{-1}$ when grown in soils with EC_e values of about 20 $dS\,m^{-1}$ (Malik *et al*., 1986). Annual forage production of the grass ranges from 20 to 30 $t\,ha^{-1}$ (Qadir *et al*., 1996a). In some cases, it may yield green fodder up to 50 $t\,ha^{-1}$ (Qureshi and Barrett-Lennard, 1998). Studies using the ^{15}N isotope dilution technique have provided evidence of N

DOI: 10.1002/ldr

conservation by grass (Malik *et al*., 1986). Although the grass is palatable to sheep, goats, buffalos and cattle (Sandhu and Qureshi, 1986), animals do not prefer it when other good-quality forages are available.

Desert grass (*Panicum turgidum* Forssk.) is rated as a moderately salt-tolerant (up to 15 dS m^{-1}) perennial forage grass, which is successfully grown with saline water irrigation in coastal Balochistan, Pakistan (Khan *et al*., unpublished data). Rhizomes are used to transplant the wild population into prepared fields. The grass attains 1 m height within 3–4 weeks in summer. However, growth rate decreases considerably during winter. The annual forage production could be above 40 t ha^{-1}. Feeding trials conducted on sheep, goats and cows for 3 years suggest that the grass is preferred by cows and sheep, but is not the first choice for goats. Experimental evidence suggests that when the species replaced maize as the conventional forage, there was no significant difference in meat weight or quality (Khan *et al*., unpublished data).

Salt grass [*Distichlis spicata* (L.) Greene] represents a typical halophyte that can be grown on highly salt-affected soils. It is used as forage for cattle near Mexico City. It is grown on 20 000 ha of salt-affected land; the world's largest area devoted to an introduced halophyte (National Research Council, 1990). It is a perennial species that can tolerate two extreme conditions—waterlogging and drought—for long periods. It is suitable for use in hot arid areas where saline water is available for irrigation as it can be grown successfully with water containing salt levels as high as those found in seawater.

The halophytic relative of wheat, tall wheat grass [*Elytrigia elongata* (Host) Nevski] grows well in marshes, seashores and areas subject to inundation by seawater. It is a perennial species that is well adapted to poorly drained saline soils (Colmer *et al*., 2006). Although it grows moderately well on saline areas that are permanently wet, best growth occurs where the soil dries out in the summer. It can be established from seed and germinates well but is slow to establish. It was introduced in Australia over 60 years ago, and since then it has been used for revegetation of highly salt-affected areas (National Research Council, 1990). The grass is considered as a maintenance fodder for grazing animals since its nutritional value is very low. Casson *et al.* (1996) reported that sheep lost about 7 per cent of their body weight over 56 days when they grazed old tall wheat grass pastures with 10 t ha^{-1} dry matter production. Its quality can be improved if it is cut and animals are allowed to graze the fresh re-growth.

Kochia is a perennial tap-rooted shrub, which is well adapted to salt-affected areas. It is also drought resistant also and because it is extremely efficient in using water, it grows on lands where other crops are difficult to grow. The bushy plants grow up to 2 m as erect stems that are light green and much branched (National Research Council, 1990). Small green flowers and large numbers of seeds are produced in narrow heads at the leaf axils. The plant is dark green when young and turns red as it matures. The seeds, when mature, are rough, flat, triangular and greyish-black in colour. The species produces dry matter (hay) yield up to 10 t ha^{-1} (Garduno, 1993). Although palatable to livestock, it may be toxic in large quantities. Basically it is a weed that may spread out of control in cereal crops as its seeds can be blown by the wind to several kilometres. This happened in Western Australia when Kochia was originally planted in 1990 for forage and to rehabilitate salt-affected agricultural land, but it soon spread and was officially declared a weed in 1992.

Several other grass species have shown promise under saline conditions. These include Rhodes grass (*Chloris gayana* Kunth), silt grass (*Paspalum vaginatum* Sw.), Russian-Thistle (*Salsola tragus* L.), channel millet [*Echinochloa turneriana* (Domin) J.M. Black], among others (National Research Council, 1990; Kumar, 1998). Rhodes grass is a perennial, leafy grass that grows to a height of 1 m and stays well once established. It is moderately tolerant to salinity, and withstands high levels of sodicity. Rhodes grass performs well under moist conditions but continues to grow under water deficit environments. It is palatable and withstands heavy grazing and makes good hay besides providing a good cover for erosion control (Qureshi and Barrett-Lennard, 1998). The grass is frequently found in India, Pakistan and Australia.

Shrubs species such as salt-bush (*Atriplex* spp.) and blue-bush (*Maireana* spp.) have been known to widely occur in saline environments (Le Houérou, 1993; Malcolm, 1993; Barrett-Lennard, 2002). Although these species are relatively salt sensitive at germination, they withstand high levels of salts when established. Similar is the case with waterlogged conditions. Therefore, these species are started in nurseries before being planted in potential grazing areas. However, this increases the cost of their establishment significantly. Salt-bush is grown throughout the world in arid areas for use as forage. The species can grow even under annual rainfall of 150–200 mm. Native stands of

DOI: 10.1002/ldr

salt-bush usually produce dry matter of 0·5–2 t ha^{-1} y^{-1} (Qureshi and Barrett-Lennard, 1998). Under certain conditions, such as rain-fed environments, even greater dry matter yield may be obtained. Salt-bush should be cut frequently and then allowed to recover. This practice is advantageous for two reasons: it increases the cumulative leaf production, and it ensures that the plants remain leafy rather than twiggy. The productivity and feed quality depend on harvesting management and soil conditions such as presence of hardpans, flooding conditions, presence of high salinity at early growth stages and waterlogging. With many species, salt-bush has high nutritive value for animals. Similarly, blue-bush has many species that are useful for grazing. Blue-bush is a small to medium woody shrub with succulent leaves. It is palatable and recovers well from grazing (Malcolm, 1993). It has crude protein levels ranging from 15 to 26 per cent on dry weight basis, and serves as nutritious forage.

In several parts of the world (Australia, Pakistan, India, North America, North Africa, Argentina, among others) several species of salt-bush such as *Atriplex amnicola, A. halimus, A. nummularia, A. canescens, A. lentiformis, A. leucoclada, A. undulata* and *A. gluca* have been widely used for fodder production on salt-affected lands (Malcolm, 1993; Barrett-Lennard, 2002). The genotypes used in blue-bush adaptation under saline environments include *Maireana brevifolia, M. polypterigia, M. aphylla*, and *M. amoena* (Qureshi and Barrett-Lennard, 1998).

Medicinal and Aromatic Species

The use of medicinal plant species to treat human beings and livestock is not new. Despite rapid advances in allopathic medicine, the use of medicinal plants is prevalent in many developing countries. In addition, there is a renewed interest in developed countries in using medicinal plants to treat humans, pets and livestock. This interest is based on the fact that many herbal medicines are free from side effects. Aromatic plant species have also gained worldwide importance because of their use as active constituents in food, flavour and cosmetic industries. The global importance of medicinal and aromatic plant species is evident from the huge volume of trade at national and international levels. In the late 1990s, the world market for herbal remedies was estimated at US$ 19·4 billion, with Europe in the lead (US$ 6·7 billion), followed by Asia (US$ 5·1 billion), North America (US$ 4·0 billion) and Japan (US$ 2·2 billion) (Laird and Pierce, 2002).

Recent studies have shown that several medicinal and aromatic plant species have the ability to tolerate ambient levels of salinity in soil and irrigation water as well as to produce adequate biomass of economic value (Patra and Singh, 1998; Dagar *et al*., 2004; Kumar *et al*., 2004). The threshold limits of some medicinal and aromatic plant species for soil salinity, sodicity and pH are given in Table IV.

Palmarosa (*Cymbopogon martini* Roxb. Wats) is a perennial species with foliage rich in geraniol, which is a natural antioxidant. The oil from palmarosa is obtained by hydro-distillation of foliage and is used in perfumes, soaps and as tobacco flavour. Although the species requires well-drained soils, it performs well on saline soils with EC_e levels in the range of 8 to 12 dS m^{-1} (Singh and Anwar, 1985). Moderate levels of soil salinity (around 5 dS m^{-1}) even increase the herb and oil yields. Palmarosa can be grown successfully with high electrolyte waters with EC levels of 16 dS m^{-1}. Similar to the soil salinity response, the herbal and essential oil yield increases when

Table IV. Maximum threshold limits of some medicinal and aromatic plant species at which yield and quality is not affected for given levels of soil salinity, sodicity and ph (Based on the data from Patra and Singh, 1998; National Research Council, 1993; Dagar *et al*., 2006a)

Plant species	Soil salinity (dS m^{-1})	Soil pH	Soil sodicity (ESP)
Palmarosa	11·5	9·5	55
Lemon grass	10·0	9·0	50
Vetiver	12·0	10·0[a]	55
Citronella	5·5	8·5	25
Cape periwinkle	10·0	9·5	—
German chamomile	12·0	9·5	—
Psyllium	8·0	9·2	—

[a]Vetiver can grow against a broad range of pH, even under acidic conditions, without any problem.

DOI: 10.1002/ldr

irrigated with saline waters (EC levels up to 12 dS m^{-1}). In terms of salinity effects, chloride-dominated salinity in irrigation waters has been shown to have more deleterious effects than sulphate-dominated salinity (Patra and Singh, 1998). Palmarosa has also potential to ameliorate sodic soils as it brings down soil ESP levels without the application of a chemical amendment (Kumar *et al*., 2004).

