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Review

Biosaline agriculture for forage and livestock production

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Abstract

There are a range of plants that are capable of growing under conditions of saline soil and water. Many of these plants represent a feed resource for livestock. At the lower levels of salinity (<15 dS m^{-1}) both legumes and grasses with moderate salt tolerance are capable of providing 5–10 t of edible dry matter (DM) $year^{-1}$, particularly when the availability of water is high. At high salt concentrations (>25 dS m^{-1}), production levels drop and the plant options decrease significantly. However, even at these high salinities there are a range of halophytic grasses and shrubs that will produce between 0.5 and 5 t of edible DM $year^{-1}$. The crude protein and digestible fibre content of these plants is variable but is probably not directly influenced by the salinity level. Importantly though, the mineral composition of the plants may be significantly altered by the concentration and type of salts in the soil and water. For plants with moderate salt tolerance, accumulation of sulfur and selenium has been reported. For the halophytic plants, particularly the chenopod shrubs, sodium, potassium, chloride, calcium and magnesium may all accumulate to be above the maximum tolerable levels for livestock. The high concentrations of sodium chloride in particular will cause depressed feed intake and under some conditions will compromise animal health. It is also not unusual to find that plants growing in saline environments accumulate a range of secondary compounds. These may have beneficial effects on grazing livestock (e.g., vitamin E and betaine) or be may be toxic (e.g., oxalate, coumarin and nitrate). Importantly, these plants can be managed so as to provide a significant contribution to a feeding system for ruminants. Prospects for the future are good, as to date, there has been little effort to improve the feeding value of salt tolerant plants through breeding or selection, or to select livestock that are more capable of tolerating high salt intakes.

Keywords: Ruminants; Sheep; Cattle; Nutritive value; Salt; Salinity; Salt tolerance

Contents

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1. Introduction

While the increase in soil and water salinity in many agricultural areas of the world has created major challenges in the production of food crops, it has also presented some new prospects for livestock agriculture. There are plants that grow under saline conditions, and historically, they have been opportunistically used as fodder for grazing livestock or as components of mixed rations to replace roughage. Limited attempts have been made to make these plants more suitable for animals either through agronomic or genetic manipulation of the plant or through identification of the species or class of animal best suited to the plants.

2. Forage plants for biosaline agriculture

There are many plants that grow under saline conditions and are also capable of being converted, by livestock, into meat, wool and other livestock products. Some of these options have been previously described and reviewed (Table 1) (Masters et al., 2001; Rogers et al., 2005). In many cases, these plants have been characterised for their ability to persist and there is limited quantitative information available on their feeding value for livestock (e.g., Semple et al., 2003). As a result, the identification of candidate plants for biosaline agriculture is relatively simple, but successful cultivation and production is less so.

Biosaline agriculture is a broad term used to describe agriculture under a range of salinity levels in groundwater, soils, or a combination of both. For example, the saline conditions may include:

- saline groundwater with non-saline, highly transmissive, permeable soils, as in parts of the Eastern Mediterranean (Ghassemi et al., 1995),
- highly saline groundwater with saline and/or sodic soils, as in Central Asia and Australia (Ghassemi et al., 1995), or
- saline irrigation waters as in the Colorado River Watershed, USA, or saline drainage waters used for irrigation on the westside San Joaquin Valley of California, USA (Ghassemi et al., 1995).

Even in these few examples there is high variation in the salinity, availability and ionic composition of the saline water, and in the hostility of the soil. No one plant will be suitable for all systems; in fact saline land is often highly heterogeneous, even within a small area. A recent study in Australia identified 35 different species growing on two highly saline sites (Norman et al., 2003), where the high levels of plant diversity were related to spatial variability at the site and indicated that an individual species is unlikely to dominate in all functional niches. These niches and complex interactions between plants (such as competition and complementarity) must be considered when evaluating options for saline land.

3. Forage production in biosaline agriculture

One of the primary determinants of livestock production in biosaline agriculture is the amount of edible biomass produced. Salinity has both osmotic and specific ion effects on plant growth. The high salt environment may cause a loss of water from the cells and a decrease in turgor. At the same time, the accumulation of specific ions such as sodium and chloride within the plant may directly interfere with internal biochemical processes. Osmotic stress is usually immediate and particularly detrimental to seed germination, emergence and seedling vigour; whereas specific ions effects are cumulative. To deal with these stresses, salt tolerant plants may be able to exclude salt at the root level, limit its transport to the shoot, move salt ions out of the cytoplasm and into vacuoles, excrete excess salt from the leaves, or utilise a combination of these mechanisms. Most mechanisms are likely to have a significant energy cost (Barrett-Lennard et al., 2003). Under such circumstances, energy used to adapt to salt stress is energy that is not available for plant growth. For this reason, saline water or soil is usually associated with reduced biomass production (Rogers et al., 1997; Noaman and El-Haddad, 2000).

Plants that are sensitive to salt tend to have a decrease in growth of 50% at 4–5 dS m^{-1} (7–9% seawater). Halophytes are highly salt tolerant and have increased growth rates at 4–5 dS m^{-1} and still only have a 50% decrease in growth at 40 dS m^{-1} (87% seawater). Salt tolerant non-halophytes maintain growth at low salinity (5–10 dS m^{-1}) and gradually reduce growth rate as salinity rises further (Barrett-Lennard et al., 2003).

