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Tropical and Subtropical Coastal Management: A Question of Carbon Flow in a Sectoral Society

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Reversing the Flow: Water and Nutrients from the Sea to the Land

One area of immediate planetary-scale concern is the increasing carbon level of the atmosphere. Another is the decreasing carbon level of the world's soils. These two phenomena are part of a single problem. We must increase the flow of carbon from the atmosphere into the soil. One technology to contribute to this is seawater-based agriculture whereby seawater and nutrients from the sea are brought onto the land for aquatic animal production and halophyte farms. Further, these farms can be constructed as integral parts of new seawater-based communities which can be developed in many locations along the coastal regions of the earth. If the world population expands at projected rates before stabilizing, and if half of that increased population continues to live within 50 km of the world's seacoasts (as half of the present population does), seawater-based communities may be one of the best alternatives for developing new forms of environmentally-enhancing communities with the associated critically-needed wealth generation.

INTRODUCTION

Humankind invented agriculture 10 000 years ago. Undoubtedly, it is our greatest technological accomplishment. The ability to produce food in abundance, and to do so with a technology that, as it evolved, gave us more and more time for other activities, is the key to development of our art, science...all culture. It is possibly unfortunate that we did not, on day one, invent sustainable agriculture. It is only "possibly" so; because, perhaps if we had started with a sustainable agriculture technology which required much more of our time, albeit in a more environmentally enhancing activity, we might have had much less time to develop the culture that we now enjoy. It could be argued that the more-time tradeoff was not a good one. On the other hand, we are an adaptable species. We have a history of recognizing problems, and, having done so, we are fairly good at "repairing the past." We have torn up nations with war, but when we finally realized that the war should end, we rebuilt nations. It is now time to recognize that the damage we have done, and are doing, to the planetary environment must not only end, but we must rebuild much of the living system, the biosphere, of our planet.

An area that has been especially mistreated is the land-sea interface. Undoubtedly, this is because of the importance of, and our fascination with, that interface. It is not random chance that 50% of the world's population lives within 50 km of the sea. In Carl Sagan's popular science book, Dragons of Eden (1), he writes about what is encoded in the reptilian core of our brain. It is likely that we look at the sea, and at some level know it, as a source for much of our existence. A source has, by definition, fluxes from it, and, if it is a beneficial source, those fluxes are positive in their effect. We understand clearly the fluxes of atmospheric water from the sea to the land, and the return of that water, via streams and rivers, back to the sea; the hydrologic cycle. But in that water and on the wind, we have seen another flux, not from and to, but only to the sea over our 10 000 years of agriculture. We have suspected, but now certainly know, that much of it is a negative flux; i.e., the horrendous erosion of our topsoil and nutrients into the sea. Much of the topsoil of the earth, that existed before we started agriculture, has been eroded.

We have some hints that flux does not have to be only one way; nutrients can come from the sea to the land. Some areas export seabird guano for fertilizer. Camels that ate mangroves, before the mangroves were destroyed by development, and then deposited their excrement on the lands of Arabia, were contributing. The Native-American Indians, who took fish from the sea and used them as fertilizers for their crops, were taking from the sea to the land, and we now import seafood to the interior of continents. All such activities combined, however, are infinitesimal relative to the erosion, but the hints of repair are there.

It is now time for humankind to begin *Reversing the Flow*, on a scale adequate to address the problem, by taking water and nutrients from the sea to help rebuild what is possibly the most important thing we have destroyed–the productive soils of our lands. In the process of doing this, we can create carbon fixation within the soil that will allow us to balance the current flux of carbon into the atmosphere and even, hopefully in the future, balance an increasing carbon flux.

In spite of increasing environmental awareness and major efforts towards energy-use efficiency, the world is not going to reduce its total use of energy. In fact, the total global use of energy will increase dramatically. It must, if the developing world is to have a fair share of "the good life." Much of the increase will come from fossil fuels.

THE PROBLEMS AND THEIR MAGNITUDE

The good news in all of the environmental bad news, is that we have recognized important environmental problems and have, or are defining, their magnitude. The source of these problems is, of course, us...the numbers of us. Agriculture started with a small group of people, probably a few dozen or less. Agriculture's success has allowed us to multiply to now over 5500 million, and we increase by another million every five days. To feed us, we have plowed 1500 million ha, used 3200 million ha of pasture for grazing, and taken timber from around 1000 million ha.

We have left only the most inaccessible parts of the remaining 9000 million ha of land in a pristine state. As we developed our agriculture, we have destroyed a large percentage of the fertility of the land by eroding it to the sea. Currently, topsoil is being eroded at an estimated rate that is at least ten times greater than the rate it is naturally being built (2). The specifics are depressing. Since the end of World War II, more than 1200 million ha of agricultural land, an area larger than China and India combined, have been seriously degraded (3). A third of the topsoil of the

United States, that was there when we began applying agriculture, is gone. The soil erosion in Haiti is so bad that, in some places that once produced food, there is now only bedrock. It is no wonder that, with a major component of their food production, the soil, disappearing, some Haitians are in boats trying to reach a land that still has two-thirds of its soil remaining, the United States (4).

But, soil is not, or at least should not be, a nonrenewable resource. It was created by a biological process. The soils of the central part of the United States were developed over many thousands of years, but we have destroyed one-third in a few hundred. Soil formation required the beneficial interaction of plants and animals. It was we human animals that took from the soil instead of contributing to it. We need to repair what we have done.

There is no adequate vocabulary for understanding what we recognize, so we can get on with fixing it. A popular term for deterioration of soil is "desertification." The United Nations Envionmental Program (UNEP) "considers desertification to be one of the major environmental problems of our time." According to UNEP, "35% of the world's land surface is currently at risk, and more than 20 million ha are reduced annually to near or complete uselessness." The image created by the word, desertification, is powerful, but there is disagreement in the scientific community about the value of the word and some of the interpretations of it. (For example, the movement of sand dunes onto agricultural land is a burden for those directly affected, but satellite data suggest that this is a miniscule issue compared to global soil erosion.)

