Again, however, these estimates can only be highly tentative. Production might well exceed 2 million lb., and less labor might be required. But it is not inconceivable that in Abu Dhabi, which is in the midst of an oil boom, wages could increase by more than the 100% we have allowed.

Although Abu Dhabi, with a population of about 40,000 and an area of some 26,000 square miles, is hotter and drier than Puerto Penasco, the 2 areas are not dissimilar climatically (Table 3). The Shaikhdom grows few vegetables of its own. These are seasonal and are cultivated at an inland oasis. Most of the high-quality vegetables available are air-freighted from Lebanon and sell for as much as $1.50/lb. But Shaikh Zaid, a progressive leader, is less interested in vegetable production than he is in the establishment of a research center. Construction of this center started late in 1969 on Jazirat as Sa'Diyat (the Isle of Happiness), about a mile and a half from the island on which Abu Dhabi city is located. The power/water/food facility is to be about 10 times the size of that in Sonora.

A desalting plant for the Laboratory's project was fabricated by our staff in Tucson before being disassembled for shipment to Abu Dhabi. A resident Environmental Research Laboratory staff of, all together, 10 to 12 persons, was in Abu Dhabi in 1970. About 2 years from now, direction of the facility will be turned over to the Shaikhdom. So 3 Abu Dhabians, the first of a number, journeyed to Tucson for a 6-month training program there and at Puerto Penasco.

Table 3. Comparative climatic data: Puerto Penasco, Tucson, and Abu Dhabi

Climatic data	Location: Puerto Penasco, Sonora, Mexico	Tucson, Ariz.	Abu Dhabi
Elevation (ft)	40	2430	6
Latitude	31°20'	32°15'	24°15'
Years of record	20	63	14
Mean rainfall (inches)			
Summer	1.76	6.38	0.16
Winter	1.64	4.53	1.42
Annual	3.40	10.91	1.58
Temperature (°F)			
January mean	51.8	50	64
Longterm low	17	6	50
July mean	84.9	86.1	93
Longterm maximum	106	115	114
Annual mean	68.2	67.3	78

Controlled-environment agriculture

The experience in Abu Dhabi then, should enrich enormously the data on controlled-environment agriculture, the potential of which should be self-evident. Adjacent to the coastal deserts and 100 ft or less above sea level (a reasonable lift to provide fresh water if it could be obtained economically from the ocean) there are 2.6 million miles^2 of land.

Economic developments have dictated the settlement of some of these areas, for many, like Abu Dhabi, are blessed with natural treasures. The diamondiferous gravels of South West Africa are another example, and the oceans off many arid shores teem with marine life. More important, however, may be the fact that on a planet beset by burgeoning population, desert coasts could become crucial refuges. And because they now are thinly populated, by and large, they might be settled in an orderly, systematic fashion. This would avoid some of the problems of the American West, where great migrations have occured without regard for ecological constraints (3).

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Because all work at the Environmental Research Laboratory is an interdisciplinary team effort, it would be impractical to name each individual who took part in this research. The authors are especially grateful, however, to F. Michael Carroll, Merle H. Jensen, Glen Richards and James J. Riley, who contributed data to this paper and read all or parts of the manuscript.

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USE OF CONTROLLED ENVIRONMENT FOR VEGETABLE PRODUCTION IN DESERT REGIONS OF THE WORLD

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Many of the world's desert areas remain uninhabited but could be made productive, even attractive for settlement, if certain necessities were present. One such necessity is food. If crops are to be grown, water for irrigation and an environment conducive to good crop production are needed. Water is not available in most desert regions and must be provided together with the required power to pump this water from wells and into the area of crop production. The daily temperatures in most desert areas are adequate for crop production during most months of the year, but such hazards as sandstorms and insect invasions often make them undesirable for vegetable production; and providing water for irrigation is expensive. Experiments now are being conducted by the Universities of Arizona and Sonora in the growing of vegetables in controlled-environment, air-inflated greenhouses. The experimental unit is located in Puerto Penasco, Sonora, Mexico, on the east coast of the Gulf of California. The following are procedures and results obtained to date from tests which have been in progress since October 1968 (Fig. 1, 2).

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Fig. 1. Cucumber Varietal trial grown in beach sand in controlled-environment greenhouse at Puerto Penasco, Sonora, Mexico. February 1969.

Fig. 2. Anaheim chili peppers grown in beach sand in controlled-environment greenhouse at Puerto Penasco, Sonora, Mexico. May 1969.

