Reports

Seawater-Based Crop Production: A Feasibility Study

Abstract. *Selections of barley,* Hordeum vulgare, *obtained from a composite cross by means of salinized solution culture, a salt-tolerant research line from Arizona, and three cultivars were grown in dune sand and irrigated with water from the Pacific Ocean. All lines grew and produced grain of good feed quality. There is evidence of considerable phenotypic plasticity and of marked genotypic diversity with respect to conditions of seawater culture. Rough estimates of yield approached half the national average for barley.*

A crop scientist familiar with the potentials and the hazards of irrigation agriculture, when contemplating the wide expanse of the ocean from a dune or a cliff, might well be tempted to paraphrase the lament in Coleridge's *The Rime of the Ancient Mariner* to read: "Water, water everywhere, Nor any drop for crops." Salinity is the feature that makes seawater unfit to drink and unfit for conventional irrigation of crops. Degrees of salinity very much lower than that of seawater are considered unacceptable in soil solutions and irrigation waters (*1*). Yet there is no fundamental biological incompatibility between plant life and highly saline conditions; witness the marine algae and the halophytic terrestrial plants—those indigenous to the seashore, to estuaries and deltas, and to salt marshes and saline desert soils. And although nearly all crop plants are sensitive to salinity, much variability nevertheless exists in this regard (*2–4*). There also are wild salt-tolerant relatives of crop plants (*4, 5*).

The leads that this evidence provides for selection and breeding for salt tolerance have not been pursued on any scale even remotely commensurate with their promise, although calls for such an approach have been voiced with increasing frequency (*2–6*). In particular, in experiments on irrigation with seawater reported in the 1960's, no advantage has been taken of the potential represented by the intraspecific genetic diversity in respect to salt tolerance existing in crop species (*7*), nor has the possibility been explored of using exotic germ plasm to transfer salt tolerance to salt-sensitive economic species (*8*).

We now report a feasibility study designed to answer the question of whether, by tapping a large gene pool within one species, such as barley, selections might be obtained that are capable of completing their entire life cycle, from seed to seed, under a regime of seawater, which could supply both irrigation and nutrients. A few cultivars of barley were included to provide both controls and information on the degree to which barley possesses phenotypic plasticity for the adjustment of its physiological processes to conditions of seawater culture. The entries of barley (*Hordeum vulgare* L.) used in our investigation were three cultivars ('Arivat', 'California Mariout', and 'U.C. Signal'), a research line from Arizona (S-68-1-11-22), and seven selections obtained from Composite Cross XXI (*9*). Composite Cross XXI, which was synthesized by intercrossing 6200 barley genotypes, is highly variable genetically.

The system used to develop the seven selections from Composite Cross XXI had two basic steps. The first step was taken in two parallel but not identical ways. Both these experiments were conducted with salinized solution cultures in greenhouses on the University of California, Davis, campus. In the first test, 4320 seeds of Composite Cross XXI, F_9, were started on two 700-l tanks, with the use of a standard nutrient solution (*2*, p. 39), except that the concentrations of boron and manganese were reduced to 1/5 of the levels given there. When the plants were 8 days old, salinization with NaCl was started. Eight equal increments of NaCl were added to the tanks at 3-day intervals, and the NaCl concentration was increased to 400 m*M*. The salinity of this solution was 75 percent that of seawater, on the basis of its specific electrical conductance (*10*). At the end of the test period, 5.9 percent of the plants had completed their life cycle and set viable seed. A parallel test was run with a synthetic sea-salt mix, Rila Marine Mix (*11*), instead of NaCl. Nine increments of 4.0 g/liter each were added at 2-day intervals starting when the plants were 20 days old. The final salt concentration was about 90 percent that of seawater. Of the 2880 seeds of Composite Cross XXI, 9.2 percent completed their life cycle. Seed of the survivors of these two screening tests was increased in the greenhouse in pots filled with Yolo loam for the second step of the selection procedure.

The increased seed of the survivors of the above tests was subjected to Rila Marine Mix salt solution (85 percent seawater) immediately at planting; we used a system of seed support in sealed chambers similar to that developed by Myhill and Konzak (*12*). This test was conducted in the laboratory. Three weeks from the day of planting, a few individuals had survived and emerged—24 percent of the entries from the NaCl test and only 1 percent of those from the Rila Marine Mix test.

