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EVALUATION, MANAGEMENT, AND CULTIVATION OF *MACROCYSTIS* KELP FORESTS

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ABSTRACT

EVALUATION, MANAGEMENT, AND CULTIVATION OF MACROCYSTIS KELP FORESTS

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Giant Kelp, Macrocystis, is a marine plant of significant commercial value with great promise for expanded usage in the future. It is widely distributed among temperate waters of the southern hemisphere, although it occurs only in the eastern Pacific in the northern hemisphere. Presumably it could be introduced in any temperate coastal zone of our planet with currently available cultivation techniques. Three species of Macrocystis are presently recognized. Holdfasts are perennial and plants growing in well-protected locations sometimes display hundreds of fronds. Maximum frond lifespan is about six months. Senescing fronds are continually replaced by rapidly developing juvenile fronds. The rapid growth requires a continuing supply of mineral nutrients which are absorbed across all exposed surfaces from the seawater. Products of photosynthesis in the canopy can be translocated down the stipes to provide organic nourishment for the shorter fronds developing in the darkly-shaded regions beneath the canopies.

Macrocystis beds harbor complex communities. The plants create a forest-like habitat that provides shelter and substrate for a diverse fauna that includes many edible species. In southern California, storms, seasonal lack of nutrients, and

grazing by sea urchins are probably the most common damaging factors affecting Macrocystis plants. Warm temperatures, certain diseases, and grazing by other animals can also, on occasion, have serious consequences. These natural factors sometimes destroy large quantities of the kelp canopy. Macrocystis is normally able to regenerate such tissues rapidly (one to four months). Canopy removal by properly conducted harvesting is apparently also similarly restored. Canopy removal introduces a number of influences which, on balance, probably result only in very minor effects on the welfare of plants.

Pollution from sewage discharges may have direct and indirect effects on Macrocystis. Components such as ammonium and phosphate can be stimulatory. On the other hand, toxicities might conceivably occur in the immediate vicinity of dispersing industrial waste waters. Attention must be given to rapid initial dilution of such effluents with surrounding seawater. Organic matter in sewage may nourish sea urchins. Large persisting urchin populations can then dominate the bottom indefinitely, preventing colonization by Giant Kelp and other vegetation. Discharge of heated water from electric power plants has apparently had minimal or no effect at two sites in southern California.

When natural processes eliminate Macrocystis populations from substantial areas, competitive weeds may dominate the bottom and prevent reestablishment by Giant Kelp. Proper management, therefore, requires continuing surveillance of stressed areas to ensure that Macrocystis is not eliminated. The species can usually be restored by artificial introductions, but such operations may be time-consuming and costly. It is nearly always more economical to protect existing stocks.

Several techniques for cultivating kelp have been developed experimentally. Some are finding use in management of beds in southern California by government and industry. Urchin control operations are now an important and commonly-used technique. Transplanting both juvenile and adult plants is frequently undertaken to reintroduce Macrocystis into territory where it is sparse or has disappeared. On many occasions we dispersed microscopic Macrocystis embryos grown in mass cultures. Restoration of Giant Kelp to certain areas followed dispersal of these cultures. The mass culturing operation, however, is difficult and costly so the technique has not found usage in southern California beyond the experimental demonstrations.

Experiments are currently underway attempting to cultivate Macrocystis on artificial structures moored well offshore in deep water. The kelp would be digested anerobically to produce the gaseous fuel methane. Low nutrient concentrations in surface layers of the oceanic environment necessitate that the kelp be fertilized before rapid growth can occur. Nutrient-rich seawater from 150 to 500 m depths is being tested as a possible fertilizing medium. Possibilities of dispersing agricultural fertilizers in coastal kelp beds during periods of low upwelling is also being studied.

INTRODUCTION

Macrocystis or Giant Kelp is a brown alga whose growth habit, large size, high productivity, and chemical composition have encouraged commercial usage. A complex community associates with and presumably benefits from Macrocystis populations. Consequently beds of Giant Kelp are often favored fishing grounds. Macrocystis in California coastal waters commonly occurs on rocky bottoms from depths of about 8 m to 20 m. The lower limit may range to 30 or more m at the margins of offshore islands where clear waters allow deep penetration of sunlight. In areas protected from waves, Macrocystis can occupy sedimentary bottoms. Where the continental shelf slopes gently, large areas fall within the depth range occupied by Macrocystis. Very wide kelp beds may develop at such locations. These large beds of California and Baja California are harvested by specialized vessels. Expense of operating the harvesting ships dictates that only large and dense beds are suitable for cutting. Kelp harvesters move through canopies at velocities up to about 2 km/hr while cutting. They may bring aboard 300 or more metric tons of kelp in a few hours.

Area covered by Macrocystis beds in southern California was officially reckoned at about 285 km^2 by the State Department of Fish and Game early in this century (cf Davies, 1968). Deterioration from unknown causes reduced the area to perhaps 70 percent of this value by the mid-1950s. Alarm at such continuing losses stimulated funding for research on Macrocystis ecology and physiology. Results opened the way for development of aquacultural techniques that greatly expanded opportunities for managing kelp beds. This paper describes these new aquacultural techniques as well as basic biological information pertinent to management of the Macrocystis resources.