Vetiver (*Chrysopogon zizanioides* L. Roberty) oil primarily occurs in its roots and is extremely complex, containing more than 60 compounds. It emits a sweet and pleasant flavour and is used particularly in heavy oriental fragrances. Because it does not decompose in alkaline medium, vetiver oil is especially good for scenting soaps. Tender leaves are used as fodder and mature leaves for thatching purpose. Since vetiver is very hardy in nature, it can be grown on a wide range of climatic conditions with the ability to withstand periodic waterlogging and saline conditions. Its yield is not affected at pH levels as high as 9·5 (Patra and Singh, 1998). Other studies show that it can grow in a broad range of pH (4–10) without any problems (National Research Council, 1993). Because of its deep-penetrating root system, it acts as a potential tillage tool in hard sodic soils with low hydraulic properties. It is propagated mainly by root division or slips. The cost of its propagation is low and it is easy to establish in the form of hedges, which have the potential to reduce erosion. That is why it is appreciated as a 'thin green line' against erosion. The plant is not difficult to remove if no longer wanted. It is important to realize that vetiver comes in two types; the 'wild type' vetiver tends to have shallow roots and it may become a weed and create problems for the farmers. The 'domesticated type' has been cultivated for centuries and is widely distributed and suitable for use around the world. It is probably a man-made selection from the wild type. Vetiver is known to exist in many countries in Africa, Asia, Americas, Caribbean and Pacific (National Research Council, 1993).

Because of the high content of citral in essential oils present in its leaves, lemon grass (*Cymbopogon flexuosus* Nees ex Steud. Wats) has a strong lemon-like flavour. The citral isolated from its oil is used for the preparation of vitamin A, cosmetics, perfumes, detergents, soaps and fumigants. Lemon grass grows well on a range of soils; it can be raised successfully without reduction in herb and essential oil yield in soils with pH up to 9·5 and salinity levels of 10 dS m^{-1} (Patra and Singh, 1998). As compared to freshwater irrigation, its growth and yield are improved when irrigated with water of salinity up to 4 dS m^{-1}. However, its growth and yield start declining when irrigation water salinity reaches 8 dS m^{-1}.

German chamomile (*Matricaria recutita* L.), also known as blue chamomile, produces in its leaves an essential oil with antispasmodic, expectorant, carminative, anthelmintic, sedative and diuretic properties. It is also used as a flavour in beverages and ice cream. It grows well on a range of soils in different parts of the world and can withstand saline conditions with soil salinity levels up to 12 dS m^{-1}. Studies in India suggest that being a winter-season crop, it fits well in local cropping systems particularly where rice is grown in summer. Its fresh-flower yield is about 4 t ha^{-1}, which can triple the net income when compared with wheat grown in winter (Mishra, 1987).

Cape periwinkle (*Catharanthus roseus* (L.) G. Don) contains more than 100 alkaloids and is used as an anti-cancerous agent. The total alkaloid content of the roots varies from 0·15 to 1·34 per cent with root bark being the richest in alkaloid content. In addition to commercial cultivation, the plant is grown as an evergreen ornamental in gardens and houses. Cape periwinkle can be grown successfully with saline waters (10 dS m^{-1}) without reduction in root and stem yields. Similarly, it can withstand soil salinity levels up to 10 dS m^{-1}, beyond which the dry matter yield declines (Anwar *et al*., 1988).

Psyllium (*Plantago ovata* Forssk.), which is also known as blond white psyllium, produces seeds that are used commercially for the production of mucilage. The mucilage is obtained by mechanically grinding away the outer layer of the seed (often referred to as husk or psyllium husk). The milled seed mucilage is a dull white fibrous material that is hydrophilic. It is laxative and mainly used as a dietary fibre. The seeds are used as a demulcent and as a bulk laxative in the treatment of constipation, dysentery and other intestinal complaints. The species can withstand irrigation water salinity up to 8 dS m^{-1} without any loss of yield. Similarly, it maintains its yield up to soil pH of 9·2 (Dagar *et al*., 2006a). It is considered as moderately tolerant to soil salinity (Patra and Singh, 1998).

There are several other aromatic and medicinal plant species that have the potential to grow successfully in salt-affected environments. These include henbane (*Hyoscyamus muticus* L.) as a source of tropane alkaloids; calamus (*Acorus calamus* L.) for the treatment of gastric and respiratory diseases, cough and cold as well as skin diseases; and umbrella's edge (*Cyperus scariosus* R. Br.) used as oil and rhizomes for the treatment of respiratory

DOI: 10.1002/ldr

disorders, arthritis and joint pains among others. Other economically valuable salt-tolerant species include *Salicornia bigelovii* Torr. for production of vegetable oil, gumweed (*Grindelia camporum* Greene) for aromatic resin and candelilla (*Euphorbia antisyphilitica* Zucc.) for wax. The last species could produce considerable amounts of biomass when grown on calcareous soils and irrigated with saline water. Many other salt-tolerant species can also be used as landscape plants, especially in areas where freshwater is not available or limited for irrigation.

Bio-Fuel Crops

Owing to gradual depletion of petroleum reserves in different parts of the world and given the impact of environmental pollution caused by increasing exhaust emissions, bio-fuel is considered an attractive source of energy that can partly substitute or complement fossil fuel (Srivastava and Prasad, 2000; Hill *et al*., 2006). Bio-fuel has several advantages; it is renewable, environment friendly and produced easily in rural areas, where there is a great need for modern forms of energy. Relative to fossil fuels, greenhouse gas emissions are reduced 12 per cent by the production and combustion of ethanol and 41 per cent by bio-diesel. Bio-diesel also releases less air pollutants per net energy gain (Hill *et al*., 2006).

Several researchers have tested the option of using vegetable oils as fuel in engines (Pramanik, 2003). Among the vegetable oils available for bio-fuel production, the use of non-edible oils is advantageous compared to edible oils, which have higher production costs and tremendous demand for food (Meher *et al*., 2006). Several plant species provide non-edible oil, such as Pongam [*Millettia pinnata* (L.) Panigrahi], Jatropha (*Jatropha curcas* L.), Neem (*Azadirachta indica* A. Juss.), Mahua (*Madhuca longifolia* L.), and switch grass (*Panicum virgatum* L.) among others (Pramanik, 2003; Meher *et al*., 2006; Hill *et al*., 2006; Dagar *et al*., 2006b). The species considered as potential bio-fuel crops vary in their capacity to withstand salinity in the growth medium.

Among the bio-fuel and bio-energy plant species, Jatropha (*J. curcas* L.) is considered to have excellent potential to produce alternative fuel for compression ignition engines. Jatropha is believed to be native of Mexico and Central America, but is commonly found throughout most of the tropical and subtropical regions of the world. Several properties of the plant, including its hardiness, rapid growth, easy propagation and wide ranging uses have resulted in its spread far beyond its original distribution. The seed oil content ranges from 30 to 50 per cent by weight. As the oil burns with clear smoke-free flame, it has been tested successfully as fuel for diesel engines (Pramanik, 2003). The oil is slow-drying, odourless and colourless when fresh but becomes yellow on standing. The fatty acid composition classifies it as a linoleic or oleic acid type, which are unsaturated fatty acids. The fatty acid composition of the oil consists of myristic, palmitic, stearic, arachidic, oleic and linoleic acids. The oil compares well against other vegetable oils. The greatest difference between Jatropha oil and diesel is viscosity, which is higher in the case of Jatropha oil and may contribute to the formation of carbon deposits in the engine and incomplete fuel combustion, reducing the life of an engine (Pramanik, 2003). Therefore, dilution or blending of the oil with diesel fuel to appropriate levels would bring the viscosity close to a specification range.

J. curcas L. is a drought-resistant perennial, which grows well on marginal lands and produces seeds for about 50 years. Studies have been carried out to evaluate the performance of Jatropha with other plant species when grown on salt-affected soils or irrigated with saline water. Dagar *et al.* (2006b) evaluated the performance of some multi-purpose plant species at different stages of growth under irrigation with waters having variable levels of salinity and sodicity. The species used were: *A. indica* A. Juss (a commercial evergreen medicinal tree; bark used in skin diseases and malarial fever, leaf used as an anthelmintic and insect-repellent in clothes, seed oil used for ulcers and several other health problems); *Cordia sinensis* Lam. (a small drought-tolerant tree; edible fruit, foliage used as fodder, bark as astringent); *Salvadora persica* L. (an evergreen perennial shrub or small tree; seeds yield 40–50 per cent fat for use in soap and candle making, seedcake suitable for livestock feed and roots used in dental diseases) and *J. curcas* L. Table V provides information about different levels of salinity and sodicity in irrigation water and their effects on the growth of these plant species.

S. persica L. grows well under saline environments and can tolerate salinity levels as high as $50\,dS\,m^{-1}$. The seedlings can also be raised by using saline water with EC levels as high as $15\,dS\,m^{-1}$. The studies conducted by the Central Soil Salinity Research Institute (CSSRI), Karnal, India reveal that 5-year-old plantations of the plant

DOI: 10.1002/ldr

Table V. Performance of some multi-purpose plant species at different stages of growth under irrigation with waters of varying levels of salinity (Based on the data from Dagar *et al*., 2006b)

Plant species	Growth period	Fresh biomass ($kg\,plant^{-1}$)		
		Irrigation treatments		
	(month)	T_1[a]	T_2[b]	T_3[c]
Azadirachta indica A. Juss.	18	2·2	3·4	5·8
Azadirachta indica A. Juss.	30	8·9	9·3	9·8
Cordia sinensis Lam.	18	4·2	10·5	16·1
Cordia sinensis Lam.	30	14·1	16·9	17·3
Salvadora persica L.	18	1·0	1·3	2·7
Salvadora persica L.	30	15·1	16·5	20·2
Jatropha curcas L.	18	1·8	5·2	8·8
Jatropha curcas L.	30	4·0	6·4	10·0

[a]Irrigation with highly saline water ($EC = 28\,dS\,m^{-1}$ and SAR = 26; both salinity and sodicity levels decreased with time).
[b]Alternate irrigation with highly saline water ($EC = 28\,dS\,m^{-1}$ and SAR = 26) and moderately saline water ($EC = 9\,dS\,m^{-1}$ and SAR = 26).
[c]Irrigation with moderate saline water ($EC = 9\,dS\,m^{-1}$ and SAR = 26; both salinity and sodicity levels decreased with time).

species can produce oil yields up to $1800\,kg\,ha^{-1}$, giving a net return of US\$ $210\,ha^{-1}$. Based upon these findings, the National Bank for Agriculture and Rural Development, India has sanctioned a scheme for financial support to the farmers to promote the cultivation of this plant species in salt-affected areas soils of Gujarat state (Gurbachan Singh, personal communication, 2007).

