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Agricultural production of halophytes irrigated with seawater

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Summary Growing agricultural crops with direct seawater irrigation has progressed within the past few years from the conceptual to the experimental phase. This has been accomplished by selecting halophytes with inherently high salinity tolerance for use as crop plants rather than by increasing the ability of traditional crop plants to tolerate seawater. Some of the halophytes being investigated for use as crops in seawater irrigation scenarios have high nutritional value as forage or fodder crops. Most of them also have high digestibility. The limiting factor in such use is their high salt content, but this limitation can be moderated. However, since seeds of halophytes do not accumulate salt any more than do those of glycophytes, the greatest promise for seawater-irrigated halophytes probably will be as seed crops. The seeds of many halophytes have high protein and oil contents and compare favorably with traditional oilseed crops. Sustained high yields of seed and biomass already have been obtained from some halophytes irrigated with seawater, and within the next few years seawater agriculture should proceed from the experimental to the operational phase.

Introduction

The notion of using seawater to grow crops probably occurred to at least one person sometime in the distant past. It would be surprising if it had not, given the proximity of such a large source of water to vast expanses of unused desert land. The first person to formally conceptualize and actively promote such a notion was Boyko[1]; however, his zeal received mixed reactions. Even though several people subscribed to his views, those views were not well received by the scientific community in general. Much of the reason lies in the faulty reasoning used by Boyko to explain why seawater irrigation of crops grown on dune sand would succeed. He coined such 'principles' as partial root contact, subterranean dew, *etc.* and assigned unreasonably beneficial roles to those 'principles.' In spite of these problems of interpretation, the use of dune sand was an important part of the reason for the limited successes reported by Boyko and his supporters[1]. The good drainage associated with sand allows for a high volume and/or high frequency of irrigation with seawater, thus preventing salt accumulation.

Nevertheless, the fact remains that no conventional agricultural crops are yet grown with undiluted seawater, even on dune sand. Successful seawater irrigation depends on the use of halophytes. In fact, in more recent times, several people have promoted the use of halophytes to solve the seawater irrigation problem[3,17,26,27], even though the roles prescribed for halophytes differed considerably among the authors. For example, even though Mudie[17] was optimistic about the significant potential contributions of halophytes to seawater-based agriculture, she thought the benefits would accrue via transfer of germplasm from halophytes to glycophytic crops. The conclusion was that 'prospects appear to be rather low for large scale use of halophytes as novel foods for human consumption'[17]. Even Chapman[3], who cited several instances of human consumption of halophytes and was fairly optimistic, concluded that 'it must be admitted that the outlook for new crops is not promising.' Others, though, such as Somers[26], have actually promoted cultivation of wild halophytes and directly irrigating them with seawater. Interest in this area has grown considerably in recent years, as attested to by the growing number of publications on the subject.

Thus, the movement from the conceptual phase to the experimental phase has been rapid. The next step, the transition from the experimental to the operational phase, *i.e.*, actual cultivation of halophytic crops, depends upon satisfactory demonstration of high yields under reasonably representative agricultural conditions and of the usefulness of the products. For forage or fodder crops, that means high yields must be obtained with halophytic crops grown in the field strictly with seawater irrigation, and utilization of the crop by animals must be demonstrated.

Within the past few years we have made substantial progress toward accomplishing these objectives. Those results will be reviewed here and used as the basis for critically assessing the future prospects of seawater-based agriculture.

Biomass yields

Several potential forage or fodder crops have been grown on the Sonoran Desert seacoast, where they were irrigated solely with hypersaline seawater[8] that had first been used in a shrimp aquaculture facility[25]. As a result of passing through the aquaculture facility, the salinity was increased to 40 parts per thousand (ppt) total dissolved solids (TDS), and the water contained approximately 20 ppm nitrate-nitrogen, 0.3 ppm ammonia-nitrogen, and 0.5 ppm phosphate-phosphorus. This constant supply of nutrient-enriched hypersaline water allowed us to grow several crops on beach sand with high-volume, high-frequency irrigation. Much of the early work was associated with evaluation of candidate species for their survival, nutritional value, and relative productivities. Preliminary results from that work have been reported[5,6,10,20]. We were also able to obtain annual productivity values for several potential halophytic crops grown under those field conditions[8].