MACROCYSTIS BIOLOGY

Distribution and Ecology

The genus Macrocystis occurs in temperate coastal waters of every major land mass in the southern hemisphere. It is restricted in the northern hemisphere to temperate-boreal shores of the Eastern Pacific. Macrocystis has, however, been successfully cultivated several times in waters of the North Atlantic Ocean. Thus it appears likely that Giant Kelp could easily be grown in any marine location where conditions of temperature, nutrient availability, wave exposure, etc., were favorable. Three species are presently recognized according to Womersley (1954): M. pyrifera, M. angustifolia, and M. integrifolia. Existence of morphologically distinct yet intergrading populations of Macrocystis along the coasts of California and Baja California has been noted by Neushul (1959) and Brostoff (1977), but the taxonomic questions involved have not been resolved.

Holdfasts and basal branches of Macrocystis are perennial. Fronds emanating from the basal branches are continually renewed, as are haptera of the holdfast. Plant mortality along exposed coastlines is typically high (half lives of 6 to 9 months among young adults), but survival in protected locations can be excellent so that very large plants occur, displaying hundreds of fronds. Presumably such specimens are many years old. Rosenthal et al. (1974) found a mean lifespan of 3-4 years for Macrocystis in the Del Mar Kelp Bed. One of their tagged plants survived an estimated seven years. Year-old plants may display perhaps ten to twenty fronds with this complement doubling by the end of the second year. Older plants, however, may consist of relatively few fronds if they continually suffer pruning from storms, grazers, etc. (Kirkwood, 1977). Gerard (1976) found that mean monthly frond additions ranged from 2 to 14 fronds per month, increasing with plant size, for beds in central California. Concomitant losses reduced the net monthly increase to one to two fronds for plants smaller than 50 fronds. Plants larger than 70 fronds showed no net gain in mean frond number.

The typical adult Macrocystis plant contains an array of juvenile, youthful, mature, and senescing fronds which have all arisen from division by basal meristems at the holdfast apex (Figure 1). Frond lifespan is of the order of six months (North, 1961; Gerard, 1976, Lobban, 1978a). As fronds senesce and become non-functional, they deteriorate or sink and are replaced by younger material developing from the basal meristems. Similarly when tops of mature fronds are removed by harvesting, the canopy is replaced from below by growth of the younger uncut fronds. Cutting removes the apical meristem and the growing but immature blades at the terminal end of the frond (Figure 2). Only the fully mature basal portion remains. This portion is believed to carry out its normal existence but does not participate significantly in canopy regeneration.