Several studies on bio-fuel crops are in progress at the research stations of the CSSRI in different parts of India. The major focus is on the performance evaluation of Jatropha and Pongam on different types of salt-affected soils. The preliminary results (Gurbachan Singh, personal communication, 2007) reveal the following:

- Jatropha and Pongam can be cultivated successfully up to $pH_{1:2}$ of 9·3 and 9·5, respectively. However, following the standard auger-hole planting technique developed by the CSSRI—making auger-bores of 0·25–0·30 m diameter and 1·0–1·4 m deep and filled with original soil blended with 3–4 kg gypsum, 8–10 kg farm yard manure and 10 kg river sand—the plants can be raised even in soils having elevated levels of sodicity, i.e. $pH_{1:2}$ 10·2 and ESP 80.
- Both Jatropha and Pongam respond favourably to irrigation and fertilizer application in ameliorated sodic soils. Two supplementary irrigations—one in last fortnight of December or first week of January to protect the plants from frost, and the second in May to coup with high temperature—are crucial for successful growth of *Jatropha* in northwestern India.
- Plant to plant variability in terms of crop yield is a limitation. Yield variations from a few grams to 2 kg can be observed in the first year and variations up to 10–12 kg have been reported in 5-year-old plants. This confirms genetic variability and offers an opportunity for crop and yield improvement.
- Jatropha plantations raised using vegetative propagation show early establishment, flowering and are more uniform than plantations raised through seeds.
- Early flowering (September–October) varieties yield better because late flowering varieties face low temperatures, which affect the seed development stage.

There is an emerging debate arguing that bio-fuel production in water scarce countries will put pressure on an already stretched resource and will turn green energy into a major threat to natural resources and sustainability of the environment. Considering that bio-fuel production will increase the demand for water and agricultural land, cultivation of bio-fuel crops on salt-affected waste lands and/or irrigation with marginal-quality water resources (saline water from agricultural drainage systems or pumped from saline aquifers; and wastewater generated from

DOI: 10.1002/ldr

Table VI. Survival of fruit tree species under different levels of salinity (ec_e expressed as $dS\,m^{-1}$) and sodicity (sodium adsorption ratio, SAR) under field conditions (Based on the data from Qureshi *et al*., 1993)

Fruit tree species	EC_e ($dS\,m^{-1}$)[a]	SAR[a]	Survival (per cent)[b]
Indian jujube	18·0	46·3	100
Date palm	7·0	12·3	96
Guava	9·5	25·4	100
Jambolan	18·0	55·2	96
Phalsa	10·0	15·1	100
Phalsa	20·3	54·8	51

[a]The EC_e and SAR values represent 0·3 m upper soil depth; these values are based on the samples collected within the furrows. The salinity and sodicity levels between the furrows were much higher than the respective levels within furrows.
[b]After 1 month.

domestic, municipal and industrial sectors) may offer an opportunity to avoid conflicts at the expense of natural ecosystems.

Fruit Trees

Several fruit tree species have shown promising results under saline environments. Research on the response of fruit trees to salinity has been modest compared to that on field crops. One of the reasons for this is the inherent belief that fruit trees (especially citrus, nuts and apple) are usually sensitive to saline conditions (Gucci and Tattini, 1997). Nevertheless, the few exceptions that exist show the high potential for fruit trees to give value to land that cannot be exploited by other plants. The prominent fruit trees for saline environments are date palm (*Phoenix dactylifera* L.), olive (*Olea europaea* L.), phalsa (*Grewia asiatica* L.), chicle [*Manilkara zapota* (L.) P. Royen], guava (*Psidium guajava* L.), jambolan (*Syzygium cumini* L.), Indian jujube (*Ziziphus mauritiana* Lam.), Indian gooseberry (*Phyllanthus emblica* L.), and karanda (*Carissa carandas* L.) (Maas and Hoffman, 1977; Qureshi and Barrett-Lennard, 1998). The performance of some fruit trees under different levels of salinity and sodicity under field conditions is presented in Table VI.

According to Maas and Hoffman (1977), date palm has the highest salinity tolerance among fruit trees. The low soil requirements and high adaptability of date palm represent another advantage in salt-affected environments. While deep sandy loams are most suitable, this species can grow on almost any type of soil, from pure sand to heavy alluvial soils, as long as it is deep and well drained. In different parts of the date palm strip from India through Morocco, studies have reported tolerance of date palm to salinity levels from 3·1 to 10·9 $dS\,m^{-1}$ (Barreveld, 1993). It is interesting to note that date palm is salt-tolerant at the seedling stage, which is usually the most sensitive to salinity and the most decisive in terms of crop establishment and yield potential (Barreveld, 1993). Ramoliya and Pandey (1993) observed that germination and seedling growth can still occur in saline soils with EC levels as high as 12·8 $dS\,m^{-1}$, although other authors reported that a salinity level of 4·7 $dS\,m^{-1}$ is the starting point for harmful effects on young seedlings (Furr, 1975; cited in Barreveld, 1993).

A field study carried out in Rajasthan, India, showed that growth of date palm seedlings under monsoon climate and good drainage was little affected by saline irrigation water ($EC \leq 9{\cdot}0\,dS\,m^{-1}$) and all trees survived. Salts accumulated in the soil were effectively leached by monsoon rainfall and carry over salts were not evident during the 5-year study (Jain and Pareek, 1989). In Saudi Arabia, the introduction of drainage systems permitted cultivation of the less tolerant 'Akhlas' cultivar in addition to the already established 'Ruzaiz' cultivar (Abderrahman and Abdelhadi, 1990).

One of the most promising fruit trees in saline environments is olive, which is a glycophytic species that avoids salinity stress essentially by salt exclusion (Gucci and Tattini, 1997). Although this species is usually classified as moderately tolerant, some cultivars have shown higher levels of tolerance to saline conditions. In a 9-year study, Bouaziz (1990) showed that irrigating olive trees with saline water (EC 6·3 $dS\,m^{-1}$) did not compromise yields for some cultivars grown on calcareous sandy soils in central Tunisia where annual rainfall ranges from 100 to 200 mm.

DOI: 10.1002/ldr

In northern Chile, Sotomayor *et al.* (1994) reported good olive growth and production in soils with salinity levels as high as 13 dS m^{-1} and irrigation water salinity of 3 dS m^{-1}. However, contrasting results have also been reported on the performance of olive under saline conditions. Aragüés *et al.* (2005) evaluated 3-year salinity response of the species by using the Maas–Hoffman 'threshold–slope' response model. Based on salinity thresholds (EC_{th}), the tolerance of olive in terms of trunk growth was high in 1999 ($EC_{th} = 6{\cdot}7$ dS m^{-1}), but declined with age and time of exposure to salts by 30 per cent in 2000 ($EC_{th} = 4{\cdot}7$ dS m^{-1}) and by 55 per cent in 2001 ($EC_{th} = 3{\cdot}0$ dS m^{-1}). These authors concluded that the initial salinity tolerance of olive was high, but declined sharply with time of exposure to salts and became sensitive due primarily to increasing toxic concentrations of Na^+ in the leaves.

The water and nutrient requirements of olive are lower than most other tree species (Pansiot and Rebour, 1961), which represents an advantage in salt-affected areas that are characterized by low nutrient availability or accessibility to plants. Olive is sensitive to waterlogging (Fernandez and Moreno, 1999), which sometimes occurs concurrently with salinity. This limits the cultivation of olive under saline-waterlogged conditions to areas with well-drained soils such as light desert soils and hilly areas.

Phalsa is a deciduous bush, which grows 3–4 m high with broad leaves. The fruits are globular with an outer fleshy layer overlying an inner hard seed. The fruits have a pleasant acid pulp. Hot and dry summers are considered essential for the ripening of fruits. In addition to its use as a fruit, there are considerable prospects for making juice and pulp. Annual pruning is necessary and the long stems removed by pruning may be used as a support for garden crops. It thrives best in tropical climates, except at high altitudes. In addition, the species can withstand light frost and tolerates drought. A 5-year field trial has demonstrated that the species performed well under saline-sodic conditions (Qureshi *et al*., 1993). The average yield of fruit is about 0·8 t ha^{-1}.

Chicle is an evergreen tree with dense foliage. It can be grown on highly saline soils and with saline water irrigation on deep sandy soils. Guava can be grown on wet and moderately saline soils, but its growth suffers under sodic conditions. Rainfall and high humidity at ripening may damage the fruit skin. It is frost sensitive. The average fruit yield is 7–8 t ha^{-1}. Jambolan, also known as rose apple or java plum, is an evergreen tree of the tropics and hottest parts of the subtropics (Qureshi and Barrett-Lennard, 1998). It can grow under saline-sodic conditions ($EC_e = 18$ dS m^{-1}; SAR = 55) with a very high survival rate. A range of soils fit with its growth, although rich loamy soils are preferable. Proper maturation of the fruit needs high temperature; humid conditions drastically reduce fruit development. Indian jujube (*Z. mauritiana* Lam.) is a small to medium-sized thorny tree that rarely exceeds 12 m height. The species can tolerate medium to high salinity and sodicity ($EC_e = 18$ dS m^{-1}; SAR = 46).