Leaching the beach sand

Once the plastic covers are in place and the greenhouses are inflated, the beach sand is leached to remove excess salt. The amount of water required for this depends upon the crop grown, but no more than 1/2 gal of water per ft^2 of growing area need be applied. Once the sand has been leached, there is no need for further leaching unless the plastic cover remains off the greenhouse for 2 months or more, as salt sprays from the Gulf will drift into the growing area during high winds. Water for leaching is applied with overhead sprinklers. The salt concn of this water is approximately 40 ppm., or of the same quality as that used to irrigate the various vegetable crops. Although this technique separates out most of the NaCl, the sand remains highly calcareous, due to deposition of shells and other marine material. Even after leaching, the pH of the sand is between 7.8 and 8.2. No fertilizers are applied prior to planting, even though the sand lacks essentially all the elements necessary for plant growth with the exception of Ca.

Initially, the plants are set out or seeded into separate plots of either beach sand or a medium of sphagnum peat moss and vermiculite. Because the vegetables grow equally well in each medium, the use of the peat moss-vermiculite medium has been abandoned.

Planting procedure

To August 1969, 18 different kinds of vegetables have been grown in the air-inflated plastic greenhouses. In all, 85 cultivars of vegetables and 6 cultivars of strawberries have been tested for growth and yield characteristics (Table 1).

Table 1. Environmental Research Laboratory greenhouse vegetable variety trial, Puerto Penasco, Sonora, Mexico, 1968-1969.

BEAN (SNAP), *Phaseolus vulgaris*
- Black valentine
- Green Crop
- Kentucky Wonder

BEET, *Beta vulgaris*
- Detroit Dark Red

BROCCOLI, *Brassica oleracea,* var. *italica*
- Spartan Early

CABBAGE, *Brassica oleracea,* var. *capitata*
- Market Prize
- Wisconsin Copenhagen

CANTALOUPE, *Cucumis melo*
- Rio Gold

CARROT, *Daucus Carota*
- Danvers Red Core

CAULIFLOWER, *Brassica oleracea,* var. *botrytis*
- White Heat

CUCUMBER, *Cucumis sativus*
- Bambino 67303
- Best Seller
- Butcher's Disease Register
- Cherokee
- Gemini Hybrid
- Green Spot
- Green Stick
- HiYield Hybrid
- MSU 69026
- Perirex 66036
- Princess
- Saticoy Hybrid
- Spartan Valor
- Spottex '61
- Tosca 66340
- Triumph Hybrid

EGGPLANT, *Solanum melongena*
- Black Beauty
- Black Magic Hybrid

LETTUCE, *Lactuca sativa*
- Bibb Head
- Buttercrunch
- Empire
- Fulton
- Grand Rapids
- Great Lakes
- Mesa 659 M.T.
- Minetto
- Minetto M.T.
- Salad Bowl
- Slobolt

OKRA, *Hibiscus esculentus*
- Clemson Spineless
- Spineless Green Velvet

ONION, *Allium cepa*
- Early Yellow Globe
- Ebenezer
- Mt. Blanc
- Red Globe
- White Spanish
- Yellow Sweet Spanish

PEPPER, *Capsicum annum*
- Anaheim Chili
- California Wonder
- Cuban
- Fresno
- Hungarian Yellow Wax
- Jalapeno
- Red Chili

RADISH, *Rhaphanus sativus*
- Cherry Belle
- Early Scarlet Globe
- Red Boy
- Red Prince

SPINACH, *Spinacia oleracea*
- America Bloomsdale

SQUASH, *Cucurbita pepo*
- Zucchini

TOMATO, *Lycopersicon esculentum*
- Ailresist
- Basket Pak
- Early Salad
- Extase
- Floradel
- Globeset
- Hotset
- Lucky
- Maascross
- Manalucie
- Manapal
- Michigan-Ohio
- Red Cherry
- Red Pear
- Red Plum
- Red Sugar
- Red Tiny Tim
- Roma
- San Marzano
- Tropic
- Tuckcross-O
- Wolverine 119
- Yellow Tiny Tim

WATERMELON, *Citrullus lanatus*
- Chris-Cross
- Seedless Hybrid 313
- Seedless Hybrid 317

SMALL FRUITS

STRAWBERRY, *Fragaria* sp.
- Aliso
- Fresno
- Sequoia
- Solana
- Tioga
- Torrey

Radishes, spinach, beets, and carrots are seeded directly into the beach sand. Other crops, with the exception of the cucurbits, are seeded in trays of pure vermiculite; approximately 1 wk after germination, the seedlings are either spotted out into peat pots that contain a peat moss-vermiculite medium and later transplanted into the greenhouse beds, or else they are spotted out directly into the beds. The latter procedure is becoming the one most often used.