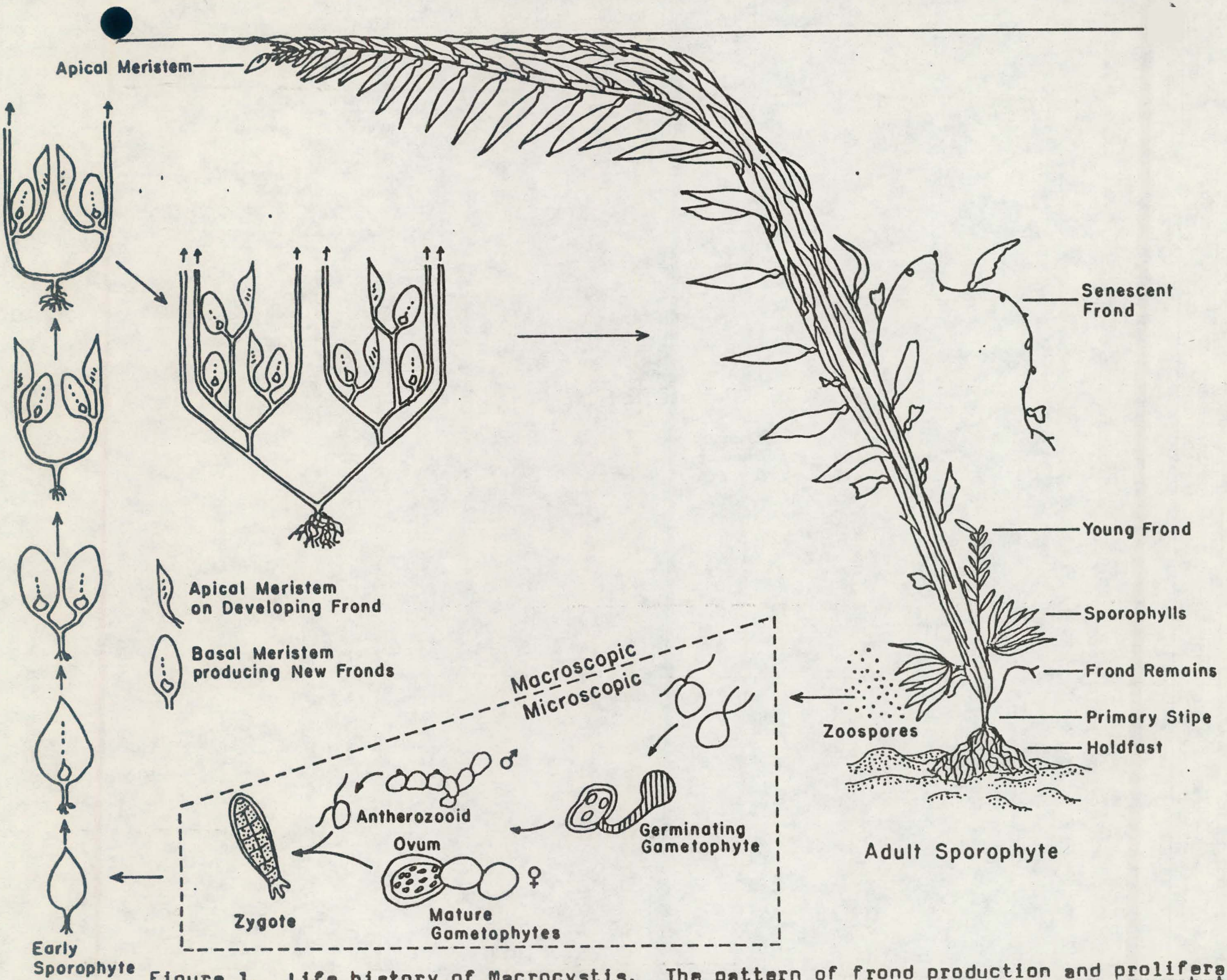

Figure 1. Life history of _Macrocystis_. The pattern of frond production and proliferation of basal meristems is illustrated by the developmental stages shown for young sporophytes.

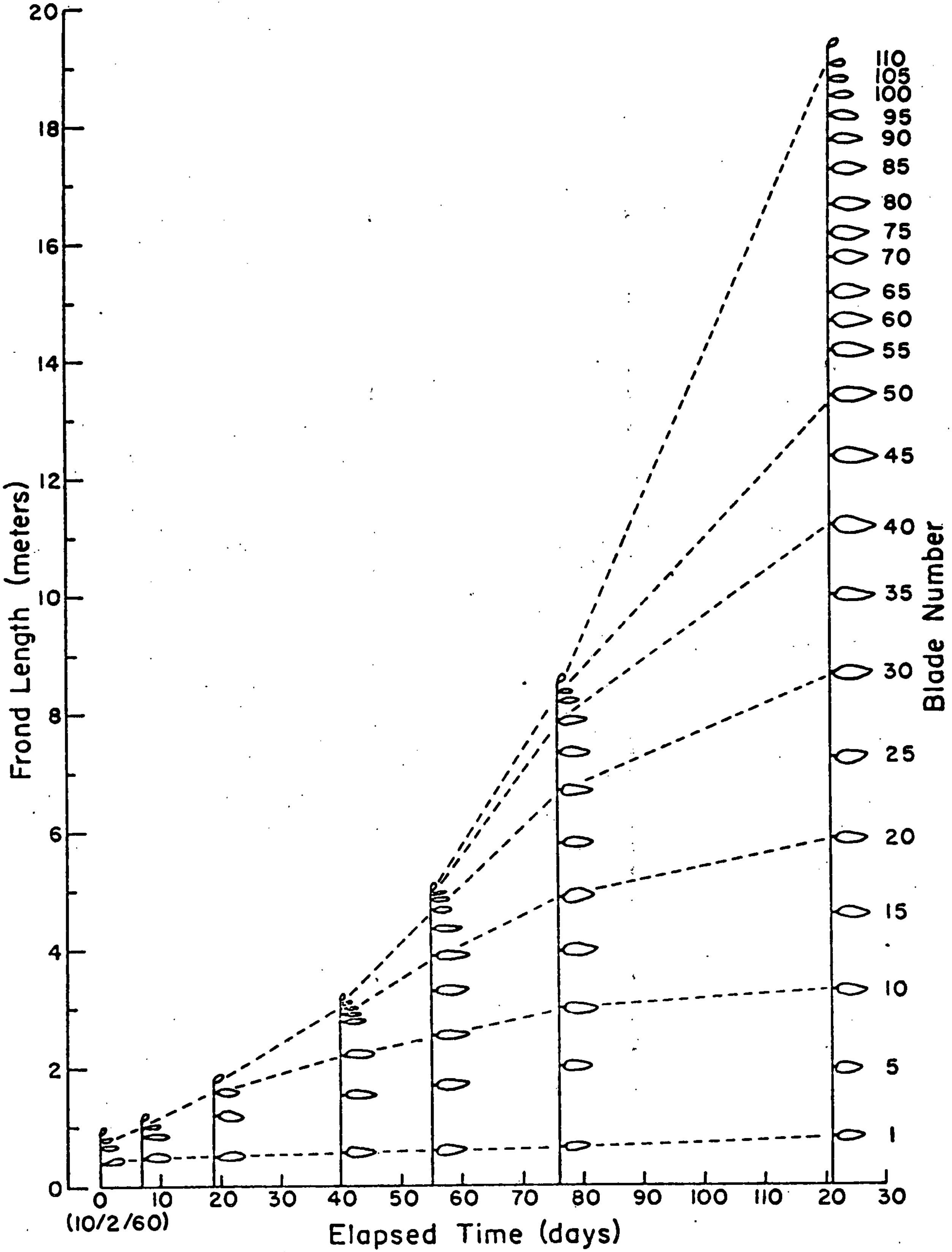

Figure 2. Diagram illustrating frond elongation in Macrocystis due to internodal growth. Note that growth in the basal portions declined while the terminal portion was still developing. Frond came from a site of 20 m depth. Internodal lengths become shorter at shallower depths (North, 1972).

