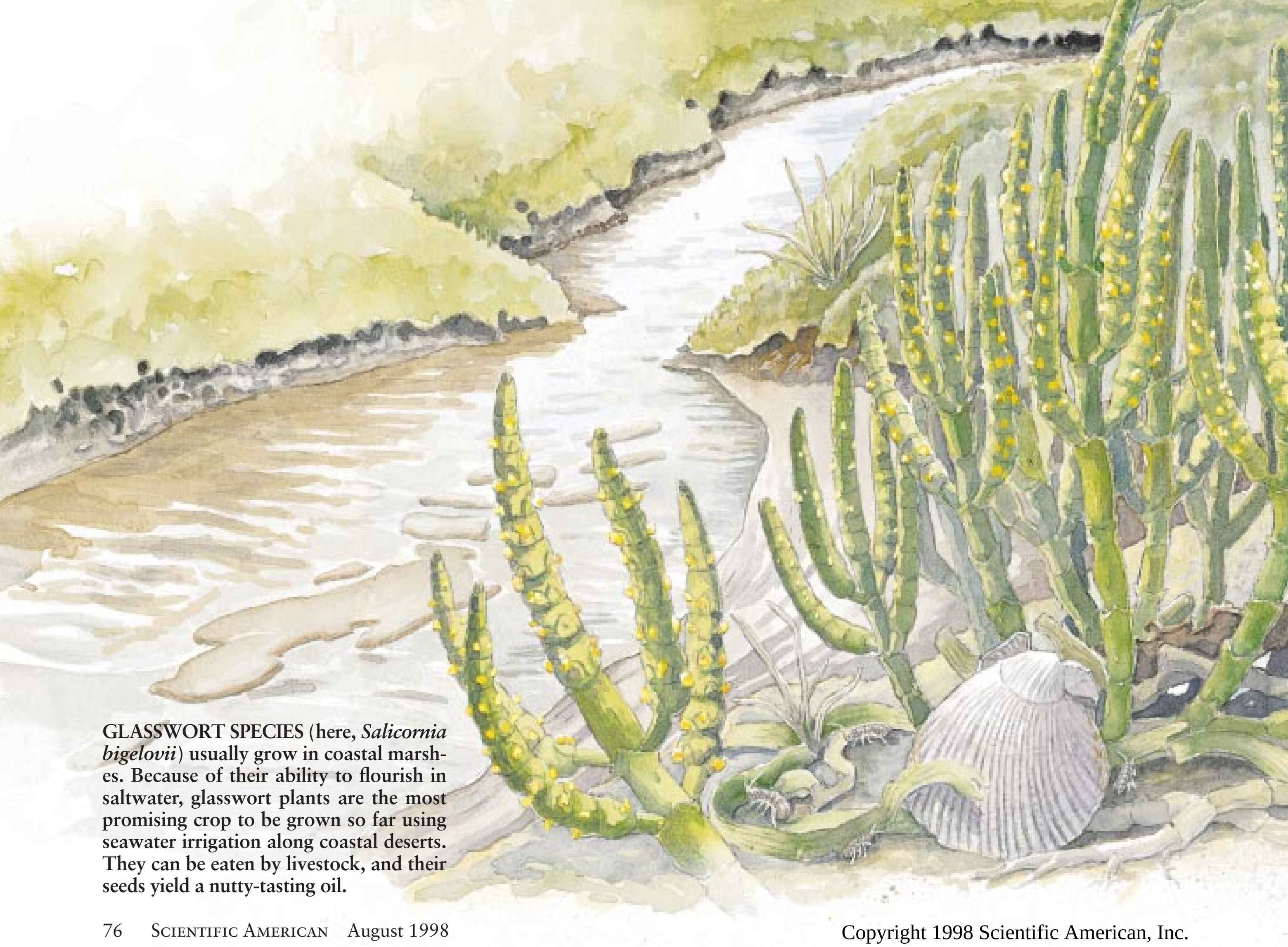
Irrigating Crops with Seawater

As the world's population grows and freshwater stores become more precious, researchers are looking to the sea for the water to irrigate selected crops

by Edward P. Glenn, J. Jed Brown and James W. O'Leary

Earth may be the Ocean Planet, but most terrestrial creatures—including humans—depend for food on plants irrigated by freshwater from rainfall, rivers, lakes, springs and streams. None of the top five plants eaten by people—wheat, corn, rice, potatoes and soybeans—can tolerate salt: expose them to seawater, and they droop, shrivel and die within days.