At low to moderate levels of salinity, plants such as puccinellia (*Puccinnelia stricta*), tall wheatgrass (*Thinopyrum ponticum*), balansa clover (*Trifolium michelianum*), Italian ryegrass (*Lolium multiflorum*), salt water couch (*Paspalum vaginatum*) and sweet clover (*Melilotus alba*) have been reported to produce 4–10 t dry matter (DM) ha^{-1} $year^{-1}$ (Warren et al., 1996; Evans and Kearney, 2003). Under abundant irrigation with saline drainage water from the westside San Joaquin Valley of California, USA and

Table 1
Plant options for livestock in biosaline agriculture[a,b]

Species	Common name	A/B/P[c]	Salt tolerance (dS m^{-1})[d]	Plant type	Comments	References
Moderate salt tolerance (5–25 dS m^{-1})						
Acacia saligna	Golden wreath wattle	P	8–16	Shrub legume	Fast growing and recovers well from grazing. Dry matter intake often low, presumably due to its high tannin content. Potential weed	Marcar et al. (1995), Degen et al. (2000), Midgley and Turnbull (2003)
Lotus tenuis		P	5–12	Legume	Variation within the species	Schachtman and Kelman (1991), Rogers et al. (1997)
Lotus corniculatus	Birdsfoot trefoil	P	5–12	Legume	Used in grazing systems in many countries. High tannins may reduce protein degradation in the rumen and have anthelmintic properties. High tannin may also restrict feed intake	Schachtman and Kelman (1991), Rogers et al. (1997), Barry and McNabb (1999)
Medicago polymorpha	Burr medic	A	13	Legume	High seed dormancy. Good feeding value. Not tolerant of waterlogging	Le Houérou (1986), Marañón et al. (1989)
Medicago sativa	Lucerne	P	2–17	Legume	Not tolerant of waterlogging	Rogers et al. (1997, 2005)
Melilotus alba	Sweet white clover	A/B	10	Legume	Highly productive in mildly saline and moderately waterlogged conditions. Contains coumarins which can lead to toxicity	Le Houérou (1986), Evans and Kearney (2003)
Melilotus indicus	King Island melilot	A/B	10–13	Legume	Highly productive in mildly saline and moderately waterlogged conditions. Contains coumarins which can lead to toxicity	Le Houérou (1986), Rogers et al. (2005)
Trifolium alexandrinum	Berseem clover	A	2–6	Legume	Forage crop in moderately saline areas of the eastern Mediterranean. Very productive	Rogers et al. (1997), Kaddah (1962), Fraser et al. (2004)
Trifolium ambiguum	Caucasian clover	P	6–8	Legume	Slow to establish and not tolerant of waterlogging	Hill et al. (1996), Rogers et al. (1997)
Trifolium fragiferum	Strawberry clover	P	6–15	Legume	Stoloniferous. Tolerates waterlogging and sodicity	Rogers et al. (1997), Dear et al. (2003)
Trifolium michelianum	Balansa clover	A	9	Legume	Very waterlogging tolerant, but low salt tolerance during establishment. Little seed dormancy	Rogers et al. (1997), Dear et al. (2002)
Trifolium resupinatum	Persian clover	A	8–13	Legume	Highly waterlogging tolerant	Rogers and Noble (1991), Rogers et al. (1997)
Trifolium squamosum	Sea clover	A	13	Legume	Low forage production	Rogers et al. (1997), Marañón et al. (1989)
Trifolium tomentosum	Woolly clover	A	12–13	Legume	Waterlogging tolerant, low-moderate forage production. High seed dormancy	Rogers et al. (1997), Norman et al. (2002a)
Enteropgon acicularis	Curley windmill grass	P	18	Grass	Low forage production	Rogers et al. (1996),
Eragrostis curvula	Weeping lovegrass	P	13–18	Grass	Good biomass production however palatability and nutritive value can be low. Weed potencial	Rogers et al. (1996), Johnston et al. (2005)
Festuca arundinacea	Tall fescue	P	10–12	Grass	Good forage quality, moderately waterlogging tolerant	Rogers et al. (1996, 2005)
Hordeum vulgare	Barley	A	10	Cereal crop		Ayres and Westcott (1976)

Leptochloa fusca	Kallar grass	P	10	Grass	Productive and tolerant of waterlogging and alkali	Sandhu et al. (1981), Miyamoto et al. (1994), Akhter et al. (2004)
Leymus angustus	Altai wild ryegrass	P	18	Grass	From cool-temperate regions and may not tolerate hot, dry conditions	Rogers et al. (1996)
Leymus triticoides	Creeping (or beardless) wildrye	P	10–13	Grass	Rhizomatous, high biomass production, acceptable forage quality, high Se accumulation	Rogers et al. (2005), Suyama et al. (2006)
Lolium perenne	Perennial ryegrass	P	13–18	Grass	Good nutritive value	Rogers et al. (1996), Smith et al. (2004)
Lolium multiflorum	Italian or winter-active ryegrass	B	5	Grass	Good nutritive value	Ben-Ghedalia et al. (2001)
Paspalum vaginatum	Paspalum or salt water couch	P	15–25	Grass	Produces little seed so propagation by runners required, highly tolerant to waterlogging and soils in poor physical condition	Forti (1986), Barrett-Lennard et al. (2003), Robinson et al. (2004)
Hordeum marinum	Sea barley grass	A	15–25	Grass	Good waterlogging tolerance. Poor biomass production and poor nutritive value when dry	McDonald et al. (2001), Colmer et al. (2005)
Pennisetum clandestinum	Kikuyu grass	P	21.5	Grass	Branching rhizomes. Good feeding value. May be considered a weed in some areas	Russell (1976), Muscolo et al. (2003)
Puccinellia ciliata	Puccinellia	P	20	Grass	Tussock-forming. Moderately tolerant of waterlogging. Prefers alkaline soils	Le Houérou (1986), Bouma et al. (2001), Barrett-Lennard et al. (2003)
Sporobolus airoides	Alkali dropseed or alkali sacaton	P	10–12	Grass	Good biomass production, but low forage quality. Warm season	Aronsen (1989), Rogers et al. (2005)
Thinopyrum ponticum (formerly *Agropyron elongatum*)	Tall wheatgrass	P	13–25	Grass	Tussock-forming. Low nutritive value if managed poorly, but high nutritive value also reported. Summer active. Does not tolerate prolonged waterlogging	Le Houérou (1986), Moxley et al. (1978), Warren and Casson (1992), Barrett-Lennard et al. (2003), Suyama et al. (2006)
Chenopodium album	Fat hen or lambs quarters	A	9	Forb	Contains oxalates and often considered to be an invasive weed	Hoffman and Shannon (1986), Angus (2000)
High salinity tolerance (>25 dS m^{-1})						
Acacia ampliceps	Salt wattle	P	17–65	Shrub legume	Small tree used for forage and fuel production	Ansari et al. (1994), Aswathappa et al. (1987)
Hedysarum carnosum		B/P	30	Legume	Tolerates arid, saline environments	Le Houérou (1986), Rogers et al. (1997), Dear et al. (2003)
Melilotus segetalis	Corn melilot	A	26	Legume	Potentially waterlogging tolerant	Marañón et al. (1989), Rogers et al. (2005)
Distichlis spicata	Saltgrass	P	31	Grass	Highly tolerant of waterlogging and salinity. Stoloniferous	Barrett-Lennard et al. (2003)
Sporobolus virginicus	Marine couch	P	25–30	Grass	Highly tolerant of salt and waterlogging. Rarely sets seeds	Barrett-Lennard et al. (2003)
Chloris gayana	Rhodes grass	P	25	Grass	Generally good biomass production but nutritive value can be low. Grazing management is very important to improve productivity	Russell (1976), Brown and Grant (2000), Karda and Dryden (2001)
Cynodon dactylon	Bermuda grass	P	8–25	Grass	Stoloniferous. Relatively good forage quality. Warm season. May be difficult to establish	Semple et al. (2003), Qureshi and Barrett-Lennard (1998)