Elongation by Macrocystis fronds usually follows S-shaped patterns. There are definable relationships between frond length, wet weight, and total blade area. Consequently growth rates for all three parameters can be derived if time changes in any one are known. North (1971a) found that elongation rate and rate of increase in blade area, measured in absolute terms, were maximal when total frond length is about 15 m. Maximal daily weight increase occurred when fronds were about 17 m long. When expressed as a percentage of the total, rates of increase in length, weight, or blade area were largest when fronds were very small. North (l.c.) proposed a mathematical model to describe growth by Macrocystis fronds. The model can be applied to field experiments that test effects of various factors on frond growth and presumably the condition of the parent plant. Thus a Q_{10} of 1.7 was found for frond growth (North l.c.). Effects of cutting and of harvesting were examined in terms of frond growth data (North, 1968a).

Physiology, Nutrition, and Productivity

When Macrocystis plants grow in close proximity to each other so that tissue densities exceed two fronds per m^2, the tops of mature fronds on adjacent plants may coalesce to form continuous canopies. When three or four blade layers have formed in the canopy, 99 percent or more of the incoming sunlight may be absorbed (Neushul, 1971). Bottom light intensities under such canopies cannot sustain the photosynthesis needed for survival by associated vegetation including juvenile Macrocystis. Plant life becomes sparse or absent and the sea floor soon harbors dense encrustations of sessile invertebrates such as sponges, hydroids, bryozoans, and tunicates. Sargent and Lantrip (1952) first showed that the shorter fronds attached to mature Macrocystis plants in dense beds also fail to receive sufficient sunlight to support the photosynthesis needed to account for the rapid growth occurring among these youthful tissues. These two workers demonstrated that photosynthesis in the canopy yielded organic matter in excess of amounts needed for growth by terminal portions of mature fronds. They reasoned that the excess must be translocated down the stipes to supply the organic matter appearing as newly-formed tissues among the shorter, dimly-illuminated, fronds. The conjectures of Sargent and Lantrip, combined with follow-up studies by Clendenning and Sargent (1971), have been amply supported by subsequent research. Conducting elements (sieve tubes), lying between the cortex and medulla in Macrocystis stipes, were photographed by Parker (1971a) in electronmicrographs. Several workers have proven the existence of translocation processes in Macrocystis by tracing movements by dye and by compounds tagged with radiocarbon (Parker, 1971b; Lobban, 1976; Wheeler, personal communication). The ability to translocate photosynthate ameliorates the self-shading problem and permits formation of the forest-like habitat created by Macrocystis.

In addition to products of photosynthesis, growing Macrocystis tissues need mineral nutrients such as nitrogen, phosphorus, and trace metals. These materials may be absorbed directly from the surrounding water or perhaps supplied by translocation from reserves or possibly moved in from senescing tissues. Absorption of dissolved material can occur across all exposed surfaces and is not confined to specialized tissues, such as roots in higher plants. Photosynthetic rates and N-uptake rates decline when flow velocities across blade surfaces fall below 6 cm/sec (W.N. Wheeler, 1976). Uptake rates rise as concentrations of compounds such as ammonia, nitrate, and phosphate increase. Haines and Wheeler (1978) measured values of K_s = 13.1 µg-at/l and V_{max} = 3.1 µg-at/gm wet/hr for nitrate uptake by juvenile Macrocystis. Corresponding values for ammonium were K_s = 5.3 µg-at/l and V_{max} = 2.4 µg-at/gm wet/hr at concentrations below 22 µM. Both of these nitrogen compounds were accumulated simultaneously when supplied together, with no influence on uptake rates. Irradiance affects nitrate uptake (48 percent slower in darkness) but not ammonium accumulation (W.N. Wheeler, 1978). P.A. Wheeler (In Press) found little or no uptake by Macrocystis of arginine, alanine, glucose, or urea, while methylamine was accumulated more slowly than ammonium (K_s = 50 µg-at/l, V_{max} = 2.4 µg-at/gm wet/hr). Thus it appears that Macrocystis depends largely on inorganic sources for supplies of nitrogen. P.A. Wheeler (personal communication) recently demonstrated translocation of methylamine in adult Macrocystis fronds. Hence nitrogen can be moved from one region to another within a plant. Nitrite is not accumulated (W.N. Wheeler, 1978).

Nitrogen contents of kelp blades rise steadily for several days when plants are switched from N-poor media to N-rich waters (Figure 3). Growth rates of juvenile tissues increased as N