One of the most urgent global problems is finding enough water and land to support the world's food needs. The United Nations Food and Agriculture Organization estimates that an additional 200 million hectares (494.2 million acres) of new cropland—an area the size of Arizona, New Mexico, Utah, Colorado, Idaho, Wyoming and Montana



GLASSWORT SPECIES (here, *Salicornia bigelovii*) usually grow in coastal marshes. Because of their ability to flourish in saltwater, glasswort plants are the most promising crop to be grown so far using seawater irrigation along coastal deserts. They can be eaten by livestock, and their seeds yield a nutty-tasting oil.

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combined—will be needed over the next 30 years just to feed the burgeoning populations of the tropics and subtropics. Yet only 93 million hectares are available in these nations for farms to expand—and much of that land is forested and should be preserved. Clearly, we need alternative sources of water and land on which to grow crops.

With help from our colleagues, we have tested the feasibility of seawater agriculture and have found that it works well in the sandy soils of desert environments. Seawater agriculture is defined as growing salt-tolerant crops on land using water pumped from the ocean for irrigation. There is no shortage of seawater: 97 percent of the water on earth is in the oceans. Desert land is also plentiful: 43 percent of the earth's total land surface is arid or semiarid, but only a small fraction is close enough to the sea to make seawater farming feasible. We estimate that 15 percent of undeveloped land in the world's coastal and inland salt deserts could be suitable for growing crops using saltwater agriculture. This amounts to 130 million hectares of new cropland that could be brought into human or animal food production—without cutting down forests or diverting more scarce freshwater for use in agriculture.

Seawater agriculture is an old idea that was first taken seriously after World War II. In 1949 ecologist Hugo Boyko and horticulturalist Elisabeth Boyko went to the Red Sea town of Eilat during the formation of the state of Israel to create landscaping that would attract settlers. Lacking freshwater, the Boykos used a brackish well and seawater pumped directly from the ocean and showed that many plants would grow beyond their normal salinity limits in sandy soil [see "Salt-Water Agriculture," by Hugo Boyko; Scientific American, March 1967]. Although many of the Boykos' ideas of how plants tolerate salts have not stood the test of time, their work stimulated widespread interest, including our own, in extending the salinity constraints of traditional irrigated agriculture.

Seawater agriculture must fulfill two requirements to be cost-effective. First, it must produce useful crops at yields high enough to justify the expense of pumping irrigation water from the sea. Second, researchers must develop agronomic techniques for growing seawater-irrigated crops in a sustainable manner—one that does not damage the environment. Clearing these hurdles has proved a daunting task, but we have had some success.

Salty Crops

The development of seawater agriculture has taken two directions. Some investigators have attempted to breed salt tolerance into conventional crops, such as barley and wheat. For example, Emanuel Epstein's research team at the University of California at Davis showed as early as 1979 that strains of barley propagated for generations in the presence of low levels of salt could produce small amounts of grain when irrigated by comparatively saltier seawater. Unfortunately, subsequent efforts to increase the salt tolerance of conventional crops through selective breeding and genetic engineering—in which genes for salt tolerance were added directly to the plants—have not produced good candidates for seawater irrigation. The upper salinity limit for the long-term irrigation of even the most salt-tolerant crops, such as the date palm, is still less than five parts per 1,000 (ppt)—less than 15 percent of the salt content of seawater. Normal seawater is 35 ppt salt, but in waters along coastal deserts, such as the Red Sea, the northern Gulf of California (between the western coast of Sonora in Mexico and Baja California) and the Persian Gulf, it is usually closer to 40 ppt. (Sodium chloride, or table salt, is the most prevalent salt in seawater and the one that is most harmful to plant growth.)

Our approach has been to domesticate wild, salt-tolerant plants, called halophytes, for use as food, forage and oilseed crops. We reasoned that changing the basic physiology of a traditional crop plant from salt-sensitive to salt-tolerant would be difficult and that it might be more feasible to domesticate a wild, salt-tolerant plant. After all, our modern crops started out as wild plants. Indeed, some halophytes—such as grain from the saltgrass *Distichlis palmeri* (Palmer's grass)—were eaten for generations by native peoples, including the Cocopah, who live where the Colorado River empties into the Gulf of California.