Agroforestry Systems

Although most efforts in the past on the utilization of salt-affected land and saline water resources mainly aimed at enhancing the production of annual crops, studies on establishing salt-tolerant tree plantations while utilizing saline drainage or groundwater have provided another opportunity of using abandoned lands. A number of tree plantations have shown promise under salt-affected environments, including: arjun [*Terminalia arjuna* (Roxb. ex DC.) Wight & Arn] (Jain and Singh, 1998); mesquite [*Prosopis juliflora* (Sw.) DC.] (Bhojvaid and Timmer, 1998); shisham (*Dalbergia sissoo* Roxb. ex DC.) (Kaur *et al*., 2002); Acacia [*Acacia nilotica* (L.) Willd. ex Delile] (Qureshi *et al*., 1993); *Parkinsonia aculeata* L. and *Prosopis cineraria* L. Druce (Qureshi and Barrett-Lennard, 1998); sesban [*Sesbania sesban* (L.) Merr.] (Singh, 1989); common ironwood (*Casuarina equisetifolia* L.); Murray red gum (*Eucalyptus camaldulensis* Dehnh.); and leucaena [*Leucaena leucocephala* (Lam.) de Wit] (Qureshi *et al*., 1993; Singh and Dagar, 1998; Tomar and Minhas, 1998).

Many species of the multipurpose tree Acacia—used for timber, pulp, fodder, fuel wood, shelterbelts, soil conservation and rehabilitation—exhibit some degree of tolerance to salinity. Most research involving Acacia species in saline environments has been conducted in Australia and South Asia. In general, annual wood production of Acacia varies between 4 and 15 m^3 ha^{-1} in a 20-year period. This wood yield does not include the biomass removed due to lopping. Average annual forage (leaves) yield as dry matter is estimated around 5 t ha^{-1}. Some of the most popular Acacia species used for agroforestry and conservation purposes on saline soils include *Acacia stenophylla, A. nilotica, A. cyclops, A. ampliceps, A. tortilis* and *A. maconochieana*. According to Craig *et al.*

DOI: 10.1002/ldr

Table VII. Survival rate and the height of some promising accessions (of the genera *Acacia*, *Eucalyptus*, and *Melaleuca*) grown on saline (range of 4·09–12·94 dS m^{-1}) and non-saline soils (adapted from Marcar *et al*., 2003)

Accession (CSIRO clone identity)	Survival (per cent)[a]		Height (m)	
	Non-saline	Saline	Non-saline	Saline
A. stenophylla (14670)	85	65	1·75	2·14
A. stenophylla (14751)	60	90	2·18	3·34
A. stenophylla (15044)	50	90	3·15	4·23
E. camaldulensis (14007)	80	85	6·48	3·36
E. camaldulensis (15024)	95	95	6·02	3·53
E. camaldulensis (15037)	65	70	6·72	4·53
E. camaldulensis (15195)	95	90	4·52	2·87
E. camaldulensis (15272)	100	90	4·81	2·78
E. camaldulensis (CML20)	55	60	3·88	2·71
E. spathulata (seedling)	40	65	3·87	4·30
E. spathulata (SPF500)	20	50	2·46	3·19
E. spathulata (SPF516)	15	65	4·13	4·09
M. bracteata (15563)	10	40	2·20	2·28
M. halmaturorum (15045)	10	50	1·94	3·21

[a]Survival data are for plants at 44 months while height was measured at 72 months.

(1990), *A. cyclops* demonstrates high tolerance to salinity although it is sensitive to waterlogging. *A. stenophylla* (CSIRO accessions 15044 and 14751) showed no growth decline up to a root zone salinity of 10 dS m^{-1} (Marcar *et al*., 2003). Overall, these two accessions showed better survival rate and height on saline soil than on non-saline soil (Table VII).

Mesquite species are considered as potential tree plantations for saline environments. A study conducted in Saudi Arabia showed that young (5–6 months old) mesquite trees survived soil salinity levels as high as 38 dS m^{-1} when irrigated with water of salinity up to 13·5 dS m^{-1} (Hussain *et al*., 1994). The tolerance of the same species under highly alkaline conditions was also shown by Ahmed (1991), reporting that the production decreased by only 25 per cent with an increase in pH from 8 to 10·5. Among the mesquite species, long thorn kiawe (*P. juliflora* (Sw.) DC.) is a small thorny tree that grows on soils of high alkalinity (pH up to 9·8) and intermittent flooding. Therefore, it can be used as an effective bio-drainage species.

Casuarina is a fast-growing evergreen tree native to Asia and Australia that has been successfully introduced to the coastal regions of Africa due to its ability to grow under the harshest and most degraded conditions. However, the species cannot withstand waterlogged conditions for long periods. A study conducted in Australia by Marcar *et al.* (2000) showed that 77 per cent of river oak (*Casuarina cunninghamiana* Miq.) trees survived in a saline soil (EC = 11·5 dS m^{-1}) for 30 months and 55 per cent survived for more than 7 years. Hussain *et al.* (1994) found a good survival rate of common ironwood (*C. equisetifolia* L.) on soils with salinity levels as high as 30 dS m^{-1} and irrigated with saline water (6·6 dS m^{-1}), although dry matter yield was reduced by 59 per cent at this salinity level. Van der Moezel *et al.* (1989) found swamp oak (*Casuarina obesa* Miq.) and longleaf ironwood (*Casuarina glauca* Sieber ex Spreng.) to be useful trees for saline and waterlogged areas.

Murray red gum (*E. camaldulensis* Dehnh.) is another evergreen tree species, which is used for timber, fuel, essential oil, and paper as well as for landscaping, sand dune stabilization and other conservation purposes. It is a medium to tall (20–45 m) tree native to Australia, but is now grown extensively in many other parts of world. This species has been effective in reducing high water tables under saline conditions. Marcar *et al.* (2000) observed a survival rate of 97 per cent of young trees grown on a saline soil (EC 8–9 dS m^{-1}) for 6 months. In another study, Marcar *et al.* (2003) showed that some accessions of *E. camaldulensis* Dehnh. and *Eucalyptus occidentalis* Endl. were among the best performers in terms of survival and tree growth; the latter species showing no growth decline up to a root zone salinity of 10 dS m^{-1}. In a 4-year field study in California, Oster *et al.* (1999) found significant

DOI: 10.1002/ldr

reductions in growth rate and water use of *Eucalyptus* when irrigated with saline-sodic waters (EC = 8–10 dS m^{-1}, SAR = 25–30) resulting in average root zone salinities of 20–22 dS m^{-1}. Elsewhere in the world, two species of *Eucalyptus* (*E. occidentalis* Endl. and *E. sargentii* Maiden) were reported to be tolerant to both waterlogging and salinity (Marcar *et al*., 1995).

Some long-term studies have been conducted to evaluate the potential of tree species under saline environments. The results of a 9-year field study with 31 tree species in a semi-arid environment (annual rainfall 350 mm) in northwest India showed that *Tamarix articulata* Vahl., *A. nilotica* (L.) Willd. ex Delile, *P. juliflora* (Sw.) DC., *Eucalyptus tereticornis* Sm., *Acacia tortilis* (Forsk.) Hayne and *Cassia siamea* Lam. were the most successful species when irrigated with saline water with EC in the range of 8·5–10·0 dS m^{-1} (Tomar *et al*., 2002). Tree saplings were planted at the sill of furrows and irrigated with saline water for the first 3 years (4–6 times each year) and thereafter, plantations were irrigated once during winter only. The highest shoot biomass was harvested from *T. articulata* (71·9 t ha^{-1}), which was followed by *A. nilotica* (23·4 t ha^{-1}), *P. juliflora* (20·2 t ha^{-1}), and *E. tereticornis* (14·8 t ha^{-1}). Salt storage in the soil profile increased during the irrigation period (5·6–10·4 dS m^{-1}), but the added salts were distributed in the soil profile as a result of seasonal monsoon rainfall and some episodic events of rainfall during the following years. The post-study soil was enriched with organic C (>0·4 per cent in upper 0·3 m) under the promising tree species.

Qureshi and Barrett-Lennard (1998) have provided important information regarding the sources of seeds, nursery raising techniques and land preparation and planting procedures for 18 different tree species with potential for growth on salt-affected soils. The selection of tree species for salt-affected lands usually depends on the cost of inputs and the subsequent economic and/or on-farm benefits. For example, Qureshi *et al.* (1993) found agroforestry systems comprising several tree species to be economically viable because of a need for firewood in local markets of Pakistan and effectiveness in amelioration of salt-affected soils. On the other hand, the market for firewood is not sufficient to make agroforestry economically viable in California (Oster *et al*., 1999). Preliminary assessments in Australia suggest that there are 26 salt-tolerant plant species capable of producing 13 products (or services) of value to agriculture (Barrett-Lennard, 2002).

CROP DIVERSIFICATION VIS-À-VIS ENVIRONMENT CONSERVATION

Crop diversification options under salt-affected environments not only provide economic or on-farm benefits to farming communities, but also help in environment conservation through improvements in physical properties of salt-affected soils and decreases in salinity and sodicity levels. Additional benefits include improvement in the availability status of nutrients and carbon storage in the post-plantation soil. Various field-scale evaluations reveal such benefits from crop-based management of salt-affected land and saline water resources (Qadir and Oster, 2004). Some examples are given below.

Ahmad *et al.* (1990) tested three plant species—Kallar grass, sesbania, and sorghum-sudan grass hybrid 'sordan'—for biomass production and amelioration of a calcareous, sandy clay loam, saline-sodic field (pH_s = 8·2–8·6, EC_e = 7·4–9·0 dS m^{-1}, SAR = 55·6–73·0). The plant species were grown for two seasons (15 months). Their efficiency as indicated by a decrease in SAR in the upper 0·3 m of soil, was as follows: sesbania (30·1) ≈ Kallar grass (32·5) > sordan (40·0) > control (57·2). Sesbania yielded the largest amount of seasonal forage, providing 40·8 t ha^{-1} of fresh biomass. Smaller amounts of forage were yielded by Kallar grass (29·3 t ha^{-1}) and sordan (24·7 t ha^{-1}), indicating a direct relationship between forage production and decreases in soil sodicity. The amelioration potential of sesbania was also equivalent to application of gypsum to the soil.