Ulf Helldén (5) presents an articulate argument for dropping "desertification" and replacing it with "land degradation." We would offer a different word so as to place soil degradation and atmospheric carbon accumulation in one mental context. We propose introducing a concerned public to the vocabulary of the problem of decarbonizing of the soils of the earth, where the term decarbonizing refers to the depletion of the organic carbon in the soil (not the inorganic carbonates). Decarbonizing of the soil does not have the visual power of desertification, which conjures images of trees disappearing to be replaced by sand dunes. But decarbonizing does link easily with global warming discussions, i.e., carbonizing of the atmosphere. By looking at atmospheric carbon increase and soil carbon depletion as a single problem, we might not only just develop, but go beyond that to implement, with public support, an effective planetary strategy to solve the problem.

Had we started on day one with sustainable agriculture, we would have composted the waste from our agricultural production and returned that, with the other waste coming from humans and animals that consumed the products of our plant production agriculture, and put them back onto the soil. Large-scale adoption of sustainable-agriculture practices, which the world is now doing on an increasing scale, will stop the continued deterioration of soil, but will not adequately address rebuilding soils and creating new soils on the planetary scale necessary. We must get into the business of soil production, and we must do it as an issue of global security. In the United States in the 1950s, we built what was then the world's largest public-works project, a new nation-wide interstate highway system by justifying it as a "national security" need. Now we need to build the social and physical infrastructure on a planetary scale to take carbon from the atmosphere to recarbonize soils as a planetary security need.

In 1975, the then president of Mitsubishi, Masaki Nakajima, gathered together a group of Japanese companies (later to include other nationalities) and formed The Global Infrastructure Fund. He did this because he thought that it was actually possible that peace might break out, and the world would need to replace military expenditures with some other economic driver. His idea was "that investment in large-scale infrastructure projects in developing countries enhances the quality of life and thus benefits the quality and stability of international commercial relations" (6). We can read "stability" as "security." Some grand dreams have been evaluated...such as World Route One, a highway from Washington, D.C. to Moscow, pipelines and canals delivering water from Alaska and Canada to the deserts of the United States and Mexico, pipelines and canals from Turkey to the Arabian desert, etc.

It is beyond the scope of this paper to discuss whether Mr. Nakajima was right about peace, but he was certainly right about the world being willing to spend money for security, at least military security. Today's military expenditures are over 10^{12} USD per year.

Our most important security issues are not military, although they get the most attention, as they are the most immediately painful.

Security of all our life systems should be above almost all other issues. Given that, one might think that soil decarbonization anywhere on the planet (Africa, Haiti...) would be of concern for all our security—but that reality is not yet broadly internalized—if it is encoded, we choose not to recognize it.

But another security reality is registering. We all feel the results of our impacts on the atmosphere. The atmosphere brings humans the results of their input into it when we cannot breathe, as in some of our cities, or if the climate changes, and if the ultraviolet rays of the sun increasingly burn us.

The Greenhouse Effect and Ozone Hole are known, and "repair" is underway with agreements that eliminate some pollutants, e.g.

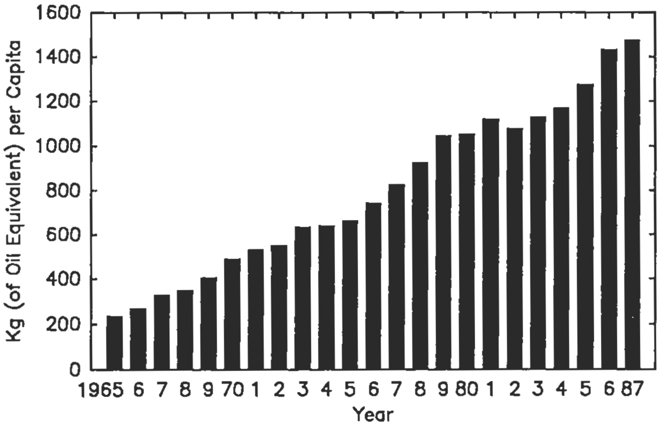


Figure 1. Energy consumption, expressed as equivalent kilograms of oil per capita, for the Republic of Korea from 1965 to 1987 (7).

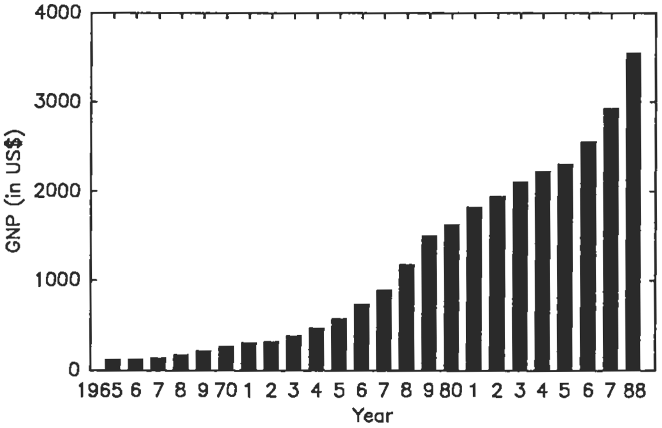


Figure 2. Gross national product (GNP), in U.S. dollars per capita, for the Republic of Korea from 1965–1988 (7).

CFCs, policies of "no regrets" on CO_2 are being unilaterally adopted by utilities and others, there is much discussion of a limitation of CO_2 emissions by international agreements, and nation-by-nation, if not planetary, carbon taxes.

The concern for increasing CO_2 in the atmosphere has been focused on our human use of fossil fuels. We are now putting six times as much carbon into the atmosphere as we were at the end of World War II by our use of petroleum, natural gas and coal. And that increase comes exactly at the time we were decarbonizing the soil of the area equivalent to an area of India and China.