Productivity varied widely among species (Table 1). The interesting observation that can be made is that the highest productivities were obtained from native species. The highest productivity from an exotic

Table 1. Annual productivity of halophytes irrigated with 40 ppt seawater at Puerto Peñasco, Sonora, Mexico. (N = native, E = exotic)

Plant species		Productivity ($gDW\,m^{-2}\,y^{-1}$)
Atriplex lentiformis	(N)	1794
Batis maritima	(N)	1738
Atriplex canescens subsp. *linearis*	(N)	1723
Salicornia europaea	(N)	1539
Atriplex barclayana	(N)	863
Atriplex nummularia	(E)	801
Atriplex glauca	(E)	514
Cressa truxillensis	(N)	394
Atriplex polycarpa	(N)	312
Atriplex canescens subsp. *canescens*	(N)	303
Atriplex repanda	(E)	61
Atriplex patula	(E)	8

species was that of *Atriplex nummularia*, but it was less than half of the productivity of the best-producing species. There were also some native species that had low productivities, but it is important to note that no exotic species had high productivity. It will be interesting to see if this result will be found in other locations, because it could be a serious constraint on widespread development of seawater-based halophyte agriculture. For example, *Atriplex nummularia* long has been promoted as one of the most promising Atriplex species for extensive use as a forage crop on marginal lands[9,13], primarily because of its relatively high protein content. It even has been grown successfully far from its native environment[12], but usually not under severe stress conditions, such as with highly saline water, and no annual productivity information was obtained. The only other attempt to grow *A. nummularia* with seawater of which we are aware is that of Pasternak[22] in Israel, which is at approximately the same latitude as our site. The yield was 429.5 $g\,m^{-2}\,y^{-1}$, even lower than ours.

The most productive halophytes yielded the equivalent of 8–17 tons of dry matter per hectare (Table 1). This compares favorably with a conventional forage crop such as alfalfa grown on fresh water, which yields 5 to 20 tons of dry matter per hectare annually[30]. Thus, at first glance it seems like very high productivity can be achieved from halophytes irrigated solely with seawater. However, it is not fair to compare total dry weights since one of the characteristics of most halophytes is a high ash content[7]. Thus, ash-free dry weight (AFDW) really should be the basis for comparison and would more accurately reflect the productivity of the crops, insofar as total organic matter production is concerned. Since typical ash contents of plants such as Atriplex grown on seawater are on the order of 20 to 30%, that would lower the actual productivities of the top performers to approximately 12 tons of AFDW per hectare annually, which still is a respectable value, albeit not outstanding. However, if the caloric or nutritional value of the dry matter is higher than that of alfalfa, then the economic productivity of the halophytes might actually be greater (see below).

Since forage or fodder crops such as alfalfa usually are harvested or cropped several times per year, it was of interest to investigate the ability of these potential halophyte crops to tolerate multiple cuttings per year and to determine the effect on annual yield. Four species of Atriplex were planted in April, irrigated solely with seawater, and clipped to a height of 30 cm three times during the first 16 months after planting[8]. There was a considerable loss of plants with *A. lentiformis* and *A. canescens* sbsp. *linearis* when they were cut back, and the annual productivity was reduced substantially as a result (Table 2).