Cucurbits are seeded directly into peat pots that contain the peat moss-vermiculite medium and are planted in the greenhouse beds approximately 6-10 days after germination. Transplants in a peat moss-vermiculite mixture are watered with a nutrient solution on a constant liquid-feed schedule, meaning that each time the plants are given water there is a dilute concentration of nutrient elements present in the correct proportions (Table 2).

Nutrient solutions and irrigation

Once the plants are growing in the beach sand, they are put on one of two constant liquid-feed solutions. Solution A (Table 2) is for fruit-bearing plants from the time they are planted in the sand until the first fruit set. From the first fruit set until crop termination, Solution B (Table 2) is used. Root crops and leafy vegetables are given Solution A from the time they are first growing in the sand until terminated.

Both nutrient solutions are made from dry commercial grade fertilizer, except for the micro-elements, which are reagent grade. The fertilizer compounds are the following: $MgSO_4.7H_2O$; KH_2PO_4; KNO_3; and $Ca(NO_3)_2$). The micronutrients are H_3BO_3; $MnCl_2.4H_2O$; $CuCl_2.2H_2O$; MoO_3; and $ZnSO_4$. All fertilizer compounds are completely water soluble and made up as stock solutions.

Table 2. Concn of elements in nutrient solutions, experiments at Puerto Penasco.

Element	Solution A (ppm)	Solution B (ppm)
N	144.00	260.00
P	62.00	62.00
K	156.00	156.00
Mg	48.00	48.00
Ca	165.00	330.00
S	64.00	64.00
Fe	5.00	5.00
B	1.00	1.00
Mn	0.40	0.40
Cu	0.02	0.02
Zn	0.09	0.09
Cl	0.50	0.50
Mo	0.30	0.30

A measured quantity from each stock solution is added to desalted water to make up the final solutions, as listed in Table 2.

The fertilizer solutions are applied through the irrigation system. Four standard types of irrigation systems have been used. One emits a fine spray over the growing area from above-ground sprinklers and is used for such closely spaced crops as radishes. Another waters each plant individually from a spaghetti-like network of tiny plastic tubes. The other two systems release the water in small droplets at soil level. The type of irrigation system depends largely on the plant spacing.

Water is applied as needed, and some crops receive as much as 4 applications each day. In each application only enough water is added to moisten the sand beds to the depth of root penetration. Spacing of the various kinds of vegetables are listed in Table 3.

Pollination

To facilitate pollination, plants that have complete flowers are vibrated daily with a battery-operated pollinator. On monoecious plants the pollen is transferred mechanically from male to female flower by a camel-hair brush. The only exception is cucumber, as all varieties grown at Puerto Penasco are parthenocarpic. New procedures are being devised to hasten pollen transfer.

Pest control

Because the growing beds are free of weeds, no weed control measures are taken. Thus far, spray materials used for disease and insect control have included Malathion and $CuSO_4$. As a precaution against bringing in diseases, personnel entering the greenhouses must walk through a shoe bath that consists of a 3% Na_3PO_4 and chlorox solution.

The tomatoes in some experiments and the cucumbers in all experiments are pruned to a single stem and trained to plastic twine suspended from an overhead wire that runs parallel to the sand surface 6 ft above the beds (1). Eggplant and pepper plants are trained to stakes.

Table 3. Vegetable plant spacing in Puerto Penasco greenhouses.

Vegetable	Distance (inches)		
	Between single rows	Between double rows[a]	Within rows
Bean (snap)	40	--	3-4
Beet	6	--	4
Broccoli	14	--	14
Cabbage	14	--	14
Cantaloupe (2 plants/hill)	96	--	60
Carrot	6	--	4
Cauliflower	18	--	18
Cucumber	18	32	18
Eggplant	12	36	24
Lettuce	9	--	9
Okra	12	--	12
Onion	6	--	4
Pepper	12	36	24
Radish	6	--	2-3
Spinach	4	--	4
Squash (2 plats/hill)	42	--	42
Tomato	12	36	24
Watermelon (2 plats/hill)	96	--	60

Growing environment

Air within the greenhouse circulates through a spray of 78°F seawater at a velocity that permits a given volume of air to be washed every 2 min. As a result, the air is maintained at close to 100% relative humidity and at a temperature very near that of the seawater. The greenhouses are shaded during the summer to deflect much of the infrared rays. A complete discussion on the growing environment and how it is maintained is presented in the previous paper in this symposium.