But these two related activities have had opposite effects. As we have put more carbon into the atmosphere, we have raised our standard of living. And, conversely, as we have caused carbon to be taken from the soil, we have lowered our quality of life.

Figures 1 and 2 are from an article by Kim and van der Oever on Demographic Transition and Patterns of Natural Resource Use in the Republic of Korea (7). Using their data for per capita gross national product (GNP in USD) and the per capita energy consumption (E) in equivalent kilograms of oil during the period 1956 through 1987 for the Republic of Korea, we show in Figure 3 that GNP and energy consumption are related as: $GNP = E^2/710$. Or, in Korea, the creation of wealth from 1956 through 1987 proceeded as the square of the rate of the increase of carbon release to the atmosphere. Figure 4 shows the associated critically important decline in total fertility over the period of extreme wealth generation and projection of a stable population in the future. Unfortunately, there are no good numerical data for presentation in graphical form to show the correlation between soil decarbonization and a declining quality of life. However, the extremes are obvious. Rich topsoil is looked upon as a resource, and people compete to exploit it. When the soil is gone, the basic technology of food production is gone, and, in many cases, the people must suffer malnutrition or migrate.

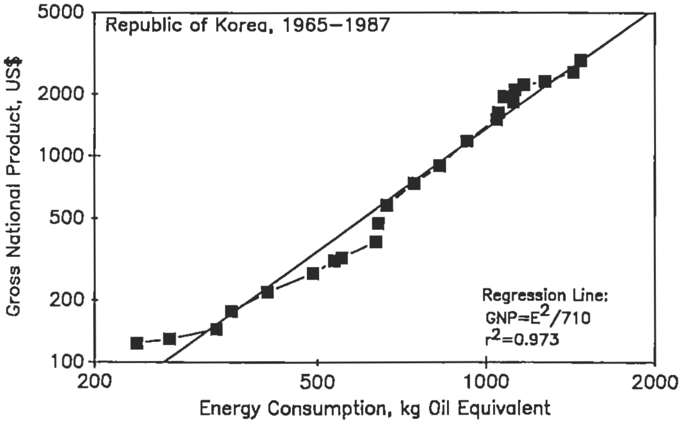


Figure 3. Relationship between the Republic of Korea GNP, USD per person per year, from Figure 2, and the energy consumption rate (E), kg of oil equivalent per person per year from Figure 1.

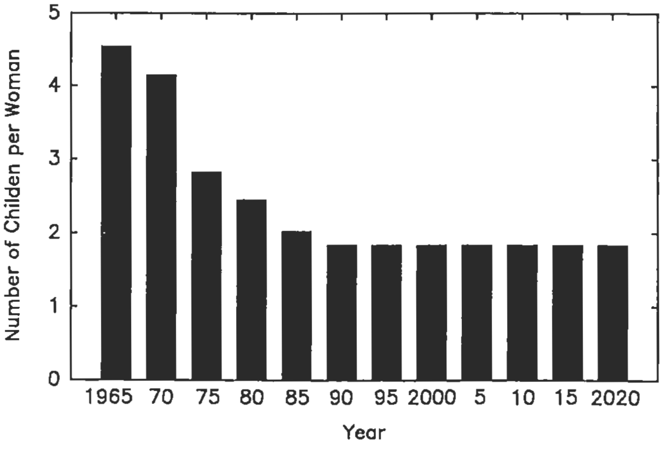


Figure 4. Total fertility rate, children per woman, Republic of Korea, from 1965 projected to 2020 (7).

What if, over the last half-century, we had still developed to annually put six times or more the carbon per year into the atmosphere from fuel, but during the same period had chosen to protect biodiversity and not cut the rainforests, had adopted sustainable agriculture, and were not now cutting the Siberian forests as fast as we can?

Undoubtedly, we would be much better off as a planet. However, the people who made, and are making, their living by cutting trees, exporting carbon from agricultural lands, instead of composting, etc., might not be as well off. At least they thought, and in many cases still think, they made the best decision for themselves. Certainly, those currently benefiting from burning fossil fuel are not rushing to stop doing so. In fact, many people are working hard to earn money to buy fossil fuel to burn more of it to have a "better" life.

What if we could change somehow and say, "Burn as much fuel (a blend of fossil and biofuel) as you want to build a better life. Yes, the fuel costs money (some think it is too cheap, some too expensive), but society will give you a job to earn the necessary funds to buy fuel...go to work in the new field of 'soil carbonizing.' The more of you employed there, the more wealth will be created...more fuel burned, more people employed building soil, producing food and biofeedstocks, more wealth created. And, the environment will continuously improve."

Is this possible?

Thomas J. Goreau has presented an excellent review of the atmospheric carbon questions (8). He linked atmospheric carbon and soil carbon and emphasized that our attention should be directed toward removing carbon from the atmosphere instead of simply reducing carbon input into the atmosphere.

However, at least in the popular media and political dialogue, the emphasis continues to be on limiting and even reducing input, while those against limiting CO_2 emissions claim either there is no problem or a need for more data to prove that there really is a problem.