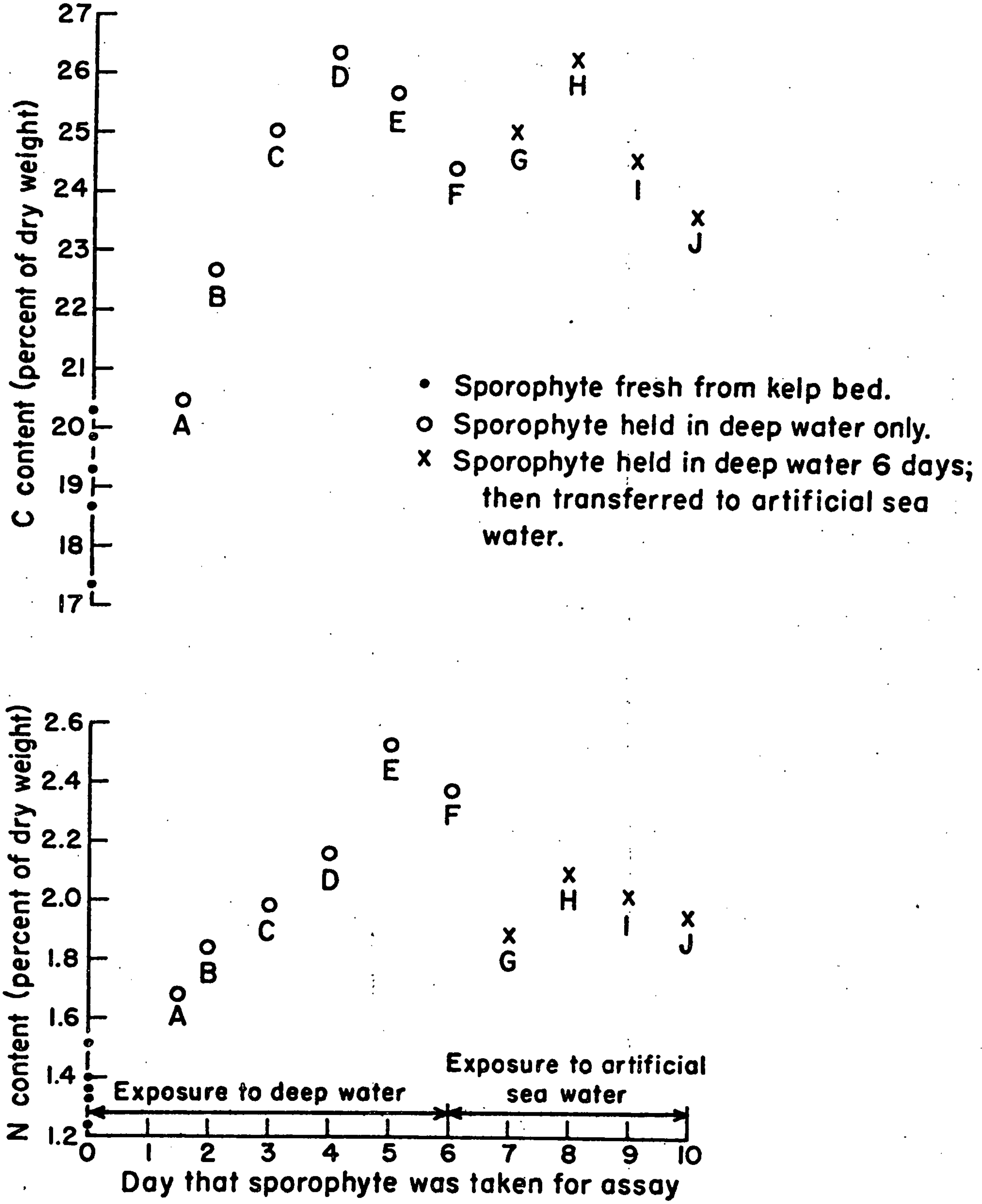

Figure 3. Carbon and nitrogen contents of juvenile *Macrocystis* sporophytes either fresh from a kelp bed, or held in seawater from 250 m deep for varying periods, or held in deep water for 6 days and then transferred to N-free artificial seawater. N-content apparently rose while plants were in deep water, then declined after transfer to the N-free medium.

content rose, but weights of fully mature blades remained constant even though their N-contents increased substantially (North *et al*., 1976). Mature blades attached to adult plants thus may serve simply as collectors and storers of nitrogen, not as utilizers. Jackson (1976) found that amino acids comprised the principal nitrogen-containing compounds in exudate from cut *Macrocystis* stipes. He calculated that nitrogen translocation flux in a stipe amounted to 0.2 mM/hr. The principal amino acid in the kelp exudate was L-alanine (Jackson, 1977) which is also true of the dried tissue (Mateus, Regenstein, and Baker, 1976).

Healthy mature *Macrocystis* blades often yield nitrogen contents in the range of 0.8 to 1.2 percent of the dry weight, but much higher values can occur if the tissues have been exposed to N-rich water. Blades with N-contents of 0.5 percent are easily perceived as pale (other deficiencies can also lead to paling, however). The usual vertical gradients in inorganic nitrogen occurring in kelp beds (low concentrations in surface waters, high in bottom waters) produce complex patterns of N-distribution among the blades of fronds spanning the entire water column (Table 1). Mature blades near the holdfast presumably accumulate nitrogen from the N-rich medium at this level, hence they display relatively high N-contents. Farther up, N-content falls among the mature blades residing in N-poor water. N-content may rise again near the frond apex where young blades and the apical meristem represent actively growing tissues receiving translocated nitrogen. Thus meaningful estimates of

Table 1

Carbon and nitrogen contents as percent of the dry weight, from every tenth blade attached to mature *Macrocystis* fronds collected at Abalone Cove on August 24, 1974. Fronds A and B appeared healthy. Fronds C and D showed some buoyancy loss, usually an indication of beginning effects from high water temperature or senescence.