When outside environmental conditions permit, each unit is maintained at a warm, moderate or cool temperature range. Listed below are the kinds of vegetables planted into each unit:

Unit 1 - Warm temperature (80-100°F day, 75-80° night)

Squash	Cantaloupe
Watermelon	Cucumber

Unit 2 - Moderate temperature (75-85° day, 60-65° night)

Tomato	Eggplant
Pepper	Onion
Okra	

Unit 3 - Cool temperature (70-80° day, 50-60° night)

Spinach	Broccoli	Beets
Radish	Carrots	Lettuce
Cabbage	Beans	Cauliflower

Temperatures are governed by the amount of water sprayed in the packed column through which the air circulates. During the summer, naturally, these temperature ranges are not maintained because of high outdoor temperatures. The temperature ranges in all units are nearly the same, approximately 70-85°F at night and 85-110° during the day.

Harvesting is done by hand, and the yields are recorded. Any other factors that seem worthy, such as quality, water used in growing the crop, etc., are noted. All vegetable plantings are replicated and statistically analyzed for any differences that occur. Because of the great quantity of data collected, only those results that seem most pertinent will be given in this publication.

Results and discussion

Of the varieties tested, it is evident that those that were developed in hot, humid areas of the world respond best to the environments maintained in the air-inflated greenhouses in Puerto Penasco.

Tomato cultivars developed in Florida, such as 'Floradel', 'Manapal' and 'Tropic', seem to do well, but those commonly grown in conventional greenhouses, such as Michigan-Ohio, 'Wolverine' and 'Tuckcross-O', do not. Undesirable characteristics, e.g., adventitious root production and extended flower clusters, were common in many tomato cultivars–except those developed in Florida or in other hot, humid environments. Color development of the tomato fruit was not always an even deep red, possibly because of the inhibition by the warm temperatures of the proper synthesis of lycopene. Another possible explanation for improper coloring may be that insufficient levels of K in the soil cause the fruit disorder termed *blotchy ripening*. While the exact role of K in tomato fruit ripening is not known, it has been speculated that K is involved in the synthesis of lycopene (5). Nutritional studies are being initiated to see if this ripening disorder can be solved either by increasing the rate of K in the first fertilizer application and/or lowering temperatures within the greenhouse.

Condensate collecting on the surfaces of the tomato fruit appears to cause excessive micro-cracking of the fruit surfaces, especially on large-fruited varieties. This also was noted in earlier work done at the Environmental Research Laboratory (2). This is not as great a problem on the European and cherry variety types.

Lettuce cultivars responded quite differently to the hot, humid environment. Although all leaf and bibb types have done well, no head cultivars, except for Minetto, have formed marketable heads.

Broccoli, cauliflower, and cabbage thus far have not produced good marketable heads under these environmental conditions, and the one variety of carrots grown has not produced roots of good color. Otherwise, there are one or two cultivars of each kind of vegetable that do well.

Eggplant and peppers grow to a much greater height in the hot, humid environment than they commonly do outdoors. Most vegetables tend to be more succulent and brittle than is usually the case when they are grown outside.

On occasions, excessive soluble salts build up in the sand medium. In environments where the relative humidity is lower than 80%, one would expect damage to the plant and reduction of yield, but this has not been true in Puerto Penasco unit, where the relative humidity is approximately 100%. Apparently the effects of moisture stress usually associated with high salinity are minimized or nullified under such conditions (Riley, J.J. 1968. Physiological response of plants to salinity. Unpub. Ph.D. dissertation, Univ. Ariz.) (4). It is possible that the standard for salinity tolerance under these conditions will have to be raised. Since the sand medium remains highly calcareous, even after leaching, P is in a form not readily available to the plants. At high pH values, complex Ca phosphates are formed; therefore, the solubility of the applied P is seriously impaired. Furthermore, at pH values above 7, excess Ca may hinder P absorption and utilization (3). Research soon will be initiated to determine if the addition of some phosphoric acid to the nutrient solution might supply the element P more readily to the plants, and at the same time neutralize the soil solution around the roots of the plant.

Despite the high Ca levels in the sand, tissue analysis shows low levels of Ca in tomato tissue. This may be due to reduced translocation of Ca from the roots to the leaves as a result of the lower transpiration rates in the high humidity atmosphere. On the other hand, it may be due to unavailability of the Ca in the sand. With the use of acid-forming fertilizers, it is possible that calcium would readily be released to the soil solution.