Table 1 (*Continued*)

Species	Common name	A/B/P[c]	Salt tolerance (dS m^{-1})[d]	Plant type	Comments	References
Pascopyrum smithii	Western wheatgrass	P	25	Grass	Drought tolerance, high water use efficiency, low productivity	Knowles (1987), Rogers et al. (1996)
Allenrolfea occidentalis	Iodine bush	P	>50	Shrub	Woody, not very palatable. Grows on the edge of saltpans	Blank et al. (1994)
Atriplex amnicola	River saltbush	P	40	Shrub	Sensitive to the cold, waterlogging tolerant, palatable and recovers well from grazing	Hoffman and Shannon (1986), Barrett-Lennard et al. (2003)
Atriplex halimus	Mediterranean saltbush	P	30–60	Shrub	Relatively high in vivo digestibility when compared to old man and river saltbushes	Le Houérou (1986), Alicata et al. (2002)
Atriplex nummularia	Old man saltbush	P	25–50	Shrub	Drought tolerant, upright growth habit and intolerant of waterlogging. Variable palatability. Difficult to establish from seed	Le Houérou (1992), Barrett-Lennard et al. (2003), Norman et al. (2004)
Atriplex semibaccata	Creeping saltbush	P	25	Shrub	Short-lived and may contain oxalates	Le Houérou (1992)
Atriplex undulata	Wavy-leaf saltbush	P	25–50	Shrub	Palatable. Not tolerant of repeated heavy grazing. Establishes readily from seed	Le Houérou (1992), Malcolm and Pol (1986)
Atriplex lentiformis	Quailbrush	P		Shrub	Rapid growth compared to other saltbushes with moderate salt, heat and drought tolerance	Barrett-Lennard et al. (2003)
Kochia scoporia		A		forb	Low metabolisable energy. Contains alkaloids and oxalate	Madrid et al. (1996), Rankins and Smith (1991)
Halosarcia spp.	Samphires	P	48	Shrub	Slow growing but very tolerant of both salinity and waterlogging. Accumulates high salt concentrations	Barrett-Lennard et al. (2003)
Maireana brevifolia	Small-leaf bluebush	P	33	Shrub	Contains nitrates and oxalates but remains palatable to sheep. Not tolerant of waterlogging. Volunteers easily by seed	Glenn (1987), Barrett-Lennard et al. (2003)
Salicornia bigelovii		A	>45	Shrub	Can produce very large quantities of biomass under irrigation with seawater. Used for oil production and rich in linoleic acid. High crude protein	Swingle et al. (1996), Attia et al. (1997), Noaman and El-Haddad (2000)
Suaeda spp.		P	50	Shrub	Saltmarsh species, considered highly palatable	Flowers (1972), Swingle et al. (1996)

[a] Plants in this list may be declared weeds in some countries or in some regions within countries. They should only be considered for use where they have been approved by the relevant authorities and have passed a weed risk assessment.

[b] Modified from (Masters et al., 2001).

[c] Annual (A), biennial (B) or perennial (P) lifecycle.

[d] Salinities at which plants have been grown without severely limiting dry matter production. Results were compiled from a number of sources and include tolerances reported to saline water (ECw) and soil (ECe).

growing in saline-sodic soils with tough surface crusts, creeping wildrye (*Leymus triticoides* cv. Rio) had high productivity (10–13.8 t DM ha^{-1} $year^{-1}$) at soil salinities averaging 13.1 dS m^{-1} ECe and at higher soil salinity (18.4 dS m^{-1} ECe), tall wheatgrass had reasonably good production (5.9–8 MT ha^{-1} $year^{-1}$). Alkali sacaton (*Sporobulus airioides*) and tall fescue (*Festuca arundinacea* cv. *Alta*) also produced 6.7 and 4.5 t DM ha^{-1} $year^{-1}$ at soil salinities of 12.4 and 12.1 dS m^{-1} ECe, respectively (Suyama et al., 2006). This biomass production is sufficient to support reasonable levels of livestock production, particularly if grazing is managed to improve the nutritive value of the plants.