Blade No.	Frond A	Frond B	Frond C	Frond D
		PERCENT NITROGEN		
1 (tip)	1.6	1.5	1.2	1.4
10	0.8	0.9	0.6	1.1
20	0.8	1.1	0.8	0.8
30	0.9	1.0	0.7	0.8
40	1.3	1.1	0.8	0.7
50	1.2	1.0	0.9	0.8
60	1.3	1.5	1.2	0.9
70	1.8	1.7	1.6	1.6
80	2.0	1.7	1.8	2.0
90	1.6	2.1	1.7	2.3
100	1.7	2.2	-	2.1
110 (bot)	-	-	-	2.5
		PERCENT CARBON		
1 (tip)	35	47	33	38
10	35	33	33	39
20	36	34	37	39
30	34	30	34	40
40	33	34	36	40
50	36	31	32	32
60	34	29	31	37
70	36	29	31	38
80	30	28	28	41
90	26	27	27	35
100	26	29	-	31
110 (bot)	-	-	-	32

N-contents should take account of location of the sampled tissue in the water column and degree of maturity. We usually sample every tenth blade on a mature frond so that the entire vertical distributional pattern can be assessed.

Senile fronds typically display very low N-contents, in the range of 0.2 to 0.5 percent of the dry weight. We do not know if tissue nitrogen is returned to the surrounding water as fronds senesce or if it is conserved by translocation to younger tissues. Perhaps both processes occur. Distributional patterns and translocation pathways of other nutrient elements have not been studied in any detail. We can only assume that processes involving nitrogen in <u>Macrocystis</u> are representative of other micronutrients.

Biomass of <u>Macrocystis</u> among established beds is variable and has been measured in different ways by various investigators (cf Gerard, 1976; North, 1971b). For our discussion here, we will relate data to a method suggested by North (1971b) involving multiplication of counts of stipes per m^2 by an average wet weight per frond of 1.5 kg (applicable to plants with well-formed canopies located in depths of 10 m or more). For stipe counts from areas of 200 m^2 or greater, biomass ranged from 2.1 to 14.3 kg/m^2 (23 separate samples from 15 kelp beds in southern California and Baja California in 1957) with a mean of about 6 kg/m^2. Frequently "thickets" of plants occur in kelp beds so that stipe densities of 20 to 30 per m^2 appear when sampling areas smaller than 200 m^2 are chosen. The highest density we ever measured was 30 fronds/m^2 for a 22 m^2 sample at Abalone Cove, Palos Verdes, on May 15, 1958.

Estimates of productivity in Macrocystis beds vary somewhat according to investigator and method of determination. Results from seven different investigations yielded values ranging from 16 to about 130 metric tons dry wt/ha/yr (cf North, 1977a). Harvest yields are, of course, lower because only a fraction of the plant is removed at any one time. Clendenning (1960) estimated less than 10 percent of the productivity was taken by harvesting.

RESOURCE ASPECTS

Total Macrocystis harvests from California waters during the 70-year period from 1916 to 1976 varied from 236 metric tons in 1931 to 358,000 metric tons in 1918 with no harvesting recorded from 1920 to 1931 (Table 2). The great variation is probably largely a reflection of the demand for kelp tissues and products. Demand has stabilized so that annual yields in recent years are less variable. Thus the harvests since 1970 have ranged from 115,000 to 155,000 metric tons.

Kelp beds in California are designated as open (harvestable by anyone) or closed (leased to specific individuals or organizations). In addition to leasing fees, harvesting companies pay royalties of 50 cents per wet ton of kelp collected and license fees of $10.00. Lease periods are 20 years. Depth of cutting is restricted to about 1.2 m (4 ft).

Table 2

Annual *Macrocystis* harvest, in metric tons, from California waters according to Pinkas (1977). Values represent wet weights.

Year	Total Tons	Year	Total Tons	Year	Total Tons
1916	122,050	1943	43,507	1960	109,134
1917	358,314	1944	48,108	1961	117,259
1918	358,425	1945	53,688	1962	127,217
1919	15,125	1946	82,616	1963	109,798
1920	23,101	1947	67,347	1964	115,443
1931	236	1948	71,342	1965	122,587
1932	9,358	1949	75,610	1966	108,376
1933	19,614	1950	91,265	1967	119,290
1934	14,406	1951	104,109	1968	122,337
1935	27,762	1952	99,935	1969	119,058
1936	44,740	1953	114,894	1970	115,248
1937	39,874	1954	96,358	1971	141,121
1938	43,270	1955	112,548	1972	147,428
1939	51,470	1956	106,881	1973	138,872
1940	53,528	1957	84,961	1974	154,386
1941	50,546	1958	103,475	1975	155,671
1942	56,153	1959	81,283	1976	143,672

The biomass harvested from Macrocystis beds has found numerous uses. The most important product currently extracted from Macrocystis is alginic acid, a colloidal polymer of mannuronic and guluronic acids. Alginic acid finds varied uses as thickening, emulsifying, and suspending agents in foods, pharmaceuticals, beverages, textiles, and many other products. Hart et al. (1976) and Lindner et al. (1977) found that alginate contents of Macrocystis from central and southern California fluctuated seasonally over a threefold range from 8 to 23 percent of the dry weight. This range agrees well with values from the older literature (cf Chapman, 1970). Macrocystis contains other potentially valuable products (Table 3). From time to time, attempts have been made to market either dried tissues or extractives. Thus kelp was processed as a source of potash in the United States during World War I (Scofield, 1959). Moss (1977) estimated that 16,100 metric tons of algin were produced worldwide from brown algae in 1976, having a total value of about $88,000,000. The U.S. production was about 1/3 of the worldwide total, presumably consisting primarily of yields from the California Macrocystis beds. According to Moss (l.c.), algin exceeded all other seaweed extractives in dollar value for 1976. Macrocystis, like many other seaweeds, concentrates a number of trace elements from seawater (Table 4), possibly contributing to values of the tissues as food and fertilizer.