In 1992, the World Resources Institute published *The Right Climate for Carbon Taxes: Creating Economic Incentives to Protect the Atmosphere* (9). The report presents considerations of the purpose of a carbon tax, strategies for implementation, questions of fairness, of cost, etc. It presents, for example, the effect on individual industrial sectors (Fig. 5). From this figure, it is easy to

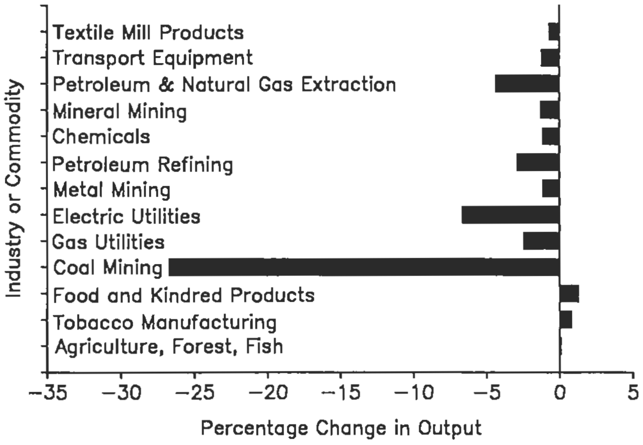


Figure 5. The estimated effect of a carbon tax on the output of selected sectors of US industry (9).

see that, in spite of the excellence of the report's argument, if individuals are in any of the majority of those industries evaluated, their enthusiasm for a carbon tax is going to be low.

We believe that any carbon tax evaluation needs a companion study, which not only "protects the atmosphere," but "enhances the soil," and the two together emphasize not how much it will cost, but rather how much new wealth can be created—even redirecting some of our military (i.e., security) expenditures into a soil carbonizing subsidy—pay farmers to plant to build soil instead of not to plant.

Goreau (8) suggests that tropical reforesting of 200 to 800 million ha, at a cost of USD 400 per ha, could remove the current atmospheric carbon buildup. Assuming that 500 million ha would be needed, the total cost is only USD 200 000 million, i.e. less than the annual subsidy, USD 250 000 million, of the developed world's agriculture (most for price supports) and less than one-fifth of the world's total annual military budget.

Of course, there are questions of displaced interest, reduced alternate production from the land, etc. FAO projects that we will need 200 million new ha of farmland to feed us before the population stabilizes (10). Nevertheless, the world needs to, and will, reverse the situation of declining rainforests, and a major contribution to balancing the carbon cycle will come from reforesting.

In this broad context, we offer a brief history of the development and some early analyses of the potential of a complementary scenario for carbon-cycle balancing and increasing food production by developing new types of communities at the edge of the sea. Much of the authors' focus has been at the desert's coastal edge (with one subtropical and one tropical exception), but many of the world's coastlines offer possible sites. The defining characteristic of what we propose is that water and nutrients come from the sea to the land and that seawater-irrigated land stores carbon.

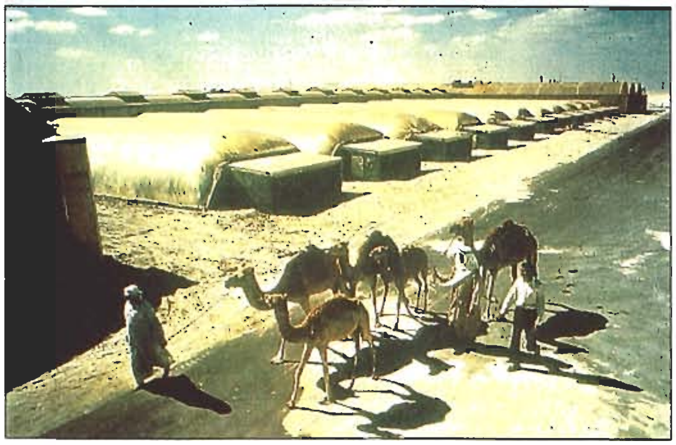
TECHNOLOGIES: REVERSING THE FLOW

In the early 1960s, staff at the Environmental Research Laboratory (ERL) of the University of Arizona naively decided to "make the deserts bloom" by pumping water from the sea, desalting it, and using it to produce "green." We thought this could be done using solar energy and developed a multiple-effect, solar-powered desalting process (11). We were addressing the problem of how to create more green on the earth for food, not green for carbon fixation. The recognition of the interlinked problems did not come until the late 1970s, when we became interested in climate defensive food production (12) and had extensive exchanges on atmospheric carbon issues with Dr. Walter Orr Roberts of the National Center for Atmospheric Research (13). We found that desalted seawater, no matter what its production energy source, was simply too expensive for outdoor agriculture; this is still the case. So we shifted our approach and decided to modify the plant environment by using seawater to cool, heat and humidify greenhouses. Because of the high humidity, plant transpiration is greatly reduced, so desalted seawater can be used for irrigation. The major constraint of Controlled Environment Aquaculture (CEA), however, is again a matter of economics. CEA systems make economic sense for specialized high-value crops. There are thousands of ha of such greenhouses now in the world. Many of them use the technologies for cooling developed in the Abu Dhabi project; although only a small number use brackish water or seawater for that purpose.

In the early 1970s, a significant course correction was made in efforts to return water and nutrients directly from the sea to the land. We decided to grow crops in the seawater without desalting it. We developed aquaculture systems for shrimp and fish (14).

In 1973, we took an important step. ERL funded the work of Dr. Richard Felger to look at growing eelgrass in seawater (15). That effort was not commercially promising. But, this was the first intellectual catalyst for us in the thought process towards moving to growing plants on land irrigated with seawater. We moved from eelgrass to the terrestrial halophytes of the world in 1975 (16). It was finally clear to us that we should use what nature provided as a start, collect halophytes from all of the coastal regions of the world, and repeat, to some extent, part of the 10 000 years of development of freshwater agronomy with saltwater crops. We thought it would take ten years and ten million dollars. It has taken 18 years and 20 million dollars, but we can now, on a significant scale, offer the starting point of a scenario to contribute to the recarbonizing of important areas of the land surfaces of the earth, while creating new wealth.