In experiments where forages were grown in indoor sand tanks and irrigated with synthetic drainage water of 25 dS m^{-1}, forage production of 9.4, 10.5, 7.8, 8.8, 6.6, 5.9, 5.6, 5.6 and 4.6 t DM ha^{-1} in less than 12 months were reported for Bermudagrass (*Cynadon dactylon* cv. Tifton), Paspalum (*Paspalum vaginatum* cv. Duncan and cv. Polo), kikuyu grass (*Pennisetum clandestinum* cv. Whittet), tall wheatgrass (*Agropyron elongatum* [now *Thinopyrum ponticum*], cv. Jose), narrow leaf trefoil (*Lotus glaber*), alkali sacaton (*Sporobolus airodes*), lucerne (*Medicago sativa* cv. SW9720 and cv. Salado) respectively (Robinson et al., 2004; Grattan et al., 2004). Importantly, the ionic composition of the saline drainage water used in these experiments was dominated by sulfates. Other researchers have shown that plants are significantly more tolerant of salinity where sulfates, rather than chlorides, predominate as the major salts (Rogers et al., 1998).

Other glasshouse experiments have identified a range of grasses and legumes with moderate salt tolerance (Rogers et al., 1996, 1997). Further field studies on these plants are justified to provide information on their potential to produce enough total biomass to justify commercial evaluation under grazing.

At much higher levels of salinity, saltbush (*Atriplex* spp.) irrigated with saline drainage water has also been reported to produce forage yields of 2.2–5.3 t DM ha^{-1} $year^{-1}$ (Watson and O'Leary, 1993). In other experiments, a broad range of halophytes from the genera *Atriplex*, *Salicornia*, *Distichlis Cressa* and *Batis* have all been shown to produce high levels of biomass even under hypersaline irrigation water (approximately 70 dS m^{-1}). While some of these plants required special care during propagation, *Atriplex lentiformis*, *Batis maritima*, *Atriplex canescens*, *Salicornia bigelovii* and *Distichlis palmeri* all produced the equivalent of over 10 t ha^{-1} $year^{-1}$ following successful establishment (Glenn and O'Leary, 1985).

More recently, highly saline groundwater (30 dS m^{-1}) has been used to produce up to 45 t DM ha^{-1} $year^{-1}$ of hay from irrigated and intensively managed inland salt grass (*Distichlis spicata*) and marine couch (*Sporobolus virginicus*) (International Center for Biosaline Agriculture, 2004).

Collectively, the results above indicate that the opportunities for forage production are high when water and soil salinity are low to moderate, or when the availability of saline water and soil infiltration rates are both high.

By far the highest proportion of saline areas of the world are found in arid and semi arid environments (FAO/AGL, 2000). The halophytic shrubs from the *Chenopodiaceae* family are particularly well adapted to this environment; they are perennial, drought resistant and tolerant of grazing. These shrubs that include the saltbushes, small-leafed bluebush (*Maireana brevifolia*), *Kochia* spp., *Tamarix* spp., glassworts (*Salicornia* spp.) and *Suaeda* spp., are all drought and salt tolerant and have been used for grazing and forage production in both saline and non-saline environments (Le Houérou, 1994; Masters et al., 2001). Edible biomass production is highly variable and may be as little as 10% of total biomass (Barrett-Lennard et al., 2003). Management of the stand, however, also influences the amount of edible biomass. Cutting or heavy grazing of woody shrubs such as saltbush encourages new growth that is less woody and more digestible. Knowledge of the appropriate cutting height is critical to avoid die-off of the existing plant material.

Le Houérou (1992) reported that edible forage production from a range of saltbush species to be 5–10 kg DM ha^{-1} $year^{-1}$ for each mm of rainfall in areas with low salinity. This means that with favourable soils and rainfall between 200 and 400 mm, yields of 2–4 t DM ha^{-1} $year^{-1}$ would be expected. Under more saline conditions such high levels are rare, with production more likely to be 0.5–1 t DM ha^{-1} $year^{-1}$ (Warren et al., 1994; Morecombe et al., 1996).

In summary, the production of dry matter is a function of the interaction between the genotype and the environment. A plant that grows well in one climate/soil/plant/animal combination may not be successful in another.

4. Feeding and nutritive value of salt tolerant and halophytic forages

Within this review, a distinction is made between the feeding value and nutritive value of feeds as defined by Ulyatt (1973). Nutritive value is the animal production response per unit of feed intake, feeding value takes into account factors that limit intake. The nutritive value is frequently a function of, and is characterised by, the digestible energy and protein provided by the diet, but is also influenced by other dietary components with pro- or anti-nutritional properties.

4.1. Energy and protein

Most of the moderately salt tolerant forage plants have a limited ability to regulate the uptake of salt and prevent accumulation in the tissues. The primary consequence of high concentrations of salt in water or soil for these plants is reduced growth or survival rather than a change in nutritive value. In the sand tank experiment described earlier, Robinson et al. (2004) compared the nutritive value of 10 forages irrigated with saline drainage water of 15 or 25 dS m^{-1}. While there were some significant differences between treatments, the differences in nutritive value were usually small and variable. Tall wheatgrass provided one exception with a consistent increase in crude protein and decrease in neutral detergent fibre (NDF) at the higher salinity level.

Conversely, at a lower range of salinities (1.4–9.8 dS m^{-1}), others have reported an increase in organic matter digestibility and water soluble carbohydrates and a decrease in NDF as the salinity of irrigation water for Italian ryegrass increases (Ben-Ghedalia et al., 2001).

There is limited data available on the nutritive value of the highly salt tolerant shrubs. The published information that is available often overestimates nutritive value through misinterpretation of dry matter digestibility (DMD) and crude protein (CP) measurements. Most of the chenopod shrubs contain high concentrations of salt (up to 30% of dry matter) and therefore, much of the apparently digestible material in these plants is salt and has no energy value. The organic matter digestibility (OMD) or digestible organic matter in the dry matter (DOMD) of the plant material are more useful indicators of available energy (Masters et al., 2001).

Crude proteins levels can also be misleading. These are usually calculated from nitrogen analysis and assume all nitrogen in the plants is in the form of protein. In reality, many salt tolerant plants contain high levels of non-protein-nitrogen. For example Benjamin et al. (1992) reported that 42% of the nitrogen in *Atriplex barclayana* was non-protein nitrogen. This nitrogen will only be available for conversion to microbial protein in the rumen if a good supply of metabolisable energy is available or if added to a protein deficient feed (Masters et al., 2001).

