SERI/STR-231-2360
UC Category: 61a
DE84004522

Cultivation and Conversion of Marine Macroalgae

Final Subcontract Report

J. H. Ryther
T. A. DeBusk
M. Blakeslee

Harbor Branch Institution
Fort Pierce, Florida

May 1984

Prepared under Subcontract No. XK-2-02172-01

SERI Technical Monitor: Robins McIntosh

Solar Energy Research Institute
A Division of Midwest Research Institute

1617 Cole Boulevard
Golden, Colorado 80401

Prepared for the
U.S. Department of Energy
Contract No. DE-AC02-83CH10093

Printed in the United States of America
Available from:
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161
Price:
Microfiche A01
Printed Copy A05

PREFACE

This report is the final report prepared under subcontract XK-2-0217-01 for FY1983. The work was performed under subcontract to SERI with funds provided by the Biomass Energy Technology Division of the U.S. Department of Energy.

Robins P. McIntosh

Robins P. McIntosh
Aquatic Species Program

Michael Z. Lowenstein
Biomass Program Office

Approved for
Solar Energy Research Institute

Stanley R. Bull

Stanley R. Bull, Director
Solar Fuels Research Division

SUMMARY

Objective

The objective of this project is to conduct research that will lead to the development of an alternative ocean energy farm concept that would not be dependent upon deep ocean water or other extraneous sources for its nutrient supply and that could be located in shallow, near shore, and protected coastal ocean areas. Specifically, there are five tasks reported in this document:

I) Determination of the annual yield of Ulva in non-intensive cultures.

II) Evaluation of the effect of carbon concentration on Gracilaria and Ulva yields.

III) Evaluation of spray/mist culture of Ulva and Gracilaria.

IV) Species screening for the production of petroleum replacement products.

V) Synthesis Analysis, and Economic/Energy Evaluation of culture data.

Discussion

An alternative concept to open ocean culture is a land-based energy production system utilizing saline waters from underground aquifers or enclosed coastal areas. Work on this concept was begun in 1979. Research began with a screening program designed to evaluate growth and biomass production of all macroscopic algal species that could be obtained in adequate quantity in the central Florida area. A total of 42 species were grown in specially adapted burial vaults. These included 16 green algae (Chlorophyta), 2 brown algae (Phaeophyta), and 18 red algae (Rhodophyta). Of these, the most successful and suitable species were a strain of Gracilaria (a red seaweed) and Ulva (a green seaweed). These two species have a high carbohydrate content that may be anaerobically digested to methane gas. The demonstrated energy yields of Gracilaria and Ulva are 2.5×10^6 and 3.0×10^6 J/m^2 day, respectively.

Gracilaria may be grown in channels or raceways on land or in shallow coastal waters in tropical to semitropical latitudes. At an offshore site, the seaweed would presumably be confined by a fence or other barrier. Within the enclosure, the culture is maintained at a density of approximately two kilograms wet weight per square meter. At this density, the algae is compacted such that normal wind and tidal action will not cause the algal mass to drift and accumulate unevenly. At brief intervals during the day, the culture is mixed and rotated by compressed CO_2 from pipes distributed throughout the culture systems.

Well-nourished Gracilaria exposed to full sunlight at such latitudes will double its biomass in 1 to 4 weeks, depending on the season, water flow, and other variables. After its biomass has doubled (i.e., from 2 to 4 kg/m^2) the incremental growth is harvested to return the crop to a starting density that will ensure continued optimal yield. The doubling of biomass will be accompanied by the utilization of all stored nutrients and a reduction of elemental nutrients in the plant tissues to roughly half the initial concentrations. Enrichment of the new starting crop following harvest could conceivably be accomplished onsite at the seaweed farm, but the rapid uptake and storage of nutrients by depleted seaweeds makes possible a simpler, more efficient enrichment process, known as pulse fertilization.

Work during the past year focused on reducing the energy inputs to the culture system.

Conclusions

1) Under non-energy intensive culture conditions Ulva yielded an average of 6.8 gdw m^2d^{-1} (10.8 dry tons/Ac/yr) (250 days).

2) Under energy intensive culture conditions Ulva yielded an average of 18.8 gdw m^2d^{-1} (30 dry tons/Ac/yr) (250 days).

3) Gracilaria photosynthesis correlated best with bicarbonate concentration, whereas Ulva photosynthesis correlated best with the total inorganic carbon concentration.

4) Total extractable lipid content was determined for 20 species of macroalgae. The total lipid content ranged from 5 mg lipid/gm for Solieria sp. to a high of 80 mg/gm for Caulerpa verticillata.

5) Aeration was decreased twelve fold with a minimal impact to productivity. Aeration with a one sixth duty cycle provided only during daylight hours was found to stimulate growth nearly as well as continuous aeration.

TABLE OF CONTENTS

Page

Task 1 - Determination of Non-intensive Ulva Culture Annual Yields 2

Task 2 - Evaluation of the Effect of Carbon Concentration on Gracilaria and Ulva Yields 4

Task 3 and 4 - Evaluation of Spray/Mist Culture of Ulva and Gracilaria; and Development of Three Dimensional Ulva Culture Technology 24

Task 5 - Species Screening for Production of Petroleum Replacement Products 25

Task 6 - Synthesis, Analysis, and Economic/Energy Evaluation of Culture Data 28

Appendix A - Energy Costs 70

Appendix B - Pumping Formulae 72

Appendix C - Blowers Operating vs. Fixed Costs 75

Appendix D - Seaweed Drying Calculations 76

Appendix E - Productivity and Carbon Demand 77

References 79

LIST OF FIGURES

Figure		Page
1	Effect of Algal Carbon Assimilation on Relative Carbon Species Concentration	9
2	Photosynthesis vs. CO_2 (*Gracilaria*)	12
3	Photosynthesis vs. HCO_3 (*Gracilaria*)	13
4	Photosynthesis vs. CO_3 (*Gracilaria*)	14
5	Photosynthesis vs. T.I.C. (*Gracilaria*)	15
6	Photsynthesis vs. pH (*Gracilaria*)	16
7	Photosynthesis vs. CO_2 (*Ulva*)	17
8	Photosynthesis vs. HCO_3 (*Ulva*)	18
9	Photosynthesis vs. CO_3 (*Ulva*)	19
10	Photosynthesis vs. T.I.C. (*Ulva*)	20
11	Photosynthesis vs. pH (*Ulva*)	21
12	Specific Growth Rate of *Gracilaria* (clone 002) as a Function of Temperature	31
13	Specific Growth Rate of *Gracilaria* (clone 017) as a Function of Temperature	32
14	Productivity vs. Aeration Time (*Gracilaria*)	39
15	Productivity vs. Aeration Time (*Ulva*)	40

LIST OF TABLES

Table		Page
1	Seasonal Productivity of Two *Ulva* Clones	3
2	Effect of Carbon Assimilation on Carbon Species in Seawater	10
3	Extractable Lipid Concentrations in Marine Algae	27
4	Pump Capital costs	35
5	Diesel Generator and Engine Capital Costs	36
6	Productivity of *Gracilaria* in Non Aerated Cultures	41
7	Effect of Aeration Time on N-Uptake by *Gracilaria*	43
8	Blower and Compressor Capital Costs	45
9	Rotary Dryer Capital and Operating Costs	47
10	Costs for Carbon and Associated Chemicals	48
11	Economic and Energy Analysis	50
12	Concentrations of Some Essential Elements in Seaweeds and Seawater	53
13	Nitrogen and Phosphorous Costs	54
14	Uptake of Nitrogen by N-Starved *Ulva*	55
15	Land Costs	57
16	PVC Pipe Prices	60
17	Labor Productivity	62
18	Summary: Economic and Energy Analysis	64
19	Total Cost Estimates I	65
20	Total Cost Estimates (Dry Seaweed)	66
21	Total Cost Estimates (Wet Seaweed)	68

FINAL REPORT

SERI Contract XK-2-02172-01

Cultivation and Conversion of Marine Macroalgae

J. H. Ryther, T. A. DeBusk and M. Blakeslee
Center for Marine Biotechnology
Harbor Branch Institution
Fort Pierce, Florida

Task 1. Determination of non-intensive *Ulva* culture annual yields.

Two clones of *Ulva lactuca* were cultured in our outdoor (700 l) tanks during 1983. The first, clone 010, was supplied by Dr. Howard Levine, who collected it from a natural population in Hingham Beach, Massachusetts. This clone was cultured at our facility from February until May, at which time the weed fragmented and could not be maintained in outdoor culture. A second clone (007), which was collected from the Indian River, Florida in 1982 and was found to grow well in small, indoor cultures, was stocked into our outdoor tanks in late July. Unlike the Massachusetts clone, the locally collected *Ulva* grew well during the late summer and continues to thrive as of the time of this report.

By combining growth data obtained with the two clones, we now have an estimate for *Ulva* productivity in meso-scale cultures which spans a period of 250 days. Under non-energy intensive conditions (no aeration, but short seawater residence times), mean *Ulva* growth over an 8 month period was 6.8 gdw m^{-2} day^{-1}. Highest *Ulva* yields in the non-aerated tanks were obtained in the spring (Table 1). However, under these quiescent conditions, the *Ulva* periodically floated to the surface and decayed (particularly during the warm months), necessitating the replacement of the entire culture. During this study, non-aerated *Ulva* tanks were restocked approximately 5-6 times with healthy, previously aerated plant material.

Ulva cultured under more energy intensive conditions (continuous aeration, short seawater residence time) grew quite well, with yields averaging 18.8 gdwm^{-2} day^{-1} for the 250 day period. Because maximum productivity was observed in May and late July (Table 1), it is probable that if continuous summer growth data were available (as would be possible with clone 007), mean *Ulva* yield over a 12 month period would be substantially higher than that of our 8 month estimate.

Although we now possess an *Ulva* clone (007) which shows promise in its ability to grow year-long in central Florida, problems with *Ulva* fragmentation have not entirely been resolved. Clone 007 occasionally fragments in isolated tanks, but not to the degree of our previously tested *Ulva* clones. In fact, this fragmentation may only be vegetative, because no small plants have grown up from the tank walls following the thallus breakup, as has previously occurred following fragmentation (spore release) by other *Ulva* clones. However, the environmental parameter(s) which trigger fragmentation of clone 007 should be identified, and if possible, controlled, before this plant is utilized on a large scale for biomass production.

Table 1

Seasonal productivity of two *Ulva lactuca* clones in central Florida. The seaweed was cultured outdoors in 700 l tanks under both aerated and non-aerated conditions.

	---------Productivity (gdw m^{-2} day^{-1})---------		
Dates	Non-aerated	Aerated	
2/4-2/11/83	8.7	17.5	
-2/18/83	5.9	16.4	
-2/25/83	10.0	15.2	
-3/05/83	4.2	14.8	
-3/11/83	2.3	20.6	
-3/17/83	1.4	18.9	
-3/25/83	8.5	24.4	
-4/04/83	14.8	20.4	Clone 010
-4/11/83	12.4	26.4	
-4/18/83	4.5	25.1	
-4/25/83	2.5	20.6	
-5/03/83	0.2	22.0	
-5/10/83	13.1	29.9	
7/19-7/27/83	10.8	35.2	
-8/04/83	7.0	28.3	
-8/11/83	3.4	17.4	
-8/24/83	14.1	14.4	
-9/01/83	5.1	28.1	
9/20-9/29/83	10.4	18.5	
-10/05/83	5.9	18.2	
-10/18/83	5.6	17.2	Clone 007
-10/27/83	8.4	16.2	
-11/03/83	0.0	13.8	
-11/11/83	5.3	1.1	
-11/18/83	9.7	14.8	
-12/02/83	4.1	6.9	
-12/13/83	2.6	9.9	
Mean (time weighted)	6.8	18.8	

Task 2. Evaluation of the Effect of Carbon Concentration on *Gracilaria* and *Ulva* Yields.

I. Introduction

Research carried out at Harbor Branch prior to 1983 implicated carbon supply as the factor linking seaweed productivity with the culture seawater flow rate. During this contract year, we formulated the relevant carbon equilibrium relationships into a BASIC computer program which gives carbon species concentrations as a function of total alkalinity and pH (see Listing 1). This was helpful in developing a novel experimental design which decouples carbon concentration from pH effects and permits the determination of the influence of individual carbon species concentrations on the photosynthetic rates of seaweeds.

The elucidation of yield vs. carbon concentration relationships is very important for the management of any high yield algal culture. If yield is found to correlate well with the concentration of a particular carbon species over the pH range of interest, knowledge of water chemistry and the costs of carbon supply by the various available methods can be used to determine the optimal operating point. Cost functions for carbon supply via seawater pumping, sparging with CO_2 or fossil fuel exhaust gases, and carbon salt (e.g. sodium bicarbonate, sodium carbonate) addition are given in Task 6. Quantitative yield vs. carbon concentration functions have unfortunately not yet been determined, so the utility of net photosynthesis vs. carbon relations as predictors of yield vs. carbon performance is unverified. The Task 6 carbon supply analysis therefore relies on a mass balance approach. Nevertheless, the photosynthesis methods described in this section are expected to have significant predictive value for algal mass culture systems.

II. Aqueous Carbon Chemistry

Carbon dioxide gas dissolves in water to form uncharged aqueous CO_2 (Stumm and Morgan, 1981). Aqueous CO_2 combines chemically with water to form undissociated carbonic acid (H_2CO_3). The equilibrium concentration of aqueous CO_2 is about 600 times that of H_2CO_3, and their combined concentration, roughly equal to the aqueous CO_2 concentration, is denoted $[H_2CO_3^*]$.

Equilibria exist between the three dissolved carbon species $H_2CO_3^*$, HCO_3^-, and $CO_3^=$:

$$H_2CO_3^* \overset{Ka1}{\rightleftharpoons} HCO_3^- + H^+$$

$$HCO_3^- \overset{Ka2}{\rightleftharpoons} CO_3^= + H^+$$

A similar equilibrium holds for boric acid, the other primary acid in seawater:

$$H_3BO_3 \overset{K_B}{\rightleftharpoons} B\ (OH)_4^- + H^+$$

The equilibrium constants Ka_1, Ka_2, are K_B and weak functions of temperature and salinity (Riley and Chester, 1971), and are included as

Listing 1
DEBUSKER Carbon Species Program
Written in Microsoft BASIC by Mark Blakeslee, January 1983.

```
10 PRINT "THIS PROGRAM COMPUTES TIC CONCENTRATION OF A SOLUTION WHEN"
15 PRINT " THE ALKALINITY AND pH ARE SPECIFIED"
20 PRINT
25 DIM TABLE(3,2,2), TBL(3,2), KAYS(3), CLIMIT(10)
30 REM
35 REM *** THIS SECTION LOADS THE pK TABLES FROM RILEY AND CHESTER
40 REM ***  INTO THE ARRAY KTABLE
45 FOR I = 0 TO 9
50   READ CLIMIT(I)
55   NEXT I
60 DATA 0,1,4,9,16,17,18,19,20,21
65 FOR I = 1 TO 3
70  FOR J = 0 TO 8
75    FOR K = 0 TO 7
80      READ KTABLE(I,J,K)
85      NEXT K
90    NEXT J
95  NEXT I
100 REM ***  THIS TABLE CONTAINS pKA1, 0 TO 35 C, 0 TO 20 ppt CHLORINITY
105 DATA 6.58, 6.52, 6.47, 6.42, 6.38, 6.35, 6.33, 6.31
110 DATA 6.47, 6.42, 6.37, 6.33, 6.29, 6.26, 6.24, 6.23
115 DATA 6.36, 6.32, 6.28, 6.24, 6.21, 6.18, 6.16, 6.15
120 DATA 6.27, 6.23, 6.19, 6.15, 6.13, 6.10, 6.08, 6.07
125 DATA 6.18, 6.14, 6.11, 6.07, 6.05, 6.03, 6.01, 5.99
130 DATA 6.17, 6.13, 6.10, 6.06, 6.04, 6.02, 6.00, 5.98
135 DATA 6.16, 6.12, 6.09, 6.06, 6.03, 6.01, 5.99, 5.97
140 DATA 6.15, 6.11, 6.08, 6.05, 6.02, 6.00, 5.98, 5.97
145 DATA 6.14, 6.10, 6.07, 6.04, 6.01, 5.99, 5.97, 5.96
150 REM ***  THIS TABLE CONTAINS pKA2, SAME LIMITS AS ABOVE  ***
155 DATA 10.62, 10.55, 10.49, 10.43, 10.38, 10.33, 10.29, 10.25
160 DATA 10.06, 9.99, 9.93, 9.87, 9.81, 9.76, 9.71, 9.66
165 DATA 9.78, 9.72, 9.67, 9.61, 9.54, 9.49, 9.43, 9.38
170 DATA 9.64, 9.58, 9.52, 9.46, 9.40, 9.34, 9.27, 9.21
175 DATA 9.46, 9.40, 9.35, 9.29, 9.23, 9.17, 9.10, 9.02
180 DATA 9.44, 9.38, 9.32, 9.27, 9.21, 9.15, 9.08, 9.00
185 DATA 9.42, 9.36, 9.30, 9.25, 9.19, 9.12, 9.06, 8.98
190 DATA 9.40, 9.34, 9.28, 9.23, 9.17, 9.10, 9.02, 8.95
195 DATA 9.38, 9.32, 9.26, 9.21, 9.15, 9.08, 9.01, 8.92
200 REM ***  THIS TABLE CONTAINS pKB, SAME LIMITS AS ABOVE  ***
205 DATA 9.50, 9.44, 9.38, 9.33, 9.28, 9.24, 9.20, 9.16
210 DATA 9.40, 9.34, 9.28, 9.23, 9.18, 9.14, 9.10, 9.06
215 DATA 9.28, 9.22, 9.16, 9.11, 9.06, 9.02, 8.98, 8.94
220 DATA 9.14, 9.08, 9.03, 8.98, 8.93, 8.88, 8.85, 8.82
225 DATA 9.00, 8.95, 8.89, 8.84, 8.80, 8.76, 8.72, 8.69
230 DATA 8.98, 8.93, 8.88, 8.83, 8.78, 8.74, 8.70, 8.67
235 DATA 8.96, 8.91, 8.86, 8.81, 8.76, 8.72, 8.69, 8.66
240 DATA 8.95, 8.90, 8.85, 8.80, 8.75, 8.71, 8.67, 8.64
245 DATA 8.94, 8.88, 8.83, 8.78, 8.74, 8.69, 8.65, 8.63
250 REM
255 REM *** THIS SECTION REQUESTS INPUT FROM THE USER
260 INPUT "ALKALINITY (meq/l) = "; MALK
265 ALK = MALK * .001
270 INPUT "pH VALUE = "; PH
275 INPUT "SALINITY (ppt) = "; SAL
280 INPUT "TEMPERATURE ( DEGREES C) = "; TEMPC
```

Listing 1 (continued)

```
285 TEMPK = TEMPC + 273.15
290 KW = 10^ -(3441!/TEMPK + 2.241 - .9415 * SQR(.001*SAL))
295 CL = (SAL - .03) / 1.805
300 BTOT = .0000227 * CL
305 REM
310 REM *** THIS SECTION PERFORMS A LINEAR INTERPOLATION OF THE pK
315 REM ***  VALUES BASED ON THE SPECIFIED TEMPERATURE AND SALINITY
320 COL1% = TEMPC \ 5
325 I = 0
330 WHILE CL < CLIMIT(I)
335   ROW1% = I
340   I = I + 1
345   WEND
350 FOR I = 1 TO 3
355   FOR J = 1 TO 2
360     FOR K = 1 TO 2
365       TABLE(I,J,K) = KTABLE(I,ROW1% + J - 1,COL1% + K - 1)
370       NEXT K
375     NEXT J
380   NEXT I
385 FOR I = 1 TO 3
390   FOR J = 1 TO 2
395     TBL(I,J) = TABLE(I,J,1) + (TEMPC - COL1% * 5) *
          (TABLE(I,J,2) - TABLE(I,J,1)) / 5
400     NEXT J
405   KAYS(I) = TBL(I,1) + (CL - CLIMIT(ROW1%)) * (TBL(I,2) -
        TBL(I,1)) / (CLIMIT(ROW1% + 1) - CLIMIT(ROW1%))
410   NEXT I
415 PKA1 = KAYS(1)
420 PKA2 = KAYS(2)
425 PKB = KAYS(3)
430 REM *** THIS SECTION PERFORMS THE CARBON CONCENTRATION CALCULATUIONS
435 REM ***  BASED ON THE SPECIFIED pH AND ALKALINITY
440 KA1 = 10^(-PKA1)
445 KA2 = 10^(-PKA2)
450 KB = 10^(-PKB)
455 HPLUS = 10^(-PH)
460 KK = KA1 * KA2
465 AL0 = 1 + (KA1 / HPLUS) + (KK / (HPLUS^2))
470 AL1 = (HPLUS / KA1) + 1 + (KA2 / HPLUS)
475 AL2 = ((HPLUS^2)/KK) + (HPLUS / KA2) + 1
480 ALB = KB / (KB + HPLUS)
485 PRINT "BORATE ALKALINITY (meq/l) = "; ALB * BTOT * 1000!
490 PRINT "BORATE ALKALINITY COMPRISES "; ALB * BTOT *100! / ALK;
      "% OF TOTAL ALKALINITY"
495 TIC = (ALK - (KW / HPLUS) + HPLUS - (BTOT * ALB)) /
      ((1 / AL1) + (2/AL2))
500 REM *** THIS SECTON PRINTS THE RESULTS
505 PRINT "TOTAL  INORGANIC CARBON CONCENTRATION (mM) = "; TIC * 1000!
510 PRINT "CONCENTRATION OF H2CO3* (mM) = "; (1000! / AL0) * TIC
515 PRINT "CONCENTRATION OF HCO3-  (mM) = "; (1000! / AL1) * TIC
520 PRINT "CONCENTRATION OF CO3=   (mM) = "; (1000! / AL2) * TIC
525 PRINT:PRINT
530 GOTO 260
535 END
```

tables in the carbon concentration program DEBUSKER. The total inorganic carbon concentration is given by

$$C_T = [H_2CO_3^*] + [HCO_3^-] + [CO_3^=], \text{ and}$$

$$[H_2CO_3^*] = \alpha 0 C_T \qquad \alpha 0 = [1 + \frac{Ka1}{[H^+]} + \frac{Ka1\ Ka2}{[H^+]^2}]^{-1}$$

$$[HCO_3^-] = \alpha 1 C_T \qquad \alpha 1 = [\frac{[H^+]}{Ka1} + 1 + \frac{Ka2}{[H^+]}]$$

$$[CO_3^=] = \alpha 2 C_T$$

$$\alpha 2 = [\frac{[H^+]^2}{Ka1\ Ka2} + \frac{[H^+]}{Ka2} + 1]^{-1}$$

The coefficients α_0, α_1, and α_2 are functions of Ka_1, Ka_2, and $[H^+]$, but at constant temperature and salinity, they are functions of pH only.

The total alkalinity (TA) of a water is its acid neutralizing capacity with respect to the $H_2CO_3^*$ equivalence point (Stumm and Morgan, 1981). Since CO_2 dissolves in water as $H_2CO_3^*$, addition or removal of CO_2 does not affect total alkalinity. The important bases in seawater are HCO_3^-, $CO_3^=$, OH^-, and $B(OH)_4^-$, so

$$TA = [HCO_3^-] + 2[CO_3^=] + [OH^-] - [H^+] = [B(OH_4^-)]$$

$$= (\alpha_1 + 2\ \alpha_2)\ C_T + [OH^-] - [H^+] + \alpha_B\ B_T.$$

Carbonate alkalinity (CA) is defined as

$$CA \equiv [HCO_3^-] + 2\ [CO_3^=] = (\alpha_1 + 2\alpha_2)\ C_T$$

Given a particular total alkalinity and pH, α_0, α_1, and α_2 are fixed, and the total carbon concentration can clearly be calculated as

$$C_T = \frac{TA = [OH^-] + [H^+] = \alpha_B\ B_T}{(\alpha_1 + 2\ \alpha_2)}$$

The individual carbon species concentrations are then found by multiplying C_T by the appropriate α's

If the concentration of a particular carbon species is to remain constant, the product of and C_T must be held constant. For example, α_0 decreases by a factor of ten as the pH goes from 7 to 8. If the C_T of a pH 8 medium is ten times that of a pH 7 medium, the media have identical $[H_2CO_3^*]$ concentrations. Meanwhile, HCO_3^- concentration has increased tenfold and $CO_3^=$ concentration has increased one hundredfold. If photosynthetic rates or yields are equal for carbon limited algae incubated in these waters, $H_2CO_3^*$ concentration is likely to be rate limiting.

Due caution should be observed when using the above relations. A number of complicating factors limit the precision of this simplified analysis. These include the existence of ion pairs between HCO_3^- and $CO_3^=$ and various metal ions and the formation of complexes between CO_2 and dissolved amino acids (Riley & Chester, 1971). Despite these limitations, the dramatically different behavior of carbon species concentrations in certain pH ranges makes this approach quite useful.

III. Experiment Objectives

The objective of this work was to determine an operationally useful correlation between seaweed photosynthesis and aqueous carbon concentration. The seaweed farmer is more interested in seaweed yield than photosynthetic rate, but the two are stoichiometrically related under carbon limited conditions (Oswald, 1977), and photosynthesis can be more accurately measured over short time intervals than can growth.