Ilyas *et al.* (1993) evaluated the effects of physical manipulation (subsoiling and open-ditch drains), gypsum application (at 25 t ha^{-1}) and the use of two crop-based treatments—alfalfa, and sesbania-wheat-sesbania rotation—on a saline-sodic field (pH_s = 8·8, EC_e = 5·6 dS m^{-1}, SAR = 49). In the alfalfa treatments, alfalfa roots penetrated deep in the soil and resulted in a twofold increase in field-saturated hydraulic conductivity (K_s) in the upper 0·8 m of soil. The sesbania-wheat-sesbania rotation resulted in a similar increase in K_s in the upper 0·4 m of soil, as the sesbania roots produced were thick and well-branched, but penetrated the soil to a depth of only about 0·3 m. The application of gypsum to the soil also resulted in a twofold increase in K_s in the upper 0·4 m of soil.

DOI: 10.1002/ldr

Neither subsoiling (by curved chisels to a depth of 0·45 m at 0·5 m intervals) nor the use of open-ditch drains (1 m deep) improved soil permeability. In another field study on a duplex soil in Australia, Cresswell and Kirkegaard (1995) found that including crops such as canola in cereal rotations did not improve the porosity of the dense B horizons. They proposed deep-rooted crops such as alfalfa to be included in mixed cropping systems to improve subsoil permeability.

Planting salt-tolerant N_2-fixing trees has been a common approach to rehabilitate salt-affected degraded lands in many parts of the world (Oba *et al*., 2001; Kaur *et al*., 2002). Tree plantations and silvo-pastoral systems have been reported to ameliorate the conditions and fertility of sodic soils in India by improving soil's organic matter and availability of inorganic N (Kaur *et al*., 2002). Australian researchers (Marcar and Crawford, 1996; Marcar *et al*., 2003) have reported amelioration of saline soils along with other direct benefits (firewood and saleable products) as well as indirect gains (increased agricultural productivity, enhanced biodiversity and carbon sequestration). Among the species studied, *A. stenophylla*, *Eucalyptus camaldulensis*, *E. occidentalis*, and *E. spathulata* performed best in terms of soil amelioration under conditions where soil salinity ranged from 4 to 13 dS m^{-1}.

Mishra and Sharma (2003) found that growing mesquite and shisham on a sodic soil ($pH_s = 10$, ESP = 71) progressively improved the soil's chemical and physical properties. Nine years after planting, there was a significant decrease in exchangeable Na^+ levels, i.e. 3·5-fold in the surface soil under mesquite plantation. The corresponding decrease for the 9-year-old shisham plantation was 2·7-fold. The rate of decrease in exchangeable Na^+ levels was more pronounced in the initial 3 years. In addition to soil sodicity amelioration, there was a significant improvement in soil organic carbon, exchangeable Ca^{2+} and Mg^{2+}, total N, plant-available K and P, soil porosity, water-holding capacity and soil permeability.

Garg (1998) monitored changes in a sodic soil under four tree species: Acacia, shisham, mesquite and Arjun. They found that shisham and mesquite were most efficient in terms of biomass production and in reducing soil sodicity. Similarly, it was observed that the soils in which these tree species were grown exhibited a higher level of microbial activity in their upper 0·6 m layer. This was due to the accumulation of humus, through root decay and the decomposition of leaf litter, which in turn increased soil organic carbon levels. The rate of increase was low for the first 2 to 4 years, exponential between years 4 and 6, and reached a plateau after year 6. Similarly, Bhojvaid and Timmer (1998) reported that the establishment of mesquite in a sodic field increased the soil organic carbon content to a depth of 1·2 m. The soil organic carbon levels increased from 11·8 t C ha^{-1} to 13·3 t C ha^{-1} in the first 5 years, rising to 34·2 t C ha^{-1} by year 7. Thirty years after planting, the soil organic carbon levels reached 54·3 t C ha^{-1}. Over the 30-year period, the average annual rate of increase in soil organic C was about 1·4 t ha^{-1} (Table VIII). Other estimates from field studies on sodic soils suggest that different land-use systems using a number of grasses and trees can sequester organic C at a rate of 0·2–0·8 t C ha^{-1} yr^{-1} (Kaur *et al*., 2002).

Additionally, the agroforestry systems in degraded lands have potential to fix C for a long time in their wood. Based on long-term studies on saline-waterlogged soils in semi-arid regions of India, Tomar *et al.* (1994) showed C sequestration potential of several forest tree species such as *Prosopis juliflora* (49 t ha^{-1}), *Casuarina glauca*

Table VIII. Changes in soil organic carbon (C) over a period of 30 years in a sodic soil planted with mesquite [*Prosopis juliflora* (Swartz) DC.] (modified from Bhojvaid and Timmer, 1998)

Soil depth (m)	Soil organic carbon (t ha^{-1})			
	Original soil	After 5 years	After 7 years	After 30 years
0·00–0·15	3·5	5·0 (0·3)[a]	14·3 (1·54)	21·5 (0·60)
0·15–0·30	3·5	3·5 (0·0)	7·2 (0·53)	10·1 (0·22)
0·30–0·60	2·7	2·7 (0·0)	7·4 (0·94)	10·8 (0·27)
0·60–0·90	1·6	1·6 (0·0)	3·7 (0·30)	8·3 (0·22)
0·90–1·20	0·5	0·5 (0·0)	1·6 (0·16)	3·6 (0·10)
Total[b]	11·8	13·3 (0·3)	34·2 (3·20)	54·3 (1·42)

[a]Values in parenthesis indicate estimates of average yearly increase in soil organic C over the initial levels at the respective soil depth.
[b]Total organic carbon for all soil depths.

DOI: 10.1002/ldr

(48 t ha^{-1}), *Casuarina equisetifolia* and *Eucalyptus tereticornis* (14 t ha^{-1}), *Casuarina obesa* (19 t ha^{-1}), *Acacia nilotica* (33 t ha^{-1}), *Acacia tortilis* (Forsk) Hyne (20 t ha^{-1}) and *Leucaena leucocephala* (15 t ha^{-1}). Under irrigation with highly saline water (Tomar *et al.* 2002), the C biomass harvested for different species 7 years after planting was: *T. articulata* (35·9 t ha^{-1}), *A. nilotica* (11·7 t ha^{-1}), *P. juliflora* (10·1 t ha^{-1}) and *E. tereticornis* (7·4 t ha^{-1}). The soil C content under different tree species was more than 3·5 g kg^{-1}.

Some field studies based on tree plantations have been only partly successful because of certain site-specific problems. Tanji and Karajeh (1993) used a tree–shrub combination by growing *E. camaldulensis* Dehnh. with subsurface drainage water collected from nearby croplands (EC = 10 dS m^{-1}, SAR = 11) while effluents from *Eucalyptus* and the perimeter interceptor drain (EC = 32 dS m^{-1}, SAR = 69) were used to irrigate *Atriplex* species. The tree plantation was successful in moving the water table from 0·6 m to 2·3 m while consumptively using the saline-sodic water. But after 5 years of drain water reuse, a substantial buildup of salinity, sodicity and boron occurred throughout the soil profile to the extent that the trees were unable to fully extract the available soil water. Cervinka (1994) used *Eucalyptus* as the first plant species followed by *Salicornia* as the second and final species. Although *Salicornia* efficiently used the saline irrigation water, the yield of its oil-bearing seeds was low. The *Eucalyptus* trees did not prove to be effective for drainage water use in the western San Joaquin Valley, California. The major deterrents were found to be: (1) lower salt tolerance than originally anticipated, (2) susceptibility to frost damage, and (3) susceptibility to low oxygen status associated with excessively wet soil conditions resulting from over watering to maintain appropriate levels of salinity in the root zone (Letey *et al*., 2001).

Of the biological and engineering measures, Schofield (1992) found tree planting in combination with other vegetation treatments as a promising solution to dryland salinity management. Dryland salinity has emerged as a major form of land degradation in many parts of Australia because of rising groundwater levels and movement of salts to the soil surface. To control dryland salinity, recharge must be reduced to maintain groundwater levels sufficiently deep to prevent any further increase in salts to the soil surface and their subsequent discharge into streams. Based on the evaluation of the role of trees in reducing recharge, Farrington and Salama (1996) reported revegetation by trees to be the best long-term option for controlling dryland salinity.

CONCLUSIONS AND FUTURE PERSPECTIVES

Salt-induced land degradation is the most common land degradation process in arid and semi-arid regions where rainfall is too low to maintain a regular percolation of rainwater through the soil and irrigation is done without the provision of a natural or artificial drainage system. Such climatic conditions and irrigation practices trigger the accumulation of salts in soils, which influence several soil properties and decrease soil productivity. In addition to the anthropogenic activities involving inappropriate management of land and water resources, salt-affected soils are formed from the weathering of parent minerals. Widespread occurrence of salt-affected land and saline water resources and future projections for their extensive use in agriculture imply the need for immediate attention and concerted efforts to improve their productivity, which is usually very low under routine management conditions.

Since salinity and sodicity levels in soil and/or irrigation water have variable effects on different plant species, selection of the species that can withstand ambient salinity and/or sodicity levels and produce adequate biomass is vital. Besides, this selection should consider market value of the produce or its potential use on the farm. In recent years, several field crops, forage grasses and shrubs, aromatic and medicinal plants and fruit tree and agroforestry species have shown promise in producing adequate biomass of economic importance under saline environments.

The important fibre and grain crops that can be grown on salt-affected soils or irrigated with saline water are rice, wheat, barley and cotton; and to a limited extent maize and sorghum. Various approaches have been used to improve the salt tolerance of these crops by introducing genes for salt tolerance into adapted cultivars, including screening of large international collections, extensive testing of selected cultivars under field conditions, conventional breeding methods and non-conventional crosses with crop-specific relatives. The aim has been to exploit variation in salt tolerance within a particular crop and its progenitors or close relatives to produce new cultivars with greater salt tolerance.