Table 2. Annual productivity and mortality of *Atriplex* species planted in April 1980 and clipped to a height of 30 cm the succeeding October, January and August

Plant species	Productivity ($gDW\,m^{-2}\,y^{-1}$)	Percent mortality
Atriplex barclayana	2336	3
Atriplex nummularia	2080	0
Atriplex lentiformis	1456	20
Atriplex canescens sbsp. *linearis*	1104	40

On the other hand, there was little or no loss in *A. barclayana* and *A. nummularia*, and their annual productivities were increased considerably, by 170% and 160%, respectively. That puts them at the upper end of the annual yield range for alfalfa grown on fresh water, even when corrected for ash content. In other studies of response to defoliation[14] *A. nummularia* was found to be superior to other Atriplex species. *A. nummularia* was capable of producing new leaves along the main stems and branches after complete defoliation and even from the base of the plant after being cut almost to ground level.

Nutritional value of forage

In contrast to the paucity of information on the annual productivity of cultivated halophytes, there is an abundance of reports giving values for protein content of potential forages such as Atriplex. Much of that information has been reviewed by Goodin[9], and the crude protein levels typically range from about 11 to 24% of the dry weight. We also have determined the crude protein content of numerous halophytes, and, depending on the age of the plant tissue at harvest and the salinity at which the plant was grown, have found that the crude protein content of most halophytes examined so far ranges from 10 to 20% of the dry weight, with a few species having higher values. For example, *Atriplex barclayana* and *A. lentiformis* grown on seawater had protein contents of 11.6% and 16.7%, respectively[8]. Salicornia, in contrast, had only 5.7% protein when grown under the same conditions (Table 3). For comparison, the protein content of alfalfa ranges from 12% to 22%, with an average of 16.9%[30]. Fat and fiber contents of the Atriplexes also compare favorably with those of alfalfa. As mentioned above, the ash content of the foliage typically is high, and this can be a serious drawback to the potential forage value of these plants. For example, *A. lentiformis* and *A. barclayana* grown on seawater had ash contents

Table 3. Nutritional analysis of halophytes irrigated with 40 ppt seawater at Puerto Peñasco, Sonora, Mexico, as percent of dry weight

	Plant species		
Constituent	*Atriplex lentiformis*	*Atriplex barclayana*	*Salicornia europaea*
Protein	16.7	11.6	5.7
Fat	1.3	1.3	0.4
Fiber	14.1	14.2	17.0
Ash	26.8	33.1	41.3
Oxalate	3.6	5.9	1.5

of 27% and 33%, respectively. As previously stated, this reduces the productivity values if yield is expressed on the basis of AFDW, but if the total protein yield is calculated, the picture is not so bad. The most productive halophytes (in Table 1) yielded the equivalent of 0.6 to 2.6 tons of protein per hectare when grown on seawater, compared to typical yields of alfalfa grown on fresh water of 0.5 to 3.0 tons of protein per hectare[30].

We recently completed a study in which *A. barclayana* and *A. nummularia* were grown in lysimeters at five different salinities and harvested at three different times. The protein levels in the leaves were determined at three different times during the growing season and averaged 18% for *A. barclayana* and 24% for *A. nummularia* at the highest salinity (30 ppt). Thus, it might make more sense to harvest only leaves rather than the entire tops of the plants. The lower annual productivity of *A. nummularia* might be more than compensated for by the higher protein content in the leaves and its great ability to regenerate new leaves[14]. The significance of this is that amenability to harvesting has to be an integral part of the evaluation of any potential halophytic forage, and as described above, there is considerable variability within a genus such as Atriplex in the ability to tolerate clipping.

Forage digestibility

To survey as many species of halophytes as possible in the shortest possible time as a prelude to conducting large-scale animal feeding trials, we conducted *in vitro* organic matter digestibility studies of 45 different halophytes[16]. Foliage samples were collected from plants growing in our halophyte germplasm collection, incubated for 48 h in a rumen fluid-buffer inoculum followed by 48-h digestion in acid pepsin. A standard alfalfa hay sample was included also. At the end of this time, the amount of *in vitro* organic matter disappearance (IVOMD) was measured. The IVOMD for the 45 halophytes ranged from 50.1 to 87.2%. The standard alfalfa hay sample had an IVOMD of 64.3%. Thirty-five of the 45 halophytes had values in excess of the standard alfalfa sample. When samples from plants grown on fresh water were compared with those grown on water with a salt content up to 20 ppt, no detrimental effect of salinity was apparent. In fact, in some cases the IVOMD was actually higher at the higher salinities. The data from the *Atriplex* species discussed here are presented in Table 4. Both the digestibility and the calculated digestible organic matter content (DOMC) compare reasonably well with alfalfa.