This is a cooperative university and private industry research and development effort. Shrimp and tilapia are produced commercially in a controlled-environment aquaculture facility. The effluent seawater, containing the initial nutrients from the sea, plus those added from the excrement of the shrimp and fish, is not returned to the sea. Instead it flows inland to irrigate seawater crops. Since 1975, we have evaluated hundreds of halophytes and done extensive work on approximately 25. The majority of work during the 1980s was in selective improvement of a worldwide collection of *Salicornia*. This focus developed upon the recognition of the potential of *Salicornia* to provide a high-quality vegetable oil and meal for human consumption, given that we could develop the necessary commercial agronomic characteristics. We now have released two proprietary selections from *Salicornia bigelovii* Torr., SOS-7 and SOS-10 (SOS stands for *Salicornia* oil seed and



A controlled-environment agriculture (CEA) seawater-based project in Abu Dhabi, U.A.E. Photo: Environmental Research Laboratory.

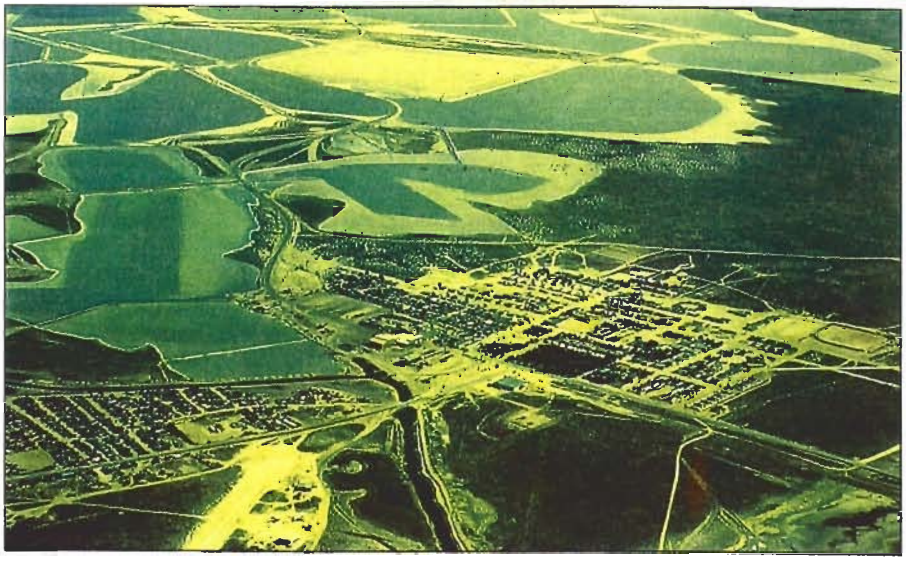
Commercial shrimp farm in Puerto Peñasco, Sonora, Mexico. Photo: Environmental Research Laboratory.

the number stands for the years in the development effort), which are now being commercialized in Mexico and Saudi Arabia (Table 1.).

The Electric Power Research Institute (EPRI) of the United States has sponsored work at ERL and in Puerto Peñasco since 1989 on the carbonizing of soil that is accomplished by halophytes (17, 18).

Seawater significantly slows the decomposition rate of biomass in the soil, hence there is an opportunity to build significant levels of soil carbon by the return of organic residues to seawater-irrigated farms. Four scenarios can be envisaged:

(i) After the seeds are removed (as in the case of oil seed production from SOS farms), the straw can be plowed under. This will decompose quickly in the soil to a C:N ratio of approximately 12:1, after which decomposition slows as the material becomes humus.


The world's largest sea salt production facility and the site of one of the Mexico halophyte research programs. Photo: Exportadora de Sal.

(ii) The straw can be fed to ruminants, and the manure from the animals can be returned to the soil. The most rapid phase of decomposition will have taken place in the animal rather than the soil. However, the manure will contribute to building of soil organic C and N nearly as efficiently as whole straw over time.

(iii) The straw can be removed and utilized elsewhere, for building material for example, and the farm soil can be enriched with aquaculture wastes. These wastes decompose similar to the ruminant wastes above. Over time, they will enrich the humic fraction in the halophyte field.

(iv) The straw can be removed, and only the root residues left behind to build soil organic matter. Although this strategy is the least effective for building soil carbon, even in this case it is expected that organic matter will accumulate, albeit slowly, over time (Table 2).

In addition to the direct seawater irrigation proposed here, carbonization can be accomplished by relieving pressure for production from other areas by moving animal production to the coast where halophytes are used as feed. Ojima, et al (19), ran two contrasting 100-year scenarios for carbon storage in rangeland soils: the first scenario was "business as usual" and assumed that decarbonization of rangeland soils would continue; the second was an "optimal management" scenario, which assumed that UNEP's 20-year program for anti-desertification (what we would call "recarbonization") would be fully implemented.

The difference between the two scenarios was significant. Under the "business as usual" scenario, dryland soils will be a net source of CO_2 into the atmosphere for the next century, due to continued soil carbon losses from over-utilization and erosion. By contrast, under optimal management with much less production pressure, dryland soils would become a net sink for carbon amounting to at least 500 million tons per year. The cost of achieving this carbon storage is between USD 10 and 20 per ton; less than estimates of the cost of reforestation and with the advantage of contributing to restoration of the drylands, which constitute 43% of the land surface of the earth. So range animals produced at the seashore can help "repair" the range by reducing and managing the number of animals on the range to contribute to building soil instead of destroying it (20). Animal production is being tested in Kino Bay, Sonora, Mexico.

Glenn et al. (21) have shown that there are potentially 130 million ha of saline lands that could be planted with halophytes, about half of them along the world's coastal deserts. Not defined is the amount of coastal area in the subtropics, and even tropics, that would benefit from seawater aquaculture and/or agriculture.

Reforesting, as proposed by Goreau (8), restoring degraded rangelands, and a move throughout the world toward "organic farming" will contribute to carbonizing the soil. At a meeting in November 1992 in Nairobi, UNEP endorsed the concept of using halophytes to sequester carbon (22). This is part of a growing awareness that the world's coastal zones have an important role to play in sequestering carbon from the atmosphere. We believe that thinking must go one more step and integrate seawater agriculture into urban environments.