The concentrations of the several dissolved carbon species ($H_2CO_3^*$, HCO_3^-, and $CO_3^=$) change at very different rates as carbon is extracted from water by growing seaweed. This effect is illustrated in Figure 1 and Table 2, where it is seen that a 25% decrease in total carbon for seawater caused by CO_2 removal results in a 87% decrease in $H_2CO_3^*$, a 47% decrease for HCO_3^-, and a 114% increase in $CO_3^=$ concentration. Determining which carbon species concentration controls photosynthetic rate under carbon limited conditions is thus clearly important if carbon is to be supplied effectively.

IV. Materials and Methods

Oxygen evolution rates were measured for Gracilaria and Ulva incubated for several hours in stirred bottles containing seawater with adjusted total alkalinity and pH values. All incubations were carried out indoors in a windowless room held at 25 ± 2°C. A light table was designed and constructed which provided 28 stirrer stations for 1080 ml glass stoppered bottles. The stirring drive was provided by belt driven pulleys rotating alnico magnets at 60 rpm. The seaweed samples were provided ample mixing with minimal snagging by 1 1/2" stirrer bars inserted into the bottles.

Light was provided by six 96" cool-white fluorescent lamps positioned as three banks of two lamps each. Two rows of fourteen bottles each fit between the three banks of lamps with a clearance of one and one half inches on each side. Light levels at the centerline of each bottle were measured using a Biospherical Instruments, Inc. QSL-100 quantum irradiometer. Light intensity was 3.45 (± 0.15) x 10^{16} quanta/cm^2.sec for the twenty-four interior bottles and 15% less at the four end positions. The end bottles were therefore not used in the photosynthetic incubations. The above intensity is 17.7% of May Ft. Pierce full sunlight (1.95 x 10^{17} quanta/cm^2.sec). Light saturation commmonly occurs betweens 10 and 20 percent of full sunlight for productive seaweeds (Ramus and Rosenberg, 1980 Luning, 1981; personal communication, Lynn Hodgson), so the incubations are assumed not to have been light-limited.

The twenty-four active stations were utilized for six different treatments replicatd in four bottles each run. One of the six treatments was a control medium of unaltered diluted seawater and the other five contained diluted seawater with modified alkalinity, TIC concentrations, and pH.

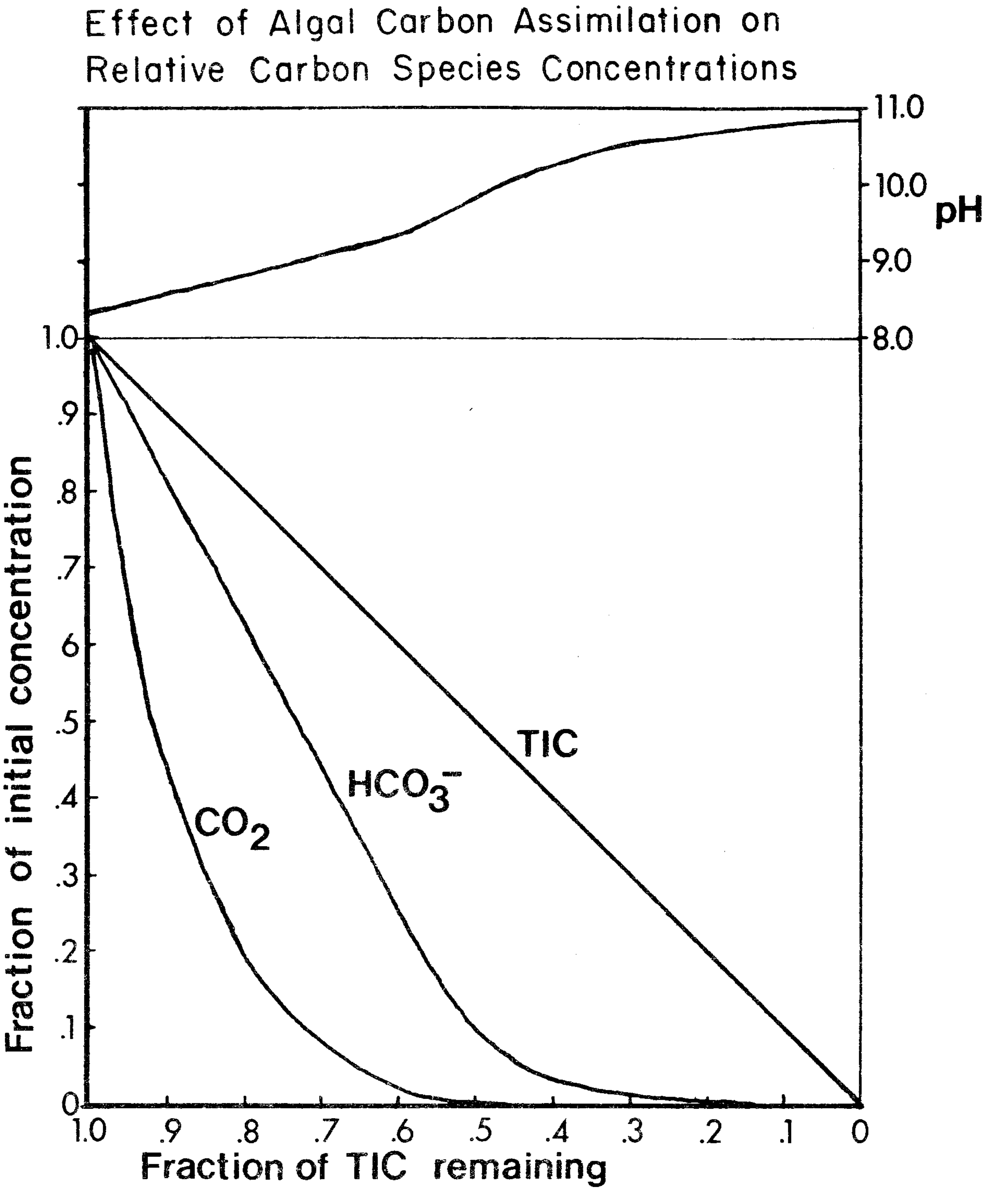

Effect of Algal Carbon Assimilation on Relative Carbon Species Concentrations
11.0
10.0
9.0
8.0
pH
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
Fraction of initial concentration
TIC
HCO_3^-
CO_2
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
Fraction of TIC remaining

Figure 1

Table 2

Effect of Carbon Assimilation on Carbon Species in Seawater

Seawater -	2.3 meq/1 Total Alkalinity	pK α_1= 6.00
	35 ppt salinity	pK α_2 = 9.09
	25°C temperature	pK_B = 8.70
	Initially pH 8.3	

pH	% TIC	mM MIC	% CO_2	μM CO_2	% HCO_3^-	mM HCO_3^-	% $CO_3^=$	mM$CO_3^=$
8.3	100	1.91	100	8.15	100	1.64	100	.265
8.4	96	1.84	74	6.03	93	1.53	117	.310
8.5	93	1.77	54	4.40	85	1.40	135	.359
8.6	88	1.69	39	3.18	78	1.28	155	.410
8.7	84	1.61	28	2.26	70	1.14	175	.463
8.8	80	1.52	20	1.59	62	1.01	194	.515
8.9	76	1.45	13	1.10	54	.881	213	.565
9.0	72	1.37	9.2	.751	46	.758	231	.612
9.1	68	1.30	6.2	.507	39	.644	247	.655
9.2	64	1.23	4.1	.338	33	.541	262	.693
9.3	61	1.17	2.7	.223	27	.450	274	.725
9.4	59	1.12	1.8	.146	23	.370	284	.751
9.5	56	1.07	1.2	.0945	18	.301	291	.770
9.6	54	1.03	.74	.0607	15	.244	296	.784
9.7	52	.986	.47	.0386	12	.195	298	.790
9.8	50	.946	.30	.0244	9.5	.155	298	.791
9.9	47	.906	.19	.0152	7.4	.122	296	.784
10.0	45	.864	.12	.00944	5.8	.0952	290	.769
10.1	43	.819	.071	.00577	4.5	.0733	282	.746
10.2	40	.768	.043	.00348	3.4	.0556	269	.713
10.3	37	.709	.025	.00206	2.5	.0414	252	.668
10.4	33	.638	.014	.00118	1.8	.0300	229	.608
10.5	29	.552	.008	.000552	1.3	.0208	200	.531
10.6	23	.446	.0041	.000335	.82	.0135	163	.433
10.7	16	.315	.0018	.000150	.46	.00760	116	.308
10.8	8.0	.152	.00056	.0000459	.18	.00291	56	.149

The incubation medium was a 7:3 mixture of Gulf Stream seawater (GSW) and de-ionized water (DIW). The GSW was collected from the intake canal of the Hutchinson Island nuclear power plant. This water had a consistent salinity of 35 ppt and a total alkalinity of 2.45 meq/l. The 7.3 dilution produced a water with 25 ppt salinity and 1.7 meq/l total alkalinity. This is similar to Indian River water used to cultivate and precondition the seaweed samples, but nutrient levels and total organic carbon were much less in the diluted ocean water.

It was initially expected that *Gracilaria* photosynthesis would correlate well with $H_2CO_3^*$ (i.e. CO_2) concentration, so DEBUSKER was used to calculate the total alkalinities required to provide identical $H_2CO_3^*$ concentrations ranging from 0.03 to 200 µM. For the purpose of comparison, ambient seawater has a $H_2CO_3^*$ concentration of about 10 µM. The range of total alkalinities was .019 to 10.6 meq/l, and the range of TIC concentrations was 71 µM to 12 µM.

In cases where the required alkalinity was greater than the 1.7 meq/l provided by the 7:3 seawater dilution, alkalinity was added as NaOH. The direct addition of strong base to seawater causes immediate precipitation of $MgCO_3$ and $CaCO_3$ due to the locally high pH where the base meets the seawater. This was avoided by adding the required NaOH to the 3 parts de-ionized water prior to adding the GSW. Since there are no Mg^{++} or Ca^{++} ions in the DIW, precipitation could not occur. Once the NaOH was mixed into the DIW, 5% CO_2 in air was sparged into the mixture to decrease the pH to near the desired final value. The 7 parts GSW were then added and immediate precipitation was not triggered because there was no region of locally high pH. There is, however, an upper limit on the amount of total alkalinity that can be added to seawater without exceeding the solubility products for $MgCO_3$ and $CaCO_3$. This constraint limited the number of total alkalinity treatments to four at pH 9.0 and two at pH 9.5.

Many of the runs required total alkalinities less than 1.7 meq/l. To lower alkalinity, a two step procedure was followed. In the first step, all alkalinity was removed by adding concentrated HCl to the 7:3 diluted GSW mix. Sufficient HCl was added to bring the pH below 4.5. This is the $H_2CO_3^*$ equivalence point for the alkalinity titration (Stumm and Morgan, 1981), and at this pH all dissolved carbon is present as dissolved CO_2. Overnight sparging with air resulted in a negligible TIC concentration (~10 µM as $H_2CO_3^*$). Zero alkalinity was achieved by adding NaOH until the pH was exactly 4.5. The second step involved adding the desired final total alkalinity as dilute NaOH and sparging with CO_2 to achieve the desired final pH.

Once the total alkalinity and pH were at their desired levels, the dissolved oxygen concentration was adjusted to 3.5 - 4.5 ppm by sparging with either N_2 or air. This provided a constant starting O_2 concentration and minimized the deleterious effects of high oxygen tension on photosynthesis (Burris, 1980; Littler, 1979).

Incubation bottles were filled with the desired medium by submersion to avoid the aeration effect of pouring. Polycarbonate sample bottles holding 250 ml were also filled in this manner. These samples were stored at 3°C in the dark for several weeks until the TIC concentration could be

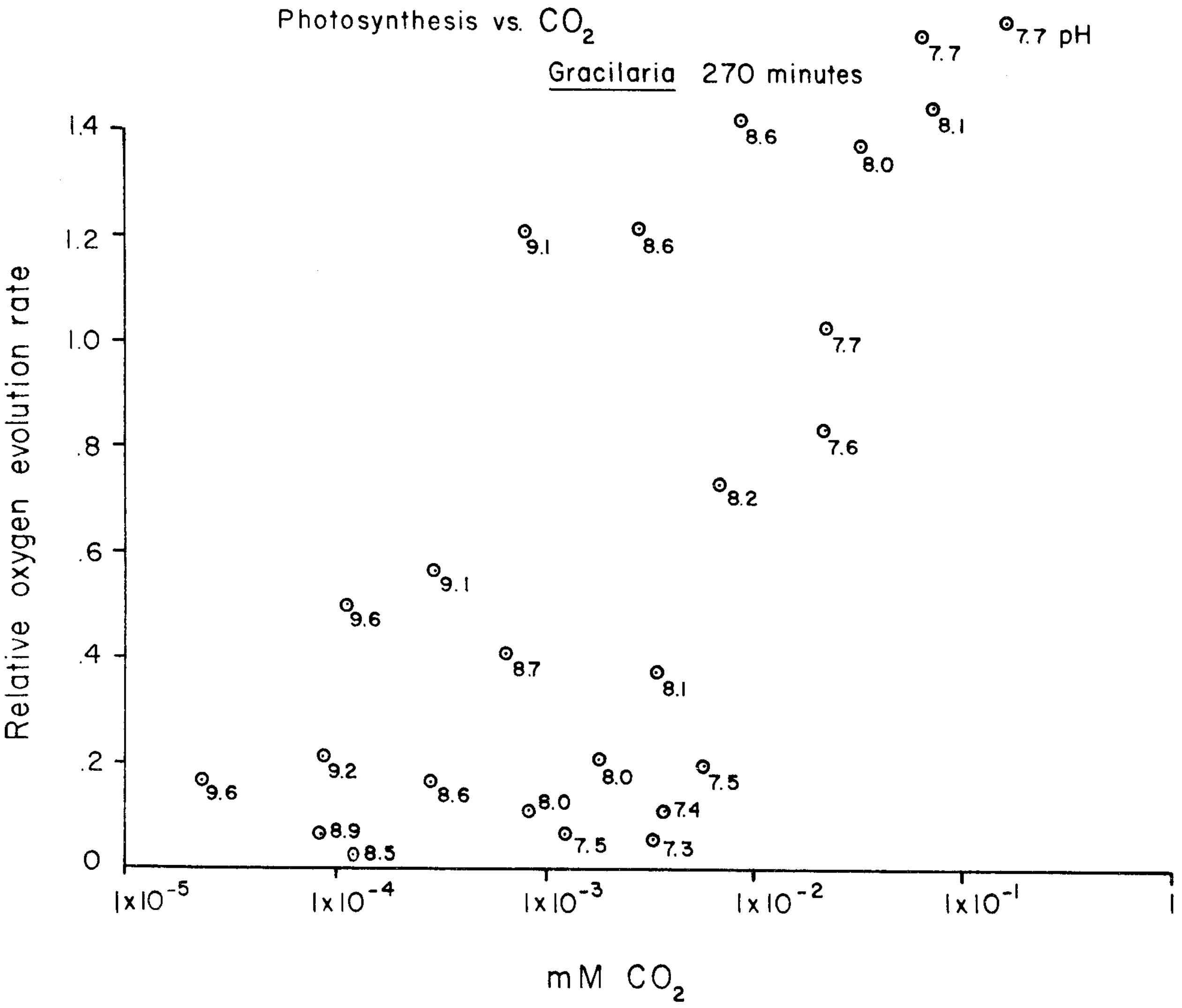

Photosynthesis vs. CO_2
Gracilaria 270 minutes
7.7
7.7 pH
8.1
8.6
8.0
9.1
8.6
7.7
7.6
8.2
9.1
9.6
8.7
8.1
9.2
9.6
8.6
8.0
8.0
7.5
7.4
8.9
8.5
7.5
7.3
Relative oxygen evolution rate
1.4
1.2
1.0
.8
.6
.4
.2
0
1x10^{-5}
1x10^{-4}
1x10^{-3}
1x10^{-2}
1x10^{-1}
1
mM CO_2

Figure 2

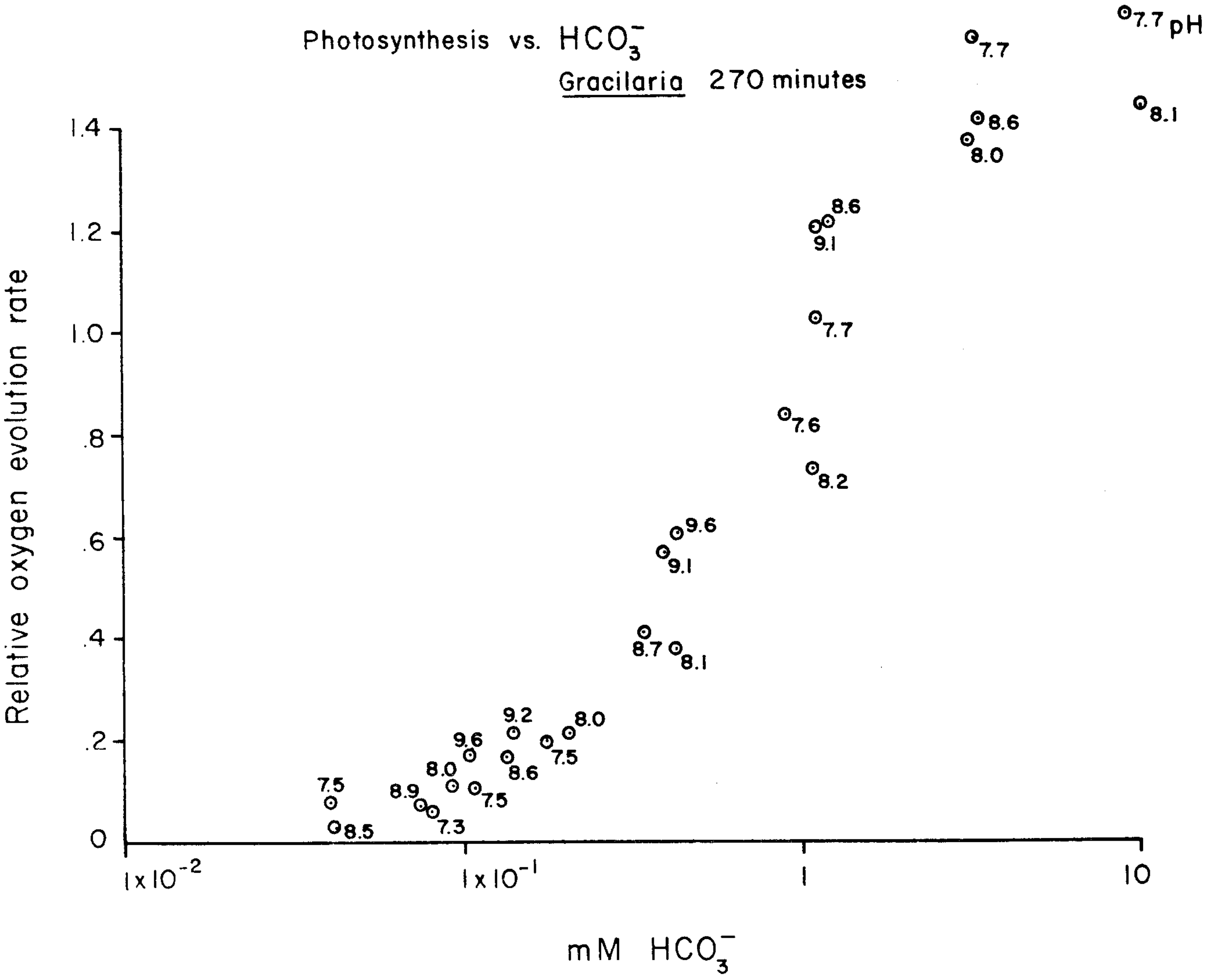
Photosynthesis vs. HCO_3^-
Gracilaria 270 minutes
Relative oxygen evolution rate
mM HCO_3^-
0
.2
.4
.6
.8
1.0
1.2
1.4
1x10^{-2}
1x10^{-1}
1
10
pH
7.5
8.5
8.9
7.3
8.0
9.6
7.5
9.2
8.6
7.5
8.0
8.7
8.1
9.1
9.6
8.2
7.6
7.7
9.1
8.6
8.0
8.6
7.7
8.1
7.7

Figure 3

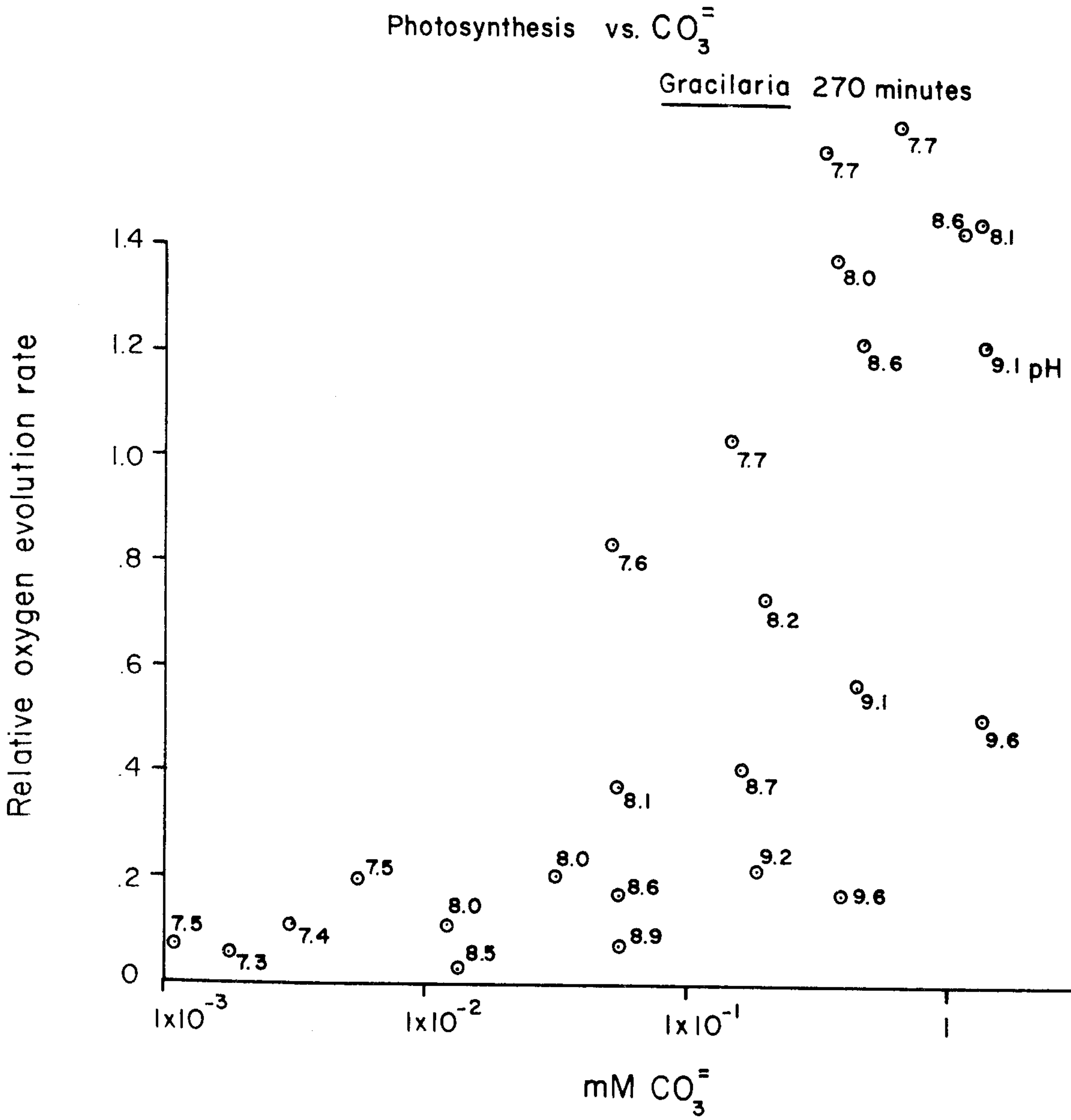

Photosynthesis vs. $CO_3^=$
Gracilaria 270 minutes
Relative oxygen evolution rate
mM $CO_3^=$
1.4
1.2
1.0
.8
.6
.4
.2
0
1x10^{-3}
1x10^{-2}
1x10^{-1}
1
10
7.7
7.7
8.6
8.1
8.0
8.6
9.1 pH
7.7
7.6
8.2
9.1
9.6
8.1
8.7
7.5
8.0
9.2
8.6
9.6
7.5
7.3
7.4
8.0
8.5
8.9