DOI: 10.1002/ldr

Among forage and grass species, sesbania has shown promise for biomass production and soil fertility enhancement on moderately salt-affected soils. Among grasses, Kallar grass, salt grass, tall wheat grass, Rhodes grass and channel millet can withstand elevated levels of salinity. Kallar grass has been widely used in different parts of the world as a potential biotic material to ameliorate salt-affected soils. Shrub species such as salt-bush and blue-bush have been known to widely occur under saline environments and provide nutritious forage for small ruminants. These species have the potential to narrow the gap between demand and supply of high-quality forage, grass and shrub species for cattle and sheep, particularly in arid and semi-arid areas where salt-affected soils exist. If a forage-livestock production system is based on the use of saline water, it can (1) contribute to poverty alleviation and food security of vulnerable rural communities, (2) transform saline water from an environmental burden into an economic asset and (3) provide the means and incentive to install needed drainage systems to sustain and improve soil and environmental quality.

Although the use of medicinal and aromatic plant species to treat human beings and livestock is not new, there is emerging evidence that many such species can withstand salinity and sodicity to a greater extent. Considering the fact that several countries have endorsed the official use of medicinal species in their healthcare programs, cultivation of these species on salt-affected soils offers a great opportunity for income generation. However, the large-scale adoption and production of medicinal and aromatic plant species under saline environments remains a challenge due to a lack of awareness among farming communities, limited scientific databases revealing the potential production capacity of these species at different levels of salinity in soil and/or irrigation water, and the lack of appropriate markets. Problems associated with post-harvest processing and storage, and marketing limitations require policy-level interventions. Consequently, adoption of these farming systems is slow as subsistence farmers in most saline environments are reluctant to choose these crops due to the uncertain market responses.

The negative environmental consequences of fossil fuels and concerns about climate change and petroleum supplies have spurred the search for renewable transportation bio-fuels. Among the bio-fuel plant species, Jatropha provides non-edible vegetable oil as a potential alternative fuel for compression ignition engines. However, there is an emerging debate on the consequences of bio-fuel production in water scarce countries, where cultivation of bio-fuel crops will further increase the demand for water and agricultural land. The cultivation of bio-fuel crops on saline waste lands and/or irrigation with saline water and wastewater may be considered as an opportunity to save freshwater and good land for other purposes.

A number of fruit tree and agroforestry species have been successfully grown on salt-affected soils for several decades. However, research on the response of fruit trees to salinity has been modest because of the inherent belief that fruit trees are usually sensitive to salt-affected environments. Nevertheless, there are emerging examples of fruit tree and agroforestry systems that have shown potential to add value to lands that cannot be exploited by other plant species. Planting salt-tolerant N_2-fixing trees and silvo-pastoral systems could help rehabilitate salt-affected degraded lands and improve soil organic matter content and N availability.

The emerging evidence on the potential of a range of plant species that can be grown successfully under saline environments provides opportunities for researchers, farm advisors and farmers to look at the possibilities of selecting appropriate crops and their combinations to achieve maximum benefits. Crop diversification and production systems based on salt-tolerant plant species are likely to be the key to future agricultural and economic growth in regions where salt-affected soils exist, saline drainage waters are generated, and/or saline aquifers are pumped for irrigation. This is pertinent to less-developed arid and semi-arid countries where most farmers cultivating salt-affected lands are resource-poor and communities face severe unemployment, poverty and male population migration. Under such situations, community-based soil and water management and crop diversification would be needed together with stronger linkages among policy makers, researchers, farm advisors, farmer groups and water user associations. These linkages will continue to be fostered as the use of salt-affected land and saline water resources becomes more common. The most challenging part would be to overcome the general perception of the affected farming communities and policy makers that it is unlikely to use salt-affected soils without accomplishing their amelioration process.

DOI: 10.1002/ldr

The development of successful saline agriculture will require a greater understanding of the potential of plant species to withstand ambient salinity and sodicity levels in soil and water, and also of the uses and markets for the agricultural products produced. In case salt-affected lands do not belong to individual farmers but to the state—a common property of the rural community used for animal grazing without any control or dusty playground used by the village youth—developing suitable combinations of plant species may be a promising option to restrict and reverse land degradation. The use of salt-affected land and saline water resources through crop diversification options should therefore be considered as an opportunity to shift from subsistence farming to income-generating ventures.

ACKNOWLEDGEMENTS

We dedicate this publication to Professor Riaz Hussain Qureshi, University of Agriculture, Faisalabad for his pioneer research initiated in Pakistan in the 1970s that demonstrated saline agriculture to be an effective strategy for the productive use of salt-affected environments. This publication is a part of the joint initiative of the International Center for Agricultural Research in the Dry Areas (ICARDA) and International Water Management Institute (IWMI) addressing the assessment and management of marginal-quality water resources and salt-affected soils.

REFERENCES

Abdel-Dayem S. 2005. Understanding the social and economic dimensions of salinity. In Proceedings of the International Salinity Forum, 25–27 April 2005, Riverside, California; 1–4.

Abderrahman WA, Abdelhadi YM. 1990. Effect of salt tolerance levels on farming of date palm varieties: A case study. *Arid Soil Research and Rehabilitation* **4**: 269–272.

Ahmed P. 1991. Agroforestry: A viable land use of alkali soils. *Agroforestry Systems* **14**: 23–37.

Ahmad N, Qureshi RH, Qadir M. 1990. Amelioration of a calcareous saline-sodic soil by gypsum and forage plants. *Land Degradation & Rehabilitation* **2**: 277–284.

Akhtar J, Gorham J, Qureshi RH. 1994. Combined effect of salinity and hypoxia in wheat (*Triticum aestivum* L.) and wheat-*Thinopyrum* amphiploids. *Plant and Soil* **166**: 47–54.

Anwar M, Singh DV, Subrahmanyam K. 1988. Safe limits of salinity for three important medicinal plants. *International Journal of Tropical Agriculture* **6**: 125–128.

Aragüés R, Puy J, Royo A, Espada JS. 2005. Three-year field response of young olive trees (*Olea europaea* L., cv. Arbequina) to soil salinity: Trunk growth and leaf ion accumulation. *Plant and Soil* **271**: 265–273.

Aslam M, Qureshi RH, Ahmad N. 1993. A rapid screening technique for salt tolerance in rice (*Oryza sativa*). *Plant and Soil* **150**: 99–107.

Aslam Z, Saleem M, Qureshi RH, Sandhu GR. 1987. Salt tolerance of *Echinochloa crusgalli*. *Biologia Plantarum* **29**: 66–69.

Barrett-Lennard EG. 2002. Restoration of saline land through revegetation. *Agricultural Water Management* **53**: 213–226.

Barreveld WH. 1993. *Date palm products*. FAO Agricultural Services Bulletin No. 101. FAO: Rome.

Beltrán JM, Manzur CL. 2005. Overview of salinity problems in the world and FAO strategies to address the problem. In Proceedings of the International Salinity Forum, 25–27 April 2005, Riverside, CA; 311–313.

Bhojvaid PP, Timmer V. 1998. Soil dynamics in an age sequence of *Prosopis juliflora* planted for sodic soil restoration in India. *Forest Ecology and Management* **106**: 181–193.

Bouaziz E. 1990. Behaviour of some olive varieties irrigated with brackish water and grown intensively in the central part of Tunisia. *Acta Horticulturae* **286**: 247–249.

Bouwer H. 2002. Integrated water management for the 21st century: Problems and solutions. *Journal of Irrigation and Drainage Engineering* **28**: 193–202.

Cai X, McKinney DC, Rosegrant MW. 2003. Sustainability analysis for irrigation water management in the Aral Sea region. *Agricultural Systems* **76**: 1043–1066.

Casson T, Warren BE, Schleuter K, Parker K. 1996. On farm sheep production from sheep pastures. *Proceedings of the Australian Society of Animal Production* **21**: 173–176.

Cervinka V. 1994. Agroforestry farming system for the management of selenium and salt on irrigated farmland. In *Selenium in the Environment*, Frankenberger WT, Benson S (eds). Marcel Dekker: NY; 237–250.

Chaudhry MR, Abaidullah M. 1988. Economics and effectiveness of biological and chemical methods in soil reclamation. *Pakistan Journal of Agricultural Research* **9**: 106–114.

Colmer TD, Flowers TJ, Munns R. 2006. Use of wild relatives to improve salt tolerance in wheat. *Journal of Experimental Botany* **57**: 1059–1078.

Craig GF, Bell DT, Atkins CA. 1990. Response to salt and waterlogging stress of ten taxa of Acacia selected from naturally saline areas of Western Australia. *Australian Journal of Botany* **38**: 619–630.

Cresswell HP, Kirkegaard JA. 1995. Subsoil amelioration by plant roots—the process and the evidence. *Australian Journal of Soil Research* **33**: 221–239.

Curtin D, Naidu R. 1998. Fertility constraints to plant production. In *Sodic Soil: Distribution, Management and Environmental Consequences*, Sumner ME, Naidu R (eds). Oxford University Press: NY; 107–123.

Dagar JC, Tomar OS, Kumar Y, Yadav RK. 2004. Growing three aromatic grasses in different alkali soils in semi-arid regions of northern India. *Land Degradation & Development* **15**: 143–151.

Dagar JC, Kumar Y, Tomar OS. 2006a. Cultivation of medicinal Isbagol (*Plantago ovata*) in alkali soils in semiarid regions of northern India. *Land Degradation & Development* **17**: 1275–1283.

Dagar JC, Tomar OS, Kumar Y, Bhagwan H, Yadav RK, Tyagi NK. 2006b. Performance of some under-explored crops under saline irrigation in a semiarid climate in northern India. *Land Degradation & Development* **17**: 285–299.

Epstein E. 1985. Salt-tolerant crops: Origins, development, and prospects of the concept. *Plant and Soil* **89**: 187–198.