The plants that survived to emergence under these conditions had their solutions reduced from the original salt concentration to that of a normal nutrient solution by seven equal increments at intervals of about 4 days. After growing in the nutrient solution for 10 days, the surviviors of this sequential selection procedure were transplanted to soil-filled pots in the greenhouse for seed production. There were 22 surviviors, out of the 7200 initial entries in the two-step sequential selection system, or 0.31 percent, evidence of the severity of the selection pressure imposed.

To determine the effectiveness of the selection procedure and the feasibility of irrigating barley with seawater on sand, a field trial under maritime conditions was essential. Seed of seven of the selections and of the four additional genotypes ('Arivat', 'California Mariout', 'U.C. 'Signal', and S-68-1-11-22) was increased for this experiment. The site for the field test was near Bodega Marine Laboratory on the Pacific Coast, 80 km north of San Francisco. [For accounts of the physical, chemical, and biological features of Bodega Head, where the laboratory is located, see Barbour *et al*. and Standing *et al*. (*13*).] The single most important characteristic of the site is the nature of the soil—a sand with a deep profile and excellent permeability. As a result of these features, no buildup of salt was visible even after 6 months and 23 irrigations with undiluted seawater. The site was fenced to keep out deer, and a bird net was installed to keep birds from eating the seedlings.

The plots were irrigated by means of a conventional furrow system. The water was delivered to the furrows of each of eight plots through polyethylene-lined ditches. Before planting, each row received a band application of a coated, slow-release fertilizer (*14*) at the rate of 266 kg/ha, and of single superphosphate at the rate of 369 kg/ha, to supply nitrogen and phosphorus. Each plot was planted with a border row of barley on either side, and the 11 test entries were randomized on the rows in between. The irrigation treatments were undiluted seawater, 0.67 seawater, 0.33 seawater, and fresh water as the control. The specific electrical conductance of the seawater used in the field test varied only slightly during the experiment, averaging 45.8 mmho/cm, compared with the nominal value of 46.3 mmho/cm (*10*). Dilution by rainwater during the growing season was minimal. The season was extraordinarily dry, with a total rainfall during the time of the experiment of only 186 mm—the lowest for that period in the 8 years of records at the laboratory. Irrigations were given at weekly intervals, except that an additional irrigation was given to the plots treated with seawater after each rain, to minimize dilution by what little rain there was. Irrigation was stopped a month before the harvest.

The seed on all plots germinated and the plants grew to maturity, flowered, and set seed. On the day of the harvest, 17 June 1976, the plants on all plots had heads of grain that looked normal, except for varying diminution in size on the seawater-treated plants compared with those of the controls. Two rows of barley in the undiluted seawater treatment are shown in Fig. 1.

Grain from the fresh-water control and from the undiluted seawater treatments was subjected to a proximate analysis (measure of feed quality) and an analysis for Na (Table 1). Seawater culture produced grain of satisfactory feed quality. Eventually, feeding trials will have to be conducted when adequate amounts of grain are available. Seed from the undiluted seawater treatment was viable, as determined by germination tests.

The scale of this biological feasibility study was too small to provide reliable yield estimates and cost estimates, as well as other economic information. But even in the present, essentially qualitative experiment, yields were far from negligible. Yields of seed treated with undiluted seawater (see legend to Fig. 1) range from 92 to 1243 kg/ha, evidence of high genotypic variation in respect to salt tolerance. The three cultivars included in the experiment had a mean yield corresponding to 833 kg/ha; the mean for the three top-yielding experimental entries was 1082 kg/ha. To put these numbers in perspective, the mean world yield of barley for 1975 was estimated at 1710 kg/ha and for the United States at 2370 kg/ha (*15*).

Several conclusions emerge, all favorable. (i) Barley has marked phenotypic plasticity enabling it to make appreciable physiological adjustments to seawater culture. (ii) There exists in barley much genotypic diversity making it possible to select and breed barley for seawater culture. (iii) Barley grown under these conditions seems qualitatively satisfactory for feed. (iv) Even this first selection experiment suggests that yields of barley grown under seawater culture need by no means be negligible. This latter find-

Table 1. Proximate and sodium analyses of grain of barley grown at Bodega and irrigated with seawater or with fresh water. Values are means for the three cultivars (cultivars) and means for the three top-yielding selections (selections). All values percentages.