We began our seawater agriculture efforts by collecting several hundred halophytes from throughout the world and screening them for salt tolerance and nutritional content in the laboratory. There are between 2,000 and 3,000 species of halophytes, from grasses and

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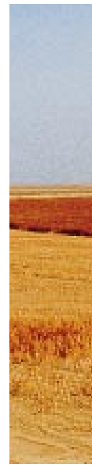

SEAWATER AGRICULTURE can require different agronomic techniques than freshwater agriculture. To grow saltbush, or *Atriplex*—a salt-tolerant plant that can be used to feed livestock—seawater farmers must flood their fields frequently (*left*). In addition, irrigation booms (*center*) must be lined with plastic piping to protect them from rusting when in contact with the salty water. But some techniques can remain the same: standard combines are used to harvest *Salicornia* seeds (*right*), for example.

shrubs to trees such as mangroves; they occupy a wide range of habitats—from wet, seacoast marshes to dry, inland saline deserts. In collaboration with Dov Pasternak's research team at Ben Gurion University of the Negev in Israel and ethnobotanists Richard S. Felger and Nicholas P. Yensen—who were then at the University of Arizona—we found roughly a dozen halophytes that showed sufficient promise to be grown under agronomic conditions in field trials.

In 1978 we began trials of the most promising plants in the coastal desert at Puerto Peñasco, on the western coast of Mexico. We irrigated the plants daily by flooding the fields with high-saline (40 ppt) seawater from the Gulf of California. Because the rainfall at Puerto Peñasco averages only 90 millimeters a year—and we flooded our plots with an annual total depth of 20 meters or more of seawater—we were certain the plants were growing almost solely on seawater. (We calculate rainfall and irrigation according to the depth in meters that falls on the fields rather than in cubic meters, which is a measure of volume.)

Although the yields varied among species, the most productive halophytes produced between one and two kilograms per square meter of dry biomass—roughly the yield of alfalfa grown using freshwater irrigation. Some of the most productive and salt-tolerant halophytes were shrubby species of *Salicornia* (glasswort), *Suaeda* (sea blite) and *Atriplex* (saltbush) from the family Chenopodiaceae, which contains about 20 percent of all halophyte species. Salt grasses such as *Distichlis* and viny, succulent-leaved ground covers such as *Batis* were also highly productive. (These plants are not Chenopodiaceae, though; they are members of the Poaceae and Batidaceae families, respectively.)

But to fulfill the first cost-effectiveness requirement for seawater agriculture, we had to show that halophytes could replace conventional crops for a specific use. Accordingly, we tested whether halophytes could be used to feed livestock. Finding enough forage for cattle, sheep and goat herds is one of the most challenging agricultural problems in the world's drylands, 46 percent of which have been degraded through overgrazing, according to the U.N. Environment Program. Many halophytes have high levels of protein and digestible carbohydrates. Unfortunately, the plants also contain large amounts of salt; accumulating salt is one of the ways they adjust to a saline environment [*see illustration on page 80*]. Because salt has no calories yet takes up space, the high salt content of halophytes dilutes their nutritional value. The high salinity of halophytes also limits the amount an animal can eat. In open grazing situations, halophytes are usually considered "reserve-browse plants," to which animals turn only when more palatable plants are gone.

Our strategy was to incorporate halophytes as part of a mixed diet for livestock, replacing conventional hay forage with halophytes to make up between 30 and 50 percent of the total food intake of sheep and goats. (These percentages are the typical forage levels used in fattening animals for slaughter.) We found that animals fed diets containing *Salicornia, Suaeda* and *Atriplex* gained as much weight as those whose diets included hay. Moreover, the quality of the test animals' meat was unaffected by their eating a diet rich in halophytes. Contrary to our initial fears, the animals had no aversion to eating halophytes in mixed diets; they actually seemed to be attracted by the salty taste. But the animals that ate a halophyte-rich diet drank more water than those that ate hay, to compensate for the extra salt intake. In addition, the feed conversion ratio of the test animals (the amount of meat they produced per kilogram of feed) was 10 percent lower than that of animals eating a traditional diet.