Where reliable estimates of nutritive value for halophytes have been published, they are variable. Measurements of *in vivo* OMD for saltbush range from 34.2 to 66.3% (Benjamin et al., 1992; Atiq-ur-Rehman et al., 1994; Alicata et al., 2002; Van der Baan et al., 2004; Abu-Zanat and Tabbaa, 2006). Not all of the halophytes in these studies were grown on saline land. OMD for *S. bigelovii* is higher than saltbush at 67.3–75.3% (Glenn et al., 1992; Abouheif et al., 2000). Watson and O'Leary (1993) reported that saltbush irrigated with saline drainage water contained crude protein ranging from 6 to 12% with ADF ranging from 26.0 to 37.3% and NDF from 40.5 to 60.5%. Similar values have been reported in other experiments where saltbush has been grown under a range of different saline conditions (Warren et al., 1990; Swingle et al., 1996; Norman et al., 2002b). Although these values are within the range found for many grass and lucerne-based hays (Ministry of Agriculture Fisheries and Food, 1992) caution in interpretation is necessary. Even with adjustment for ash, the plants may contain organic compounds such as betaine, proline, oxalates and tannins (Masters et al., 2001) that may be digested or absorbed but do not contribute to the metabolisable energy of the diet.

Because salt tolerant plants have been a small component of the landscape, grazing has tended to be opportunistic with few attempts to improve feeding value. Selection for nutritive value in traditional pasture species is still a new concept but is now being included in some plant breeding programs (see Coleman and Henry, 2002). With the availability of near infrared spectroscopy (NIRS) to rapidly scan plants for digestibility and crude protein, selection is now a practical option. Many of the plants used to revegetate saline land are wild types and show a broad range in biomass production, palatability, digestibility and protein content (Norman et al., 2004). Significant improvements in potential livestock production should be possible through a systematic process of plant selection.

4.2. Minerals

Saline soils are defined by the presence of a range of salts, in particular, sodium, potassium, calcium or magnesium as chlorides, sulfates or bicarbonates. Sodium and chloride are usually in the highest proportions. Saline water may occur with saline soils or in some cases independently of saline soils. Saline waters range from simple sea water intrusion in coastal areas, with a composition similar to sea water, through to underground water or contaminated saline drainage water with a far more complex composition. Saline drainage waters, for example, may contain high levels of molybdenum, selenium, sulfate, boron, arsenic, uranium and vanadium, as well as the macro minerals (Retana et al., 1993). Livestock grazing in salinised agricultural areas will therefore often be exposed to high concentrations of various minerals in either feedstuffs or drinking water or both.

4.3. Consequences of high mineral intakes by livestock

There are specific problems for livestock associated with consumption of salt in feed and water, for most salts, but particularly sodium, potassium and chloride. The body has little or no capacity to store excess electrolytes or to actively excrete through the faeces. Acute excess of sodium has been associated with lower rectal temperature, raised pulse and respiration rates and water retention (Marai et al., 1995). Digestive function is also changed with an increase in the rate of passage of feed through the digestive tract, reduced concentrations of protozoa and selenomads in the rumen and decreased OMD (Weston et al., 1970; Hemsley et al., 1975b). High levels of sodium in the diet also depress appetite (Wilson, 1966b) and the efficiency of energy use for production (Arieli et al., 1989).

A summary of results from a range of experiments indicate that sheep and cattle are able to tolerate 7–10% of sodium chloride in the diet before feed intake is depressed (National Research Council, 2005), deer can tolerate at least

6% (Ru et al., 2004) and chickens only around 3% (National Research Council, 2005). Based on these and other studies, the National Research Council (2005) define the ''maximum tolerable levels'' of sodium chloride in the diet (i.e., the levels that will not impair health and performance), as 3–6% for ruminants and 2–3% for swine and poultry. Studies on sodium chloride in drinking water indicate the order of tolerance as camels > sheep = goats > cattle > horses > pigs > poultry (Marai et al., 1995; Assad et al., 1997; Ru et al., 2000; McGregor, 2004). This order of tolerance is consistent with an interrelationship between genetically determined low water turnover and salt tolerance suggested by Squires (1988). Similarly, the high tolerance by sheep is consistent with high renal secretory power reported for this species (McDonald and Macfarlane, 1958).

Under practical conditions sheep and cattle grazing a mixed bladder saltbush (*Atriplex vesicaria*) and volunteer understorey pasture showed no differences between species in body weight production per ha over a 4 year period (Wilson and Graetz, 1980). Similarly, Meyer et al. (1955) reported that sheep and cattle were both unaffected by addition of up to 9.4% sodium chloride to a feedlot diet.

Within species, it would be expected that livestock breeds originating from arid environments would be better able to conserve water and manage high salt intakes. For cattle this would suggest *Bos indicus* would be better suited to high salt diets than *Bos taurus*. Similarly sheep adapted to arid environments such as Merinos have been shown to approach camels in their ability to conserve water and concentrate urine (Macfarlane et al., 1956). Direct comparative studies do not appear to have been published. Even within breeds there may be high variability in the ability of individual animals to tolerate high levels of salts in the diet.

There is some indication that reproducing livestock are more susceptible to high salt intakes than non-reproducing livestock. Meyer and Weir (1954) reported increased weight losses during lactation in ewes consuming 13.5% sodium chloride in the diet compared to similar sheep consuming 9.1% or less. The same authors (Meyer et al., 1955) reported no detrimental effects when 12.8% sodium chloride was fed to growing lambs. A number of reports indicate that reproducing ewes are less tolerant of high salt in drinking water than wethers, with consequences including occasional decreases in lambing percentage and increased lamb mortality (Peirce, 1968a,b; Potter and McIntosh, 1974).