Figure 4

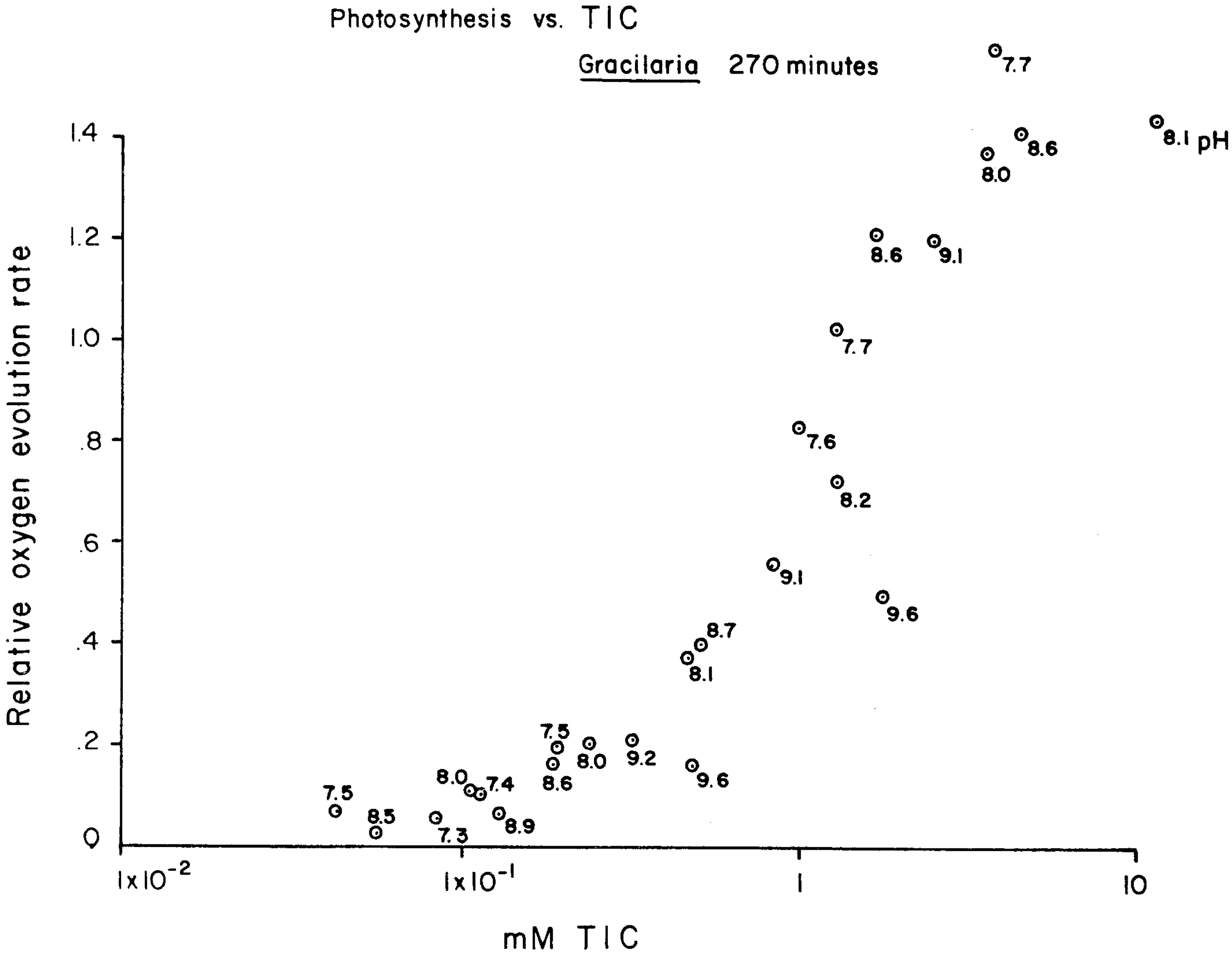

Photosynthesis vs. TIC
Gracilaria 270 minutes
Relative oxygen evolution rate
1.4
1.2
1.0
.8
.6
.4
.2
0
1x10⁻²
1x10⁻¹
1
10
mM TIC
7.7
8.1 pH
8.6
8.0
8.6
9.1
7.7
7.6
8.2
9.1
9.6
8.7
8.1
7.5
8.0
9.2
8.6
9.6
8.0
7.4
7.5
8.5
7.3
8.9

Figure 5

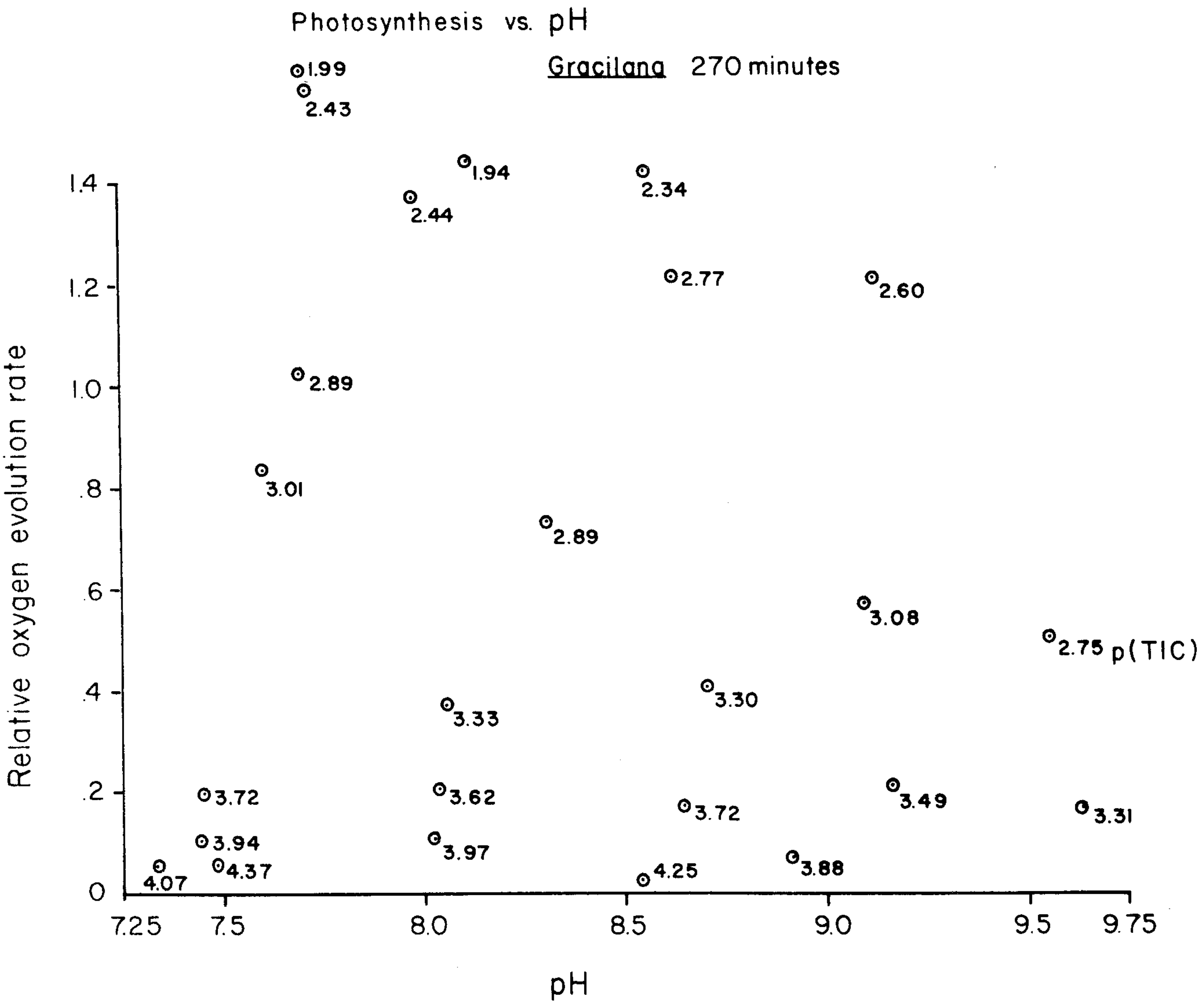

Photosynthesis vs. pH
Gracilana 270 minutes
Relative oxygen evolution rate
pH
1.4
1.2
1.0
.8
.6
.4
.2
0
7.25
7.5
8.0
8.5
9.0
9.5
9.75
1.99
2.43
1.94
2.34
2.44
2.77
2.60
2.89
3.01
2.89
3.08
2.75 p(TIC)
3.33
3.30
3.72
3.62
3.49
3.72
3.31
3.94
3.97
4.07
4.37
4.25
3.88

Figure 6

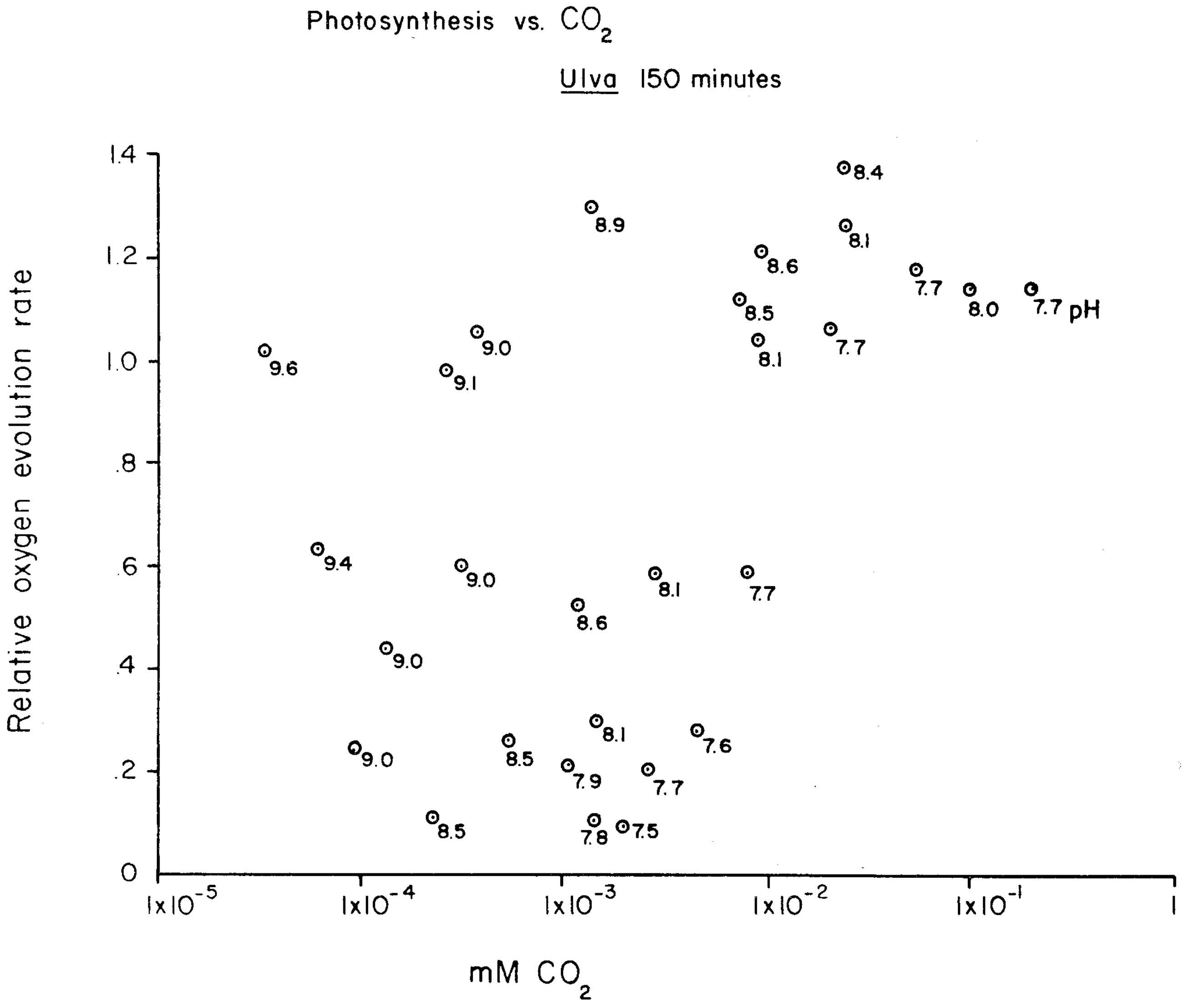

Photosynthesis vs. CO_2
Ulva 150 minutes
Relative oxygen evolution rate
0
.2
.4
.6
.8
1.0
1.2
1.4
mM CO_2
1x10^{-5}
1x10^{-4}
1x10^{-3}
1x10^{-2}
1x10^{-1}
1
9.6
9.1
9.0
8.9
8.4
8.1
8.6
8.5
8.1
7.7
7.7
8.0
7.7 pH
9.4
9.0
8.6
8.1
7.7
9.0
9.0
8.5
8.1
7.6
7.9
7.7
8.5
7.8
7.5

Figure 7

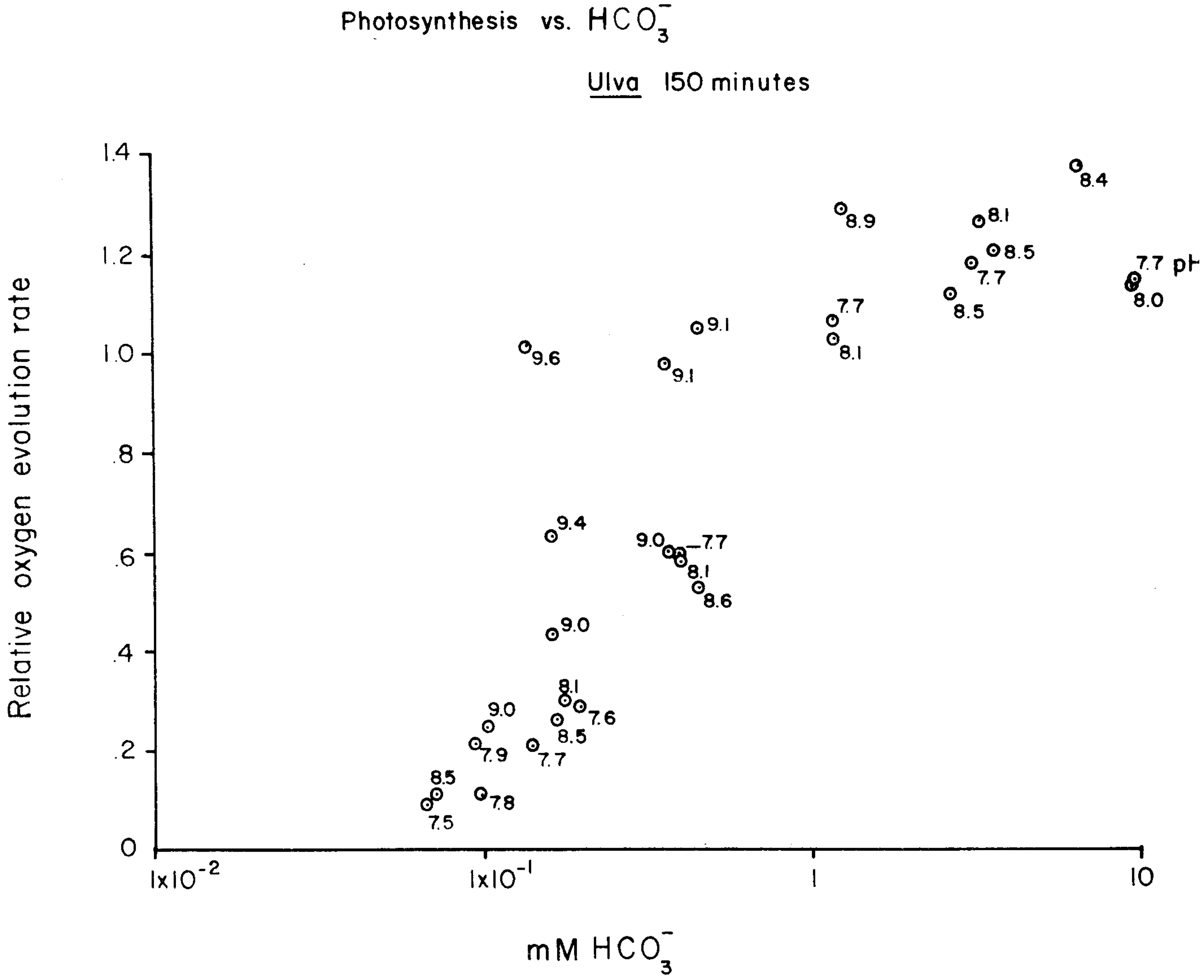
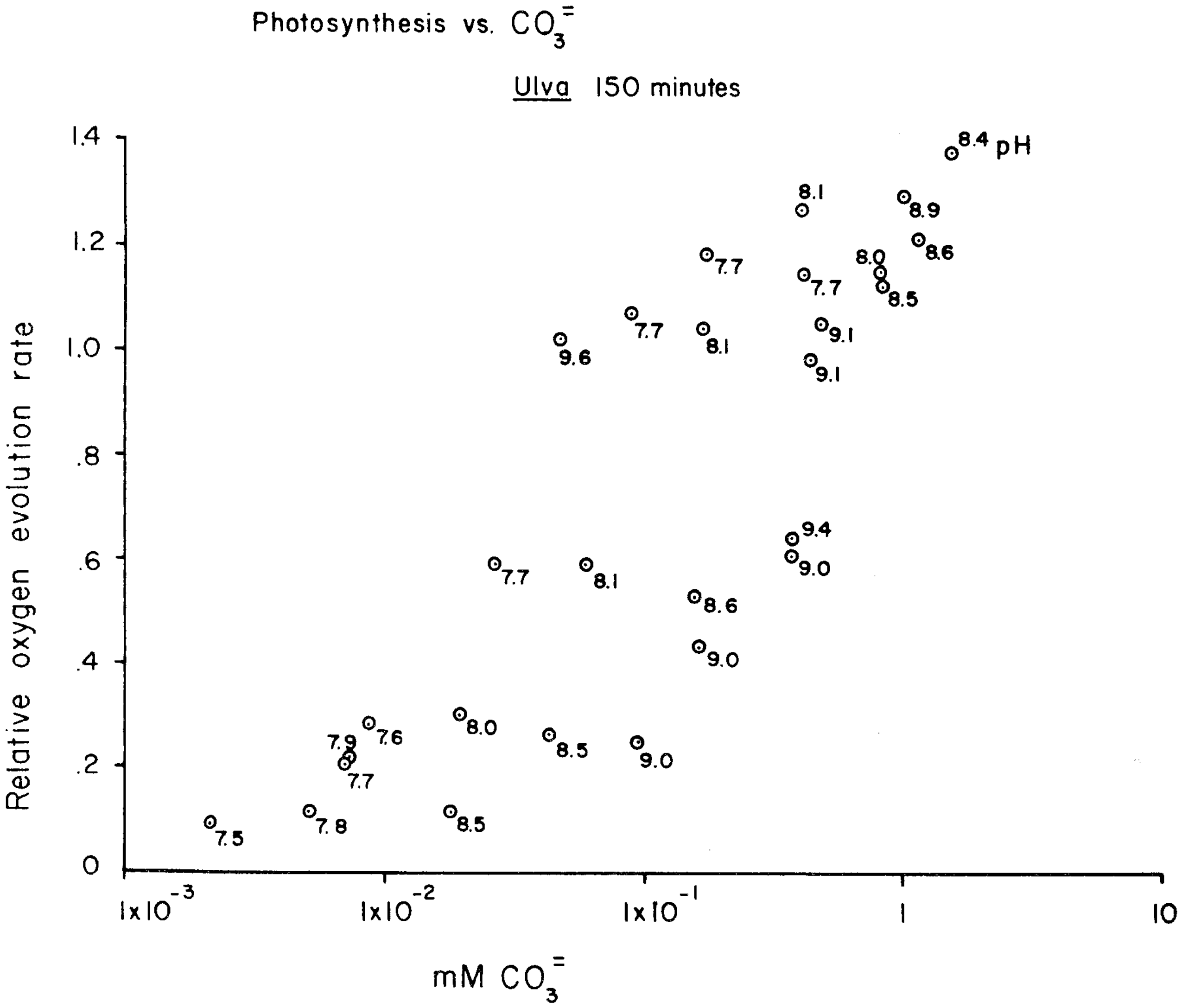

Photosynthesis vs. HCO_3^-
Ulva 150 minutes
Relative oxygen evolution rate
mM HCO_3^-
0
.2
.4
.6
.8
1.0
1.2
1.4
1x10^{-2}
1x10^{-1}
1
10
8.4
8.9
8.1
8.5
7.7 pH
7.7
8.0
8.5
7.7
9.1
8.1
9.6
9.1
9.4
9.0
7.7
8.1
8.6
9.0
8.1
9.0
7.6
8.5
7.9
7.7
8.5
7.8
7.5

Figure 8



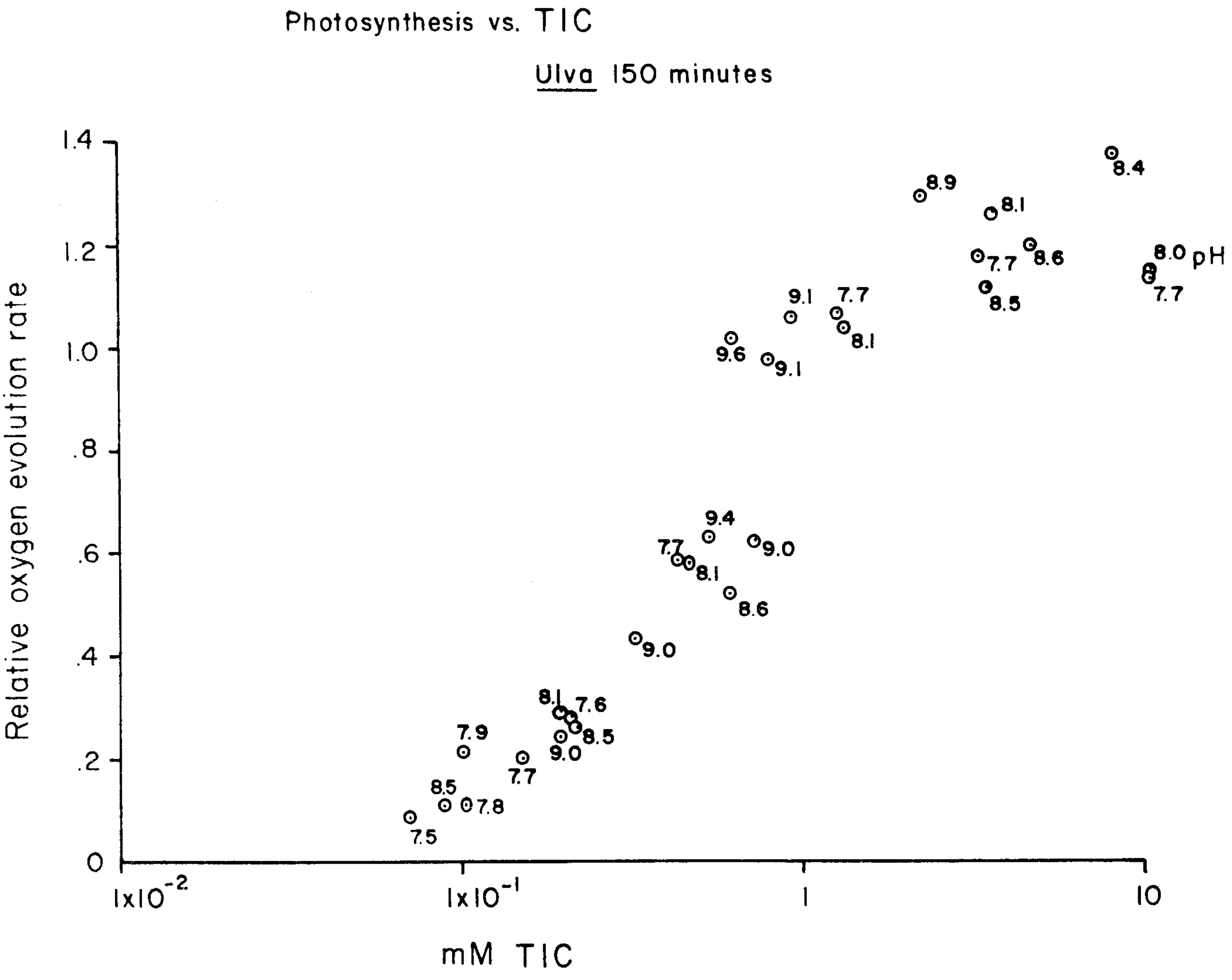

Photosynthesis vs. TIC
Ulva 150 minutes
Relative oxygen evolution rate
1.4
1.2
1.0
.8
.6
.4
.2
0
1x10^{-2}
1x10^{-1}
1
10
mM TIC
8.4
8.9
8.1
7.7
8.6
8.0 pH
7.7
8.5
9.1
7.7
8.1
9.6
9.1
9.4
9.0
7.7
8.1
8.6
9.0
8.1
7.6
8.5
9.0
7.9
7.7
8.5
7.8
7.5

Figure 10

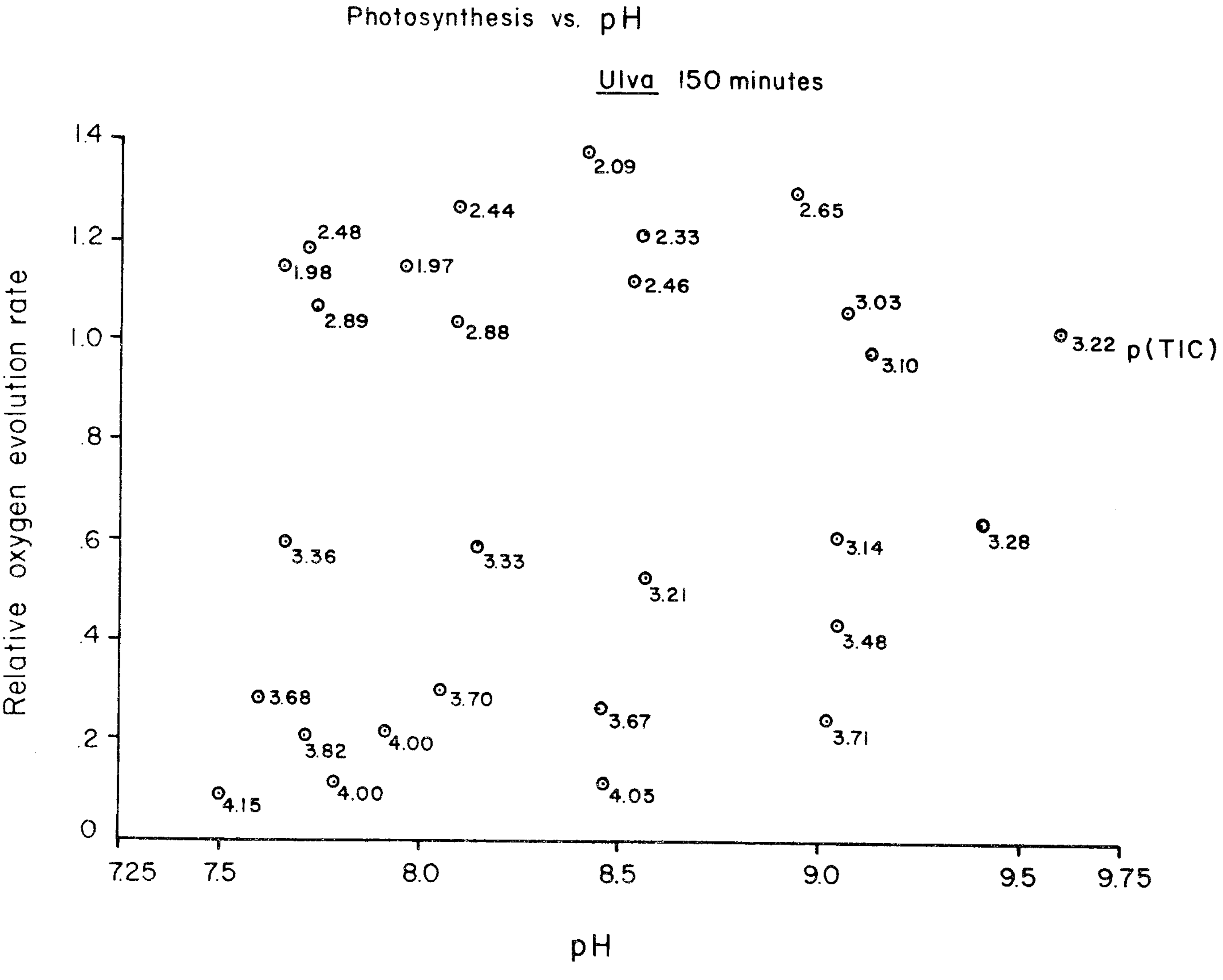

Photosynthesis vs. pH
Ulva 150 minutes
Relative oxygen evolution rate
pH
1.4
1.2
1.0
.8
.6
.4
.2
0
7.25
7.5
8.0
8.5
9.0
9.5
9.75
2.09
2.44
2.65
2.48
2.33
1.98
1.97
2.46
2.89
2.88
3.03
3.10
3.22
p(TIC)
3.36
3.33
3.14
3.28
3.21
3.48
3.68
3.70
3.67
3.82
4.00
3.71
4.15
4.00
4.05

Figure 11

determined using the Oceanography International Corporation Total Carbon Analyzer located at the Mote Marine Laboratory in Sarasota, FL.