Farming for Oil

The most promising halophyte we have found thus far is *Salicornia bigelovii*. It is a leafless, succulent, annual salt-marsh plant that colonizes new areas of mud flat through prolific seed production. The seeds contain high levels of oil (30 percent) and protein (35 percent), much like soybeans and other oilseed crops, and the salt content is less than 3 percent. The oil is highly polyunsaturated and similar to safflower oil in fatty-acid composition. It can be extracted from the seed and refined using conventional oilseed equipment; it is also edible, with a pleasant, nutlike taste

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and a texture similar to olive oil. A small drawback is that the seed contains saponins, bitter compounds that make the raw seeds inedible. These do not contaminate the oil, but they can remain in the meal after oil extraction. The saponins thus restrict the amount of meal that can be used in chicken diets, but feeding trials have shown that *Salicornia* seed meal can replace conventional seed meals at the levels normally used as a protein supplement in livestock diets. Hence, every part of the plant is usable.

We have participated in building several prototype *Salicornia* farms of up to 250 hectares in Mexico, the United Arab Emirates, Saudi Arabia and India. During six years of field trials in Mexico, *Salicornia* produced an average annual crop of 1.7 kilograms per square meter of total biomass and 0.2 kilogram per square meter of oilseed. These yields equal or exceed the yields of soybeans and other oilseeds grown using freshwater irrigation. We have also shown that normal farm and irrigation equipment can be modified so that it is protected from salt damage from the seawater. Although the irrigation strategies for handling seawater are different from those used for freshwater crops, we have not encountered any insurmountable engineering problems in scaling up from field tests to prototype farms.

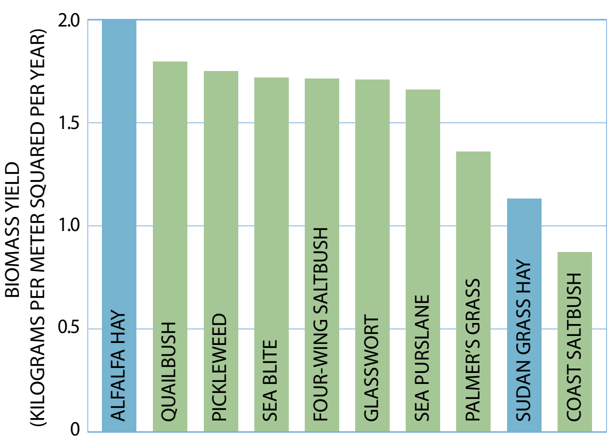
Normally, crops are irrigated only when the soil dries to about 50 percent of its field capacity, the amount of water it is capable of holding. In addition, in freshwater irrigation, farmers add only enough water to replace what the plants have used. In contrast, seawater irrigation requires copious and frequent—even daily—irrigation to prevent salt from building up in the root zone to a level that inhibits growth.

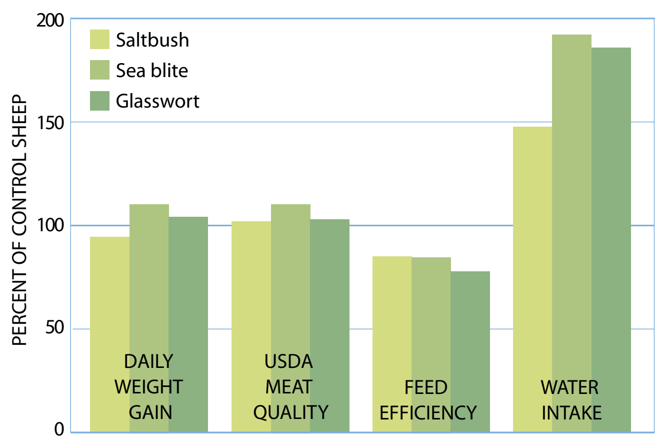
Our first field trials used far more water (20 meters a year) than could be applied economically, so in 1992 we began experiments to determine the minimum amount of seawater irrigation needed to produce a good yield. We grew test plantings of *Salicornia* in soil boxes buried within open, irrigated plots of the same crop during two years of field trials. The boxes, called lysimeters, had bottom drains that conveyed excess water to several collection points outside the plots, allowing us to measure the volume and salinity of the drain water. Using them, we calculated the water and salt balances required for a seawater-irrigated crop for the first time. We found that the amount of biomass a seawater-irrigated crop yields depends on the amount of seawater used. Although *Salicornia* can thrive when the salinity of the water bathing its roots exceeds 100 ppt—roughly three times the normal saltiness of the ocean—it needs approximately 35 percent more irrigation when grown using seawater than conventional crops grown using freshwater. *Salicornia* requires this extra water because as it selectively absorbs water from the seawater, it quickly renders the remaining seawater too salty for use.

