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Three halophytes for saline-water agriculture: An oilseed, a forage and a grain crop

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ABSTRACT

Greenhouse and field trials and nutritional studies are reviewed for three halophytes that are candidate species for salt-water crop production. *Salicornia bigelovii* is a leafless, C3, succulent annual salt marsh plant that produces an oilseed on seawater irrigation in coastal desert environments. Yields on seawater are similar to conventional oilseeds under ideal conditions but are reduced under mechanical harvest due to uneven seed ripening and shattering of seeds. Water management requires frequent irrigation to keep the shallow-root zone at field capacity and to ensure a leaching fraction to prevent accumulation of salts. Nutritional value of oil, seed meal and biomass are adequate to replace conventional animal feed ingredients in formulated diets, despite presence of saponins in the meal and high salt content of the biomass. A breeding program showed that this species is amendable to improvement using conventional breeding approaches. *Atriplex lentiformis* is a perennial C4 xerohalophyte shrub valued as a forage species in North American rangelands. Under cultivation it produces as much biomass and protein as alfalfa on salinities ranging from mildly saline (1.8 g L^{-1} TDS) to full seawater salinity (40 g L^{-1}). Greenhouse trials show that salinity increases dry matter production and water use efficiency of *A. lentiformis* on drying soils, making it a good candidate for deficit irrigation for forage production. As with other *Atriplex* spp., its crop potential is currently limited by a tendency to become woody with successive cuts and with non-protein nitrogen and anti-nutritional compounds present in leaves. *Distichlis palmeri* is a perennial C4 saltgrass endemic to the delta of the Colorado River in the northern Gulf of California that produces a grain similar in size and nutrition composition to rice. It was a staple summer food source for the Cocopa people before upstream water diversions disrupted flood flows to the delta. It is productive on full-strength seawater and produces aerenchyma tissue allowing it to grow under flooded conditions similar to paddy rice. However, only limited experiments have been conducted with this plant, and therefore its ultimate agronomic potential is unknown. Despite initial pessimism about the production potential of halophytes, these examples show that euhalophytes can maintain high productivity of useful agricultural products up to a root-zone salinity of 70 g L^{-1} TDS, double the salinity of seawater.

1. Introduction

Current interest in saline-water agriculture began with experiments by Hugo and Elisabeth Boyko in the 1950s and 1960s (Boyko, 1966, 1967; Boyko and Boyko, 1959), leading to an international effort in the 1970s and enunciation of the "biosaline concept" in 1979 (Holaender, 1979). This concept, set forth by Lewis Mayfield, James Aller and Oskar Zaborsky of the U.S. National Science Foundation, stated that "...poor soils, high solar insolation and saline water, which prevail in arid lands, should be viewed as useful resources rather than as disadvantages...for non-traditional production of food, fuels and chemicals" (Holaender, 1979). Two themes were developed in the 1970s and continue today: introduction of salt tolerance traits into conventional crops (Epstein et al., 1980) and domestication of wild halophytes as new crops (Mudie, 1974; Flowers et al., 1977; Somers, 1979).

Work with conventional crops has produced much new knowledge on the mechanisms and genetics of salt tolerance in glycophytes (e.g., Munns and Tester, 2008), but for the most part has not produced economic new varieties that extend the salinity rage of conventional agriculture (Yeo, 1998; Flowers, 2004). Work with halophytes has demonstrated that well-adapted plants can maintain high yields of useful products up to seawater salinity

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(Glenn et al., 1998, 1999; Rozema and Flowers, 2008), but agronomic problems have prevented them from being widely adopted for crop production so far. This paper reviews progress that has been made in developing three halophytes for crop production: *Salicornia bigelovii*; *Atriplex lentiformis* and *Distichlis palmeri*. These represent an oilseed, forage and grain crop, respectively. Each emerged as a potential crop from screening trials with halophytes beginning in the 1970s (Glenn and O'Leary, 1984, 1985; Glenn, 1987). They illustrate the opportunities and remaining problems in bringing the biosaline concept into widespread application.

An advantage of working with halophytes is that it is possible to proceed directly to agronomic trials, since they already have the requisite salt tolerance mechanisms (Flowers and Colmer, 2008). The problems in irrigating with highly saline water are considerable, even with well-adapted germplasm. We will describe greenhouse and field trials as well as nutritional studies that have been conducted with each candidate species. *S. bigelovii* is a shallow-rooted, C3, leafless, succulent, annual species found in North American salt marshes (Lonard et al., 2011) (Fig. 1A). *A. lentiformis* is a deep-rooted, perennial North American C4 desert riparian shrub (Fig. 1B) (Meyer, 2005). *D. palmeri* is a C4 perennial saltgrass endemic to hypersaline tidal estuaries in the Northern Gulf of California, Mexico (Fig. 1C) (Pearlstein et al., 2012). Distinctly different management strategies are needed for each plant, and the range of salinities and soil types over which they can be grown differ as well. As wild plants, each has its own set of undesirable agronomic traits that must be overcome through genetic improvement programs before they can be competitive with conventional crops.