Seaweed samples of roughly 60 mg dry weight for each bottle were selected the evening before each run. *Gracilaria* samples were taken from ORCA clone plants being grown outdoors in 700 l tanks. Five two inch long growing tips for each bottle were cut from healthy plants. *Ulva* samples consisted of five one inch diameter discs for each bottle cut from relatively unwrinkled areas of healthy clone 007 plants growing the the HBI greenhouse. Samples were held overnight in aerated tanks of Indian River water of 25 ppt salinity. A nutrient solution giving 10 μM P and 40 μM N was added to each tank to ensure that the samples would have sufficient stored nutrients to maintain non-nutrient limited photosynthesis during the incubation. NaOH was added to raise the pH to the incubation level for those samples destined for pH 9.0 and 9.5 incubations. These preconditioning procedures provided time for wound healing (Ramus, 1978) and adaptation to the salinity and pH conditions employed in the incubations.

Photosynthesis incubations were started each day between 11 a.m. and 1 p.m. *Gracilaria* incubations lasted 4 1/2 hours and *Ulva* incubations lasted 2 1/2 hours., Starting and ending oxygen concentrations and pH's were measured using a YSI Model 51 oxygen meter and a Fischer model 650 pH controller, respectively. Seaweed samples were strained from the bottles at the end of each run, washed with fresh water to remove salt, and dried on tared aluminum foil squares in a 90°C oven for three days. Dry weights were measured with a Metler model H33AR balance.

The net photosynthetic rate as mg O_2 per dry g seaweed per hour was calculated for each bottle. The results for each of the four replicate bottles were then averaged to give a mean photosynthetic rate and standard deviation. The average photosynthetic rate resulting from each carbon treatment was then normalized by dividing by the average control photosynthetic rate for that run. The logarithmic average of the starting and ending pH's for each bottle was also calculated, and the arithmetic average and standard deviation for the four replicate bottles per treatment were then calculated. The average pH was used with the TIC concentration (determined with the IR spectrophotometer) to calculate the average concentration of each of the dissolved carbon species for each treatment.

V. Results and Discussion

Figures 2 to 11 show the results plotted as normalized net oxygen production rate vs. the concentrations of CO_2, HCO_3^-, $CO_3^=$, TIC, and of the pH. Plots where points fall more or less along a common line occur when the net photosynthesis is strongly correlated with the substrate concentration. In plots with great scatter, correlation of photosynthesis with the substrate concentration is poor. Substrates which show poor correlation are unlikely to be directly involved in the carbon metabolism of the seaweed under the experimental conditions.

Inspection of the graphs shows that *Gracilaria* net photosynthesis correlates fairly well with bicarbonate concentration, but poorly with CO_2 concentration. *Ulva* net photosynthesis correlates best with TIC concentration. Neither *Gracilaria* nor *Ulva* photosynthesis correlates well with pH.

The correlation of Gracilaria photosynthesis with HCO_3^-, rather than CO_2 concentration does not coincide with our previous estimate of the role of carbon in the yield vs. pH relationship for this species (Ryther, 1982b; Ryther and DeBusk, 1982). In 1982, we found that Gracilaria productivity was significantly higher in pH-controlled seawater (8.0) than in tanks in which the seawater pH was allowed to increase to ca. 9.5. We assumed that poor seaweed growth at high pH resulted from a decrease in CO_2, the carbon species whose equilibrium concentration declines to almost negligible levels over this pH range. However, the HCO_3^- concentration also decreases sharply between pH 8.0 and 9.5 (Figure 1). Hence, the close correlation of Gracilaria photosynthesis with HCO_3^- concentration does not contradict past experimental evidence, only its interpretation.

The correlation of Ulva photosynthesis with TIC concentrations is also surprising because there is no known mechanism for the uptake of the doubly charged carbonate ion. There is, however, a continuing controversy on the mechanism of exogenous HCO_3^- uptake. Lucas (1983) reviewed the various theories and included mention of the so-called "HCO_3^-/OH^- Antiport" scheme whereby H^+ is extruded from the plant surface in certain regions and converts bicarbonate to free CO_2. The flux of H^+ is balanced by the extrusion elsewhere of OH^-. In conditions where the carbonate concentration is high relative to the bicarbonate concentration, it seems reasonable that this same mechanism could convert carbonate to bicarbonate and thence to CO_2.

VI. Conclusion

An experimental design has been developed which permits the determination of an operationally useful correlation between a seaweed's net photosynthesis and the concentration of dissolved carbon species in the growth medium. This approach may be used with slight modification for similar experiments with microalgae. Such a correlation is useful over the range of alkalinities and pH's used in the particular experiment, and is empirical rather than mechanistic.

Experiments were carried out with Gracilaria and Ulva over the pH range of 7.5 to 9.5 and with total alkalinities from miniscule to the maximum permissible short of $MgCO_3$ and $CaCO_3$ precipitation. Gracilaria photosynthesis correlated well with bicarbonate concentration whereas Ulva photosynthesis correlated best with the total inorganic carbon concentration.

These results are provocative, and would ideally be confirmed with yield experiments using the same carbon manipulation approach. Such experiments were initiated at HBI but thus far have neither confirmed nor refuted these results. A thorough understanding of the growth response of cultivated algal specie and potential invading competitors could be very useful in the management of an algae production system. Such information in conjunction with economic data on carbon supply systems is essential for the proper design and operation of large scale algae farms.

Task 3. Evaluation of spray/mist culture of *Ulva* and *Gracilaria*; and
Task 4. Development of three dimensional *Ulva* culture technology.

The concept of growing seaweeds out of the water in a fine mist or spray of seawater was first proposed by L. A. Hanic of Dalhousie University, Halifax, N. S., and has since been tested with the brown alga *Ascophyllum nodosum* by several investigators (Rheault and Ryther, 1983; Moeller et al., 1982). Because the culture of seaweeds in a seawater mist may have some economic advantage over traditional, submersed methods (Huguenin, 1981b), there remains considerable interest in this cultivation technique.

We devoted a small portion of our contract work this year to investigating the ability of *Gracilaria* and *Ulva* to grow in a 0.25 m^2 chamber out of the water, suspended in a fine mist. Because we had previously found that *Gracilaria* grows slowly when placed on flat trays beneath a seawater mist (Ryther et. al., 1980), our intent was to determine whether yields would improve with the alga suspended from rods in a three-dimensional (3-D) fashion. Similar studies were also conducted with *Ulva*.

During our May-June experimental period, yields of both *Ulva* and *Gracilaria* in the spray culture chambers were generally poor: maximum growth observed for the two species was 5.2 and 13.8 gdw m^{-2} day^{-1}, respectively. A comparison of average 2-D (on flat trays) with 3-D *Gracilaria* growth did show, however, that productivity may be increased by orienting the seaweed vertically in tiers. Three-dimensional *Gracilaria* growth averaged 10.1 while 2-D growth averaged only 7.4 gdw m^{-2} day^{-1} over a two week period. Hence, the vertical display of seaweeds may facilitate thallus light utilization on an areal basis. However, this growth stimulation may also have been due to unobstructed light penetration into the small culture chamber growing area from the open sides. It remains to be demonstrated that yields can be enhanced by culturing seaweeds in vertical rows or tiers on a large scale, where the proportion of plants growing around the open edge or perimeter is small.

The spray culture experiments were terminated with the onset of summer because of high temperatures which developed in the culture chambers. *Ulva* seemed particularly sensitive to the heat, so it is possible that the low yields obtained for this species in the spray chambers may be improved upon under cooler conditions.

Task 5. Species screening for production of petroleum replacement products

The extractable lipid content was determined for twenty species of macroscopic algae, listed in Table. 3. The analyses were made by Dr. Richard H. Pierce, Mote Marine Laboratory (1600 City Island Park, Sarasota, Florida 33577) under contract to the Center for Marine Biotechnology.

Methods

The algae were harvested at Harbor Branch Institution (HBI), freeze-dried and then shipped to Mote Marine Laboratory (MML) for extraction and analysis.

Extraction:

Hydrocarbons were extracted from the algae according to a modification of the procedure of Tornabene et al. (1982). Briefly, the procedure with modifications is described below.

1) Weigh samples of 2 to 5 g dry-weight algae with internal standard 5 α-androstance and O-terphenyl added to verify extraction and separation of saturated and unsaturated hydro-carbon fractions;

2) Add 100 ml of extraction solvent (methanol:methylene chloride:H_2O, 10:5:4, by volume), homogenize and let sit for 24 hours;

3) Filter through glass fiber filter and repeat extraction;

4) Wash residue and filter with 50 ml acetone; followed by 50 ml CH_2Cl_2;

5) Add CH_2Cl_2 and H_2O to solution and recover CH_2Cl_2 (lower) phase in separatory funnel and transfer to tared vial;

6) Evaporate CH_2Cl_2 to just dry, at room temperature and weigh to determine total lipid content;

7) Redissolve residue in hexane for column clean-up and fractionation.

Clean-Up and Fractionation:

The lipid extract was passed through a column of silica gel and alumina to separate three major lipid fractions: the saturated (f_1) and unsaturated (f_2) hydrocarbons; and the more polar lipid material including fatty acids and triglycerides (f_3).

1) Dissolve extract in 2 ml hexane and elute through column with 12 ml hexane, to provide f_1 fraction.

2) Wash extract vial with 2 ml of dichloromethane (CH_2Cl_2) and elute through column with 12 ml CH_2Cl_2 to provide f_2 fraction.

3) Wash vial with 2 ml of methanol (CH_3OH) and elute column with 12 ml CH_3OH to provide fraction f_3.

4) Evaporate to desired volume for Gas Chromatography/Flame Ionization Detector (GC-FID) analysis.

Because the f_3 triglycerides could not be analyzed by GC-FID, the f_3 fraction was reduced to 0.5 ml in hexane and saponified by heating 15 min in 2 N KOH in methanol. The fatty acids were then methylated with BF_3 in methanol in preparation for GC-FID analysis. Verification of extraction and derivitization methods was extablished with an external standard triglyceride, triolein. Although this was accomplished for standards and a few samples, time did not permit saponification and derivitization of all samples. For this report, therefore, the f_3 fraction is reported as the dryweight of material eluted from the silica/alumina column with methanol (f_3).

GC-FID Analysis:

The eluants were reduced to an appropriate volume and analyzed by glass capillary gas chromatography with flame-ionization detector (GC-FID). Analyses were performed with a Varian model 6000 GC coupled with a VISTA 401 chromatography data system. The column was an SE-30, 30 m x 0.25 mm I.D. with a temperature program of 100 to 280^{o}C at 8^{o}/min, holding at 280^{o}C for 10 min.

Results and Discussion

The total extractable lipid content for the twenty species of marine algae are listed in Table 3. Also listed are the total saturated (f_1) and unsaturated (f_2) hydrocarbons determined by GC-FID analysis and the mass of the f_3 fractions determined gravimetrically.

The total lipid content of marine algae ranged from 5 mg lipid/g freeze-dried algae, for *Solieria* sp. to a high of 80 mg/g for *Caulerpa verticillata*. Surprisingly, there does not appear to be a direct correlation between total extractable lipids and saturated hydrocarbon content (Table 3). However, the species containing the largest lipid content, *Caulerpa verticillata* also contained the greatest amount of saturated hydrocarbons. Other algae containing high lipid content include *Caulerpa prolifera* (58 mg/g); *Pistia stratiodes* (35 mg/g); *Caulerpa mexicana* (33 mg/g); *Anadyomene stellata* (32 mg/g); *Caulerpa racemosa* (30 mg/g); and *Dictyota* sp. (30 mg/g) (Table 3).

Caulerpa prolifera, which has the second highest total lipid content of the seaweeds tested, is currently in both indoor and outdoor culture at our laboratory. It would therefore be of interest to investigate the possibility of increasing its lipid content by nitrogen limitation and/or other manipulation of environmental conditions and culture management practices, as has been found necessary to increase the lipid fraction of unicellular algae.

Table 3. Extractable lipid concentration in marine algae: Total lipid, f_1 (saturated hydrocarbons), f_2 (unsaturated hydrocarbons), f_3 (polar lipoidal material).

Harbor Branch I.D. II	Algae	Total Lipid[1] mg/g	f_1[2] mg/g	f_2[2] mg/g	f_3[1] mg/g
HB-26	*Caulerpa racemosa*	30	0.13	0.05	12
HB-33	*Caulerpa prolifera*	58	0.94	0.12	15
HB-36	*Scinaia complanta*	19	0.22	0.07	8
HB-38	*Sargassum cymosum*	26	0.43	0.18	8
HB-48	*Laurencia poitei*	9	0.25	0.20	4
HB-28	*Stypopodium zonale*	21	0.10	0.05	4
HB-34	*Encheuma* sp.	14	0.12	0.21	2
HB-39	*Dictyota* sp.	30	0.22	0.48	11
HB-51	*Digenia simplex*	7	0.03	0.03	15
HB-59	*Padina* sp.	38	0.42	0.10	6
HB-73	*Patoglossum* sp.	39	0.32	0.18	8
HB-30	*Heterosiphonia gibbesii*	14	0.09	0.08	4
HB-40	*Caulerpa mexicana*	33	1.08	0.31	10
HB-41	*Caulerpa sertularioides*	22	0.21	0.12	4
HB-42	*Caulerpa verticillata*	80	1.65	0.34	10
HB-64	*Halymenia floresia*	10	0.20	0.10	3
HB-70	*Solieria* sp.	5	0.07	0.02	1
HB-11	*Gelidiella taylori*	24	0.34	0.02	3
HB-76	*Pistia stratiodes*	35	0.25	0.02	9
HB-84	*Anadyomene stellata*	32	0.53	0.05	8

[1] Total mass of sample determined gravimetrically.

[2] Mass of fraction observed with GC-FID relative to mass of internal standard hydrocarbons added to the sample.

Task 6. Synthesis, Analysis, and Economic/Energy Evaluation of Data

Introduction

Intensive algae cultivation requires energy and nutrient inputs. Energy in different forms has different economic costs, but in the currency of fossil fuels, different forms of energy also provide different amounts of exhaust carbon. Inasmuch as carbon is the primary constituent of dry algae, the energy and carbon requirements of an algae farm must be considered together to arrive at a configuration which produces algal products at the lowest possible cost.

Research carried out at Harbor Branch during 1982 and 1983 centered on the response of *Gracilaria* and *Ulva* yields to aeration and seawater retention time. Aeration and seawater pumping are considered to be the major energy sinks in a land-based submersed seaweed culture system, and their cost is a large fraction of the total production cost. Both species suffer diminished yields at seawater flows below about 3 $m^3/m^2 \cdot$day (i.e. 6 turnovers/day in the Harbor Branch tanks), but *Ulva* is slightly more tolerant of low flows. This sensitivity to seawater flow is believed to be due mainly to carbon limitation, and zero-flow systems with carbon dioxide additions have produced yields equal to those in flow through systems (DeBusk, unpublished data).

Aeration has been shown to be essential for high seaweed yields, but the exact function that aeration fulfills has not yet been pinpointed. Aeration has been demonstrated *not* to supply significant carbon to algal cultures, so to a first approximation, seawater flow and aeration may be considered independent requirements.

Dried seaweed may be required for off-site hydrocolloid extraction or foodstuff applications. Drying is extremely energy intensive, and therefore is not feasible for seaweed energy farms. Where a dry product is required, significant amounts of exhaust carbon are available if fossil fuels are used as a heat source.

Carbon may be provided by seawater pumping or from the exhaust carbon resulting from powering pumps, blowers, and dryers. There are several other alternative carbon sources. The cost and the effect on facility energy balance of the various potential carbon sources must be evaluated before one carbon source can be chosen over another.

Part 1 of this economic and energy analysis concerns itself with pumping, aeration, drying, and carbon supply. Part 2 deals with the cost of the other operations and systems which must be part of a seaweed farm. The cost of non-carbon nutrients are estimated by a mass balance approach. Costs of land, construction, plumbing, harvest, labor, and maintenance are all highly system and site specific, but "reasonable" values are postulated. In Part 3, estimated total operational and fixed costs are calculated for three likely product streams, and unit production costs are presented.

Part 1 - Pumping, Aeration, Drying, and Carbon Supply

I. Pumping Water

The flow of seawater through a seaweed culture system serves three main purposes. First, the dissolved CO_2 and bicarbonate in the water provide carbon required for algal growth. Second, the addition of new water moderates the temperature of the water in the culture unit. Third, the renewal of the culture water flushes out potentially toxic chemicals and eliminates species of planktonic algae which have growth rates less that the dilution rate. Each of these effects may be important in different system configurations, and each may provide a minimum pumping requirement which cannot be further decreased.

As demonstrated in Task II, low carbon concentrations can diminish the productivity of seaweeds. One way of bringing carbon into a seaweed farm is to pump in large volumes of water with a certain levels of dissolved carbon. The cost of providing carbon by this method depends on several factors. The pump capital and operating costs are obviously important, as is the total inorganic carbon (TIC) concentration in the water. The ability of the seaweed to extract the dissolved carbon from the water is also very important, and this varies from species to species and from season to season. Work under Task II demonstrated that _Ulva_ net photosynthesis correlated well with TIC over the pH range of 7.5 to 9.5, whereas _Gracilaria_ net photosynthesis correlated better with the bicarbonate (HCO_3^-) concentration. Studies to validate these relationships for growth rather than photosynthesis have not yet been concluded, but for the purposes of this analysis those relationships will be assumed to be true.

The differences in the carbon metabolism of _Ulva_ and _Gracilaria_ are reflected in their performance in batch mode (zero flow) culture with no carbon addition. _Gracilaria_ can withdraw carbon from the water and raise the pH to about 9.5 whereas _Ulva_ can raise the pH to about 10.2. For seawater, this represents 40% and 60% removal of TIC, respectively. Thus, providing carbon by seawater pumping requires about 50% higher flow rate for _Gracilaria_ than for _Ulva_.

The importance of pumping for temperature control varies with the species being grown, the location of the farm, the season, and the weather conditions occurring in a particular year. The temperature of fully mixed natural water bodies depends on heat fluxes from influent and effluent streams, incident solar short wave and atmospheric long wave radiation, long wave radiation from the water to the atmosphere, evaporative heat losses, and thermal conduction (Ryan & Harleman,1973). Of these factors, incident radiation, long wave radiation from the water, and evaporative losses are generally most important in low flow systems.

Solar radiation in Florida averages about 211 watts/m^2 (1.82×10^4 KJ/m^2.day). The sensible heat energy embodied in a cubic meter of seawater is about 4.31×10^3 KJ/m^3 ^oC. In order that the heat flux in the pumped water equals the radiant flux, the product of the pumped volume per unit area and the temperature difference between the supply water and the culture water must be about 4.2 M^3/M^2.^oC. That is, with one turnover per day in a 1 m depth system, a 4.2^oC ΔT will balance the incoming radiant heat flux.

In real systems, however, long wave radiation from the water to the atmosphere reradiates a large fraction of the incident radiation. Evaporative cooling is also very important. In an aerated seaweed farm, evaporative cooling would be much increased due to the bubbling, so the equilibrium temperature would be less than is seen in unaerated systems. A precise analysis would require detailed wind speed, temperature, relative humidity, and insolation data, but it appears likely that flow rates well below 0.5 m^3/m^2.day will maintain the culture temperature within 2°C of the supply temperature during the summer. During the winter, nighttime radiation from the water surface is very significant, and higher flow rates may be required to keep the culture from becoming much cooler than the supply water.

The importance of temperature control for seaweed culture lies in the effect of temperature on the growth rate. Figures 12 and 13 (excerpted from Ryther and Hanisak, 1982) show that both *Gracilaria* and *Ulva* enjoy limited temperature ranges where the growth rate is maximal and independent of temperature. At temperatures below this plateau (<24°C for *Gracilaria*, <18°C for *Ulva*), growth rate falls off sharply. Data not shown in the figures indicate that the growth rates at 36°C are also much less than the 30°C growth rate for both species.

The temperature of the Indian River estuary water used for seawater supply at Harbor Branch frequently exceeds 30°C during the summer and falls below 18°C during the winter. Thus, even in the relatively benign climate of central Florida, temperature extremes of the water supply can depress the growth of *Gracilaria* and *Ulva* during as many as four months per year. Increased pumping rates serve to bring the culture water temperature close to that of the supply, but when the supply temperature is unfavorable to seaweed growth, the options available to modify the culture temperature are few.

One other way to avoid temperature limitation to growth is to choose several species of algae with different temperature optima. This complicates the management of the system because operational modes must be switched when species are switched, but it does permit continuous operation year-round.

The importance of pumping for the flushing of planktonic algae and potentially toxic metabolites has not been thoroughly studied. Algae are well known to secrete numerous compounds (Khailov and Burlakova, 1969), and aerated *Ulva* cultures, in particular, often form thick layers of foam due to the presence of secreted surface-active organics. The exact nature of these compounds has not been determined (VanVleet and Williams, 1983), and their effects on productivity are unknown.