The high salt content of the foliage is a serious constraint to consumption by animals. Thus, halophytic forages probably will be limited to use as components in feed mixes rather than as sole sources of food. Limited feeding trials with goats were conducted using *Atriplex barclayana* and *Atriplex lentiformis* that had been irrigated with seawater[32]. When the halophytes were included as 25% of the total diet, their acceptability and digestion were high. *A. lentiformis* seemed superior to *A. barclayana* in acceptability by the animals. Some of the plant forage was washed to leach out salts. Approximately 10 kg of dried Atriplex was placed in a revolving drum mixer and rinsed with fresh running water for 2 to 3 h and then air-dried. That treatment

Table 4. Percent *in vitro* organic matter disappearance (IVOMD) and calculated digestible organic matter content (DOMC) of halophytes grown with 0, 10 or 20 ppt total dissolved salts in the irrigation water

Plant species	Salinity level (ppt)	IVOMD	DOMC
Atriplex barclayana	0	59.8	51.0
	10	61.7	46.5
	20	67.6	47.0
Atriplex lentiformis	0	58.8	53.3
	10	55.7	47.6
	20	63.1	50.0
Atriplex nummularia	0	77.0	59.7
Standard alfalfa hay	0	64.3	58.4

reduced the ash content to approximately two-thirds of the original amount but did not improve the acceptability or digestibility.

Nutritional content of the seeds

Salt content of the tissue is not a problem with seeds. Even though the vegetative tissues of plants may have extremely high salt contents, the seeds of those plants normally have low salt levels, even when irrigated with highly saline water (Table 5). Some halophytes, such as Spartina and Distichlis, might become crop plants analogous to rice, as suggested by Somers[26], but our observations lead us to give serious consideration to the use of halophytes as potential oilseed crops. Our own seed analyses, as well as those of others, indicate that there is a wide range of protein and oil contents among halophyte seeds; however, several species compare very favorably with the major oilseed crops of the world (Table 5). Thus, we propose that the greatest promise for halophytes may be as oilseed crops. The plants could be grown with seawater with no serious salt accumulation in the portion of the plant of economic interest. The seeds could be harvested and processed with extant equipment, yielding a vegetable oil for food or industrial use and a protein-rich seed meal that could be incorporated into animal feeds, much like soybeans are presently utilized. We have just begun to obtain seed yield data, and so far the results are promising. Details of this work are still being prepared for publication, but we can report that the annual seed yield of Salicornia irrigated with seawater is consistently greater than $250\,g\,m^{-2}$, which is equivalent to 2.5 tons per hectare. Thus, not only does the seed compare well with soybeans qualitatively (Table 5), but it has yields that are comparable[31].

Table 5. Protein, oil, and ash contents of seeds, as percents of dry weight

Plant	Protein	Oil	Ash
Present oilseed crops[a]			
Soybean	40.0	18.8	4.8
Safflower	14.3	30.4	2.5
Sesame	18.6	49.1	5.3
Sunflower	17.5	36.0	3.6
Crambe	25.0	47.0	5.1
Halophytes[b]			
Mesembryanthemum crystallinum	31.2	7.8	5.0
Atriplex canescens	5.4	1.0	6.5
Atriplex lentiformis	12.5	2.1	13.6
Chenopodium quinoa	12.1	7.5	3.1
Salsola pestifer	16.9	1.3	17.2
Halophytes[c]			
Atriplex triangularis	16.4	9.4	3.5
Cakile edentula	28.6	51.2	5.2
Cakile maritima	21.5	47.1	5.0
Crithmum maritimum	21.5	41.4	8.0
Kosteletzkya virginica	23.8	18.1	5.0
Salicornia europaea	30.2	28.0	7.5

[a] from Weiss[31].
[b] from Earl and Jones[4].
[c] original data by authors this paper.