While differences in species, breed and physiological state need to be considered when managing livestock that are grazing salt tolerant pastures, possibly of more significance is the ability of livestock to adapt. Squires (1993), concluded there was no evidence of adaptation of micro-organisms in the rumen, whereas, Potter (1968) observed that sheep accustomed to drinking saline water were better able to withstand loading with sodium chloride. If this is the case, grazing management may be more important than the class of animal.

Grazing ruminants can tolerate at least 1% sodium chloride in drinking water before there is a depression in feed intake and growth. A level of 1.5–2.0% has been reported to cause a depression in feed intake, loss of body weight, general weakness and emaciation in sheep, goats and cattle (Peirce, 1957; Weeth and Haverland, 1961; McGregor, 2004). Of critical importance is the combination of salt in feed and water. When the high salt intake comes from feed alone, and there is an unlimited supply of fresh water, the animal can cope by increasing water intake and therefore increasing the salt excreting capacity of the kidneys. This cannot be done if the salt is present in both feed and water. This has significant practical consequences, Wilson (1966a) reported that sheep fed oldman saltbush *Atriplex nummularia* (containing 8.2% sodium, 2.7% potassium and 10.7% chloride) ate 554 g digestible DM day^{-1} and gained weight when given fresh water. A comparable group ate only 202 g digestible DM day^{-1} and lost weight when the water supply contained 1.2% sodium chloride. Even 0.9% sodium chloride in the drinking water caused a 50% reduction in feed intake. Any level of salt in drinking water will compound the effects of a high dietary salt intake. Such an interaction is likely to be more important during the hotter, dry periods of the year, when livestock have an additional requirement for water for thermoregulation than during colder, wetter times of the year when evaporative cooling is less important and fresh water intake may increase through the ''contamination'' of feed by rain (Weeth and Haverland, 1961; Wilson, 1975).

The primary focus of most studies on livestock production in saline environments has been sodium, chloride and occasionally potassium. Other elements may also be important, either through the high concentrations in salt tolerant plants or through interactions between minerals or between minerals and other dietary components. For example, Tomas et al. (1973) reported that consumption of water containing 0.8 or 1.2% sodium chloride not only increased excretion of sodium and chloride, but also calcium, magnesium, potassium and phosphorus. Such changes may be due to specific effects of high sodium in the kidney or may be related to the increased consumption and excretion of water alone. The increased excretion of other essential elements has the potential to cause depletion and deficiency and may be particularly important in young or reproducing livestock with higher requirements for calcium and phosphorus.

The highly salt tolerant, halophytic plants may also accumulate other minerals. Norman et al. (2002b) reported that potassium, calcium and magnesium can be above or close to the maximum tolerable levels of 2, 1.5 and 0.6% respectively for ruminants (National Research Council, 2005). Accumulation of sulfur is also a consideration. The margin between adequate and harmful intakes of sulfur is small for ruminants. Bird (1972), recommended that sulfur intakes for sheep should not exceed 4 g day^{-1} (equivalent to 0.4% in a sheep consuming 1 kg DM day^{-1}). Higher levels result in excess sulfide production in the rumen and depressed appetite. Sulfur concentrations in halophytes and in other forage plants grown on saline drainage waters are frequently above 0.5% (Grattan et al., 2004). In the case of halophytes, the accumulation of sulfur is not necessarily caused by high levels of sulfur in the soil or water, whereas sulfur accumulation in forage plants irrigated with saline drainage may result from the high levels of sodium sulfate in the water. Sulfur also interacts with molybdenum in the rumen to reduce the availability of copper (Suttle, 1991). Under conditions of low to moderate copper intakes, high sulfur and molybdenum can cause severe copper deficiency resulting in anemia, fragile bones and reproductive disorders. High molybdenum has also been reported in some salt tolerant plants (Retana et al., 1993; Grattan et al., 2004).

Potentially toxic levels of selenium can also be a problem in forages irrigated with saline drainage water over the long term. Selenium accumulated to 10.7 mg kg^{-1} DM in the herbage of creeping wildrye when irrigated with saline drainage water for 5 years (Suyama et al., 2006). Sheep and cattle are at definite risk from selenosis when the diet contains more than 6 mg kg^{-1} DM (Underwood and Suttle, 1999).

In addition to the impacts of mineral imbalances on animal metabolism, a recent publication indicates that increasing sodium chloride in irrigation water (i.e., in the root zone of the plant) of river saltbush (*Atriplex amnicola*) significantly reduces the concentrations of a range of cations in the plant (Masters et al., 2005a). These include potassium, calcium, magnesium, copper and zinc. These results, together with similar observations in non-halophytic plants grown at increased salinity levels (de Dios Guerrero-Rodriguez et al., 2004) indicate the possibility of specific mineral deficiencies or imbalances in salt tolerant plants that may subsequently produce deficiencies or imbalances in grazing livestock.

The nature of saline agriculture is that there is high variability in the level and type of salts contributing to salinity, these in turn have a critical effect on the types of plants that can be grown, the composition of those plants and the quality of the water supply. For these reasons, the management of mineral nutrition in grazing livestock will need to be site specific with full consideration of the potential impact on productivity.

4.4. Benefits of high salt intakes

Although excessive salt intakes depress feed intake, digestibility and the growth of ruminants, moderate levels of salt have been shown to have benefits to production. Hemsley (1975a) reported an improvement in wool growth efficiency in sheep fed an oilseed based diet and drinking water high in sodium chloride. Wool growth is highly responsive to protein available for absorption in the small intestine and this result may be a consequence of the higher water intake leading to an increased rate of passage of nutrients. Increased rate of passage will mean lower degradation of protein by microorganisms in the rumen and therefore more undegraded protein available for absorption in the small intestine. The result reported by Hemsley was from feeding sheep high salt levels in a diet made up of 89% protein concentrate. More recently, Masters et al. (2005b) reported that the amount of wool grown per kg of organic matter intake increased by up to 50% when sodium and potassium chloride were included as part of a normal roughage based diet at 25% of the dry matter. From the point of view of a specialist wool-growing enterprise, this result is highly significant. It indicates that total wool production per kg of available organic matter could be increased by including plant material with a high salt concentration.