The growth of planktonic algae at low flow rates can be avoided by maintaining nitrogen and phosphorus concentrations at low levels in the culture water. Both *Gracilaria* and *Ulva* have been found to absorb N and P very rapidly when they are nutrient starved, so the pulse feeding method discussed later can be used to provide nutrients. This method both eliminates waste and avoids high nutrient concentrations in the culture water. Under some low nutrient conditions, however, nitrogen fixing blue-green algae still invade the cultures and compete for light and carbon

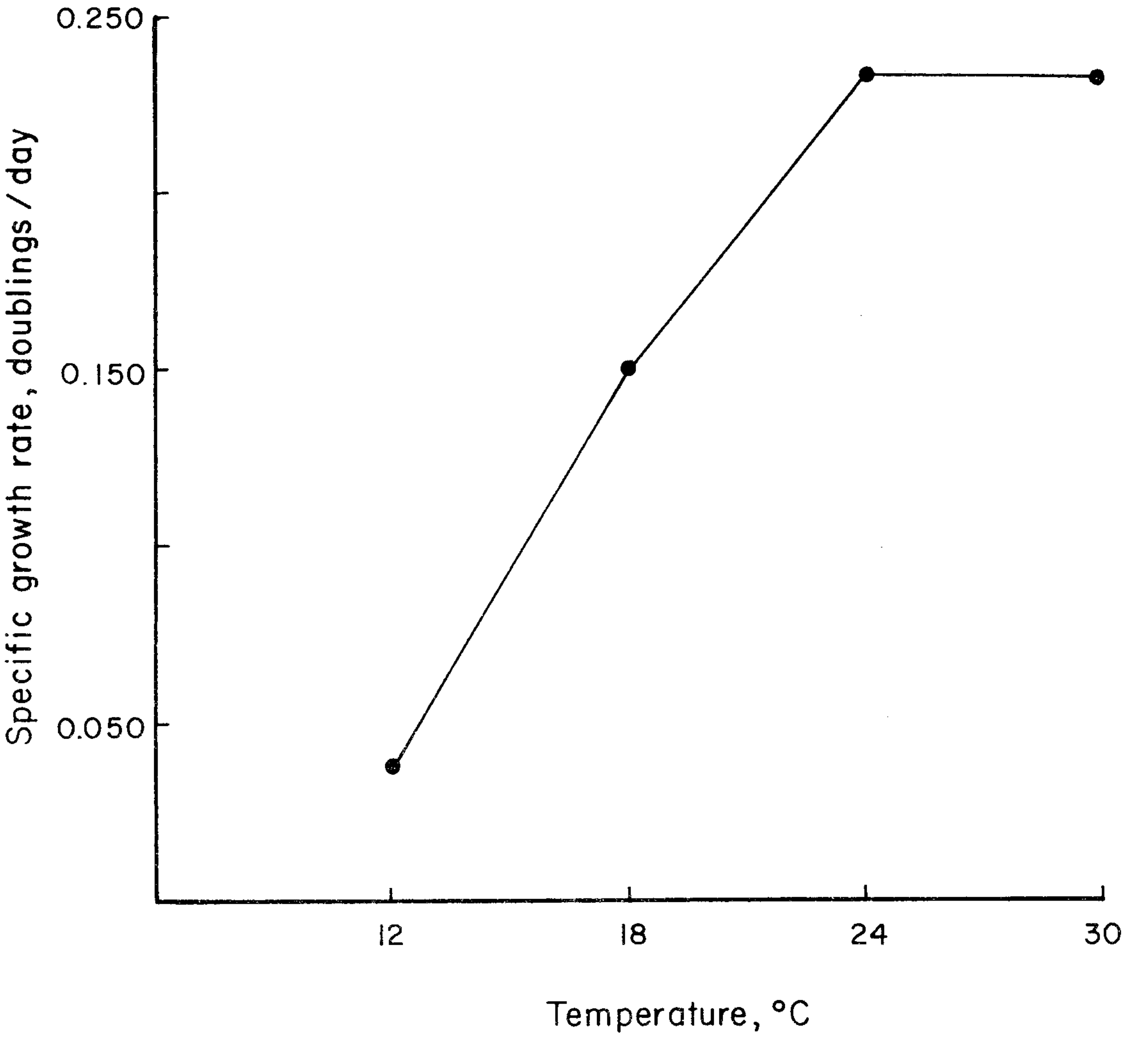


Figure 12

Specific growth rate of Gracilaria (clone 001) as a function of temperature (n=9 for each point).

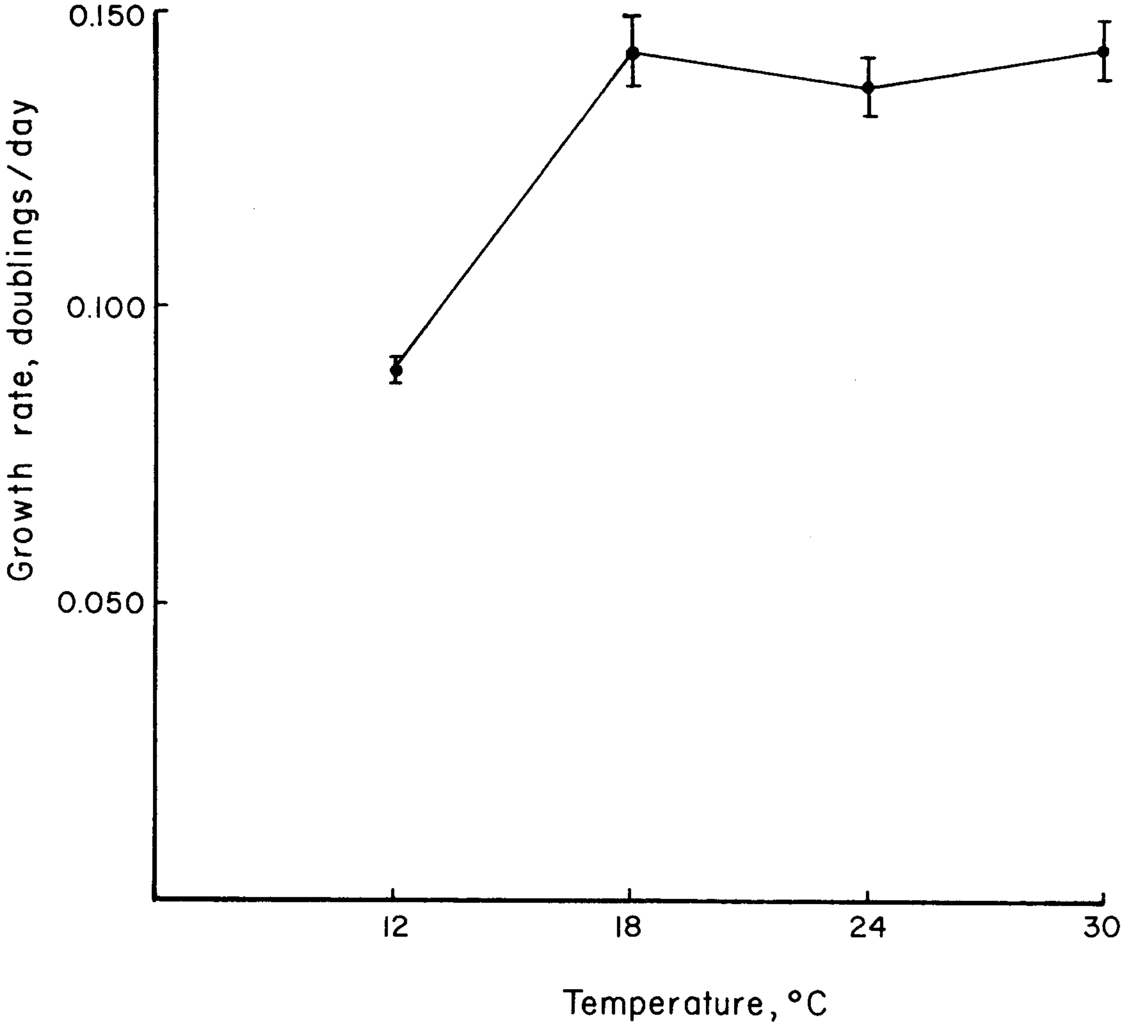


Figure 13

Specific growth rate of Ulva (cone 017) as a function of temperature (bars around data points indicate standard errors, n=9 for each point).

(personal communication, Tom DeBusk). Further work at the pilot scale is required to determine the importance of these problems.

Pumping costs are comprised of operational costs and fixed (capital) costs. The bulk of the operational cost is due to the energy used to move the water against the acceleration of gravity. The energy costs and carbon contents of electrical power and fossil fuels are shown in Appendix A. The equations describing pumping energy requirements are developed in Appendix B. Comparison of electric and diesel powered pumps yields the following expressions for the energy cost of carbon and the energy storage: energy input ratio.

Electric Motor Drive:

$$\frac{E_P}{\dot{C}_A} = \frac{1.26 \times 10^4 \ h}{fA \ [TIC]/h}$$

Diesel Engine Driven with exhaust carbon use:

$$\frac{E_P}{\dot{C}_A}_{\ tot} = \left(7.94 \times 10^{-5} \ \frac{fA \ [TIC]}{h} + 5.78 \times 10^{-5} \ f_E\right)^{-1}$$

$$\frac{E_A}{E_D} = [2.54 \times 10^{-5} \ f_A[TIC]/h + 1.91 \times 10^{-5} \ f_E] \ Q_A$$

where $\dot{C}_A$ = algal carbon flux in kg

[TIC] = total inorganic carbon concentration in mg/l

f_A = fraction of TIC available to the seaweed

f_E = fraction of CO_2 in diesel exhaust which is assimilated by the seaweed

E_P = pumping brake energy in KJ

E_A = gross energy fixed by the algae in KJ

E_E = electrical energy consumed by electric motor in KJ

E_D = fuel energy consumed by diesel engin in KJ

h = pumping head in meters

Q_A = heating value of algae determined by bomb calorimetry in KJ/kg algal C

The example case for Gracilaria with a carbon utilization fraction, f_a, equal to 40% and a 2 meter pumping head gives gross energy output to input ratios of 10.8 and 4.3 for electric and diesel drives, respectively. This difference reflects the fact that the thermal losses involved in electric power generation at the power plant are not experienced a second time in conversion to mechanical energy. When the generating losses are included in the energy balance, the net efficiencies from fuel to mechanical energy are roughly equal for electrical and diesel pump drivers (Fluck and Baird, 1983).

The pump literature (e.g. Karassik, et al., 1976) was searched and many vendors were contacted for quotes on pumps suited to the high volume, low head application envisioned for land-based seaweed farms. The model seaweed farm, consisting of 100 active hectares one meter deep, requires a 23.1 m^3/sec flow rate 12 hours per day to achieve one turnover per day. This flow rate with a 2 meter head requires 582 brake kw.

Pumps of two types were considered for this application. Archimedes screw pumps are available in diameters up to twelve feet with flow rates as high as 90,000 gpm (5.67 m^3/sec). They also have a wide flow range with fairly low sacrifices of efficiency at low flows. On the other hand, these pumps have relatively low efficiency (less that 70%) and require elaborate site preparation. For these reason, screw pumps were abandoned in favor of axial flow (propeller) pumps.

Axial flow pumps are generally about 80% efficient, and they require somewhat less earthwork than do screw pumps. M & W Pump Corporation of Deerfield Beach, Florida, manufactures hydraulically driven pumps with up to 53,000 gpm (3.34 m^3/sec) capacity which require virtually no site preparation other than provision of a piece of flat ground on which to set the skid mounted drive and hydraulic power unit. Purchase price data are compiled in Table 4. Prices vary considerably depending on the materials of construction and the type of driver included. An estimate for pump cost which will be used in this analysis is $200K/100K gpm ($317K/10 m^3/sec) capacity, including diesel drive. Only about $15K of this is dedicated to the drive unit. Substitution of an electric motor for the diesel would decrease the capital cost by less than 4%.

Prices for Caterpiller diesel powered generator sets, including breakouts for the engine costs alone, are compiled in Table 5. Since axial flow pumps suffer markedly decreased pumping efficiencies when operated significantly below the design flow, the best approach is probably to have many (perhaps 3 to 6) smaller pumps which can be brought on-line as flow requirements increase with high photosynthesis or pond filling operations. A centralized generator set of a capacity sufficient to electrically power all pumps would be a poor idea because it would operate far below capacity most of the time. The additional power requirements for aeration discussed later level the load somewhat, however, because aeration is presently considered to be required independent of the rate of photosynthesis, and therefore does not fluctuate daily with light intensity. A more nearly constant power load makes centralized diesel powered generator sets more attractive.

A comparison of pump capital and operating costs for a one turnover per 12 hr day system is shown in Appendix B. Operational costs are directly

Table 4

Pump Capital Costs - all for 6' total head

Vendor/ Material	Flow (gpm)	Discharge D (inches)	Pump efficiency	Brake H.P.	H.P./ 100K gpm	Price ($)	Price/ 100K gpm($)	Comments
PEERLESS - AXIAL FLOW PUMPS								
Bronze	75K	54	78	146.0	195	139K	185K	No driver,
Bronze	50K	48	78	97.1	194	97K	194K	gear reducer included
Bronze	40K	42	82	73.9	185	67K	168K	
Bronze	30K	36	80	56.8	189	50K	167K	
Bronze	20K	30	80	37.9	190	40K	200K	
ALLIS-CHALMERS - AXIAL FLOW PUMPS								
Stainless	90K	60	82	170	185	230K	256K	Including diesel driver
Coated iron	90K	60	82	170	185	133K	148K	" " "
PASSAVANT - SCREW PUMPS								
Coated iron	80K	144	70	173	216	110K	138K	Including electric motor

Table 5

Diesel Generator Set and Diesel Engine Capital Costs

Caterpiller Tractor Corporation, 60 hz power

Model #	Prime Power (KW)	Generator & Engine Price ($)	Price/ 100 kw w/gen.	Engine only Price ($)	Price/ 100 kw eng. only ($)	Price/ 100 hp eng. only ($)
3208T	115	23.5K	20.4K	11.8K	10.2K	7.6K
3406TA	250	35.9K	14.4K	20.0K	8.0K	6.0K
3412TA	440	73.5K	16.7K	50.0K	11.3K	8.5K
3512TA	800	145.0K	18.1K	97.0K	12.1K	9.0K

Additional Performance Data for 3512TA:

Fuel consumption at 800 kw is 229 l/hr (60.5 gal/hr). Specified diesel fuel has higher heating value of 45570 KJ/kg (19590 BTU/lb) and a density of 848 g/l (7.076 lb/U.S. gallon). It is 87% carbon by weight. Exhaust gas flow rate is 215 m^3/min (7610 cfm) at 470° (878°F). The heat rejection to the exhaust is 911 kw (51,808 BTU/min). The efficiency from fuel energy to electric energy is 32.5%.

Prices courtesy of Pantronic Power Products, Miami, Florida.

proportional to the pumping head, h, while capital costs scale with the pumping flow capacity. Calculations show that the electrical energy cost (at .053$/kw.hr., 90% motor efficiency), is about 75,100.h $/yr. The diesel energy cost (at $1.00/gallon, 33% engine efficiency) is about 94,600.h $/yr while liberating 263,000 h kg carbon in the exhaust. If the difference in the energy costs is attributed to the carbon in the exhaust, the equivalent carbon cost is $74.60/metric ton C. This is about one third the cost of commercially available liquid CO_2, and roughly equal to the cost of 2 m head pumped seawater carbon, depending on exhaust carbon sparging efficiency and the algal assimilation fraction. Thus, the choice of pump drive depends on factors other than carbon cost at pumping heads around 2 m. For heads much less that 2 m, electrical motors would be preferred.

As stated above, capital costs for pumps are about $200,000 per 100,000 gpm ($317,000 per 10 m^3/sec) capacity. This implies that the capital cost for a one turnover per day system is about $734,000. Thus, for a pump with a two meter head, the annual energy cost is approximately 51% of the total capital cost.

II. - Blowing Air

The estimation of aeration cost in this analysis must be based on our limited experience at Harbor Branch. Most of the seaweed growth experiments use rectangular tanks which are equipped with a perforated PVC pipe lying longitudinally along the bottom of the tank. Air forced through the holes by a high volume, low pressure air blower creates a curtain of bubbles which rises to the surface of the tank. A current is thus established which, at the center of the tank, acts to lift the seaweed from the bottom, and at the sides of the tanks, pulls the seaweed from the surface back under water. Although previous studies have shown that seaweed growth in aerated tanks is much greater than that in non aerated tanks (Ryther, 1980), the actual means by which aeration increases seaweed growth is unknown. Benefits derived from aeration may include: increased thallus exposure to light, elimination of nutrient diffusion barriers, and improved sediment and epiphyte removal. Whatever the function, aeration is a major cost and energy input that should be reduced to a minimum level consistent with high seaweed yields. Much of the outdoor experimental work undertaken this year was therefore devoted to aeration studies.

Yield vs. Aeration Studies

In the spring of 1982, we demonstrated that aeration to Gracilaria tanks could be reduced by 75% (from 24 hr/day to 6 hr/day) with only a 10% reduction in seaweed yields (Ryther, 1982b). Whether the six hours of aeration was provided in two hour pulses, three times a day, or in 15 minute pulses each hour did not seem to affect Gracilaria growth. New timers were purchased in 1983 so that aeration could be supplied to Gracilaria and Ulva tanks at very brief intervals. Total aeration times of 1, 2, 4, and 12 hours were provided by the following regimen: 1) 1 minute on:23 minutes off, 2) 1 minute on:11 minutes off, 3) 1 minute on:5 minutes off, and 4) 1 minute on:1 minute off. Both species were also grown with continuous (24 hr) aeration, and with no aeration. Aeration experiments were conducted in both warm and cool months in order to determine whether aeration requirements are seasonal.

We found that maximum *Gracilaria* yields were obtained with continuous (24 hr) aeration, although down to and including the 4-6 hour aeration times, seaweed yields decreased just slightly (Figure 14). Moreover, we found that this trend persisted during both warm and cool months, despite the wide seasonal fluctuations in yields which occurred as a result of changes in solar radiation and temperature. The only seasonal deviation (interaction) in the yield vs aeration time relationship was observed in the non-aerated treatment where it appeared that under passive conditions, *Gracilaria* grew better in cool, rather than in warm months (Figure 1). Previous attempts at culturing *Gracilaria* in stagnant ponds produced similar results, with maximum growth occurring during the winter and the seaweed essentially dying in the summer. These data indicate that if sufficient energy is not available for year-round aeration, maximum biomass production and crop survival would be best ensured by warm month aeration only.

As with *Gracilaria*, growth of *Ulva* decreased continuously with decreasing aeration time (Figure 15). However, the decline in productivity from 24 to 4 hours of aeration was proportionately greater for *Ulva* than for *Gracilaria*. Seasonal changes in light and temperature did not greatly affect the aeration time vs productivity relationship for *Ulva*. Unlike *Gracilaria*, it was unclear whether *Ulva* cultured without aeration grew more rapidly in the colder or in the warmer months.

In summary, it appears that regardless of season, 4 hours of aeration (17% of the operating energy required for 24 hr aeration), will support *Gracilaria* and *Ulva* yields 80% and 66% respectively, of those attainable with continuous aeration. Moreover, it is possible that these same yields could be attained with only 2 hours of aeration, by providing the "4 hour" (1 min. on:5 min. off) aeration cycle during daylight only.

Effect of Culture Tank Aeration

Several experiments were conducted in 1983 which provide some insight into the true function of aeration in seaweed cultures. In the first experiment, *Gracilaria* was cultured under two regimes: a) in non-aerated tanks, with the seaweed weighed weekly and then harvested back to the original density and restocked, and b), in non-aerated tanks, with fresh, previously aerated seaweed stocked after each weekly weighing. We found that *Gracilaria*, following transferral from an aerated tank, grows quite well for one week under non-aerated conditions (Table 6). However, if kept in a non-aerated tank for 2 or 3 weeks, yields drop precipitously. These results indicate that both the light and carbon supply to non-aerated tanks (with a high water flow) is sufficient to support relatively high seaweed yields. The reason for the subsequent decline in growth after one week is unknown, but may be due to the seaweed becoming light or nutrient (including carbon) limited through the interference of sediment or epiphytes which settle on the thallus under passive conditions.

Another experiment was conducted to determine the extent to which the atmosphere supplies carbon (via aeration) to the seawater in our outdoor growth tanks. The diffusion of oxygen into a 1.7 m^2 (700 l) aerated tank, devoid of seaweed, was measured using an oxygen meter. Oxygen was first purged from the seawater in the tank to a level of ~3.0 ppm, using N_2gas. Aeration was then started, and the rate at which oxygen diffused into the tank was used to determine the coefficient K_La in the expression:

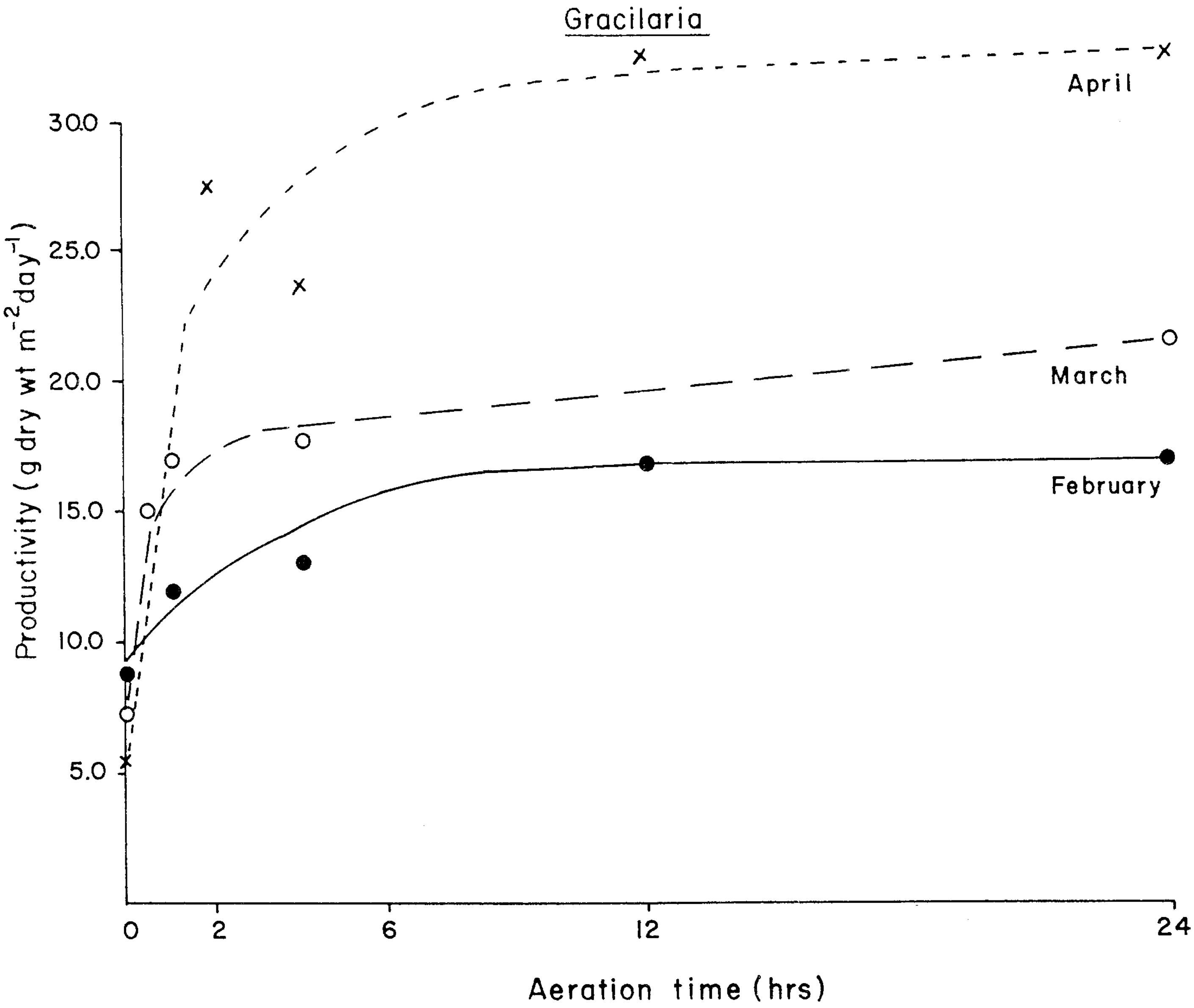

Gracilaria
April
March
February
30.0
25.0
20.0
15.0
10.0
5.0
Productivity (g dry wt m^{-2} day^{-1})
0
2
6
12
24
Aeration time (hrs)

Figure 14

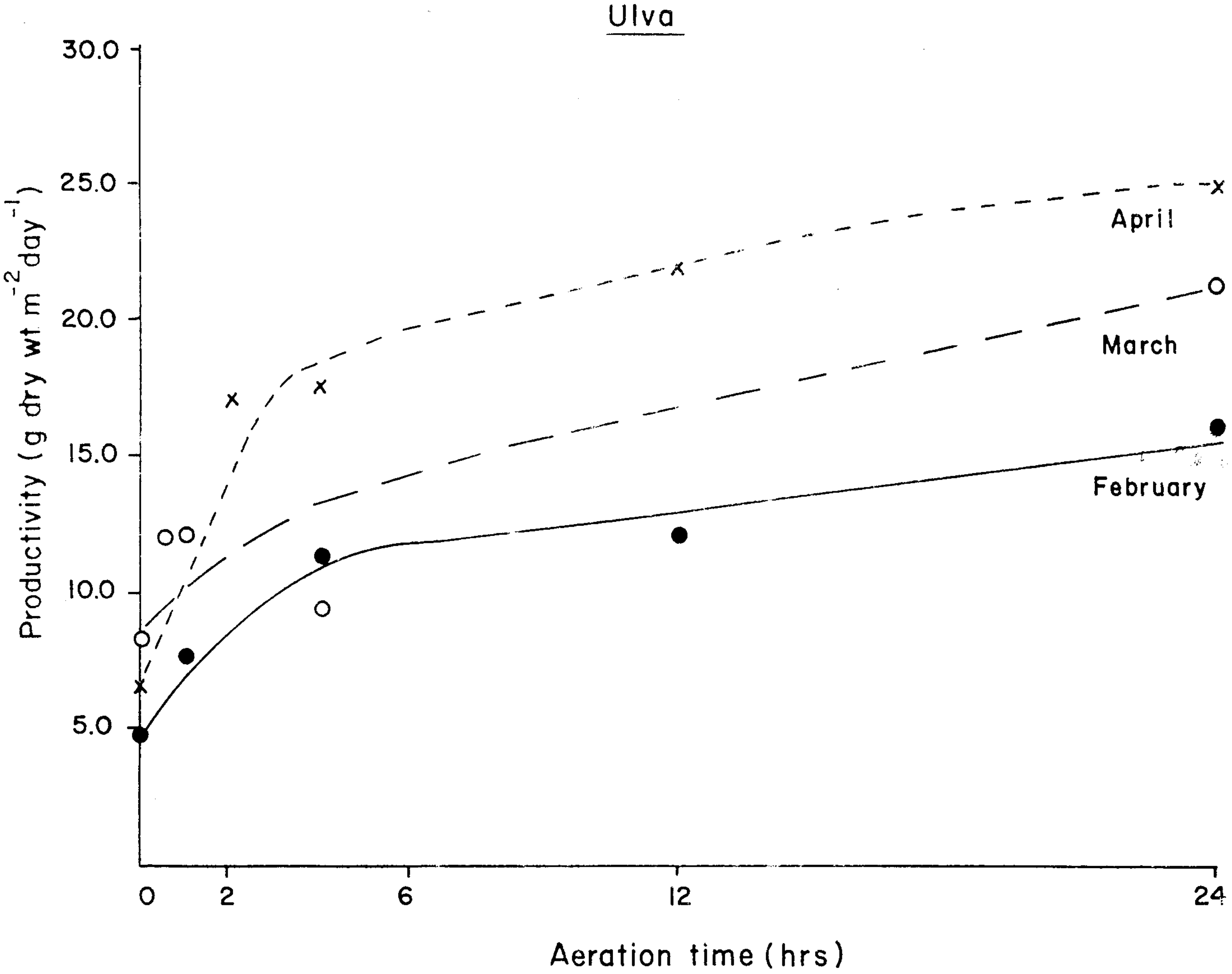

Ulva
30.0
25.0
20.0
15.0
10.0
5.0
Productivity (g dry wt m^{-2} day^{-1})
April
March
February
0
2
6
12
24
Aeration time (hrs)

Figure 15

Table 6

Productivity of *Gracilaria* in non-aerated cultures: Seaweed maintained continuously without aeration (continuous) vs "preconditioned" in aerated cultures, then placed in non-aerated tanks (replaced)

	---------Productivity (gdw m^{-2} d^{-1}---------	
	Continuous	Replaced
Week 1:	27.3	28.5
Week 2:	17.9	29.7
Week 3:	4.4	27.9

$$\frac{dc}{dt} = K_La \quad (Cs-C)$$

where:

$^{dc}/_{dt}$ = rate of change in concentration
K_La = overall mass transfer coefficient
Cs = saturation concentration of gas in solution
C = concentration of gas in solution

Because CO_2 is much more soluble than O_2 in seawater, a factor of

$\frac{K_L\ (CO_2)}{K_L\ (O_2)}$ = 17.8 was used to convert the mass transfer of oxygen to that of CO_2 (Ashare, et al., 1978). The calculated diffusion rate of 2.14 x 10^{-3} mmole/l hr for atmospheric CO_2 into free CO_2 depleted water shows that the bubbling of air (0.03%CO_2) into our tanks supplies at most enough carbon to support a daily seaweed production of only 0.5 ash free dry grams m^{-2}. This is consistant with the observation of the above experiment that enough carbon is present in non-aerated (high flow) Gracilaria cultures to support fairly rapid growth.