Making It Pay

Can seawater agriculture be economical? The greatest expense in irrigated agriculture is in pumping the water. The pumping costs are directly proportional to the amount of water pumped and the height to which it is lifted. Although halophytes require more water than conventional crops, seawater farms near sea level require less water lifting than conventional farms, which often lift water from wells deeper than 100 meters. Because pumping seawater at sea level is cheaper than pumping freshwater from wells, seawater agriculture should be cost-effective in desert regions—even though its yields are smaller than traditional, freshwater agriculture.

Seawater irrigation does not require special equipment. The large test farms we have helped build have used either flood irrigation of large basins or moving-boom sprinkler irrigation. Moving booms are used in many types of crop





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YIELDS of salt-tolerant crops grown using seawater agriculture are comparable to those of two freshwater-irrigated plants often used for livestock forage: alfalfa hay and Sudan grass hay (*left, blue bars*). Sheep raised on a diet supplemented with salt-tolerant plants such as saltbush, sea blite and glasswort gain at least as much weight and yield meat of the same quality as control sheep fed conventional grass hay, although they convert less of the feed to meat and must drink almost twice as much water (*right*).

production. For seawater use, a plastic pipe is inserted in the boom so the seawater does not contact metal. *Salicornia* seeds have also been successfully harvested using ordinary combines set to maximize retention of the very small seeds, which are only roughly one milligram in weight.

Yet *Salicornia,* our top success story so far, is not a perfect crop. The plants tend to lodge (lie flat in the field) as harvest approaches, and the seeds may shatter (release before harvest). In addition, seed recoveries are only about 75 percent for *Salicornia,* compared with greater than 90 percent for most crops. Further, to support high seed yields *Salicornia* must grow for approximately 100 days at cool temperatures before flowering. Currently production of this crop is restricted to the subtropics, which have cool winters and hot summers; however, some of the largest areas of coastal desert in the world are in the comparatively hotter tropics.

The second cost-effectiveness requirement of seawater agriculture is sustainability over the long term. But sustainability is not a problem limited to irrigation using seawater: in fact, many irrigation projects that use freshwater cannot pass the sustainability test. In arid regions, freshwater irrigation is often practiced in inland basins with restricted drainage, resulting in the buildup of salt in the water tables underneath the fields. Between 20 and 24 percent of the world's freshwater-irrigated lands suffer from salt and water buildup in the root zone. When the problem becomes severe, farmers must install expensive subsurface drainage systems; disposing of the collected drain water creates additional problems. In California's San Joaquin Valley, for example, wastewater that had drained into a wetland caused death and deformity in waterfowl because of the toxic effects of selenium, an element that typically occurs in many western U.S. soils but had built up to high concentrations in the drain water.

Seawater agriculture is not necessarily exempt from such problems, but it does offer some advantages. First, coastal desert farms on sandy soils generally have unimpeded drainage back to the sea. We have continuously irrigated the same fields with seawater for over 10 years with no buildup of water or salts in the root zone. Second, coastal and inland salt desert aquifers often already have elevated concentrations of salt and so should not be damaged by seawater. Third, the salt-affected soils that we propose for seawater agriculture are often barren—or nearly so—to start with, so installing a seawater farm may have far less effect on sensitive ecosystems than conventional agriculture does.

No farming activity is completely benign, however. Large-scale coastal shrimp farms, for example, have caused algal blooms and disease problems in rivers or bays that receive their nutrient-rich effluent [see "Shrimp Aquaculture and the Environment," by Claude E. Boyd and Jason W. Clay; Scientific American, June]. A similar problem can be anticipated from large-scale halophyte farms, caused by the large volume of high-salt drainage water containing unused fertilizer, which will ultimately be discharged back to the sea. On the other hand, seawater farms can also be part of a solution to this problem if shrimp-farm effluent is recycled onto a halophyte farm instead of dis-