Farrington P, Salama RB. 1996. Controlling dryland salinity by planting trees in the best hydrogeological setting. *Land Degradation & Development* **7**: 183–204.

Fernandez JE, Moreno F. 1999. Water use by the olive tree. *Journal of Crop Production* **2**: 101–162.

Flowers TJ, Troke PF, Yeo AR. 1977. The mechanisms of salt tolerance in halophytes. *Annual Review of Plant Physiology* **28**: 89–121.

Francois LE, Maas EV. 1999. Crop response and management of salt-affected soils. In *Handbook of Plant and Crop Stress*, Passarakli M (ed.). Marcel Dekker: New York, NY; 169–201.

Furr JR. 1975. *Water and Salinity Problems of Abadan Island Date Gardens*, (Vol. 52), Date Growers' Institute: Indio, California.

Garduno MA. 1993. Kochia: A new alternative for forage under high salinity conditions of Mexico. In *Towards the Rational Use of High Salinity Tolerant Plants*, (Vol. 1), Lieth H, Al Masoom A (eds). Kluwer: Dordrecht; 459–464.

Garg VK. 1998. Interaction of tree crops with a sodic soil environment: Potential for rehabilitation of degraded environments. *Land Degradation & Development* **9**: 81–93.

Ghai SK, Rao DLN, Batra L. 1988. Nitrogen contribution to wetland rice by green manuring with *Sesbania* spp. in an alkaline soil. *Biology and Fertility of Soils* **6**: 22–25.

Ghassemi F, Jakeman AJ, Nix HA. 1995. *Salinisation of Land and Water Resources: Human Causes, Extent, Management and Case Studies*. CABI Publishing: Wallingford.

Gill KS, Qadar A. 1998. Physiology of salt tolerance. In *Agricultural Salinity Management in India*, Tyagi NK, Minhas PS (eds). Central Soil Salinity Research Institute: Karnal; 243–258.

Gorham J, Forster BP, Bndrewicz E, Wyn Jones R, Miller TE, Law CN. 1986. Salt tolerance in the Triticeae: Solute accumulation and distribution in an amphiploid derived from *Triticum aestivum* cv. Chinese spring and *Thinopyrum bessarabicum*. *Journal of Experimental Botany* **37**: 1435–1449.

Grattan SR, Grieve CM. 1999. Salinity–mineral nutrient relations in horticultural crops. *Scientia Horticulturae* **78**: 127–157.

Grieve CM, Suarez DL. 1997. Purslane (*Portulaca oleracea* L.): A halophytic crop for drainage water reuse systems. *Plant and Soil* **192**: 277–283.

Gucci R, Tattini M. 1997. Salinity tolerance in olive. *Horticultural Reviews* **21**: 177–214.

Gupta RK, Abrol IP. 1990. Salt-affected soils: Their reclamation and management for crop production. *Advances in Soil Science* **11**: 223–288.

Gupta RK, Abrol IP. 2000. Salinity build-up and changes in the rice-wheat system of the Indo-Gangetic Plains. *Experimental Agriculture* **36**: 273–284.

Herczeg AL, Dogramaci SS, Leany FWJ. 2001. Origin of dissolved salts in a large, semi-arid groundwater system: Murray Basin, Australia. *Marine and Freshwater Research* **52**: 41–52.

Hill J, Nelson E, Tilman D, Polasky S, Tiffany D. 2006. Environmental, economic, and energetic costs and benefits of biodiesel and ethanol biofuels. *Proceedings of the National Academy of Sciences of the United States of America* **103**: 11206–11210.

Hussain G, Sadiq M, Nabulsi YA, Helweg OJ. 1994. Effect of saline water on establishment of windbreak trees. *Agricultural Water Management* **25**: 35–43.

Ilyas M, Miller RW, Qureshi RH. 1993. Hydraulic conductivity of saline-sodic soil after gypsum application and cropping. *Soil Science Society of America Journal* **57**: 1580–1585.

Jain BL, Pareek OP. 1989. Effect of drip irrigation and mulch on soil and performance of date palm under saline water irrigation. *Annals of Arid Zone* **28**(3–4): 245–248.

Jain RK, Singh B. 1998. Biomass production and soil amelioration in a high density *Terminalia arjuna* plantation on sodic soils. *Biomass Bioenergy* **15**: 187–192.

Kaur B, Gupta SR, Singh G. 2002. Bioamelioration of a sodic soil by silvopastoral systems in northwestern India. *Agroforestry Systems* **54**: 13–20.

Kumar A. 1988. Long-term forage yields of five tropical grasses on an extremely sodic soils and the resultant soil amelioration. *Experimental Agriculture* **24**: 89–96.

Kumar A. 1998. Growing forages in salt-affected soils. In *Agricultural Salinity Management in India*, Tyagi NK, Minhas PS (eds). Central Soil Salinity Research Institute: Karnal; 489–498.

Kumar A, Abrol IP. 1984. Studies on the reclaiming effect of Karnal-grass and para-grass grown in a highly sodic soil. *Indian Journal of Agricultural Sciences* **54**: 189–193.

Kumar A, Batra L, Chhabra R. 1994. Forage yield of sorghum and winter clovers as affected by biological and chemical reclamation of a highly alkali soil. *Experimental Agriculture* **30**: 343–348.

Kumar D, Singh K, Chauhan HS, Prasad A, Beg SU, Singh DV. 2004. Ameliorative potential of palmarosa for reclamation of sodic soils. *Communications in Soil Science and Plant Analysis* **35**: 1197–1206.

Laird SA, Pierce AR. 2002. *Promoting Sustainable and Ethical Botanicals: Strategies to Improve Commercial Raw Material Sourcing*. Rainforest Alliance: New York, NY.

Läuchli A, Epstein E. 1990. Plant responses to saline and sodic conditions. In *Agricultural Salinity Assessment and Management*, Tanji KK (ed.). *Manuals and Reports on Engineering Practices No. 71*. American Society of Civil Engineers: New York, NY; 112–137.

DOI: 10.1002/ldr

Le Houérou HN. 1993. Salt-tolerant plants of the arid regions of the Mediterranean isoclimatic zone. In *Towards the Rational Use of High Salinity Tolerant Plants*, (Vol. 1), Lieth H, Al Masoom A (eds). Kluwer: Dordrecht; 403–422.
Letey J, Grattan SR, Oster JD, Birkle DE. 2001. Findings and recommendations to develop the six-year activity plan for the department's drainage reduction and reuse program. *Final Report* (Task Order No. 5). California Department of Water Resources: Sacramento, California.
Maas EV, Grattan SR. 1999. Crop yields as affected by salinity. In *Agricultural Drainage*, Skaggs RW, van Schilfgaarde J (eds). ASA-CSSA-SSSA: Madison, WI; 55–108.
Maas EV, Hoffman GJ. 1977. Crop salt tolerance—current assessment. *Journal of the Irrigation and Drainage Division ASCE* **103**: 115–134.
Malcolm CV. 1993. The potential of halophytes for rehabilitation of degraded lands. In *Productive Use of Saline Land* ACIAR Proceedings No. 42, 10–14 May, 1991, Davidson N, Galloway R (eds). ACIAR: Perth; 8–11.
Malik KA, Aslam Z, Naqvi M. 1986. *Kallar grass: A Plant for Saline Land*. Nuclear Institute for Agriculture and Biology: Faisalabad.
Marcar NE, Crawford DF. 1996. Tree growing strategies for the productive use of saline land. *Australian Journal of Soil and Water Conservation* **9**: 34–40.
Marcar N, Crawford D, Leppert P, Jovanovic T, Floyd R, Farrow R. 1995. *Trees for Saltland: A Guide to Selecting Native Species for Australia*. CSIRO: Canberra.
Marcar NE, Hossain AKMA, Crawford DF, Nicholson AT. 2000. Evaluation of tree establishment on saline seeps near Wellington and Young in New South Wales. *Australian Journal of Experimental Agriculture* **40**: 99–106.
Marcar NE, Crawford DF, Hossain AKMA, Nicholson AT. 2003. Survival and growth of tree species and provenances in response to salinity on a discharge site. *Australian Journal of Experimental Agriculture* **43**: 1293–1302.
Marion GM, Babcock KL. 1976. Predicting specific conductance and salt concentration in dilute aqueous solutions. *Soil Science* **122**: 181–187.
Meher LC, Dharmagadda VSS, Naik SN. 2006. Optimization of alkali-catalyzed transesterification of Pongamia pinnata oil for production of biodiesel. *Bioresource Technology* **97**: 1392–1397.
Minhas PS. 1996. Saline water management for irrigation in India. *Agricultural Water Management* **30**: 1–24.
Mishra PN. 1987. German chamolile. In *Eco-development of Alkali Land: A Case Study*, Khoshoo TN (ed.). National Botanical Research Institute (NBRI): Lucknow; 80.
Mishra A, Sharma SD. 2003. Leguminous trees for the restoration of degraded sodic wasteland in eastern Uttar Pradesh, India. *Land Degradation & Development* **14**: 245–261.
Moreno F, Cabrera F, Fernandez-Boy E, Giron IF, Fernandez JE, Bellido B. 2001. Irrigation with saline water in the reclaimed marsh soils of south-west Spain: Impact on soil properties and cotton and sugar beet crops. *Agricultural Water Management* **48**: 133–150.
Munns R, James RA, Lüachli A. 2006. Approaches to increasing the salt tolerance of wheat and other cereals. *Journal of Experimental Botany* **57**: 1025–1043.
Naidu R, Rengasamy P. 1993. Ion interactions and constraints to plant nutrition in Australian sodic soils. *Australian Journal of Soil Research* **31**: 801–819.
National Research Council. 1990. *Saline Agriculture: Salt-Tolerant Plants for Developing Countries*. National Academy Press: Washington, DC.
National Research Council. 1993. *Vetiver Grass: A Thin Green Line Against Erosion*. National Academy Press: Washington, DC.
Oba G, Nordal I, Stenseth NC, Stave J, Bjorå CS, Muthondeki JK, Bii WKA. 2001. Growth performance of exotic and indigenous tree species in saline soils in Turkana, Kenya. *Journal of Arid Environments* **47**: 499–511.
Oster JD, Grattan SR. 2002. Drainage water reuse. *Irrigation and Drainage Systems* **16**: 297–310. DOI:10.1023/A:1024859729505.
Oster JD, Kaffka SR, Shannon MC, Grattan SR. 1999. Saline-sodic drainage water: A resource for forage production? In Proceedings of the 17th International Congress on Irrigation and Drainage, 11–19 September, 1999, Poster Session Q49–P6. Granada; 67–79.
Pansiot FP, Rebour H. 1961. *Improvement in Olive Cultivation*. FAO Agricultural Studies, FAO: Rome.
Patra DD, Singh DV. 1998. Medicinal and aromatic crops. In *Agricultural Salinity Management in India*, Tyagi NK, Minhas PS (eds). Central Soil Salinity Research Institute: Karnal; 499–506.
Pramanik K. 2003. Properties and use of *Jatropha curcas* oil and diesel fuel blends in compression ignition engine. *Renewable Energy* **28**: 239–248. DOI:10.1016/S0960-1481(02)00027-7
Qadir M, Oster JD. 2002. Vegetative bioremediation of calcareous sodic soils: History, mechanisms, and evaluation. *Irrigation Science* **21**: 91–101.
Qadir M, Oster JD. 2004. Crop and irrigation management strategies for saline-sodic soils and waters aimed at environmentally sustainable agriculture. *Science of the Total Environment* **323**: 1–19. DOI:10.1016/j.scitotenv.2003.10.012
Qadir M, Schubert S. 2002. Degradation processes and nutrient constraints in sodic soils. *Land Degradation & Development* **13**: 275–294.
Qadir M, Qureshi RH, Ahmad N. 1996a. Reclamation of a saline-sodic soil by gypsum and *Leptochloa fusca*. *Geoderma* **74**: 207–217.
Qadir M, Qureshi RH, Ahmad N, Ilyas M. 1996b. Salt-tolerant forage cultivation on a saline-sodic field for biomass production and soil reclamation. *Land Degradation & Development* **7**: 11–18.
Qadir M, Qureshi RH, Ahmad N. 1997. Nutrient availability in a calcareous saline-sodic soil during vegetative bioremediation. *Arid Soil Research and Rehabilitation* **11**: 343–352.
Qadir M, Noble AD, Schubert S, Thomas RJ, Arslan A. 2006. Sodicity-induced land degradation and its sustainable management: Problems and prospects. *Land Degradation & Development* **17**: 661–676. DOI:10.1002/ldr.751
Qadir M, Sharma BR, Bruggeman A, Choukr-Allah A, Karajeh F. 2007a. Non-conventional water resources and opportunities for water augmentation to achieve food security in water scarce countries. *Agricultural Water Management* **87**: 2–22. DOI:10.1016/j.agwat.2006.03.018
Qadir M, Oster JD, Schubert S, Noble AD, Sahrawat KL. 2007b. Phytoremediation of sodic and saline-sodic soils. *Advances in Agronomy* **96**: 197–247.
Quirk JP. 2001. The significance of the threshold and turbidity concentrations in relation to sodicity and microstructure. *Australian Journal of Soil Research* **39**: 1185–1217.
Qureshi RH, Barrett-Lennard EG. 1998. *Saline Agriculture for Irrigated Land in Pakistan: A Handbook*. ACIAR: Canberra.
Qureshi RH, Nawaz S, Mahmood T. 1993. Performance of selected tree species under saline-sodic field conditions in Pakistan. In *Towards the Rational Use of High Salinity Tolerant Plants*, (Vol. 1), Lieth H, Al Masoom A (eds). Kluwer: Dordrecht; 259–269.