Discussion

It has been demonstrated that halophytes can be cultivated and irrigated solely with seawater and have productivities within the range of conventional crops. Several questions require answers, however, before the actual seawater farming of halophytes becomes a reality. One of these questions is the geographic range within which high productivities can be achieved with a given species. If, as the meager evidence so far obtained suggests, productivity is less when the plant is grown out of its native range, then ecotypic selection should be intensively investigated. This should not be a major obstacle to the domestication of a given halophyte, since many of our contemporary crops are grown in areas well beyond the native range of their wild progenitors, but it will limit the areas within which successful cultivation of that plant can be conducted at first. We have established test plantings within and outside of the native range of Salicornia with several ecotypes collected from widely separated areas to make comparative productivity measurements. The same should be done for other halophytes, such as Atriplex.

The protein content of the leading halophyte candidates should be studied in greater detail. The standard procedure for calculating crude protein content (6.25 x total N) probably is not valid for these plants. This conversion factor was based on the assumptions that all of the Kjeldahl-N is protein-N and that the proteins contain 16% N. Even though this factor has been found to be invalid for many plant tissues[2,21], it still is used in virtually all proximate analyses[11], probably since the percent error is not unusually high in most cases, and it is, in fact, usually emphasized that it is 'crude' protein that is being reported. However, for halophytes the error may be considerable, since the nitrate levels can be very high. Even in sugar beet (a crop with some halophytic ancestry), nitrate-N has been reported to represent 88% and 38% of the total N in petioles and blades, respectively[15]. The levels of other non-protein nitrogen compounds, such as quaternary ammonium compounds and proline, also are often very high in halophytes[28,29] and would bias the calculated value as well. This will not be an easy question to resolve, since all methods for determining the protein content of plant tissues have their shortcomings; yet we must attempt to do a better job of reporting the protein content of halophyte forage than we have been doing.

The question of what to do about the inevitable high salt content of seawater-irrigated halophyte forage is one that also must be addressed concurrent with the productivity question in any evaluation. We have emphasized the utilization of this forage as one component of a multicomponent feed mix, but there are other alternatives that have not yet been subjected to serious investigation. One alternative is to use the foliage for extraction of leaf protein (LP). The technology is improving, and interest is increasing rapidly enough now that LP will soon become an important part of the world food budget. It has been emphasized before[23,24] that LP should be extracted from those plant sources that are not now consumed, even those that might contain undesirable or toxic substances (since those substances should be lost in the extraction process), in order to make a significant impact on increasing the world protein supply. Halophytes meet these criteria pretty well. The high salt content and even high levels of oxalic acid or other undesirable constituents would be no constraint to their utilization as source material for extraction of LP. The halophytes could even serve as sources of more purified leaf protein concentrate (LPC), which has great promise for use as human food because it is odorless, colorless, and tasteless and also has high, uniform nutritional quality (Fraction I protein). We have been able to extract relatively pure Fraction I protein from Salicornia tissue (Bourque, unpublished results) and will be scaling up that work as well as extending it to other halophyte species.

In conclusion, it looks like halophytes irrigated solely with seawater have great potential as crop plants, in spite of some problems such as high salt content of tissues. In particular, it looks like high yields of good quality protein can be produced. There is a lot of work yet to be done before the story is complete, particularly, determination of the acceptability and utilization of the material by animals, but there is good reason to be highly optimistic, even for those of us who were originally very pessimistic[18, 19], and the transition from the experimental phase to the operational phase should occur within the present decade.

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