With all vegetable crops, except cantaloupe, there is good fruit set and no problem in pollination. Possibly bees will have to be used to get good fruit set on cantaloupe, provided the bees are not hindered by the high temperatures and humidity.

Because of the heat and the intensive light, many crops mature more rapidly (Table 4) than those same crops grown outside. Bibb lettuce in the greenhouses matured in 35 to 40 days; in open fields, 58 to 62 days are required. Consequently, it should be possible to harvest more crops per year from the controlled environment.

Yields from the first winter crops at Puerto Penasco (Table 5) were far higher, predictably, than those of open fields. Compared to harvests that would be expected from conventional greenhouses, the quantities of lettuce and radishes were about the same, the tomato yield higher, and that of cucumbers less. Production from the tomato experiment probably would have been greater had it not been for a short harvest period, 60 days in the Sonoran tests vs. the usual 90 days in conventional greenhouses.

One reason the yields of some crops are much greater in the Puerto Penasco experiments than outdoor field production (Table 5) is because in the greenhouse, no space is left between beds for tractor implements. With radishes, etc., the entire greenhouse planting area is planted except for a center aisle. Also, higher yields are a result, in some cases, of a harvest period longer than those in the field.

Crops in the Puerto Penasco greenhouses remained virtually free of disease. Except for a minor infestation of mature tomatoes and cucumbers by the fungus *Rhizoctonia*, which was suppressed with $CuSO_4$, there has been no disease problem thus far. Experimental trials presently are being conducted with the use of systemic fungicides for fungus controls. Most plant specialists would expect fungus diseases to be a problem in an environment so humid. A possible reason fungus diseases are not a real problem might be because a given volume of air within the greenhouse is put through a spray of seawater every 2 min. Also, all circulating air is washed.

The results of research done to date in Puerto Penasco, Sonora, Mexico, on vegetable production in air-inflated greenhouses looks most promising for the very near future.

Table 4. Growing and harvest periods in days for winter crops grown in greenhouses at Puerto Penasco, Sonora, Mexico[a] (1968-1969).

Puerto Penasco greenhouses			Comparative data for U.S.			
			Field crops		Greenhouses	
Kind of vegetable	Growing period	Harvest period	Growing period	Harvest period	Growing period	Harvest period
Carrots	70	--	70	--	--	--
Cucumber	100	60[b]	90	30	--	--
Eggplant	130	50	130	40	--	--
Lettuce[c]	40	--	70	10	--	--
Okra	100	60	118	60	--	--
Peppers (bell)	146	41	155	55	--	--
Chili	146	41	--	--	--	--
Radish	30	--	30	--	--	--
Squash Zuchini	105	60	80	30	--	--
Tomato	140	60	140	50	190	90
Water-melon	125	45	120	30	--	--

[a]Growing periods and harvest periods depend greatly on local conditions. Above field yields are based on summer data. Harvest period - growing period = no. of days to first harvest.

[b]European type.

[c]Bibb and leaf types

Table 5. Winter crops grown in greenhouses at Puerto Penasco, Sonora, Mexico, (1968-1969).

Puerto Penasco		Comparative per acre yields for U.S.		
Kind of vegetable	Marketable yield/acre, greenhouse	Approx. avg, greenhouses	Approx avg, field	Good field
Carrots	800 bu (50 lb)	--	390 bu[b]	600 bu[b]
Cucumber	3000 bu (48 lb) (European type)	--	155 bu[b]	500 bu[b]
Eggplant	760 bu	--	300 bu[b]	500 bu[b]
Lettuce[c]	3500 crtn[d]	3500 crtn	360 bu[b]	600 crtn[b]
Okra	40 T	--	--	5 T
Peppers (Bell)	1200 bu @25 lb	--	245 bu[b]	500 bu[b]
(Chili)	640 bu @25 lb	--	--	--
Radish	40,000 bunch[e]	40,000 bunch	--	20,000
Squash[f]	555 bu	--	--	400 bu[b]
Tomato	46 T	40 T[a]	10 T	30 T
Watermelon	5.5 T	--	3.5 T	6.5 T

[a]Based on a harvest period of 90 days.
[b]From: Knott, James E. 1957. Handbook for vegetable growers. John Wiley & Sons, Inc., New York.
[c]Bibb and leaf types
[d]2 doz heads/carton
[e]12/bunch
[f]zucchini

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