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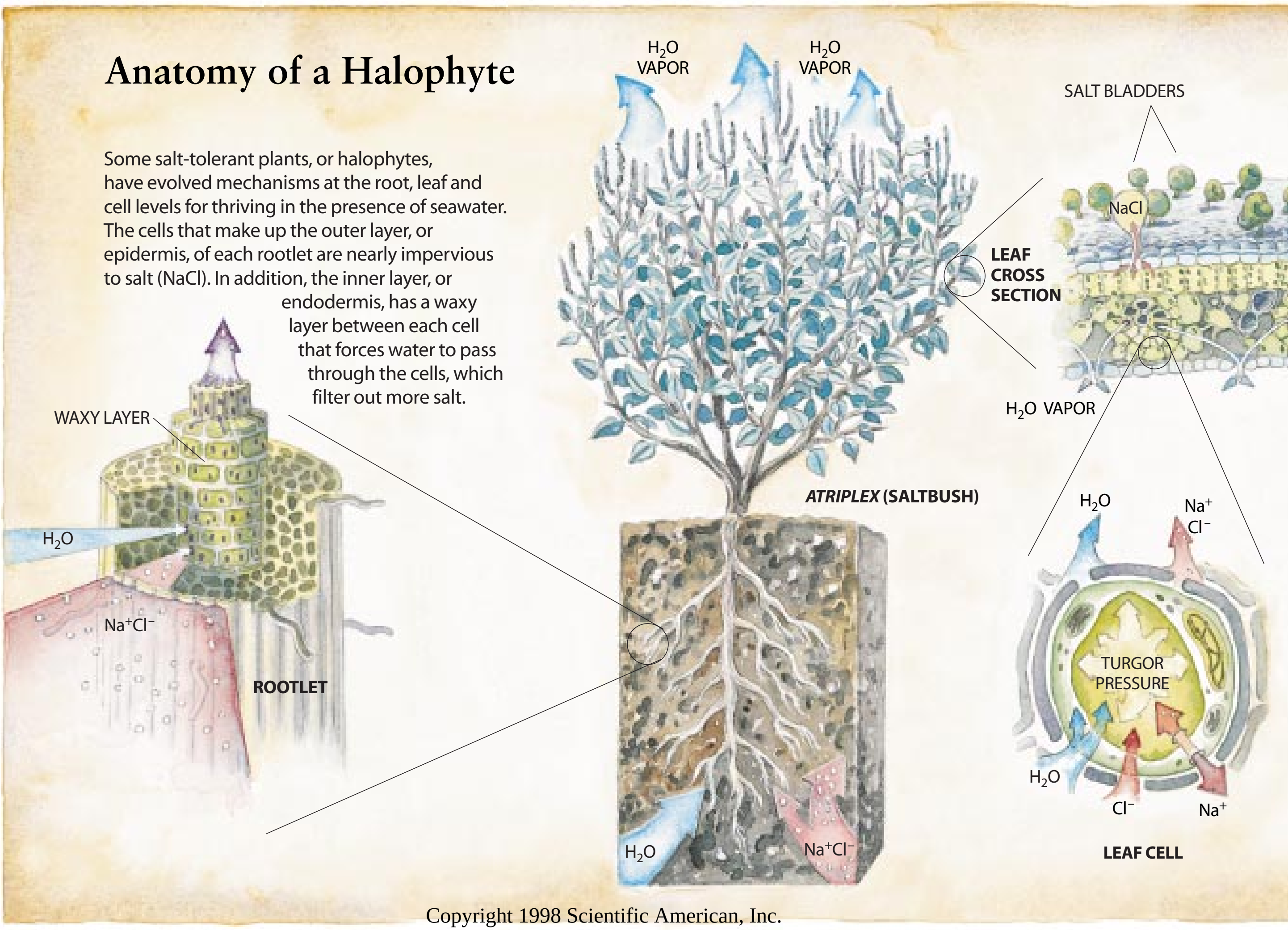
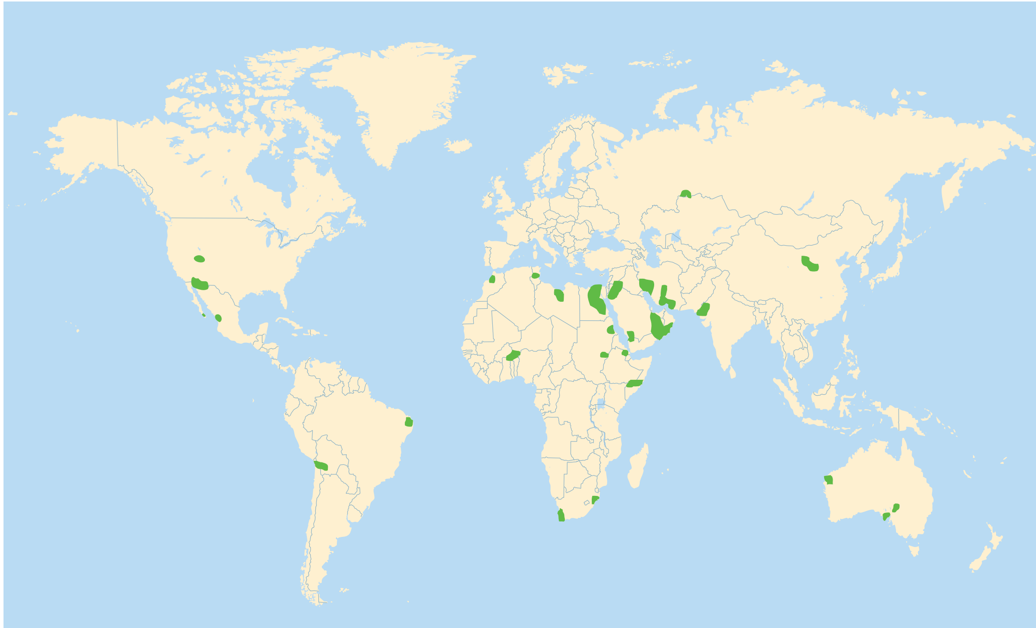
Anatomy of a Halophyte