Item	Protein	Ash	Fat	Fiber	NFE*	Na
Seawater cultivars	12.8	3.4	2.12	8.0	73.7	0.30
Seawater selections	12.9	3.4	2.46	7.9	73.3	0.30
Fresh-water cultivars	10.9	2.8	2.05	7.1	77.2	0.15
Fresh-water selections	11.5	3.1	2.51	7.9	75.1	0.21

*Nitrogen-free extract.

Fig. 1. Two rows of barley, a week before harvest, in a plot irrigated with undiluted seawater. The lines in these two rows are selections from Composite Cross XXI. Note the difference in stature of the two lines. These same lines were not different in stature in the fresh-water control plots. The yield of line 7 under undiluted seawater culture was 31.3 g per meter of row and that of line 8, 56.4 g/m. These values were near the mean for the undiluted seawater plots, 45.0 g/m. The range was 5.6 to 75.8 g/m. The measuring stick at the left is measured in 10-cm intervals.

ing is especially encouraging in view of the fact that the composite cross used represents a gene pool whose diversity has been attenuated by growth for nine generations at Davis. Selections for salt tolerance made directly from the thousands of strains of barley in the world collection, followed by a breeding program, can confidently be expected to increase yields under saline conditions. Evidence already at hand (*8*) indicates that this genetic approach to saline crop production is applicable to crops other than barley. The scheme could also lend itself to the production of forage and fiber and to the generation of energy from biomass—an attractive means for the utilization of solar energy (*16*).

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Pleistocene Volcanism and Glacial Initiation

Abstract. *During the past 2 million years, major Northern Hemisphere eruptions occurred within 0.01 million years before 22 of 24 maximum-temperature dates which preceded the ten European glacial stages and 42 of 60 maximum-temperature dates which preceded the 22 cooling episodes. Massive eruptions were even more closely associated with the glacial stages and the cooling episodes. Within the errors of Pleistocene dating, major eruptions apparently occurred at the crucial moments to have triggered each of the ice ages.*

The recent increase in observational (*1*) and theoretical (*2*) evidence for the volcanic climatic hypothesis has been accompanied by suggestions that volcanic eruptions may have influenced the distribution of late Pleistocene (*3*) and Holocene (*4*) glaciation and that massive eruptions may have triggered the formation of the large Pleistocene ice sheets (*5*). In this report I will attempt to catalog the periods of rapid temperature decline and glacial advance during the Pleistocene to see if they were preceded by evidence of massive explosive eruptions.

Any correlation of episodes of rapid Pleistocene temperature decline with volcanism must be based on an understanding of the mechanism by which volcanic eruptions may trigger glaciation. Two mechanisms have so far been suggested. An early summary by Wexler (*6*) concluded that periods of increased volcanism may have reduced global temperatures and developed an increased storminess and precipitation as a result of a greater reduction in land than in ocean temperature. Glaciation would have resulted from these conditions and perhaps also from increased haziness and from a positive feedback due to a greater global albedo resulting from increased areas of snow and ice. In a more recent proposal (*5*), I suggested that massive volcanic eruptions may have been a trigger for the "instantaneous glacierization" mechanism described by Flohn (*7*) and by Ives *et al.* (*8*). According to this mechanism, if there were a survival of snow for a single summer over the subarctic plateaus, then various autocatalytic processes might have occurred which would have led to permanent snowfields and subsequent continental ice sheet formation. One or a series of several closely spaced massive eruptions may have been one means by which subarctic snow survival over a single summer was stimulated (*5*). Furthermore, the climatic effects of such massive eruptions would last, in diminishing degree, over at least several years and would thus promote snow survival in subsequent summers and enhance the feedback processes which accompany a greatly increased snow cover. If the climatic effects of one or several contiguous massive eruptions were responsible for an extensive subarctic summer snow survival leading to subsequent glaciation, then for intervals during the Pleistocene in which there were steep temperature declines followed by ice-sheet formation there should be evidence of volcanism around the beginning of each decline. It is not necessary under this hypothesis that every major eruption should be followed by glaciation, but only that every glacial age should have been preceded by one or more massive volcanic eruptions. There would be shorter to more extended periods during the Pleistocene when conditions of either climate or weather would be such that volcanic triggering could not occur. Eruptions occurring during times of ice advance or in the early or even later stages of ice retreat could not be expected to influence glaciation or have any appreciable climatic significance (*5*). Some massive eruptions would also have occurred at times when weather conditions were not favorable for a volcanic trigger mechanism—for example, during