SEAWATER COMMUNITIES

We all want an improving world environment because it is important for our, and all of life's, survival. We want it also so that we can go beyond survival and enjoy the best aspects of the cultures that we have developed and hopefully will additionally

Table 1. Properties of *Salicornia bigelovii* Torr. seed and oil (range of values in parentheses). Amounts for fatty acids are the percentage of total fats, while for the other constituents the percentage of seed weights are listed.

Constituent	Amount	
Oil	28.2	(26–33)
Protein	31.2	(30–33)
Fiber	5.3	(5–7)
Ash	5.5	(5–7)
Fatty acids:		
Palmic	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	(2.4–2.7)

Table 2. Annual biomass and carbon yields of seawater-irrigated halophytes at Puerto Peñasco, 1990–1992. Sample size (n) refers to number of individual plots of a species except for *Sesuvium*, where individual plants within a single plot were sampled (21).

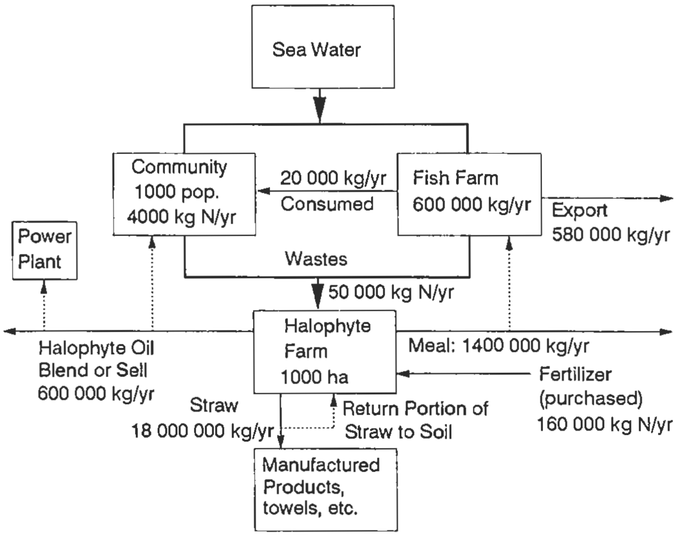
	n	Annual biomass	Yield	($t\ ha^{-1}$) Carbon
		mean	SE	mean
Batis maritima	8	33.95	(.99)	8.2
Atriplex linearis	5	24.27	(1.23)	6.7
Salicornia bigelovii (SOS-7, SOS-10)				
Year one	22	22.40	(.70)	5.6
Year two	9	17.72	(1.32)	4.3
Suaeda esteroa	9	17.22	(1.12)	4.3
Sesuvium portulacastrum	9	16.70	(2.00)	4.2

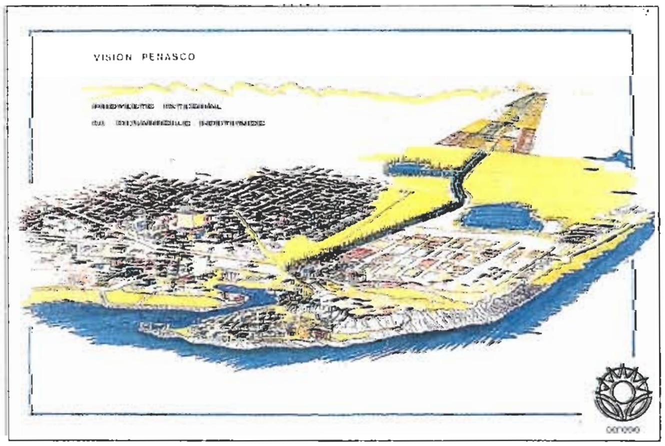
invent. Major civilizations and their cultures have developed over all of human history along the river banks and at the edges of the sea. The locations at the edges of the sea have been limited to where a source of fresh water is available. The peoples of the world have exploited, in many cases, essentially all of the fresh water that is readily available. And, as supplies of fresh water become more and more critical, studies are made of grand new projects such as those considered by the Global Infrastructure Fund and some, such as Libya's new "artificial river," are implemented (23). But only basing our civilizations on fresh water is limited thinking. Nature has provided us with the plants and animals for us to develop seawater-based agriculture (including aquaculture). And with the time freedom that it will bring, as freshwater agriculture did 10 000 years ago, we can add new cultures to the world's existing palette.

Table 3. Essential elements in seawater and *Salicornia bigelovii* Torr. straw.

Element	Seawaler conc.	kg ha^{-1} in 3 meters sea water	Halphyte conc.	kg ha^{-1} in straw	Recovery %
Potassium	380 mg/l	1.17 10^7	1.76%	317	2.7 10^{-3}
Calcium	412 mg/l	1.27 10^7	0.98%	176	1.4 10^{-3}
Magnesium	1290 mg/l	3.96 10^7	0.37%	66.6	1.7 10^{-4}
Sulfur	905 mg/l	2.78 10^7	0.30%	54	1.9 10^{-4}
Phosphorus	60 µg/l	1842	0.07%	12.6	0.7
Iron	2 µg/l	61	118.0 ppm	2.1	3.4
Manganese	0.2 µg/l	6.1	33.6 ppm	0.60	9.8
Boron	4.4 mg/l	1.35 10^5	30.4 ppm	0.55	4.1 10^{-4}
Zinc	4.9 µg/l	150	6.2 ppm	0.11	0.07
Copper	0.5 µg/l	15.4	3.1 ppm	0.056	0.36

Figure 6. Concept of a community based on fish and halophyte farming.





Artist's concept of the project to pump seawater from Puerto Peñasco's harbor. Source: Environmental Research Laboratory.

We can produce fish, shrimp—a myriad of aquatic animals—via marine aquaculture. Then the seawater that the aquatic plants and animals inhabit, with their nutrients added, will flow inland and be utilized to create Venice-like cities, where the canals, human-sewage system, mineral extraction, food production, landscaping, and parks and even golf courses are all based on seawater.