Although supplying atmospheric carbon to the seawater in a culture tank is not a critical function of aeration, the agitation or water movement created by this process may greatly enhance algal carbon (or other nutrient) uptake by reducing "diffusion barriers". Moreover, aeration may be important not only during the growth period, but also while the seaweed is being pulse-fed. We therefore conducted an experiment in which nitrogen uptake by N-starved Gracilaria was examined under various aeration regimes. The seaweed was soaked for 24 hours in seawater containing either high (no water exchange, 7 mgN/L) or low (10 exchanges water/day, ambient seawater at 0.1 mgN/L) levels of nitrogen. The "high" levels are similar to nitrogen concentrations used during pulse feeding, and the "low" levels simulate nitrogen concentrations which the seaweed is exposed to during its growth period.

As expected, we found that N uptake (as determined by change in thallus N content) increases with increasing aeration time (Table 7). In addition, N uptake under all aeration regimes was greater in the high N than in the low N seawater, indicating that water motion or agitation of the thallus is essential for the uptake of nutrients present in low concentrations. Whether aeration was provided in the day or night did not seem to affect N uptake by Gracilaria. These data indicate that the goal of pulse fertilization (increasing thallus N-content) can be achieved most rapidly by utilizing high seawater N concentrations and continuous aeration. In addition, the poor N uptake under low N, stagnant conditions indicates that Gracilaria may be susceptable to a nutrient limitation during a non-aerated growth period, especially if "luxury consumption" of the particular nutrient does not occur during fertilization.

Aeration Cost

The 1.7m^2 culture vaults used for most outdoor experimental work at Harbor Branch are aerated at a rate of about 2 standard cubic feet per minute (scfm). The 100m^2 pond described in the section on construction costs was aerated by a 1.72 kw blower supplying 100 scfm at 40" H_2O pressure. Given that circulation can be maintained with a slightly greater spacing

Table 7

Effect of aeration time on N-uptake by *Gracilaria*. Thallus N content is reported after 24 hrs. exposure to one of eight treatments (2 nitrogen levels x 4 aeration regimes). Initial thallus N content was 0.9%.

	Nitrogen content (% of dry weight)[1]	
Aeration	Low-N Culture	High-N Culture
None	1.0	1.2
12 hrs, daytime	1.2	1.5
12 hrs, nighttime	1.2	1.6
24 hrs.	1.4	1.7

[1] mean of triplicate samples

between air lines, a minimal aeration rate of 0.5 scfm/m^2 culture area is assumed for this analysis. The power required by a blower or compressor to increase the pressure of a flow is approximately given by $p = \Delta pQ/\eta$ where P is the power, p is the pressure rise, Q is the flow rate, and Δp is the compressor efficiency (Shepherd, 1965) . This holds exactly only when the pressure rise results in negligible change in gas density.

Most of the pressure drop in an aeration system is due to the hydrostatic pressure of the aerated water, so aeration energy use is directly proportional to water depth. For a 1 meter deep 100 hectare system with 0.5 scfm/m^2 air flow, the instantaneous power requirement with a 100% efficient blower is 2310 kw (3100 hp). The gross energy storage rate for <u>Gracilaria</u> growing at 35 dry g/m^2·d on 100 hectares is 9160 kw (12,300 hp), so aeration accounts for a significant fraction of gross energy production. Anaerobic digestion typically recovers about 40% of the gross energy in seaweeds (Habig and Ryther, 1983), so the net power available from seaweed drops to 3660 kw (4910 hp). It is thus clear that aeration energy must be decreased if there is to be net energy production.

The growth experiments described above have shown that four hours of aeration per day can support <u>Gracilaria</u> and <u>Ulva</u> yields 80% and 66% of continuously aerated yields, respectively. It is likely that energy use can be further halved by restricting aeration to daylight hours. The installed flow capacity in this case would be one sixth of that for continuous aeration because the air flow could be time-shared. The energy use would be one twelfth that for continuous aeration because the one sixth blower capacity would operate only half of each day. The capacity for 100 hectares aerated in this fashion is 83,300 cfm, and the ideal power for 1m H_2O pressure is 386 kw.

Prices and efficiencies for blowers of different types are compiled in Table 8. There is somewhat of a problem in specifying the proper blower because the pressure corresponding to one meter water depth (1.4 psi) is below the range of most efficient operation for centrifugal blowers. Positive displacement blowers operate at these pressures, but they are unavailable with capacities above 5000 cfm. For the purposes of this analysis, it is assumed that a suitable blower is available with 80% efficiency at a cost of 3.5K $/1000 scfm. The operating and capital costs for the 100 hectare time-sharing system are calculated in Appendix C. Electrical energy cost (at 5.3 cents /kw-hr, 90% motor efficiency) is about $124,000/yr. The diesel energy cost (at $1.00/gallon, 33% engine efficiency) is about $157,000/yr. Once again, diesel power furnishes exhaust carbon which can be utilized if economically beneficial. Capital cost for the blowers is about $291,000. Operating costs thus exceed capital cost within three years.

III. Drying Seaweed

Fresh seaweed is about 90% water. As shown in Appendix D, the energy required to dry seaweed to 20% moisture is more than the gross energy fixed in the biomass. A seaweed energy farm therefore cannot afford to use fossil energy solely for drying. The exhaust heat from diesel engines powering the aeration blowers and pumps may be available, however, and this can be used as process heat.

Table 8

Blower and Compressor Capital Costs

Vendor/ Model	Flow (inlet cfm)	Pressure (psig)	Efficiency (%)	Price ($)	Price/ 1000 cfm ($)	Comments
ROOTS-DRESSER						
OIB-250	100,000	5	90	640K	6.4K	Centrifugal with motor
OIB-150	50,000	5	90	320K	6.4K	Centrifugal with motor
MVI-112	16,700	5	83	45.5K	2.7K	Centrifugal with motor
MVG-73	12,000	5	82	39K	3.2K	Centrifugal with motor
RAS-J	3,600	2	83	13K	3.6K	Positive displacement with motor
SPENCER TURBINE						
12250-MOD	21,000	1.25	38	24.4K	1.2K	Turbo-blower with motor
GARDNER-DENVER						
11-PDR27	4040	2	67	?	?	Positive displacement

For a farm using aeration and one turnover of water per day (23.1 m^3m/sec) at 2 m head, the installed brake power for blowers and pumps is (482 + 582) kw = 1064 kw. Diesel engines reject about 115% of their brake power as exhaust heat, so about 1220 kw of waste heat would be available in the blower and pump driver exhaust for drying. As the drying power requirement is 26,700 kw, exhaust heat is inadequate for drying unless the pumping head (hence power) increases dramatically or fossil fuels are burned as a carbon source.

The capital and operating costs for Aeroglide rotary dryers are compiled in Table 9. The dryer is about 60% efficient in using the energy in natural gas, so the energy consumed per kg wet weed dried from 90% to 20% moisture is 110 x 10^3 KJ/kg algal C. The operating cost with $5/MMBTU gas is .53 $/kg algal C, and the capital cost is about $1000/kg algal C per hour capacity.

Few hard data exist on the economics of solar drying. This technology requires a great deal of land and labor. It is also susceptible to the vagaries of the weather, and would perform poorly during the humid windless summers characteristic of Florida and some other tropical sites. Solar drying has not been investigated thoroughly, but it is assumed to be incompatible with an intensely productive land-based seaweed farm.

IV. Supplemental Carbon Sources

The projected carbon demand for a 100 ha. seaweed farm producing 35 dry g/m^2.day is 10,500 kgC/day (see Appendix E). If this is supplied solely by seawater pumping, 1.31 and 0.87 m^3 seawater/m^2·day are required for Gracilaria and Ulva, respectively. In some situations this may be very costly. If the carbon demand is satisfied solely by sparging with the exhaust from diesel engines or other fossil fuel heat machines, over 50,000 kw of shaft power could be supported. This is over five times the gross energy fixation rate of the seaweed, and nearly fifty times the energy required for aeration and the pumping of one turnover per day with a 2m head. It is thus clear that sources of inorganic carbon other than natural carbonate alkalinity and fossil fuel exhaust gases should be evaluated.

Costs for various forms of carbon and for bulk acids and bases are tabulated in Table 10. Prices for acids and bases are included because alkalinity control may be desirable in some situations. Seawater carbon is less expensive than liquid CO_2 at low pumping heads. The cost of carbon from pumping at 40% carbon utilization equals the cost of carbon from liquid CO_2 when the pumping head is 16 m. For 60% utilization, the break even head is 24m. At greater heads, lesser TIC concentration or algal carbon utilization levels, liquid carbon dioxide is less expensive than pumped seawater.

Geologic CO_2 of high purity is abundant in certain areas of the U.S. (primarily the Four Corners states), and it is less expensive than liquid CO_2 by a factor of about four (Hare, et al., 1978). High transportation costs to reach the nearest coastal area may make this source of carbon uneconomical for coastal sites. If a seaweed farm were situated in a Southwest desert region, however, this carbon source might very well be more economical than pumping highly alkaline saline groundwater if the aquifer were more than 5 m below the surface.

Table 9

Rotary Dryer Capital and Operating Costs

All information courtesy of Aeroglide Corporation, Raleigh, NC
Seaweed enters @ 90% water, exits @ 20% water

Model	Heating Power Required (KW)	(MMBTU/hr)	Capacity (kg wet/hr)	Capacity (kg dry/hr)	Energy/kg wet (KJ/kg)	Price ($)	Price/kg wet/hr ($) Capacity	Comments
R1-96-40	2490	8.5	2720	340	3300	155K	57	mild steel
	2490	8.5	2720	340	3300	200K	74	stainless
R3-144-48	11700	40	12700	1590	3300	360K	28	mild steel
	11700	40	12700	1590	3300	470K	37	stainless

The 100 hectare farm producing 350 wet $g/m^2 \cdot 12$ hrs produces 29,200 wet kg/hr. Capital cost is assumed to be $30/wet kg per hr capacity for a dryer that will not corrode.

The energy cost for 1 kg wet seaweed with $5/MMBTU gas is:

$$\left(\frac{3300\ \text{KJ}}{\text{wet kg}}\right)\left(\frac{\$5}{10^6\text{BTU}}\right)\left(\frac{10^6\ \text{BTU}}{1.054 \times 10^6\text{KJ}}\right) = .0157\ \$/\text{kg wet seaweed}$$

Table 10 Costs for Carbon and Associated Chemicals (from Chemical Marketing Reporter, May 9, 1983)

	$/1000 kg	Purity (%)	molecular weight	%C	$/kgC	KJ/kgC	$/eq alkalinity
CARBON							
CO_2 well head	18	100	44	22.27	.066		
CO_2 liquid	66	100	44	22.27	.24		
$NaHCO_3$	254	100	84	14.29	1.78		2.13×10^{-2}
Na_2CO_3	93	58	106	11.33	1.41		8.45×10^{-3}
#2 Fuel Oil	326			87	.36	52.4×10^3	
Natural gas							
@$5/mcf	243			72	.34	72.3×10^3	
@10/mcf	485			72	.68	72.3×10^3	
COAL (from Wall Street Journal, Dec. 1983)							
Low Volatile Metallurgical	48			80	.060		
Low Sulphur Bituminous	25			70	.036	43.0×10^3	
High Sulphur Bituminous	24			70	.034		
Seawater Alkalinity							
@2m head, $1.00/gallon diesel fuel							
Ulva 60% carbon utilization					.040	1.93×10^3	
Gracilaria 40% carbon utilization					.057	2.79×10^3	
ACIDS					$/1/12 kg equiv. (Same alkalinity as kg carbon HCO_3^-)		
Hydrochloric	42	32	36.47		.40		4.77×10^{-3}
Sulfuric	69	100	98.08		.28		3.40×10^{-3}
Nitric	215	70	63.02		1.61		1.93×10^{-2}
Phosphoric	181	53	98.00		1.47		1.76×10^{-2}
BASES							
NaOH	331	73	40.01		1.51		1.81×10^{-2}
KOH	264	45	56.10		2.75		3.30×10^{-2}

The utilization of either sodium bicarbonate ($NaHCO_3$) or sodium carbonate (Na_2CO_3) is more expensive that the use of liquid CO_2 by a factor of about six. Furthermore, equivalent amounts of acid must be added with the carbon salt if alkalinity is to be conserved. In some cases, increased alkalinity may be desired (e.g. to increase the total carbon concentration at a given pH). Sodium carbonate is the least expensive source of alkalinity.

Coal combustion gases stand out as the least expensive carbon source for situations where seawater pumping heads are greater than about 2 meters. The heating valve of coal is roughly 40 x 10^3 KJ/kgC (Babcock and Wilcox, 1978). The gross heating valve of seaweed is roughly 38 x 10^3 KJ/kgC, but only about 40% of that energy is recovered as methane from anaerobic digestion. It would thus obviously be inadvisable to burn coal in order to produce carbon dioxide to be used for seaweed energy farming.

In some cases, flue gas from the combustion of fossil fuels may be available from on-line power plants or other industrial operations. Flue gas is likely to be an even less expensive carbon source than coal, but transportation costs for the gas could be substantial. If the seaweed depends upon the combustion of fossil fuels for its carbon, it is no longer truly a renewable energy resource, but rather an energy conservation technology.

A further alternative for carbon supply is to recycle all the seaweed carbon after extracting the energy. If the biogas or ethanol produced from seaweed were used on-site to produce electrical energy, there would ideally be no carbon lost from the system. Carbon could simply serve as a vehicle for the transport of fixed solar energy, and carbon supply would be required only to cover losses from the system. Such an approach may be technically feasible, but the efficiency of this biological photovoltaic system is likely to be low because of the multiple conversions involved.

V. Conclusion for Part 1: Pumps, Blowers, Dryers, and Carbon Supply

The preceeding sections have dealt with the economic and energy costs associated with seawater pumping, aeration, drying, and alternative carbon supply. The results of these analyses are summarized in Table 11. The three forms of seaweed product to be considered here are seaweed energy, dry seaweed (20% moisture), and wet seaweed (90% moisture). Each product stream has different energy demands and performance criteria. Probable energy and economic costs for these systems are discussed below.

A. Energy Production

The first requirement of a seaweed farm is carbon. Table 8 shows the cost of carbon from different sources. If methane is to be exported from the system, it makes little sense to use a carbon source which is more expensive than carbon from methane. This eliminates carbon salts from consideration.

A figure of 35 dry g/m^2.day is used here and throughout this analysis as a reasonable annual average productivity. This has not yet been exceeded in intensive small scale cultures, alghough productivity for Gracilaria over one week periods under optimum conditions has approached 50 dry g/m^2.d.

Table 11

Summary: Economic and Energy Analysis - Part 1

OPERATION	OPERATING COST	FIXED COST	POWER (12 hr. day)
Pumping (1 $m^3/m^2 \cdot day$)	75 x 10^3 h $/yr	734 x 10^3 $	291 h kw
Aeration (0.5 scfm/m^2 @ 1/6, 12 hrs)	124 x 10^3 $/yr	291 x 10^3 $	482 kw
Drying (@35 dry g/$m^2 \cdot$day yield)	2001 x 10^3 $/yr	875 x 10^3 $	26,700 kw
Gross Productivity (@ 35 dry g/$m^2 \cdot$d)	3830 x 10^3 kg algal C/yr		9,160 kw
Net Energy Productivity (@ 40% energy recovery by digestion)			3,660 kw
Equivalent power from fuel carbon for 35 dry g/$m^2 \cdot$d			
#2 Fuel Oil			12,700 kw
Natural Gas			17,600 kw
Low Sulphur Bituminous Coal	138 x 10^3 $/yr		10,500 kw
Seawater at 2 m head - Ulva			469 kw
Gracilaria			678 kw

Further research on strain selection, system design, or improved siting may result in annual yields approaching the maximum short term yields, but this analysis uses the lower figure as a realistic productivity achievable with presently existing knowledge.

The maximum annual average productivity seen thus far at Harbor Branch for intensively cultured Ulva is about 25 dry $g/m^2.d$. Although Ulva is somewhat more effective at utilizing seawater carbon than is Gracilaria, non-carbon costs exceed carbon supply costs for most production systems. The more efficient carbon uptake of Ulva therefore does not compensate for its lower yield, so the growth rates and conversion efficiencies characteristic of Gracilaria are used in production calculations.

Table 11 compares the various system power requirements with the potential energy fixation rate (i.e. power) from seaweed. The gross algal power at 35 dry $g/m^2 \cdot d$ is 9160 kw for a 100 hectare system. Drying to 20% moisture requires 26,700 kw for the same production, and is thus clearly not feasible if net energy production is desired. Combustion of fossil fuels for their carbon is also infeasible.

Only CO_2 and pumped seawater remain as energetically and economically feasible carbon sources for energy production. Commercial liquid CO_2 carbon costs 70% of carbon in $5/MMBTU natural gas. Considering the other costs involved in producing methane from seaweed, liquid CO_2 is unlikely to be an economical carbon source while gas cost are around $5/MMBTU even if no carbon is lost from the system except as methane. Geologic CO_2 may be an economical carbon source if transportation costs are not excessive. This is not, however, a renewable resource, and the use of geologic CO_2 for enhanced oil recovery (EOR) is projected to exhaust reserves in the United States (Hare et al., 1978).

The energy break-even pumping head for carbon supply from seawater depends on the carbon assimilation characteristics of the species being grown. Assuming 40% energy recovery from seaweed by anaerobic digestion no CO_2 recycle, and diesel powered seawater pumps (.33 x .80 efficiency), the break-even head for Gracilaria is 3.5 meters. The break-even head for Ulva under the same conditions is 5.2 meters. When blower energy is included, the break-even heads decrease to 1.8 and 3.5 m for Gracilaria and Ulva, respectively. When allowances for other production costs and energy requirements are made, break-even heads are decreased even further. On the other hand, partial or total recycle of CO_2 produced in the digestion process could increase the break-even head as much as 2.5 fold.

A seaweed energy farm must thus be sited near a source of geologic CO_2 or near seawater with an elevation above the water supply of less than about 3 meters. High carbon ground waters may also be economical carbon sources at inland sites, but the energy cost of pumping, which varies with the TIC concentration, initial pH, and algal assimilation characteristics, may exceed the potential algal energy production.

B. Dry Seaweed Production

The drying of seaweed is extremely energy intensive because of the high water content of fresh seaweed. Table 10 shows that drying consumes sufficient natural gas to completely meet the carbon requirements of the seaweed. In this case pumping would be required only for temperature control and system flushing, and a pumping rate of .1 turnover per day would probably be adequate (Huguenin, 1976). At this level, pumping costs become small relative to aeration costs. Drying costs exceed pumping and aeration costs combined by 15 and 3 fold for energy and capital cost, respectively. Assuming $5/MMBTU natural gas as a fuel, drying energy alone contributes $125 per metric ton of 20% moisture seaweed.

C. Wet Seaweed Production

Wet seaweed is desired as a feedstock for feed, fertilizer, and for chemical extraction processes which tolerate solids concentrations around 10%. In this case, the least expensive carbon source is desired. In situations where seawater is unavailable at heads less than about two meters, or where coastal lands are expensive or unavailable, the exhaust gases from combusted coal may be the least expensive carbon source. With forced draft blowers located upstream from the burner, corrosion problems due to sulphur compounds could be minimal. The sulphur concentration in seawater is normally 905 ppm (see Table 10), so sulphur scrubbing might be unnecessary. Research is required to determine the extent to which exhaust gases must be cleaned prior to use an an algal carbon source.

Since seawater flow is not required for carbon supply, pumping could probably be maintained at .1 turnover/day for temperature control and flushing. In this case, coal and aeration energy costs are roughly equal and contribute about $68 per metric ton algal carbon. Pumping costs are negligible for heads less than five meters.

Table 12 Concentration of some essential elements in seaweeds and seawater.

Element	Mean concentration in seawater ($\mu g\ g^{-1}$)	Concentration in dry matter		Ratio of supply in seawater to concentration in tissue
		Mean ($\mu g\ g^{-1}$)	Range ($\mu g\ g^{-1}$)	
Macronutrients				
H	105 000	49 500	22 000-72 000	2.1×10^{0}
Mg	1 290	7 300	1 900-66 000	1.8×10^{-1}
S	905	19 400	4 500-82 000	4.7×10^{-2}
K	406	41 100	30 000-82 000	1.0×10^{-2}
Ca	412	14 300	2 000-360 000	2.9×10^{-2}
C	27.3	274 000	140 000-460 000	1.0×10^{-4}
N	0.488	23 000	500-65 000	2.1×10^{-5}
P	0.068	2 800	30-12 000	2.4×10^{-5}
Micronutrients				
B	4.39	184	15-910	2.4×10^{-2}
Zn	0.004	90	2-680	4.4×10^{-5}
Fe	0.0003	300	90-1 500	1.0×10^{-5}
Cu	0.002	15	0.6-80	1.7×10^{-4}
Mn	0.001	50	4-240	2.0×10^{-5}

From <u>The Biology of Seaweeds</u> Lobban and Wynne (Eds.)

Table 13

Nitrogen and Phosphorous Costs
From Chemical Marketing Reporter, May 9, 1983, and The Merck Index

Compound	Percentage N or P	Price ($/ton)	Price for N or P ($/ton)		
NITROGEN:					
NH_4NO_3	33.5	91	268	=	0.29 $/kgN
NH_4Cl	26	360	1385		
$NaNO_3$	16	130	813		
Urea	46	200	435		
KNO_3	14	267	1900		
PHOSPHORUS:					
NaH_2PO_4	22	885	4020		
Na_2HPO_4	22	860	3910		
Na_3PO_4	8	955	11,700		
$(NH_4)_2HPO_4$	23.5 (21%N)	165	700	(785 $/ton N =	$\begin{cases} 0.77\ \$/kgP \\ 0.86\ \$/kgN \end{cases}$
$(NH_4)\ H_2PO_4$	22.5 (13%N)	155	690	(1190 $/ton N)	
Triple Super Phosphate	20	160	800		

Table 14

Uptake of nitrogen by N-starved Ulva. Seaweed of an original thallus N-content of 1.3% was soaked in 2000 μM N as either NO_3 or NH_4. Nitrogen uptake was measured both in the light (approx. 12 hr. day:12 hr. night cycle) and dark.