Some salt-tolerant plants, or halophytes, have evolved mechanisms at the root, leaf and cell levels for thriving in the presence of seawater. The cells that make up the outer layer, or epidermis, of each rootlet are nearly impervious to salt (NaCl). In addition, the inner layer, or endodermis, has a waxy layer between each cell that forces water to pass through the cells, which filter out more salt.



LOCATIONS in coastal deserts and inland salt deserts (*green areas*) could be used for seawater agriculture—or agriculture using irrigation from salty underground aquifers—to grow a variety of salt-tolerant crops for food or animal forage.



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charged directly to the sea: the halophyte crop would recover many of the nutrients in the effluent and reduce the volume. The first halophyte test farm we built in Mexico was installed to recycle shrimp-farm effluent, and further research linking marine aquaculture effluent with halophyte farms is under way.

Halophyte farms have also been proposed as a way to recycle the selenium-rich agricultural drain water generated in the San Joaquin Valley of California. Selenium is an essential nutrient at low levels but becomes toxic at high levels. Halophytes grown on drain water in the valley take up enough selenium to make them useful as animal-feed supplements but not enough to make them toxic.

Will seawater agriculture ever be practiced on a large scale? Our goal in the late 1970s was to establish the feasibility of seawater agriculture; we expected to see commercial farming within 10 years. Twenty years later seawater agriculture is still at the prototype stage of commercial development. Several companies have established halophyte test farms of *Salicornia* or *Atriplex* in California, Mexico, Saudi Arabia, Egypt, Pakistan and India; however, to our knowledge, none have entered large-scale production. Our research experience convinces us of the feasibility of seawater agriculture. Whether the world ultimately turns to this alternative will depend on future food needs, economics and the extent to which freshwater ecosystems are withheld from further agricultural development. SA

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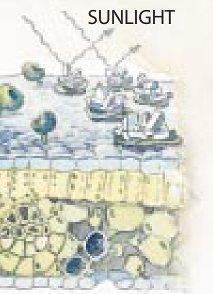

Some halophytes, such as this *Atriplex* (saltbush), have specialized cells called salt bladders on their leaves for storing excess NaCl. When full, the salt bladders burst, releasing salt in a silvery layer that reflects light and cools the leaf. Water vapor escapes through pores on the undersides of the leaves.

Cells inside each leaf are specially equipped to handle any salt that is absorbed by the plant. The central vacuole, or storage area, of each cell bears molecules that specifically import sodium ions (Na^+), and chloride ions (Cl^-) follow. The high concentration of Na^+ and Cl^- attracts water, maintaining the turgor pressure of the cell.

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EDWARD P. GLENN, J. JED BROWN and JAMES W. O'LEARY have a combined total of 45 years of experience studying the feasibility of seawater agriculture in desert environments. Glenn began his research career as a self-described "marine agronomist" in 1978 after receiving his Ph.D. from the University of Hawaii; he is now a professor in the department of soil, water and environmental science at the University of Arizona at Tucson. Brown received his Ph.D. from the University of Arizona's Wildlife and Fisheries Program in May. O'Leary is a professor in the University of Arizona's department of plant sciences. He received his Ph.D. from Duke University in 1963. Author of more than 60 publications on plant sciences, O'Leary served in 1990 on a National Research Council panel that examined the prospects of seawater agriculture for developing countries.

Further Reading

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