Ramoliya PJ, Pandey AN. 1993. Soil salinity and water status affect growth of Phoenix dactylifera seedlings. *New Zealand Journal of Crop and Horticultural Science* **31**: 345–353.
Sandhu GR, Qureshi RH. 1986. Salt-affected soils of Pakistan and their utilization. *Reclamation and Revegetation Research* **5**: 105–113.
Sarraf M. 2004. Assessing the Costs of Environmental Degradation in the Middle East and North Africa Countries. Environmental Strategy Notes (No. 9), Environment Department, World Bank: Washington, DC.
Schofield NJ. 1992. Tree planting for dryland salinity control in Australia. *Agroforestry Systems* **20**: 1–23.
Shainberg I, Letey J. 1984. Response of soils to sodic and saline conditions. *Hilgardia* **52**: 1–57.
Shannon MC. 1997. Adaptation of plants to salinity. *Advances in Agronomy* **60**: 76–120.
Singh B. 1989. Rehabilitation of alkaline wasteland on the Gangetic alluvial plains of Uttar Pradesh, India, through afforestation. *Land Degradation & Rehabilitation* **1**: 305–310.
Singh DV, Anwar M. 1985. Effect of soil salinity on herb and oil yield and quality of some *Cymbopogon species*. *Journal of the Indian Society of Soil Science* **33**: 362–365.
Singh G, Dagar JC. 1998. Agroforestry in salt-affected soils. In *Agricultural Salinity Management in India*, Tyagi NK, Minhas PS (eds). Central Soil Salinity Research Institute: Karnal; 474–487.
Singh MV, Singh KN. 1989. Reclamation techniques for improvement of sodic soils and crop yields. *Indian Journal of Agricultural Sciences* **59**: 495–500.
Singh MV, Chabra R, Abrol IP. 1987. Interaction between application of gypsum and zinc sulfate on the yield and chemical composition of rice grown on an alkali soil. *Journal of Agricultural Research (Cambridge)* **108**: 275–279.
Skaggs RW, Van Schilfgaarde J. 1999. Introduction. In *Agricultural Drainage*, Skaggs RW, van Schilfgaarde J (eds). ASA-CSSA-SSSA: Madison, WI; 3–10.
Soil Science Society of America. 2006. Internet Glossary of Soil Science Terms. Accessed on 21 October, 2006; Available at http://www.soils.org/sssagloss/
Sotomayor EM, de La Riva FP, Leiva AJ. 1994. Olive adaptation to the edaphoclimatic conditions in the Lluta Valley, Arica-Chile. *Acta Horticulturae* **356**: 189–192.
Srivastava A, Prasad R. 2000. Triglycerides-based diesel fuels. *Renewable and Sustainable Energy Reviews* **4**: 111–133. DOI:10.1016/S1364-0321(99)00013-1
Stenhouse J, Kijne J. 2006. Prospects for Productive Use of Saline Water in West Asia and North Africa. *Comprehensive Assessment Research Report 11*. Comprehensive Assessment Secretariat, Colombo, Sri Lanka; 41.
Suarez DL. 2001. Sodic soil reclamation: Modelling and field study. *Australian Journal of Soil Research* **39**: 1225–1246.
Sumner ME. 1993. Sodic soils: New perspectives. *Australian Journal of Soil Research* **31**: 683–750.
Sumner ME, Rengasamy P, Naidu R. 1998. Sodic soils: A reappraisal. In *Sodic Soil: Distribution, Management and Environmental Consequences*, Sumner ME, Naidu R (eds). Oxford University Press: New York, NY; 3–17.
Szabolcs I. 1994. Soils and salinization. In *Handbook of Plant and Crop Stress*, 1st edn, Pessarakli M (ed.). Marcel Dekker: New York; 3–11.
Taeb M, Koebaer RMD, Forster BP. 1993. Genetic variation for waterlogging tolerance in the Triticeae and the chromosomal location of genes conferring waterlogging tolerance in *Thinopyrum elongatum*. *Genome* **36**: 825–830.
Tanji KK. 1990. Nature and extent of agricultural salinity. In *Agricultural Salinity Assessment and Management*, Tanji KK (ed.). *Manuals and Reports on Engineering Practices No. 71*. American Society of Civil Engineers: New York; 1–17.
Tanji KK, Karajeh FF. 1993. Saline drainwater reuse in agroforestry systems. *Journal of Irrigation and Drainage Engineering ASCE* **119**: 170–180.
Tomar OS, Minhas PS. 1998. Afforestation of salt-affected soils. In *Agricultural Salinity Management in India*, Tyagi NK, Minhas PS (eds). Central Soil Salinity Research Institute: Karnal; 453–471.
Tomar OS, Minhas PS, Gupta RK. 1994. Potentialities of afforestation of waterlogged saline soils. In *Agroforestry Systems for Degraded Lands*, (Vol. 1), Singh P, Pathak PS, Roy MM (eds). Oxford and IBH Publishing Co. Ltd: New Delhi; 111–120.
Tomar OS, Minhas PS, Sharma VK, Singh YP, Gupta RK. 2002. Performance of 32 tree species and soil conditions in a plantation established with saline irrigation. *Forest Ecology and Management* **177**: 333–346.
U.S. Salinity Laboratory Staff. 1954. *Diagnosis and Improvement of Saline and Alkali Soils*. USDA Handbook No. 60. U.S. Government Printing Office: Washington, DC.
Van der Moezel PG, Walton CS, Pearce-Pinto GVN, Bell DT. 1989. Screening for salinity and waterlogging tolerance in five *Casuarina* species. *Landscape Urban Planning* **17**: 331–337.
Van Schilfgaarde J. 1994. Irrigation—a blessing or a curse. *Agricultural Water Management* **25**: 203–232.
Wichelns D, Oster JD. 2006. Sustainable irrigation is necessary and achievable, but direct costs and environmental impacts can be substantial. *Agricultural Water Management* **86**: 114–127.
Zhu JK. 2001. Plant salt tolerance. *Trends in Plant Science* **6**: 66–71. DOI:10.1016/S1360-1385(00)01838-0