There are also reports of improvements in carcass quality in sheep consuming moderate amounts of sodium chloride. Increased intake of sodium chloride in either drinking water or feed has been associated with a reduction in fat and an increase in protein in the carcass (Walker et al., 1971; Kraidees et al., 1998).

4.5. Other pro and anti-nutritional compounds in salt tolerant plants

It is not unusual to find that plants that grow in inhospitable environments contain secondary compounds that play a role in their survival. These may enable the plant to tolerate the soil, water and climatic stress (e.g., salt, betaine, antioxidants) or may act as deterrents to grazing herbivores (e.g., tannin, oxalate, coumarin and nitrate). A summary of these compounds and their potential effects on animal production and health is given in Table 2. In addition to the compounds in the table there are likely to be a range of others that are less well characterised but may influence both palatability and nutritive value. These include triterpenoids, steroids, glycosides, saponins and alkaloids (Gihad and El Shaer, 1994). As with nutritive value, the identification of secondary compounds, together with the development of techniques for measurement and rapid screening will provide an opportunity to select plants with lower levels of anti-nutritional compounds.

5. Livestock performance on salt tolerant forages

5.1. Grazing systems

While there are many publications that provide qualitative information on performance of salt tolerant pastures and some quantitative information on plant growth and nutritive value, information on the performance of grazing livestock is scarce. Table 3 provides a summary of published reports on the stocking rate, growth and grazing times of sheep on a range of saline sites in Australia. This table provides a range of results under different conditions. At low to moderate levels of salinity (<15 dS m^{-1}), particularly where water availability is high (as a result of seasonal or landscape conditions), there is good potential for livestock production in biosaline agriculture (Thompson et al., 2001; Lee et al., 2002; Fenton et al., 2004). This could be further enhanced by appropriate grazing management. For example, tall wheatgrass and puccinellia are known to go rank when overgrown and lightly grazed and also tend to be low in crude protein. Regular grazing together with incorporation of a legume into the sward can increase liveweight gain (Warren et al., 1996). Timing of feed availability is also important in gaining value from saline pastures. In seasonal environments that are characterised by periods of low quality feed, the saline areas may still have subsoil moisture and a capability to produce feed out of season. Thompson et al. (2001), for example, achieved far higher stocking rates on saline land sown to sweet clover and tall wheatgrass over summer than in adjoining non-saline areas.

The arid and semi arid areas that are more suitable for the salt accumulating shrubs require a different management system. The plants still have the ability to provide green feed, often during the dry season, at a time of feed scarcity, but livestock production is limited by the low feed intakes associated with high salt content. Prior to the research of Warren and Casson (1994) and Morecombe et al. (1996) in the 1990s there were optimistic expectations on potential for livestock performance on halophytic shrubs. Much of this optimism was based on the performance of similar shrubs grown in non-saline environments (Le Houérou, 1992). It is now clear that the limited edible biomass available from these shrubs grown in saline soils, together with the effects of high salt concentrations on voluntary feed intake and OMD, means that liveweight gain is unlikely, even at low stocking rates. However, significant opportunities still exist in the design and management of livestock feeding systems that maximise the feeding value of these plants and integrate them with other available feed resources. For example, providing a source of metabolisable energy to ruminants consuming chenopods with high levels of non-protein-nitrogen improves microbial protein production, liveweight gain and protein retention (Benjamin et al., 1992). Conversely, salt tolerant plants may improve the intake and utilisation of poor quality dry pastures or crop residues (Le Houérou, 1992; Warren and Casson, 1992; Nawaz and Hanjra, 1993; Chriyaa et al., 1997) and it may be that the greatest value of these shrubs is in the improvement in utilisation of low quality pasture (or understorey) and crop residues, particularly in mixed farming enterprises. Heavier rotational grazing of salt tolerant shrubs has also been reported to rejuvenate the plants and produce more palatable new growth with lower salt levels in the leaves (Le Houérou, 1992; Schultz, 1996).

5.2. Intensive feeding systems

Intensive livestock production, integrated with mixed feeding of formulated rations offers other opportunities for the use of salt tolerant forages. Glenn et al. (1992), Abouheif et al. (2000) and Kraidees et al. (1998) all included

Table 2
Some of the nutritional and anti-nutritional compounds found in salt tolerant plants

Compound	Pro- (+) or anti-(−) nutritional	Plant sources[a]	Comments	References
Vitamin E	+	*Atriplex* spp.	Antioxidant that protects sheep against nutritional myopathy and improves shelf life of meat	Pearce et al. (2005)
Betaine	+ or −	Many halophytes	May improve methionine use in ruminants and lower fat content of tissues. Major role in osmoregulation in plants	Storey et al. (1977), Fernández et al. (1998)
Tannins	+ or −	*Acacia* spp., many legumes	May be beneficial or detrimental to ruminants depending on concentration. Low concentrations (2–4%) improve protein availability, high concentrations (4–10%) depress intake	Barry and McNabb (1999), Degen et al. (1995)
Coumarin	−	*Melilotus* spp.	May decrease palatability or cause taint in milk or meat. Conversion to highly toxic dicoumarol during spoilage of plant material in bad weather	Arnold and Hill (1972)
Oxalates	−	Many chenopods	Binds to calcium to decrease availability. Possible kidney damage, rumen stasis and gastroenteritis. Reduced feed intake	Davis (1981), Rankins and Smith (1991), Waghorn et al. (2002)
Nitrate	−	Atriplex and Maireana spp.	Converted to nitrites in the rumen, converts haemoglobin to methaemoglobin and cause anoxia. May also cause reduced feed intake	Norman et al. (2002b), Waghorn et al. (2002)

[a] Examples only, limited information on most salt tolerant plants.