2. *S. bigelovii*: an annual oilseed halophyte for seawater irrigation

S. bigelovii was first grown in seawater (38–42 g L^{-1} TDS) plots in a coastal desert environment at Puerto Penasco, Mexico, from 1982 to 1988 (Glenn et al., 1991). (Note that salinities in this paper are expressed in units of weight of total dissolved salts to volume of water, with 1 g L^{-1} TDS approximately equal to 1.6 dS m^{-1} by electrical conductivity.) Seed yields ranged from 139 to 246 g m^{-2} yr^{-1} averaging 208 g m^{-2} yr^{-1}, similar to soybeans and other oilseed crops. Biomass yields were also high, ranging from 1.39 to 2.46 kg m^{-2}. Seeds contained 26–33% oil and 30–33% protein, and were low in fiber and mineral contents (5–7%); the polyunsaturated oil contained 74% linoleic acid, similar to safflower oil (Table 1) (Anwar et al., 2002, 2003; Glenn et al., 1991). Seeds germinated directly on seawater, a distinct advantage for an annual crop. The crop cycle required about 220 days, with seeds sown in March and the crop harvested in October at this location.

Table 1
Properties of *Salicornia bigelovii* seed and oil. Values are means of five or more determinations (range of values in parentheses). Amounts are the percentage of total fats for fatty acids and the percentage of seeds weights for other constituents.

Constituent	Amount
Oil	28.2 (26–33)
Protein	31.2 (30–33)
Fiber	5.3 (5–7)
Ash	5.5 (5–7)
Fatty acids	
Palmitic	8.1 (7.7–8.7)
Stearic	2.2 (1.6–2.4)
Oleic	12.5 (12.0–13.3)
Linoleic	74.0 (73.0–75.2)
Linolenic	2.6 (3.4–2.7)

Source: From Glenn et al. (1991).

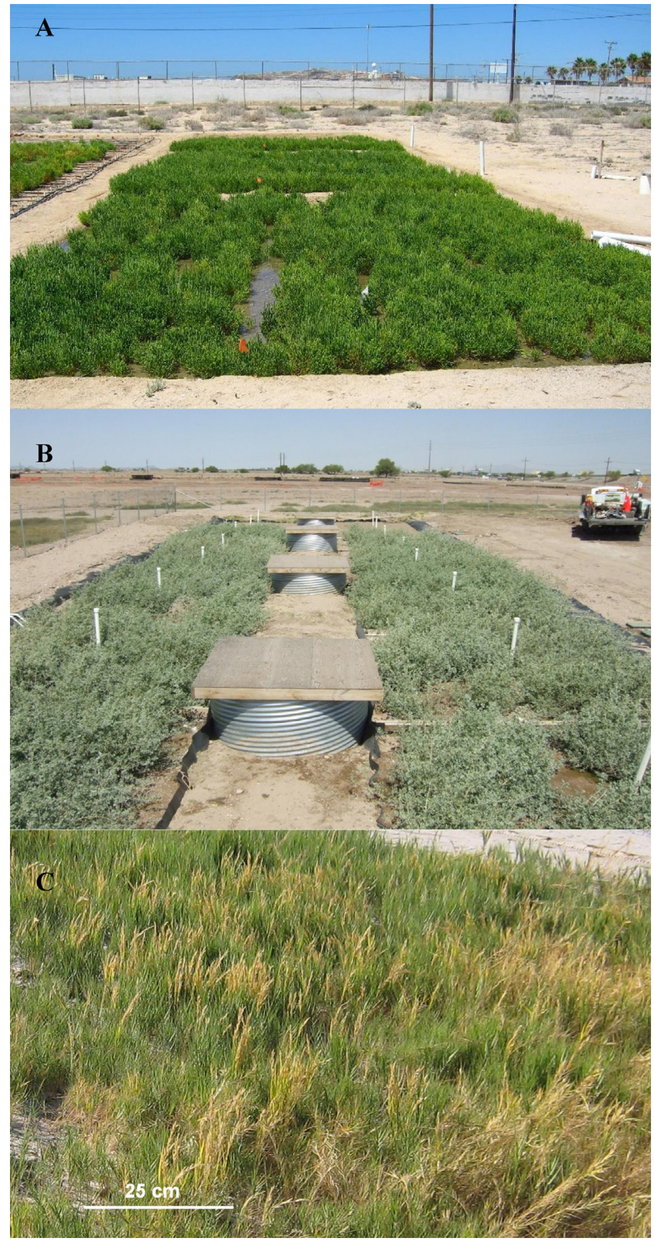

Fig. 1. Halophytes evaluated as agronomic crops in this review: (A) *Salicornia bigelovii* flood-irrigated with seawater at Puerto Penasco, Mexico (Glenn et al., 1991); (B) first-year growth of *Atriplex lentiformis* irrigated with reverse-osmosis brine in drainage lysimeter plots in Marana, Arizona (Jordan et al., 2009); (C) *Distichlis palmeri* plants with seed heads in the delta of the Colorado River, Mexico (Pearlstein et al., 2012).

Numerous obstacles have been encountered in developing a practical cropping system for this plant. Perhaps the most serious is the water management problem. Roots are confined to the top 7.5 cm of the soil profile (Weeks, 1986), and the plant requires the soil to be moist at all times to prevent wilting (Troyo-Dieguez et al., 1994). The sensitivity of *S. bigelovii* to drying soils is illustrated by experiments in which *S. bigelovii* (Martinez-Garcia, 2010) and *A. lentiformis* (Glenn et al., 2012) were grown in 2 L capacity, sealed pots given an initial charge of water, then allowed to grow to the end point at which they could no longer extract water from the soil (Fig. 2). Both plants grew root systems that proliferated throughout the soil in each pot. However, *A. lentiformis* was able to extract moisture from the soil down to 0.02 g g^{-1} whereas *S. bigelovii* reached the wilt point when soil moisture decreased to 0.18 g g^{-1}