Some fresh water will be required for direct human consumption and specialized processes, but limited freshwater resources can be sparingly used, or fresh water imported or produced by desalting for specific purposes at a cost that does not limit community development.

Minerals from the sea can be extracted directly, as is done in large seawater evaporation facilities. At Guerrero Negro, Baja California, Mexico (a subtropic area), 40 000 ha of "land" are used to produce 7 million metric tons of salt per year; utilizing solar energy directly for heating the water and evaporating it or by the energy transferred from the wind that is driven by the sun. Half of that salt is transported to Japan, and it represents half of all of Japan's import of sodium chloride. Sodium chloride is used to produce many chemical products, including polyvinyl chloride, sodium hydroxide, sodium carbonate, sodium sulfate, hydrochloric acid, sodium phosphates, sodium chlorate, and sodium chlorite. The electrolysis of sodium chloride provides most of the chlorine. Seawater is also a major source of magnesium metal. These resources from the sea are used by Japanese industry and distributed around the world as part of Japanese automobiles and other products from a culture that has limited land area, and, as a result, brings more from the sea into their land than any other peoples (24).

Mineral extraction from the sea is also now done at Guerrero Negro in the process of biological plant production. The principal oil seed halophyte being developed on a commercial scale (SOS-10) extracts 317 kg ha^{-1} of potassium in its aboveground straw mass per year, and amounts of other minerals (Table 3) (25). If the straw is simply plowed back into the ground at the production site, the minerals are added to the soil close to the sea. If the straw is used in a product that is imported inland, the minerals are more widely distributed. A project is underway to pump seawater from Puerto Peñasco's currently contaminated harbor to be blended with freshwater municipal sewage and used for irrigation of ornamental halophytes (including a golf course) to beautify the town and as the principal source for a major new industry of food, fodder and fuel production by large-scale SOS farms. Preliminary tests have been conducted using the harbor water, and, to date, the hydrocarbon and other contaminants from a 400-vessel shrimp fleet have not proved detrimental.

Puerto Peñasco is a community with an existing infrastructure. Figure 6 presents proposed flows for a new 1000 person village conceptualized for Mexico.

In Ras Al Zawr, Saudi Arabia, where there is now a 300-ha SOS-10 farm, conceptual plans are being developed for a completely new integrated rural and urban community based on seawater, with a population in the multiples of 10 000 people. Figure 7 shows an initial concept of a community which covers a total area of 45 000 ha, with 15 000 ha of seawater-irrigated SOS farms. The conceptual community includes natural ecological preserves, created wetland including reforested mangrove areas, fish and shrimp production area, large-scale SOS farms, and developmental industries using products from the farms for a blended petro- and biochemical future. A major feature is the integration of what are normally considered rural and urban functions (26).

A requirement for the proposed Saudi saltwater community is that, in its total activities, it remove more carbon from the atmosphere than it adds to the atmosphere as a result of its combined use of fossil and biofuels.

The current planning for Saudi Arabia includes developing 200 000 ha of seawater-irrigated farms to produce 120 million kg of high-quality vegetable oil per year for human consumption. That will be good business, and with the increasing world demand for food, millions of additional ha of halophytes will be developed primarily for food production. It is possible that the straw, as a byproduct, could be used for fuel; particularly for stationary power production. The straw can also serve as a biochemical feedstock. An illustrative example of halophytes as a source of fuel for transportation is given in Figure 8. The figure presents a concept that will only be realized several years in the future and will require that a decision be made to "balance the contribution of carbon from transportation." This could be done by powering the correct percentage of vehicles completely on biofuel or, alternatively (and metaphorically more interesting), we could move to a blend of fossil and biofuels. If SOS oil is blended with diesel fuel, in this analysis at a 30% level, then whether the fuel is used for power production, burned in an automobile, whatever, its total contribution of CO_2 to the atmosphere will be exactly balanced by that removed by the complete plant and stored. This is true for the most conservative scenario of simply plowing the straw back into the ground; however, if there is any use of the straw, which is expected, where a greater percentage is stored such as in the manufacture of "wood-like products," then for every mile an automobile is driven using the blend fuel, there will be a positive contribution to the carbon balance of the atmosphere. There, of course, remain other exhaust components besides CO_2 to be addressed; which is not impossible with resources (wealth) and effort.

We do not suggest that blended-fuel vehicles will happen immediately. Nevertheless, the senior author of this paper drives, on an experimental basis, a "diesel"-powered automobile that is run on a blend of fossil and SOS fuel.

Also, we have used *Salicornia* straw to produce pulp for paper manufacturing in a preliminary way. One day, minerals from the sea might flow inland in the form of paper products–to be used, composted and returned to the land along with the stored carbon.

A principal objective is to provide a variety of inputs and possibilities for what will undoubtedly need to be a large number of scenarios to balance the carbon cycle of the atmosphere, where a criterion for serious consideration is degree of wealth creation.

With the world population growing at a rate that is the equivalent of adding a new Mexico into the earth's population every year–and as our associates in Mexico tell us, Mexico is adding the equivalent of a new Costa Rica to its population every year–population stabilization has to be a major objective for the future. If we do not make that effort, we will have what Norman Myers referred to as "discontinuities ahead" (27). We can only avoid those discontinuities and have an improved environment if we can offer the peoples of the earth increased wealth. Our current economic pie is simply too small. It must be dramatically improved, and with that improvement will come, as it was shown for Korea, the necessary population stabilization.