Table 3
A summary of sheep production on saline sites

Predominant pasture species[a]	Time of the year	Sheep age (years)	Grazing period (days)	Stocking rate (sheep/ha)	Liveweight change (g d^{-1})	References
Tall wheatgrass/sea barley grass	Summer	1	52	10	−21	Thompson et al. (2001)
Sweet clover/tall wheatgrass	Summer	1	28	75	80	Thompson et al. (2001)
Tall wheatgrass/tall fescue/phalaris/perennial ryegrass/annual legumes[b]	Autumn	1	48	31	77	Lee et al. (2002)
Sea barley grass	Winter/spring	1.5	227	2	66	Fenton et al. (2004)
Puccinellia	Winter/spring	1.5	227	5	83	Fenton et al. (2004)
Sea barley grass	Summer	2	56	9	−140	Warren et al. (1996)
Balansa clover/ryegrass (*Lolium multiflorum*)	Summer	2	56	10	18	Warren et al. (1996)
Tall wheatgrass	Summer	2	56	10	−140	Warren et al. (1996)
Puccinellia (*Puccinellia stricta*)	Summer	2	56	8	18	Warren et al. (1996)
Sea barley grass	Summer	0.5	56	9	−71	Warren et al. (1996)
Balansa clover/ryegrass (*Lolium multiflorum*)	Summer	0.5	56	10	48	Warren et al. (1996)
Tall wheatgrass	Summer	0.5	56	10	−71	Warren et al. (1996)
Puccinellia (*Puccinellia stricta*)	Summer	0.5	56	8	43	Warren et al. (1996)
Atriplex spp./small leaf bluebush/volunteer grasses	Autumn	3	42	15	−105	Morecombe et al. (1996)
Atriplex spp./small leaf bluebush/volunteer grasses	Autumn	3	42	15	−10	Morecombe et al. (1996)
Atriplex spp./small leaf bluebush/volunteer grasses	Autumn	3	42	15	−2	Morecombe et al. (1996)
Puccinellia/balansa clover	Summer/autumn	1	63	10.5	−44	Edwards et al. (2002)
Atriplex spp.	Autumn	1	50	13.3	15	Norman et al. (2004)
Atriplex spp./balansa clover	Summer/autumn	1	19	8	80	Norman et al. (2002c)

[a] Genus/species as shown in Table 1 unless otherwise specified.

[b] Tall fescue (*Festuca arundinacea*), phalaris (*Phalaris aquatica*), perennial ryegrass (*Lolium perenne*). Annual legumes include balansa clover, strawberry clover (*Trifolium fragiferum*) and subterranean clover (*T. subterraneum*).

salicornia (*S. bigelovii*) in mixed rations as a substitute for Rhodes grass (*Chloris gayana*). With salicornia stems at up to 30% of the total ration and 50–60% of the roughage component of the diet fed to young goats or rams, digestion and growth were not adversely affected. Similar observations were made when salicornia was substituted for Rhodes grass in camel diets (Al-Owaimer, 2000). The results indicated that dried salicornia is a suitable substitute for forage in mixed rations. Similar results have been reported for a range of other halophytes. Inclusion of *A. barclayana*, *Suaeda esteroa* or *S. bigelovii* straws at 30% of a diet based on sorghum grain, cottonseed meal and cane molasses, allowed rapid daily gain (>200 g day^{-1}) when fed to wether lambs (Swingle et al., 1996). In the same study, replacement of cottonseed meal (at approximately 10% of the diet) with salicornia meal did not depress production. More recently, *Atriplex halimus* and *A. nummularia* have been fed as part of a mixed concentrate/forage ration to pregnant and lactating ewes. While substitution of barley straw with dried saltbush (either partially or completely) had no effect on milk production or lamb weight and growth, saltbush fed ewes lost significantly more body weight through lactation (Abu-Zanat and Tabbaa, 2006). These studies indicate that the high concentrations of salt in some halophytes can be managed through ration formulation for some classes of livestock. Feeding a diet with 100% halophyte does not allow growth. Warren (Warren et al., 1990; Warren and Casson, 1993) fed Merino wethers a mixture of stem and leaf material from either *A. undulata*, *A. lentiformis*, *A. amnicola* or *A. cinerea*. Organic matter intakes were below 800 g day^{-1} and the sheep lost between 162 and 225 g day^{-1} during the experiment. Importantly in this experiment, when the sheep were fed a mixture of halophyte with a low quality oaten hay (50% of each), liveweight gain and feed intake were significantly higher than when each component was fed alone. With high salt restricting the intake of the halophyte and high fibre restricting the intake of oaten hay, a mixture allows complementarity in feed formulation and may provide a strategy for improved utilisation of a range of available feed resources (Masters et al., 2005a).

Salt tolerant plants have also been used as feed components for non-ruminants, with salicornia meal being used as a replacement for maize and soybean meal in broiler diets (Attia et al., 1997) and as a replacement for fishmeal in fish diets (Belal and Al-Dosari, 1999).

The commercial feasibility of using salt tolerant plants in formulated feeding systems would be highly dependant on yield of edible biomass from the plant and costs of harvesting and diet preparation.

6. Conclusions

At low to moderate salinity in water and soil, high levels of forage and livestock production are possible. In some cases, the availability of saline ground water or irrigation water may provide an opportunity for a significant out-of season feed supply. At higher salinity in soil and water, particularly in the semi-arid and arid climatic zones, production potential is low, although, even in these regions, salt tolerant plants may provide a valuable complementary feed source for use with crop residues or grain supplements.

The forage plants used for biosaline agriculture have had very little selection for improved feeding value. Selection and management for improved metabolisable energy and protein, together with the identification of plants that accumulate less salt and anti-nutritional compounds, will further improve prospects for profitable livestock systems. At the same time, there appears to be potential to select livestock that are more capable of tolerating high salt intakes within and across species, breed and class to improve the conversion of organic matter into livestock products.

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