	------Thallus N content (% of dry wt)[1]------			
	NH_4		NO_3	
Exposure Time	"Light"	Dark	"Light"	Dark
3 hours	2.1	2.8	2.1	2.0
12 hours	3.5	3.7	2.7	2.7
24 hours	4.6	3.9	3.6	3.1

[1] Mean of duplicate samples

Part 2 - Other Systems and Operations

I. Non-carbon Nutrient Supply

Table 12 shows the concentrations of the major elements found in seaweed as well as their concentrations in seawater. The macronutrients, present in seaweeds at concentrations greater than one miligram per gram dry weight, consist of C, H, O, K, N, S, P, Ca, and Mg. Of these nutrients, carbon, nitrogen, and phosphorus are most commonly limiting to algal growth in seawater. The trace (micronutrient) elements B, Zn, Fe, Cu, and Mn are also required.

In natural conditions or in cultivation systems with high seawater flows, the ambient seawater concentration of many of the above elements prevents nutrient limitation. As shown in the supply ratio columm of Table 10, C, N, and P among the macronutrients and Zn, Fe, Cu, and Mn among the micronutrients must be concentrated by a factor of 10,000 or more from seawater. These elements are thus most likely to limit growth. Trace nutrient growth limitation can be a serious problem in intensive culture, but once it is recognized, the cure is relatively inexpensive because the quantities required are very small.

Among the potentially growth limiting macronutrients, carbon has been discussed elsewhere. For the purposes of this analysis it is assumed that only nitrogen and phosphorus are required in economically significant amounts. It is recognized, however, that other macronutrients may also be depleted in systems where the seawater flow rate is very small.

Costs of various forms of nitrogen and phosphorus are shown in Table 8. A typical C:N:P ratio for healthy Gracilaria is 30:3:0.5 (unpublished data, Tom DeBusk). Assuming that the N and P contribution from the seawater flow is negligible and that there is no recycling of nutrients, 0.1 kg of nitrogen and .017 kg of phosphorus must be added as fertilizer for every kg of algal carbon produced. Using the prices given in Table 13 for ammonium nitrate and diammonium phosphate, the N and P nutrient cost is .0375 $/kg algal carbon.

Several factors may affect the nutrient usage in a real system. Losses due to inefficiencies in applying nutrients lead to increased nutrient costs. During the previous contract year, we demonstrated that nitrogen starved Gracilaria, when soaked in seawater at a high N concentration, can assimilate and store enough nitrogen in a matter of hours (3 to 24 h) to support rapid growth for at least one week (Ryther, 1982a). These findings led to the implementation of periodic, external nutrient soaking, which is efficient in terms of seaweed nutrient utilization and also affords considerable epiphyte control. Because of our emphasis on Ulva cultivation this year, we conducted an experiment to determine whether this alga could take up and store N in a manner similar to Gracilaria.

Nitrogen starved Ulva was placed in tank waters containing 2000 μM N as either NH_4 or NO_3. Nitrogen uptake (as measured by changes in thallus N content) was examined both in the dark and under normal day/night conditions. As shown in Table 14, N uptake by Ulva was extremely rapid, with thallus N levels in the NH_4-N exposed weed tripling within 24 hours. Ulva exposed to NO_3-N assimilated N at a slightly slower rate, with thallus

N levels approximately doubling during the experiment. For both the NO_3 and NH_4-N treatments, N uptake by Ulva was greater when exposed to the normal day/light cycle than in the dark. These data indicate that Ulva and Gracilaria can be handled similarly in terms of non-carbon nutrient management.

Significant amounts of nitrogen and phosphorus may be extracted by seaweed from the seawater flow through the system. This is particularly true if flows are high or nutrient-rich estuarine water is used. Nutrient recycle is also a distinct possibility for many system configurations, and this decreases nutrient inputs. Energy farms will export either electricity, methane, or ethanol. None of these forms contain N or P. Nutrient recycle from anaerobic digester liquid residue has been accomplished with 52% nitrogen loss from seaweed to digester and back to seaweed (Ryther 1982a). Hydrocolloids are composed mainly of complex sugar molecules, so onsite hydrocolloid extraction would also permit recycle of N and P in the extraction liquor.

The above factors together would tend to lower the cost of providing nitrogen and phosphorus. On the other hand, trace nutrients and pehaps lesser macronutrients may need to be provided. The figure of 0.375 $/Kg algal carbon will therefore be used as a catch-all nutrient cost.

II. Land Costs

Land costs are highly site specific. Algae farms which utilize pumped seawater as a carbon source require coastal sites with low elevation. However, such land tends to be expensive or protected in the United States. Information on commercial land costs near Ft. Pierce is shown in Table 15. Acreage in this area averages over $5,000/acre. Acreage in less developed countries, however, is available at much lower cost. A twenty thousand acre solar salt works on Long Island, Bahamas, was recently sold at a cost of about $150/acre. A seaweed farm consists mainly of shallow water, so in some cases it may be more practical to start with a tidal flat and create the needed land rather than start with land and dig the needed ponds.

Coastal siting is less important for facilities that do not rely on seawater for carbon supply. Costs of interior land are variable, but flat desert lands are available in the American Southwest at very low cost.

It appears that finding and purchasing a site for a seaweed farm will not be a major problem in comparison with the other problems to be overcome. A land cost of 0.10 $\$/m^2$ (405 $/acre) is assumed for this analysis.

III. Pond construction

Facility design for a land-based seaweed farm remains a subject for debate. Huguenin (1976) proposed a system consisting of ten meter wide raceways with triangular cross-sections. These raceways had centerline depths of one meter and bottoms which sloped up to the surface at both sides. He estimated a consutruction cost for such raceways at $\$10.80/m^2$ in 1975 dollars. This design included lining each raceway with a two inch layer of soil cement painted with two coats of white epoxy coating. He stressed that alternative raceway cross sections could reduce costs substantially.

Table 15 - Land Costs (Ft. Pierce data courtesy of Hardwick Realty, Ft. Pierce, FL)

Location	Land Type	Distance from Seawater (mi.)	Cost ($/ac)
Ft. Pierce	Grove	3	5K-8.5K
	Improved Pasture	3	3K ($15/yr lease)
	Raw land (scrub)	3	6K
	Mangroves	0	6.5K
	Buildable Oceanfront	0	50K
Bahamas	Grand Bahama Island	<1	5K
	Long Island Salina	0	150

$5,000/acre = $1.22/m^2

$150/acre = $.037/m^2

A flat-bottomed seaweed cultivation pond was constructed and operated a Harbor Branch during 1983. This consisted of a 10 meter square PVC-lined pond with parallel air lines spaced one meter apart. Alternate air lines were activated together so that air consumption was cut in half. The hydraulic performance of this configuration was excellent, with no apparent dead zones. Due to low seawater flows and possible nutrient limitations, the yield over a three week period was only 15.5 dry $g/m^2 \cdot day$. Nevertheless, this configuration has great potential for large scale systems because of its simplicity of construciton. Pond lining is less important for flat bottomed ponds than for ponds with sloped bottoms, and it is assumed that lining can be dispensed with if a sand, gravel, or crushed coral soil exists.

An estimate of excavation costs for twenty 200 m by 20 m ponds was provided by John Holt of HBI based on his experience in excavating forty smaller ponds on Harbor Branch property. His estimate of $25,000 for this 4 hectare pond system is equivalent to $0.62\ \$/m^2$. PVC liner with a five year life costs about $\$.20/ft^2$, or $\$2.15\ \$/m^2$. Lining thus costs much more than either land or excavation, and it is well worth selecting land with a soil type that does not require lining.

IV. Plumbing

The flat-bottomed unlined pond design described above must be provided aeration and water supply. An effective design must almost certainly utilize gravity flow for water distribution, and open channel flow has many advantages over piping for such a layout. Among these advantages are lower cost, easier inspection, and less maintenance.

The aeration system must be plumbed, and the cost of pipe is a major expense. If aeration pipes are spaced one meter apart, as was the case for the 100 m^2 pond at Harbor Branch, each square meter of pond surface must bear the cost of one meter of pipe. A portion of the cost of distribution piping from the compressor to the pond must also be assigned to the pond area.

Operating experience in the 100 m^2 pond at Harbor Branch showed that friction losses in 1/2" aeration lines led to inadequate air distribution after about ten meters. Assuming, as before, that 0.5 $scfm/m^2$ provides adequate aeration, the total air comsumption for a 200 m x 20 m pond is 2000 scfm. If this flow were passing through an 8" diameter PVC pipe, the presure loss would be about 0.13 psi per 100 ft; if through a 10" pipe, about .04 psi per 100 ft. (Crane technical paper #410). For the in-pond aeration lines, the flow through a given cross secion is one fiftieth the total flow if air is supplied at both pond ends and at three central points. the use of 1 1/2" pipe for the in-pond aeration lines would result in pressure losses of less than .04 psi/100 ft. Table 16 shows PVC pipe prices quoted to Harbor Branch for thousand foot quantities.

If each square meter of pond must bear the cost of one meter of 1 1/2" pipe and one twentieth the cost of one meter of 10" pipe, the plumbing cost is then about $.40 + (1/20 x $10) = $\$.90/m^2$. Additional distribution piping from the compressors is likely to add substantially to the plumbing cost, but a rough estimate of $\$1.50/m^2$ is assumed for this analysis. Less expensive pipe materials could probably be found, and this would decrease

Table 16 - PVC Pipe Prices (for 1000 ft or more)

Description	Price ($/m)
3/4" Sch 160	.21
1" Sch 160	.26
2" Sch 160	.66
4" Sch 125	1.84
6" Sch 125	3.97
8" Sch 125	6.69

plumbing costs. A detailed analysis including compressor cost vs. capacity figures and multi-point supply versus straight run piping options would be justified prior to final design.

V. Fertilization and Harvest

A best management procedure has not yet emerged for the operation of large scale seaweed farms. Pulse feeding has been shown to be a very effective way of supplying nitrogen and phosphorus to Gracilaria abd Ulva. The elimination of high nutrient levels in the growth medium greatly limits epiphyte growth. In the interst of nutrient conservation and product quality, it thus appears that such "pulse feeding" will be preferable to other fertilizaiton techniques. The practice of pulse feeding and the high growth rate of seaweeds (one to five doublings per week) requires that frequent harvesting take place. Pulse feeding further requires that at each harvest a portion of the harvestable biomass must be soaked in a nutrient solution and retained in the growth pond as an innoculum for further growth.

Fertilization and harvesting operations will almost certainly take place together. It remains to be seen whether pond draining will be advisable and whether fertilization should occur in the growth pond or in a separate vessel. A high degree of mechanization of these operations is certainly desirable for systems sited in developed nations. Labor intensive approaches are more appropriate in less developed countries.

Any estimate of costs for fertilization and harvesting based on the available published data would be very speculative. These costs will therefore be considered unknown for the purposes of this analysis. Due to the large percentage of water in seaweeds, however, handling is likely to be quite expensive if the seaweed must be lifted from the water. Further experience at the pilot scale is required before operational procedures and cost estimates can be developed.

VI. Labor

Labor costs are also extremely location and design dependent. Huguenin (1981a) presented the labor productivity figures given in Table 17. the numbers presented for algae are all highly speculative, and could be greatly influenced by differing system designs or further mechanization. Rather than propagate weak numbers, labor costs are not estimated in this analysis. Quantification of labor costs must await further definition of system design, level of mechanization, and operational methods.

VII. Maintenance

Huguenin (1981a) states that typical maintenance costs are 4 to 5% per year of initial cost for large machines and 1 to 2% per year of initial cost for buildings and other faciliteis. He qualifies this with the statement that this estimate is "highly uncertain and is a function of many decisions of design, equipment selection and operating policies which have not been completely defined or made." Mr. H. R. Bradley, former vice-president of Diamond Crystal Salt, stated that a 50,000 gpm Couch axial flow pump had functioned realiably for over ten years with virtually no maintenance at the Long Island, Bahamas, salina. Centrifugal blowers experience wear only at the main bearings, so they would probably require relatively less

Table 17 Labor Productivity

Crop	Productivity of Labor	Circumstances	References
Hay	1,136 mt/man-yr	Avg. US Agriculture	USDA 1980
Corn	1,364 mt/man-yr	Avg. US Agriculture	USDA 1980
Sugar Beets	1,399 mt/man-yr	Avg. US Agriculture	USDA 1980
Red Seaweeds	182 mt (dry)/man-yr	14 ha raceway culture system for high value products, (estimate).	Huguenin, 1976
Macrocystis	4,700 mt(dry)/man-yr	Open ocean kelp farm includes large ship and digester crews	Intg. Sci. Corp., 1976
Phytoplankton	4,500 mt(dry)/man-yr	100 sq miles of ponds	Dynatech, 1978
Gracilaria	30 - 150 mt(dry)/man-yr	1 ha floating bag units, (extrapolated data) for high value products	Lindsay & Saunders, 1980

From Huguenin (1981a)

maintenance than the typical "large machine". For these reasons, maintenance is assumed to be 2% of both equipment and facilities.

As for fertilization, harvest, and labor, this estimate must be regarded as highly speculative. If fossil fuel exhaust is used as a carbon source, maintenance costs may increase significantly. Maintenance costs will further increase if dryers are required.

Part 3. Summary and Conclusions

I. Total Costs

The cost of operations analyzed in Part 2 are shown in Table 18. Nutrient costs vary depending on the extent of recycle. Land costs vary depending on locale. If a tidal flat were modified for seaweed farming purposes, land costs might approach zero. Fertilization, harvest, and labor costs are unknown but probably substantial. Systems producing energy, dry seaweed, and wet seaweed are considered in turn below.

A. Energy Production

It was found in Part 1 that a seaweed energy farm requires a supply of geologic CO_2, seawater at a pumping head of less that 3 meters, or high carbon groundwaters at pumping heads commensurate with the dissolved carbon content and pH. Seawater is available with the least restriction, and a 1 m head is probably the smallest head which will ensure flows throughout a 100 hectare system. Gracilaria requires 1.31 m^3 seawater/m^2.d (Appendix E). Costs for such a configuration are shown in Table 19A. The bottom line is 332 K$/yr operating costs to produce 54,800 MMBTU, neglecting fertilization, harvesting, and labor expenses. If there is no repayment of the investment cost of 3472K$ plus fertilization and harvest hardware, the resultant biogas cost is $6.06 per MMBTU at the digester.

A seaweed energy farm would be most economical in coastal or island locations where tidal flows can be harnessed to provide seawater exchange. A clever farm layout could use tide gates, sluices, and screens not only to provide seawater carbon but also to move the seaweed for harvesting, fertilizing, and stocking operations. Estimated costs for such a system are shown in Table 19B. Operating costs of 215K$/yr produce $3.92/MMBTU biogas with no investment payback. The total investment is 2411 K$ plus the unknown costs mentioned previously. This could be a very attractive energy resource for those less developed countries with appropriate climate and topography and few fossil energy resources.

B. Dry Seaweed Production

Estimated costs for a system producing dry seaweed are shown in Table 20 for a system with .1 turnover per day at a 2 m head, operating costs are 2351 K$/yr and the investment is 3459 K$. The total production is 16,000 metric tons of 20% moisture seaweed, giving a cost of $147 per metric ton with no investment payment. Fertilization, harvesting, and labor costs would undoubtedly increase this cost significantly, but the energy cost for dryng dominates.

C. Wet Seaweed Production

Table 18 - Summary: Economic and Energy Analysis Part 2

OPERATION	OPERATING COST	FIXED COST
Nutrient Supply:		
Without recylce	$144x10^3$ \$/yr	
With 70% efficient recycle	$43x10^3$ \$/yr	
Land:		
Ft. Pierce		$1220x10^3$ \$
Long Island Salina		$37x10^3$ \$
Analysis Assumption		$100x10^3$ \$
Pond Construction:		
Unlined		$620x10^3$ \$
Lined		$2770x10^3$ \$
Plumbing		$1500x10^3$ \$
Fertilization and Harvest	Unknown	Unknown
Labor	Unknown	Unknown
Maintenance	2% of equipment and facilities	

Table 19 - Total Cost Estimates

A. Energy Farm, 1 m pumping head

OPERATION	OPERATING COST	FIXED COST ($)	POWER
Pumping	98×10^3 $/yr	961×10^3 $	381 kw
Aeration	124×10^3 $/yr	291×10^3 $	482 kw
Nutrients @ 70% recycle	43×10^3 $/yr		
Land @ $.10/m^2		100×10^3 $	
Pond Construction		620×10^3 $	
Plumbing		1500×10^3 $	
Maintenance	67×10^3 $/yr		
	332×10^3 $/yr	3472×10^3 $	863 kw

B. B. Energy Farm, tidal pumping, zero land costs

Aeration	124×10^3 $/yr	291×10^3 $	482 kw
Nutrient @ 70% recycle	43×10^3 $/yr		
Pond Construction		620×10^3 $	
Plumbing		1500×10^3 $	
Maintenance	48×10^3 $/yr		
	215×10^3 $/yr	2411×10^3 $	482 kw

Net energy production is $\left(\frac{3830\times10^3\ \text{kg algal C}}{\text{yr}}\right)\left(\frac{37.7\times10^3\ \text{KJ}}{\text{kg algal C}}\right)$ (.4 digestion efficiency) X

$$\left(\frac{\text{MMBTU}}{1.054\times10^6\ \text{KG}}\right) = 5.78\times10^{10}\ \frac{\text{KJ}}{\text{yr}} = 54{,}800\ \frac{\text{MMBTU}}{\text{yr}}$$

Power (12 hrs/day) is 3660 kw

Table 20 - Total Cost Estimates

Dry Seaweed Production, .1 turnover/day @ 2m head

OPERATION	OPERATING COST	FIXED COST
Pumping	15×10^3 \$/yr	73×10^3 \$
Aeration	124×10^3 \$/yr	291×10^3 \$
Drying	2001×10^3 \$/yr	875×10^3 \$
Nutrients, no recycle	144×10^3 \$/yr	
Land		100×10^3 \$
Pond Construction		620×10^3 \$
Plumbing		1500×10^3 \$
Maintenance @ 2%	67×10^3 \$/yr	
	2351×10^3 \$/yr	3459×10^3 \$

Total Production is $\left(\frac{3830\times10^3 \text{ kg algal C}}{\text{yr}}\right)\left(\frac{\text{kg dry}}{.3 \text{ kg algal C}}\right)\left(\frac{1.25 \text{ kg 20\% moisture}}{\text{kg dry}}\right)$

= 16,000 metric tons @ 20% moisture

Estimated costs for a system producing wet seaweed are shown in Table 21. Assuming .1 turnover/day at a 2 m head, operating costs are 471K$/yr and the investiment is 2584 K$. The zero-payback cost of wet seaweed is 3.68 $ per metric ton, equivalent to 0.123 $/kg algal carbon. Costs for aeration, carbon from coal, and non-carbon nutrients are roughly equal. Once agan, processing and labor costs could increase this cost significantly.

II. Conclusion

Recent advances in seaweed cultivation made at Harbor Branch have contributed significantly to reducing estimated operating and capital costs for land based seaweed production systems. The most important findings are that aeration can be decreased twelve fold with minimal yield sacrifices and that flat bottomed ponds can be used for large scale production.

The major points which shape the design of a land-based seaweed farm are summarized as follows. Aeration is required for the rapid growth of seaweeds in submersed culture, although it does not provide significant amounts of carbon. Aeration with a one sixth duty cycle provided only during daylight hours was found to stimulate growth nearly as well as continuous aeration. Because aeration contributes significantly to total system operating and fixed costs, further research geared toward reducing this expensive operation is needed.

Seawater pumping provides dissoloved carbon, temperature regulation, medium flushing, and non-carbon nutrients. Pumping is expensive at high heads, but where carbon from fossil fuel driven processes (e.g. seaweed drying) is available, flow rates can be substantially reduced.

Carbon limitation is a serious problem for highly productive seaweed cultures, and different species have differing capacities for assimilation of the dissolved carbon in water. Coal combustion exhaust gases are a less expensive carbon source than pumped seawater in many cases. Non-carbon nutrients can be recycled with high efficiency if the seaweed product is a hydrocarbon (e.g. methane) or carbohydrate (e.g. agar) and pulse-feeding is practiced.

Site selection is extremely important. Sites with very low elevation above sea level and with soil types which do not require pond lining are essential for energy farms, and very beneficial to the economics of other systems. Construction costs can be minimized by building unlined flat bottom ponds. Finally, fertilizing and harvesting methods must be custom designed to take advantage of the combination of labor costs and capital limitations extant for a particular application.

The 1976 analysis of a dry seaweed farm by Huguenin arrived at a zero payback price for dry seaweed of 480 $ per metric ton. This is a great deal higher than the 147 $ per metric ton found in this analysis, principally because of the following differing assumptions. Huguenin assumed: 1) a productivity of 27.3 rather than 35 dry g/m^2.d, 2) continuous aeration rather than one sixth duty aeration during daylight only, 3) 4% rather than 3% tissue nitrogen in the harvested seaweed, and 4) substantial labor changes in his operating cost. His raceway system was approximately six times more expensive that the present system because it required elaborate

Table 21 - Total Cost Estimates

Wet Seaweed Production, .1 turnover/day @ 2 m head

OPERATION	OPERATING COST	FIXED COST
Pumping	$15x10^3$\$/yr	$73x10^3$\$
Aeration	$124x10^3$\$/yr	$291x10^3$\$
Carbon from Coal	$138x10^3$\$/yr	
Nutrients, no recycle	$144x10^3$\$/yr	
Land		$100x10^3$\$
Pond Construction		$620x10^3$\$
Plumbing		$1500x10^3$\$
Maintenance @ 2%	$50x10^3$\$/yr	
	$471x10^3$\$/yr	$2584x10^3$\$

Total production is $3830x10^3$ kg algal C/yr = 128,000 metric tons wet weight earthwork, grading, sealing and painting. This high system cost resulted in high maintenance costs, and these also are reflected in the higher production cost. Each of the improved performance values used in the present analysis have been experimentally verified at some level at Harbor Branch. The precision of the estimates is not great, due both to underestimaione (e.g. labor, fertilization, harvest) and to possible overestimation (e.g. plumbing cost). In some cases, uncertainties in system design and configuration have been so great that no estimate was attempted. This analysis cannot, therefore be considered comprehensive, complete, or final.

The value of the present analysis lies more in its approach than in its results. The application of mass-balance methods, similar to those used in chemical engineering, permits fairly accurate estimation of some production costs. Costs associated with agricultural processes such as fertilization and harvesting are much more difficult to estimate without pilot scale experience. Further work should concentrate on the development of economical operating methods applicable to large scale systems. The relationships set forth above for pumping, aeration, and carbon supply should serve as a foundation for the evaluation of system refinements. The low production costs given above do suggest that if the proper product, algal species, system design, and site are selected, seaweed can be grown profitably as a source of energy or higher value products.

Appendix A

Energy Costs

A. Electrical Energy

Mr. Louis Gillaland at the Fort Pierce Utilities Authority was contacted for electric power rate schedules. There are many different rate schedules applicable to customers with different maximum power requirements. Fees generally include a flat monthly charge, a demand charge based on the maximum power requirement sustained over a thirty minute period, and an energy charge based on the monthly energy usage. "Time of Use" schedules enforce different rates for on-peak and off-peak energy whereas "General Service" schedules do not.

The General Service rates applied to a 1000 kw load run 12 hours per day, thirty days per month, yield an energy cost of 5.7 cents/kw-hr. The Time of Use rates applied to a similar load, with 6 on-peak and 6 off-peak hours per day, yield an energy cost of 5.6 cents/kw-hr. The large demand Time of Use rates applied to a 3000 kw load under the same conditions also yield an energy cost of 5.6 cents/kw-hr.

It is assumed that by judicious scheduling of power use to avoid on-peak rates, a 5% cut in power cost can be achieved. The electric power cost used in the remainder of this analysis is thus 5.3 cents/kw-hr.

In \$/KJ (\$/10^3Joules)

$$.053 \frac{\$}{\text{kw.hr}} \left(\frac{\text{hr}}{3600 \text{ sec}}\right) = 15 \times 10^{-6} \ \$/\text{KJ}$$

The brake efficiency of electric motors is about 90%, so the energy cost must be multiplied by 1.11 if brake energy is desired.

B. Natural Gas

Natural gas exhibits various prices and heating values, but a typical current price is \$5/10^3 ft^3 ≈ \$5/10^6 BTU.

In \$/KJ

$$\frac{5 \ \$}{10^6 \text{ BTU}} \left(\frac{\text{BTU}}{1.054 \text{ KJ}}\right) = 4.7 \times 10^{-6} \ \$/\text{KJ}$$

Natural gas with a price of \$10/mcf thus costs 9.5 x 10^{-6} \$/KJ.

Natural gas is typically about 70% carbon by weight and about 21,800 BTU/lb. The cost per kg C for \$5/MMBTU gas is thus

$$\frac{5 \ \$}{10^6 \text{ BTU}} \quad \frac{21{,}800 \text{ BTU}}{\text{lb gas}} \quad \frac{\text{lb gas}}{.70 \text{ lb C}} \quad \frac{\text{lb}}{.4536 \text{ kg}} = 0.34 \ \$/\text{KgC}$$

The energy embodied per kg C is then

$$\frac{0.34 \ \$/\text{kg C}}{4.7\text{x}10^{-6} \ \$/\text{KJ}} = 72.3 \times 10^3 \ \text{KJ/kg C}$$

The brake thermal efficiency of natural gas powered internal combustion engines is roughly 25%, so the energy cost must be quadrupled if brake energy is desired.