Even under the most optimistic of scenarios, we are going to have to add extensively to existing communities and build many totally new ones. The new constructions will be as many as humans have built since we began building our communities. The edge of the sea will continue to be a major attractant for us. If, in

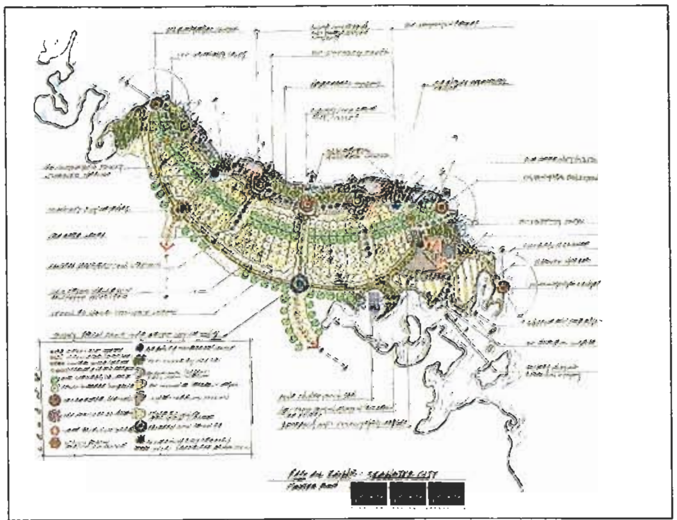
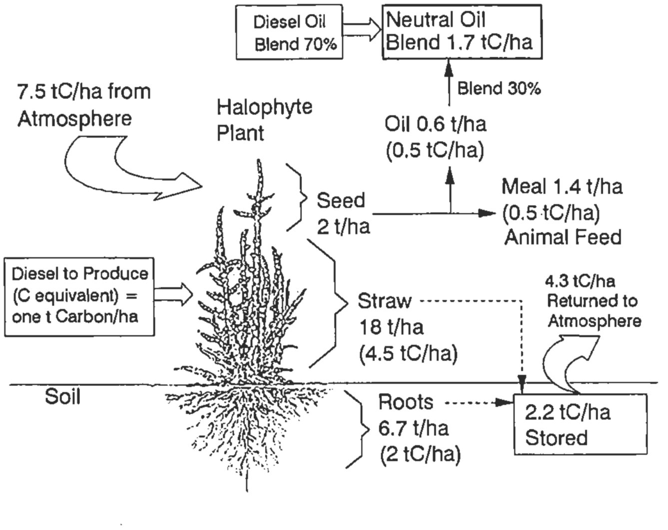
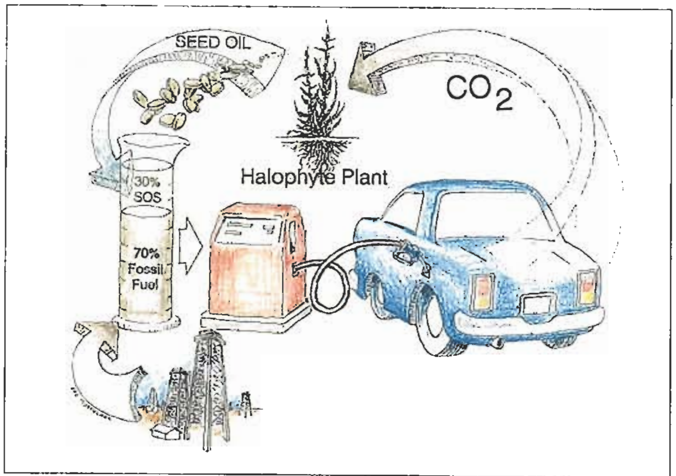


Figure 7. Conceptual plan for Ras Al Zawr seawater community, Saudi Arabia. Total area equals 42 012 hectares, of which 15 220 hectares are SOS farms. Note the seawater canals, created wetlands and ecological preserves.

Figure 8. The halophyte, *Salicornia bigelovii* Torr., yields roughly 20 tons ha^{-1} yr^{-1} of biomass (aboveground); the roots are around one-third of the aboveground biomass, or 6.7 t. The oilseed yield is 2 tons ha^{-1} yr^{-1}, which is 30% oil (0.6 t) and 70% meal. The balance of the aboveground biomass is straw containing 25% carbon (C), while the root is estimated to be roughly 30% carbon, and the oil 85% carbon. Diesel oil equivalent to 1 ton ha^{-1} yr^{-1} is required to grow the crop. Decomposition experiments have indicated that one-third of the carbon in the soil can be expected to enter long-term storage. If the straw is plowed under, the biomass carbon committed to long term storage is (1/3) x [(18 x 0.25) + (6.7 x 0.3)] = 2.2 t C ha^{-1} yr^{-1}. From this must be deducted the carbon equivalent of the diesel fuel, leaving a net retired carbon of 2.2 - 1.0 = 1.2 tons ha^{-1} yr^{-1}. The halophyte oil carbon amounts to 0.85 x 0.6 = 0.5 tons ha^{-1} yr^{-1}. To produce a mixture of petroleum-based diesel and halophyte oil, neutral with respect to the atmospheric carbon balance, the percent of halophyte oil in the mixture should be 100 x 0.5/(1.2 + 0.5) - 30%.





Halophytes as a source of fuel for transportation.
Source: Environmental Research Laboratory.

50 years, one-half of us, i.e., the equivalent of the entire world's population today, continue to live within 50 km of that interface, many existing and new communities will have to utilize resources that are currently being lost in flows into the sea. But, even with a maximum effort, to use those now wasted resources, it seems likely to us that we will only have a world that has an increasing quality of life if we have "reversed the flow" for a large number of new communities which will receive water and nutrients from the sea instead of sending water and pollutants into it.

If one-half the increased population lived within our 50-km coastal zone, and if one-half of that one-half lived in new cities, we would need the equivalent of 200 new Cairos; a staggering, but not impossible, vision. These new communities will not develop by four new large-scale starts every year for 50 years (to give us 200). Instead, they will grow over the next 50 years from many embryonic beginnings, such as those reported here. And, instead of 200, we will have many more smaller communities and cities, which evolve in many diverse ways.

Whatever their number and size, these new communities will have the advantage that their "Nile" will flow from an infinite source (31).

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