The forest-like environment created by Macrocystis populations provides food, shelter, and settling substrate for

Table 3

Gross composition of Macrocystis, combining data from Point Loma and San Clemente Island in southern California (Lindner *et al.*, 1977) and from Monterey Bay, Santa Cruz, and Soquel Point in central California (Hart *et al.*, 1976). Standard deviations are shown for solids, ash, and alginic acid for all samples combined.

Substance or Compound	Percent Composition			
	All Samples	So. Calif.	Cen. Calif.	Basis
Water	88.2			Percent of wet wt
Solids	11.8 ± 1.0[a]	12.2	11.3	"
Ash (550°C)	38.96 ± 6.24[b]	37.29	40.49	Percent of dry wt
KCl	29			"
NaCl	7			"
Na_2SO_4	4			"
Other	4			"
Volatiles (550°C)	66-53			"
Mannitol	6-22			"
Laminarin		1-2		"
Fucoidan		0.5-2		"
Alginic Acid	15.71 ± 2.56[c]	18.6	11.4	"
Cellulosics	3-8			"
Protein	5-14			"
Fat	0.5-2.0			"

[a] 42 samples

[b] 44 samples

[c] 35 samples

Table 4

Concentrations in μM of selected elements in wet *Macrocystis* tissues (modified from North, In Press, C) and in seawater, according to Brewer (1975). The ratio of these two sets of values was determined, representing the concentration factor.

Element	Concentrations μM/gm wet tissue	 μM/l seawater	Concentration Factor
Phosphorus	11.6	0.2	58,000
Beryllium	0.025	0.00063	40,000
Nitrogen	10.5	0.5	21,000
Antimony	0.0125	0.002	6,000
Iron	0.175	0.05	5,000
Cobalt	0.00375	0.0008	4,700
Arsenic	0.175	0.05	3,500
Manganese	0.0125	0.0036	3,500
Aluminum	0.120	0.074	1,600
Copper	0.01	0.008	1,300
Iodine	0.588	0.5	1,200
Zinc	0.0688	0.076	900
Vanadium	0.0375	0.05	750
Nickel	0.00625	0.028	220
Molybdenum	0.00125	0.01	130
Boron	3.13	410	8
Lithium	0.19	26	7
Strontium	0.475	91	5
Silicon	0.35	71	5
Potassium	15	10,200	1.5
	UNCERTAIN		
Selenium	<0.00125	0.0025	<500
Chromium	<0.00125	0.0057	<220

Bromine, rubidium, and fluorine are not concentrated.

hosts of marine animals. Many of the associated fishes and shellfishes are edible by humans. The California kelp beds contribute significantly to commercial and recreational fishing (Davies, 1968; Quast, 1968a, b, c, d, e). Organic production by *Macrocystis* in excess of consumption by herbivores eventually becomes drift material that provides nourishment for organisms beyond as well as within the confines of kelp beds (Gerard, 1976).

CONTROLLING FACTORS IN *MACROCYSTIS* ECOLOGY

Five factors appear to be quite important in regulating healthiness and survival of *Macrocystis* populations in California:

1. Degree of exposure to waves and storms
2. Water temperature
3. Nutrient concentrations
4. Activities of grazing animals
5. Competition from other seaweeds for substrate

These and factors of lesser importance were recently discussed by North (In Press, A). The relative importance of each factor can vary from place to place and from season to season.

Waves and Storms

Exposure to waves probably determines location of the inshore border of many kelp beds. Damage to kelp during severe storms is usually greatest in the shallower reaches. Rosenthal *et al.* (1974) listed storm damage as the primary source of plant mortality in their study area off Del Mar. Gerard (1976) reached a similar conclusion. Although high waves can remove nearly all adult Macrocystis from a given area, other competitive weeds also usually suffer damage. Hence competitive relationships remain more or less unchanged. Populations of the species involved are usually restored as juvenile plants fill in gaps left by the uprooted adults.

Temperature

Water temperatures can affect Macrocystis adversely. Gametophytes in culture do poorly whenever temperatures exceed 18°C. Juvenile sporophytes can withstand exposures of a few hours to 21° to 22°C. Adult sporophytes in southern California waters have survived 23° to 25°C surface temperatures lasting a week or two, but canopies begin sloughing at that point. Slightly higher temperatures are apparently tolerated by a strain of Macrocystis existing in central Baja California near the southern limit of the geographical range in the northern hemisphere (North, 1977b). Temperatures above the thermocline may rise to damaging levels during summer but remain cool in the underlying water. Canopies may be sloughed and disappear under these circumstances, but lower portions of plants remain intact and regenerate the canopies after cooler surface temperatures appear during fall. Elevated water temperatures extended to the bottom in kelp beds during the exceptionally warm years of 1957 to 1959 in southern California. Entire kelp beds were lost and few, if any, populations escaped serious damage. Other competitive weeds such as Egregia, Pterygophora, and Eisenia were affected less severely. These species proceeded to take over very significant territory formerly occupied by *Macrocystis*.