C. Diesel Fuel

Diesel fuel presently costs about \$1.00/gallon in large quantities. In \$/KJ,

$$\frac{1.0\ \$}{\text{gal}}\left(\frac{\text{gal}}{3.785\ \text{l}}\right)\left(\frac{1}{.848\ \text{kg}}\right)\left(\frac{\text{kg}}{45{,}570\ \text{KJ}}\right) = 6.8 \times 10^{-6}\ \$/\text{KJ}$$

Diesel fuel is typically about 87% carbon by weight and about 45,570 KJ/kg fuel. The cost per kg C for \$1.00/gallon fuel is thus

$$6.8 \times 10^{-6}\ \frac{\$}{\text{KJ}}\left(\frac{45{,}570\ \text{KJ}}{\text{kg fuel}}\right)\left(\frac{\text{kg fuel}}{.87\ \text{kg C}}\right) = 0.36\ \$/\text{kg C}$$

The energy embodied per kg C is then

$$\frac{0.36\ \ \$/\text{kg C}}{6.8\text{x}10^{-6}\ \$/\text{KJ}} = 52.4 \times 10^{3}\ \text{KJ/kg C}$$

The brake thermal efficiency of supercharged diesel engines is roughly 33%, so the energy cost must be tripled if brake energy is desired.

D. Coal

Coal costs and heating values vary greatly, but representative values for low sulphur bituminous coal are \$25/metric ton and 13,000 BTU/lb. In \$/KJ,

$$\frac{25\ \$}{1000\ \text{kg}}\left(\frac{.4536\ \text{kg}}{\text{lb}}\right)\left(\frac{\text{lb}}{13{,}000\ \text{BTU}}\right)\left(\frac{\text{BTU}}{1.054\ \text{KJ}}\right) = 0.83 \times 10^{-6}\ \$/\text{KJ}$$

Such coal is about 70% carbon by weight, yielding a cost per kg C of:

$$\frac{25\ \$}{1000\ \text{kg coal}}\left(\frac{\text{kg C}}{.70\ \text{kg coal}}\right) = 0.036\ \$/\text{kg C}$$

The energy embodied per kgC is then

$$\frac{0.036\ \ \$/\text{kgC}}{0.83\text{x}10^{-6}\ \$/\text{KJ}} = 43.0 \times 10^{3}\ \text{KJ/kg C}$$

Appendix B

Pumping Formulae

A. Pumping Energy Requirements

$$E = mgh/\eta_p$$

E = pumping brake energy in kilojoules
m = mass of pumped water
g = acceleration of gravity = 9.81 m/s^2
h = pumping head
η = pump efficiency = .80 for axial flow pumps
p = density of pumped water = 1025 kg/m^3 for seawater
V = volume of pumped water in m^3

for seawater and axial flow pumps,

$$E = 12.6\ Vh\ KJ$$

B. Carbon Flux

From water:

$$C_w = TIC\ (10^{-3}\ 1kg/m^3 \cdot mg)\ V$$

C_w = carbon flux (kg C) in pumped water
TIC = total inorganic carbon concentration in mg C/liter

In diesel engine pump driver exhaust

$$C_{Ex} = \frac{E_f f_D}{Q_H\ \eta_D}$$

$$C_{Ex} = 5.78x10^{-5}\ E_p$$

C_{Ex} = carbon flux (kg C) in exhaust stream
E_p pumping brake energy in kilojoules
f_D = weight fraction of carbon in diesel fuel = 0.87
Q_H = higher heat of combustion = 45,570 KJ/kg for diesel fuel
η_D = mechanical efficiency of diesel engine $\simeq$ 0.33

C. Energy Cost of Carbon from Pumped Seawater

From pumping energy requirements,

$$V = \frac{E_p}{12.6\ h}$$

From water carbon flux,

$$V = \frac{C_w}{[TIC]\ (10^{-3})}$$

Equating,

$$\frac{E_p}{C_w} = \frac{1.26 \times 10^4\ h}{TIC} \quad \text{in} \quad \frac{KJ}{kg\ C}$$

For electrically powered pumps, there is no CO_2 available in an exhaust stream. The fraction of total inorganic carbon entering the system which can be utilized by the seaweed varies with the carbon metabolism of the species being grown. In no case will it exceed the fraction which results in the elevation of pH to the extent that growth ceases. In general, it will be significantly less than that fraction because as growth rates decline near the carbon extraction limit, the incremental saving in carbon supply cost is exceeded by the additional capital costs for land and facilities due to slow growth.

Thus,

$$C_A = f_A \, C_w$$

$$E_P = \frac{1.26 \times 10^4 \, h \, C_A}{f_A \, [TIC]}$$

C_A = carbon flux (kgC) in algal tissue
f_A = fraction of TIC available to the seaweed
C_w = carbon flux (kgC) in pumped water

The gross energy fixed in <u>Gracilaria</u> and <u>Ulva</u>, as determined by bomb calorimetry, is 37.7×10^3 and 36.0×10^3 KJ/kg algal carbon, respectively.

The gross energy fixed vs. the electrical pumping energy consumed is thus

$$\frac{E_A}{E_E} = \frac{Q_A \, C_A n_E}{E_P} = \frac{Q_A f_A C_w n_E}{E_P} = \frac{Q_A f_A \; [TIC] \; 10^{-3} \; (0.90)}{12.6 \; h}$$

$$\frac{E_A}{E_E} = 7.14 \times 10^{-5} \; \frac{Q_A f_A [TIC]}{h}$$

E_A = gross energy fixed in the algae
E_E = electrical energy consumed
Q_A = heat of combustion of the seaweed in KJ/kg algal carbon
n_E = efficiency of the electric motor - 0.90

For <u>Gracilaria</u> with f_A assumed 40%, seawater with 20 mg C/1, 2m pumping head,

$$\frac{E_A}{E_E} = 10.8$$

For fossil fuel powered pumping, the carbon in the fuel is converted to CO_2 in the exhaust on a stoichiometric basis. It is assumed that this exhaust CO_2 can be injected into the aeration system with minimal cost. The CO_2 thus injected is absorbed by the water and fixed by the algae with some losses. The fraction which ends up as algal carbon is f_E

Then, algal carbon flux

$$C_{A_{TOT}} = f_A C_w + f_E C_{EX} \quad = \quad 7.94 \times 10^{-5} \; \frac{[TIC]}{h} \; f_A E_P + 5.78 \times 10^{-5} \; f_E E_P$$

and the energy vs carbon relationship is

$$\frac{E_P}{C_{A_{TOT}}} = \left(7.94 \times 10^{-5} \; f_A \frac{[TIC]}{h} + 5.78 \times 10^{-5} \; f_E\right)^{-1}$$

For diesel powered pumping, the gross energy fixed vs. the diesel fuel energy consumed is

$$\frac{E_A}{E_D} = \frac{Q_A C_A n_D}{E_P} = Q_A n_D \left[7.94 \times 10^{-5} f_A \frac{[TIC]}{h} + 5.78 \times 10^{-5} f_E\right]$$

for Gracilaria with f_A assumed 40%, n_D = 33%, seawater with 20 mgC/1, 2 m

pumping head, f_E 70%

$$\frac{E_A}{E_D} = 4.3$$

D. Pump Operating vs Fixed Costs

Pump operating costs consist primarily of energy costs. For one turnover per day in a 1 m deep system (i.e. 1 m^3/m^2), the flow rate over a 12 hour day is .0833 m^3/m^2.hr. This is equivalent to 23.1 m^3/sec for the entire 100 hectare system. The required brake power is

$$P = \frac{\rho Vgh}{n_P} = \left(\frac{.0833\ m^3}{m^2\ hr}\right)\left(\frac{1025\ kg}{m^3}\right)\left(10^6\ m^2\right)\left(9.81\ m/s^2\right)\left(\frac{hr}{3600\ sec}\right)\frac{h}{(0.80)} = 291\ h\ kw$$

The brake energy requirement per m^2 over 1 year is

$$E_P = \frac{\rho Vgh}{n_P} = \left(\frac{1025\ kg}{m^3}\right)\left(\frac{1\ m^3}{m^2.da}\right)\left(\frac{365\ day}{yr}\right)\left(\frac{9.81\ m}{s^2}\right)\frac{h}{(0.80)} = 4590.h\ KJ/m^2.yr$$

For electric power @ 5.3 cents/kw.hr, 90% efficiency,

$$\text{Energy cost} = \left(\frac{4590\ KJ}{m^2.yr}\right)\left(\frac{10^6\ m^2}{0.90}\right)\left(\frac{.053\ \$}{kw.hr}\right)\left(\frac{hr}{3600\ sec}\right) h = 75{,}100\ h\ \$/yr$$

For diesel power @ $1.00 per gallon, 33% engine efficiency,

$$\text{Energy Cost} = \left(\frac{4590\ KJ}{m^2.yr}\right)\left(\frac{10^6\ m^2}{0.33}\right)\left(6.8 \times 10^{-6}\ \frac{\$}{KJ}\right) h = 94{,}600\ h\ \$/yr$$

$$\text{While liberating } \frac{94{,}600\ h\ \$/yr}{0.36\ \$/kgC} = 263{,}000\ h\ kg\ \text{exhaust carbon}$$

As estimated from Table 1, the purchase price for a 100,000 gpm pump with driver is roughly $200,000. This is equivalent to 6.34 m^3/sec. For 1 $m^3/m^2\cdot$day flow, the proportional capital cost is then $734,000. Thus, for a 2m head pumped to a 1 turnover per day 100 hectare system:

Annual Operating Cost for electric motor = $150 K
Annual Operating Cost for diesel = $189 K
Capital Cost = $734,000

The heads at which annual operating cost is equal to total capital cost are:

Electrical Head = 9.77 m
Diesel Heal = 7.76 m

Appendix C

Blower Operating vs Fixed Costs

Assume 80% efficiency
3.5 K$/1000 scfm
100 ha. farm 1 m deep
0.5 scfm/m^2 @ one sixth duty cycle
12 active hours/day

The total flow is 83,300 cfm

Power is given as:

$$P = pQ = 1\ \text{m}\ H_2O\ \left(98.1 \times 10^2\ \frac{\text{nt/m}^2}{\text{m}\ H_2O}\right)\left(83{,}300\ \frac{\text{ft}^3}{\text{min}}\right)\left(2\ 832 \times 10^{-2}\ \frac{\text{m}^3}{\text{ft}^3}\right)\left(\frac{\text{min}}{60\ \text{sec}}\right)\left(\frac{1}{0.80}\right)$$

$$= 482\ \text{kw}$$

The brake energy requirement per m^2 over 1 year is

$$\left(\frac{482\ \text{kw}}{10^6\ \text{m}^2}\right)\left(\frac{12\ \text{hrs}}{\text{day}}\right)\left(\frac{365\ \text{days}}{\text{yr}}\right)\left(\frac{3600\ \text{secs}}{\text{hr}}\right) = 7602\ \text{KJ/m}^2\text{.yr}$$

For electric power @ 5.3 cents/kw.hr, 90% motor efficiency

$$\text{Energy cost} = \frac{7603\ \text{KJ}}{\text{m}^2\text{.yr}}\left(\frac{10^6\ \text{m}^2}{0.90}\right)\left(\frac{.053\ \$}{\text{kw.hr}}\right)\left(\frac{\text{hr}}{3600\ \text{sec}}\right) = 124{,}000\ \$/\text{yr}$$

For diesel power @ 1.00 per gallon, 33% engine efficiency

$$\text{Energy cost} = \frac{7602\ \text{KJ}}{\text{m}^2\text{.yr}}\left(\frac{10^6\ \text{m}^2}{0.33}\right)\left(6.8 \times 10^{-6}\ \frac{\$}{\text{KJ}}\right) = 157{,}000\ \$/\text{yr}$$

While liberating $\frac{157{,}000\ \$/\text{yr}}{.36\ \$/\text{kg C}} = 435{,}000$ kg exhaust carbon

The capital cost for 83,300 cfm @ $/100 scfm is $291,000.

Operating costs thus equal fixed cost after 2.3 and 1.8 years for electrical and diesel power, respectively.

Appendix D

Seaweed Drying Calculations

Seaweed
dry weight = 10% of wet weight
carbon weight = 30% of dry weight
heat of vaporization for water = 2260 KJ/kg
heat value for Gracilaria bomb calorimetry) = 37.7 x 10^3 KJ/kg C

For 1 kg wet seaweed, drying to 20% water content gives .125 kg "dry" seaweed with ending water weight of .025 kg.

Water removed is then (.900 - .025) kg = .875 kg

Ideal Energy required is $\left(\frac{2260 \text{ KJ}}{\text{kg } H_2O}\right)$ (.875 kg) = 1980 KJ

Ideal Energy per kg "dry" weight is then $\left(\frac{1980 \text{ KJ}}{\text{wet kg}}\right) \left(\frac{\text{wet kg}}{.125 \text{ "dry" kg}}\right) = 15{,}840 \frac{\text{KJ}}{\text{"dry" kg}}$

Ideal Energy per kg algal C is $\left(\frac{1980 \text{ KJ}}{\text{wet kg}}\right) \left(\frac{\text{wet kg}}{.03 \text{ kg algal C}}\right) = 66 \times 10^3 \frac{\text{KJ}}{\text{kg algal C}}$

Gross Energy available from 1 kg wet Gracilaria is

1 kg wet Gracilaria $\left(\frac{.1 \text{ kg dry}}{\text{kg wet}}\right) \left(\frac{.3 \text{ kg C}}{\text{kg dry}}\right) \left(\frac{37.7 \times 10^3 \text{ KJ}}{\text{kgC}}\right) = 1131 \text{ KJ}$

at \$5/MMBTU for gas (equivalent to \$.69/gal diesel or \$.017/kw hr electricity)

The cost to dry 1 kg wet seaweed to 20% moisture (i.e. to .125 kg) is

$$(1980 \text{ KJ}) \left(\frac{\$5}{10^6 \text{ BTU}}\right) \left(\frac{10^6 \text{ BTU}}{1.054 \times 10^6 \text{ KJ}}\right) = \$.0094$$

The drying cost per kg of algal C is $.0094 \frac{\$}{\text{wet kg}} \left(\frac{\text{wet kg}}{.03 \text{ kg algal C}}\right) = \frac{0.31 \text{ \$}}{\text{kg algal C}}$

The drying cost for 1 kg of 20% moisture seaweed is $\frac{\$.0094}{.125 \text{ kg}}$ = \$.075/kg "dry" seaweed

The above assumes perfect combustion and heat transfer. Actual efficiences for drum driers are about 60%, so drying energy and cost would be 70% more than above.

For a 100 hectare farm producing 350 wet g/m^2· (12 hr. day) of Gracilaria

The drying power over a twelve hour day is:

$$(10^6 m^2) \left(\frac{.35 \text{ wet kg}}{m^2 \cdot 12 \text{ hr}}\right) \left(\frac{1980 \text{ KJ}}{\text{wet kg}}\right) \left(\frac{\text{hr}}{3600 \text{ sec}}\right) = \frac{16{,}000 \text{ kw}}{0.6 \text{ efficiency}} = 26{,}700 \text{ kw}$$

Appendix E

Productivity and Carbon Demand

Assume
100 hectare seaweed farm
35 dry $g/m^2 \cdot day$ *Gracilaria* productivity
37.7×10^3 KJ/kg algal C
dry weight = 10% of wet weight
carbon weight = 30% of dry weight
12 active hours/day

Productivity = .035 dry $kg/m^2 \cdot d$ = .35 wet $kg/m^2 \cdot d$ = 0.0105 kg algal $C/m^2 \cdot d$

Energy Fixation Rate:

$$0.0105 \frac{\text{kg algal C}}{m^2 \cdot \text{day}} \left(\frac{\text{day}}{12 \text{ hrs}}\right)\left(\frac{37.7 \times 10^3 \text{ KJ}}{\text{kg algal C}}\right)\left(\frac{\text{hr}}{3600 \text{ sec}}\right) = 9.16 \times 10^{-3} \text{ kw/m}^2 \text{ for 12 hrs. per day.}$$

The total annual gross energy fixed by *Gracilaria* is then

$$0.0105 \frac{\text{kg algal C}}{m^2 \cdot \text{day}} \left(\frac{365 \text{ day}}{\text{yr}}\right)\left(\frac{37.7 \times 10^3 \text{KJ}}{\text{kg algal C}}\right) = 145000 \text{ KJ/m}^2 \cdot \text{yr}$$

The carbon demand may be satisfied by seawater pumping only. In this case, for a yield of 35 dry $g/m^2.day$, with *Gracilaria* which can utilize 40% of the carbon in seawater, the required water flow is

$$\left(\frac{.035 \text{ dry kg}}{m^2.d}\right)\left(\frac{.3 \text{ kg algal C}}{\text{dry kg}}\right)\left(\frac{\text{kg seawater C}}{.40 \text{ kg algal C}}\right)\left(\frac{\text{liter seawater}}{20 \text{ mg seawaterC}}\right)\left(\frac{10^3 \text{ mg m}^3}{\text{kg liter}}\right)$$

$$= \frac{1.31 \text{ m}^3 \text{ seawater}}{m^2 \cdot d}$$

The flow for *Ulva* which utilizes 60% of the seawater carbon is

$$(.035)\ (.3)\ \left(\frac{1}{6}\right)\ \left(\frac{1}{20}\right)\ (10^3) = 0.873 \frac{m^3 \text{ seawater}}{m^2 \text{ day}}$$

References

Ashare, E., et al., 1978. Cost Analysis of Aquatic Biomass Systems. Dynatech R/D Company. Report to DOE under contract #HCP/ET-4000-78/1, Cambridge, MA. 2 volumes.

Babcock and Wilcox Company, 1978. Steam/Its Generation and Use. Babcock and Wilcox Company, New York, N.Y. 827 pp.

Burris, J. C., 1980. Respiration and Photorespiration in Marine Algae. In: P.G. Falkowski (Ed.), Primary Productivity in the Sea, Plenum Press, New York, N. Y. pp 411-432.

Chemical Marketing Report, May 9, 1983. Schnell Publishing Comapny, New York, N.Y.

Crane Company, 1976. Flow of Fluids through Valves, Fittings, and Pipes Technical Paper No. 410. Crane Company, New York, N. Y. 132 pp.

DeBoer, J. A., 1981. Nutrients. In: C. S. Lobban and M. J. Wynne (Eds.), The Biology of Seaweeds. University of California Press, Berkeley, CA pp. 356-392.

Fluck, R. C. and Baird, C. D., 1983. Thermodynamic considerations of electric power in agriculture. Transactions of ASAE Summer Meetings, June 2-29, 1983.

Habig, C. and Ryther, J. H., 1983. Methane production from the anaerobic digestion of some marine macrophytes. Resources and Conservaiton 8, 271-279.

Hare, M., et al., 1978. Sources and Delivery of Carbon Dioxide for Enhanced Oil Recovery. Pullman Kellogg Corporation Report to DOE under contract #EX-76-C-01-2515. 380 pp.

Huguenin, J. E., 1976. An examination of problems and potentials for future large-scale intensive seaweed culture systems. Aquaculture 9, 313-342.

Huguenin, J. E., 1981a. Evaluation study of large-scale seaweed raceway culturing systems for methane gas production. Special report for J. H. Ryther under SERI subcontract XR-9-8133-1.

Huguenin, J. E., 1981b. Preliminary study on large-scale seaweed spray culturing systems. Special report for J. H. Ryther under SERI subcontract XR-9-8133-1

Karassik, I. J., et al., 1976. Pump Handbook. McGraw Hill Book Company, New York, N. Y. 1102 pp.

Khailov K. M. and Z. P. Burlakova, 1969. Release of Dissolved Organic Matter by Marine Seaweeds and Distribution of their Total Organic Production to Inshore Communities. Limnology and Oceanography 14, 521-527.

Littler, M. M., 1979. The effects of bottle volume, thallus weight, oxygen saturation levels, and water movement on apparent photosynthetic rates in marine algae. Aquatic Botany 7, 21-34.

Lucas, W. J., 1983. Photosynthetic assimilation of exogenous HCO_3^- by aquatic plants. Ann. Rev. Plant Physiology 34, 71-104.

Luning, K., 1981. Ligh. In: C. S. Lobban and M. J. Wynne (Eds.), The Biology of Seaweeds. University of California Press, Berkeley, CA. pp. 326-355.

Moeller, H. W., Griffen, G. and Lee, V. 1982. Aquatic biomass production on sand using seawater spray. Symp. Papers, Energy from Biomass and Wastes VI, Lake Buena Vista, FL., Jan. 1982. Inst. Gas Technol., Chicago, ILL. pp 237-248.

Oswald, W. J., 1977. Municipal Sewage Waste Treatment with Microalgae. In: Proceedings of KISR Seminar on Microbial Conversion Systems for Food and Fodder Production and Waste Management, Nov. 12 - 17, 1977.

Ramus, J., 1978. Seaweed anatomy and photosynthetic performance: the ecological significance of light guides, heterogeneous absorbtion and multiple scatter. J. Phycol 14, 352-362.

Ramus, J. and Rosenberg, G., 1980. Diurnal phtosynthetic performance of seaweeds measured under natural conditions. Marine Biology: 56, 21-28.

Rheault, R. B. and Ryther, J. H., 1983. Growth, yield and morphology of *Ascophyllum nodosum* (Phaeophyta) under continuous and intermittant seawater spray culture regimes. J. Phycol. 19:252-254.

Riley, J. P. and R. Chester, 1971. Introduction to Marine Chemistry. Academic Press. 465 pp.

Ryan, P. J. and Harleman, D. R. F., 1973. An analytical and experimental study of transient cooling pond behavior. MIT report to NSF under Grant #GK-32472, 439 pp.

Ryther, J. H., 1980. Cultivation of macroscopic marine and freshwater aquatic weeds. Report to SERI, subcontract #XR-9-8133-1. January 1980, 88 pp.

Ryther, J. H., 1982a. Cultivation of macroscopic marine algae and freshwater aquatic weeds. Report to SERI, subcontract #XR-9-8133-1, February 1982, 142 pp.

Ryther, J. H., 1982b. Cultivation of macroscopic marine algae. Report to SERI, subcontract #XR-9-8133-1. November, 1982. 31 pp.

Ryther, J. H. and DeBusk, T. A., 1982. Significance of carbon dioxide and bicarbonate uptake in marine biomass production. Proceedings of IGT Symposium "Energy from Biomass and Wastes VI." January 25-29, 1982.

Ryther, J. H. and Hanisak, M. D., 1982. Growth, nutrition, and genetics of marine plants. Annual Report to GRI, project 2219.

Shepherd, D. G., 1965. Elements of Fluid Mechanics. Harcourt, Brace, and World, New York, N.Y. 498 pp.

Stumm, W. and J. J. Morgan, 1981. Aquatic Chemistry. John Wiley and Sons, New York, N.Y. 780 pp.

Tornabene, T. G., Ben-Amotz, A., Hubbard, J. S., 1982. Isolation, analysis and identification of lipds. Report for the Aquatic Species Program of the Solar Energy Research Institute. 24 pp.

VanVleet, E. S. and Williams, P. M., 1983. Surface potential and film pressure measurements in seawater systems. Limnology and Oceanography 28(3), 401 - 414.

Document Control Page	1. SERI Report No. SERI/STR-231-2360	2. NTIS Accession No.	3. Recipient's Accession No.

4. Title and Subtitle
Cultivation and Conversion of Marine Microalagae

5. Publication Date
May 1984

6.

7. Author(s)
J. H. Ryther, T. A. DeBusk, M. Blakeslee

8. Performing Organization Rept. No.

9. Performing Organization Name and Address
Harbor Branch Institution

10. Project/Task/Work Unit No.
4625.10

11. Contract (C) or Grant (G) No.
(C) XK-2-02172-01
(G)

12. Sponsoring Organization Name and Address
Solar Energy Research Institute
1617 Cole Boulevard
Golden, Colorado 80401

13. Type of Report & Period Covered
Technical Report

14.

15. Supplementary Notes
Technical Monitor: R. McIntosh

16. Abstract (Limit: 200 words) An alternative concept to open ocean culture of microalgae is a land-based production system utilizing saline waters from underground aquifers. Research on this concept has been carried out at Harbor Branch Institution since 1979, and this past year concentrated on lowering production costs. Yields under non-energy-intensive culture averaged 10.8 dry tons/Ac/yr for 250 days. This compares with a yield of 30 dry tons/Ac/yr when grown under energy-intensive culture. It was found that aerating could be decreased twelve-fold without substantially affecting productivity. Carbon limitation was found to be a serious problem for highly productive seaweed cultures, and different species were found to have differing capacities for assimilation of dissolved carbon in water. Gracilaria photosynthesis correlated best with bicarbonate, whereas Ulva correlated best with the total inorganic concentration. Lipid yield of macroalgae ranged from 5 mg lipid/g dry wt to 20 mg/lipid dry wt.

17. Document Analysis
a. Descriptors Algae ; Aquatic Organisms ; Biomass ; Carbon ; Cost ; Economics ; Gracilaria ; Productivity ; Seaweeds ; Ulva

b. Identifiers/Open-Ended Terms

c. UC Categories
61a

18. Availability Statement
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22161

19. No. of Pages
89

20. Price
A05

Form No. 0069 (3-25-82)