Nutrients

The role of dissolved nutrients in *Macrocystis* ecology is just beginning to receive attention. Preliminary evidence suggests that *Macrocystis* beds can function normally for three months without a major input of nutrients from upwelling or runoff. Very significant kelp losses were, however, recorded in one instance when nutrient-depleted conditions occurred for some six months (Figure 4). Presumably reserves accumulated when nutrients were plentiful sustain the biomass for three but not six months.

We have found that *Macrocystis* fronds grow slowly when total inorganic nitrogen (i.e. $NH_4 + NO_2 + NO_3$) amounts to about 0.5 μg-at/l. Water temperature and concentration of total nitrogen are inversely correlated in southern California (Jackson, 1977). Jackson's data indicate the relationship was especially clearcut for temperatures above 16°C. That is, nitrogen is almost always depleted at the warmer temperatures. Thus when temperatures exceeded 18°C, total nitrogen always amounted to less than one μg-at/l. Our own data indicate that when temperatures were 20°C or more, nitrate concentrations were nearly always only a small fraction of one μg-at/l. Hence the adverse consequences on kelp canopies, so frequently noted as correlating with high ocean temperatures, may have resulted from a combination of harmful temperatures as well as low levels of nutrients.

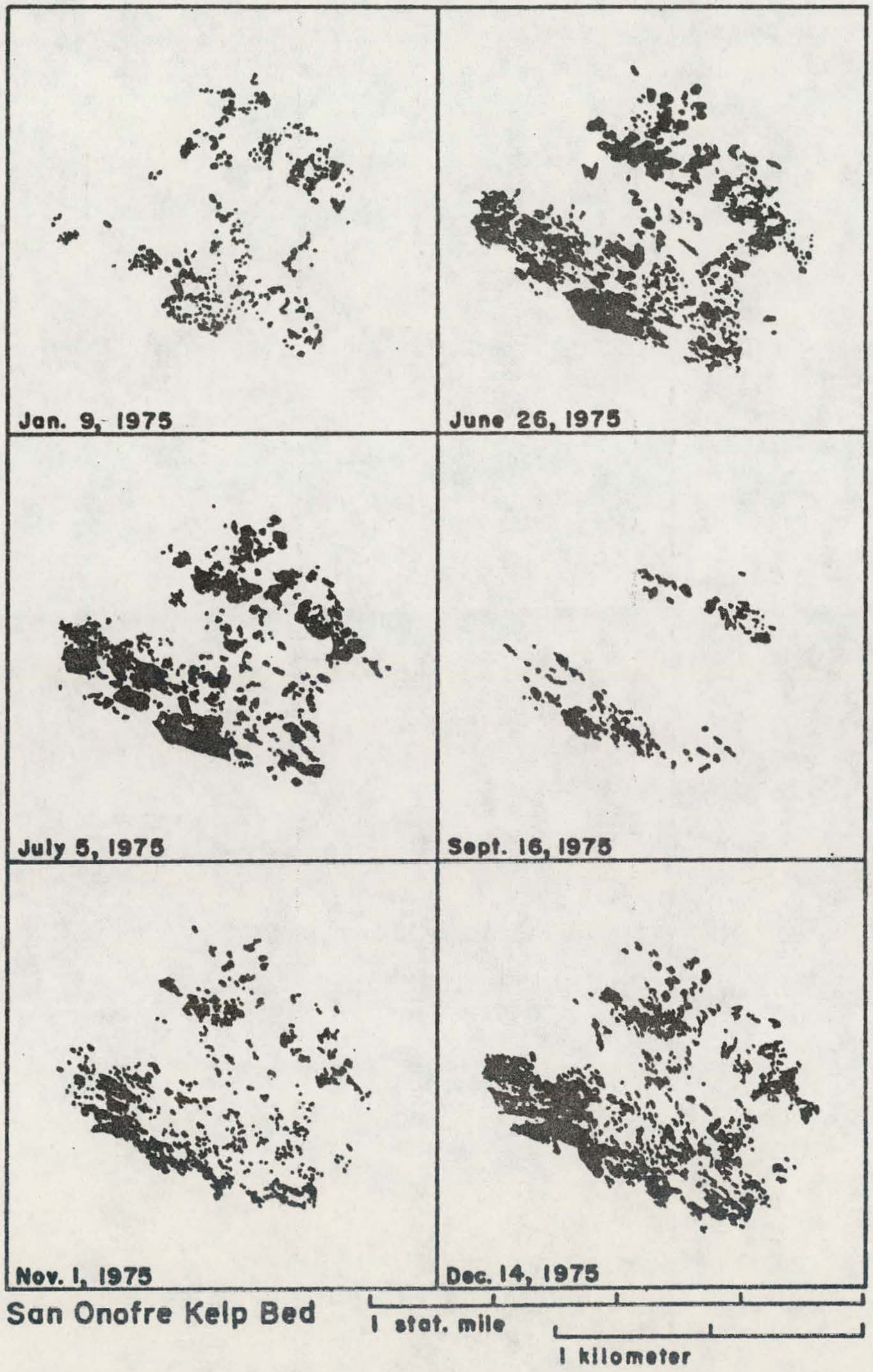

Figure 4. Changes in canopy coverage of the San Onofre Kelp Bed, drawn from infra-red aerial photos taken at 3 km altitude. A. Normal pattern, showing decline in late summer due to warm surface temperatures.

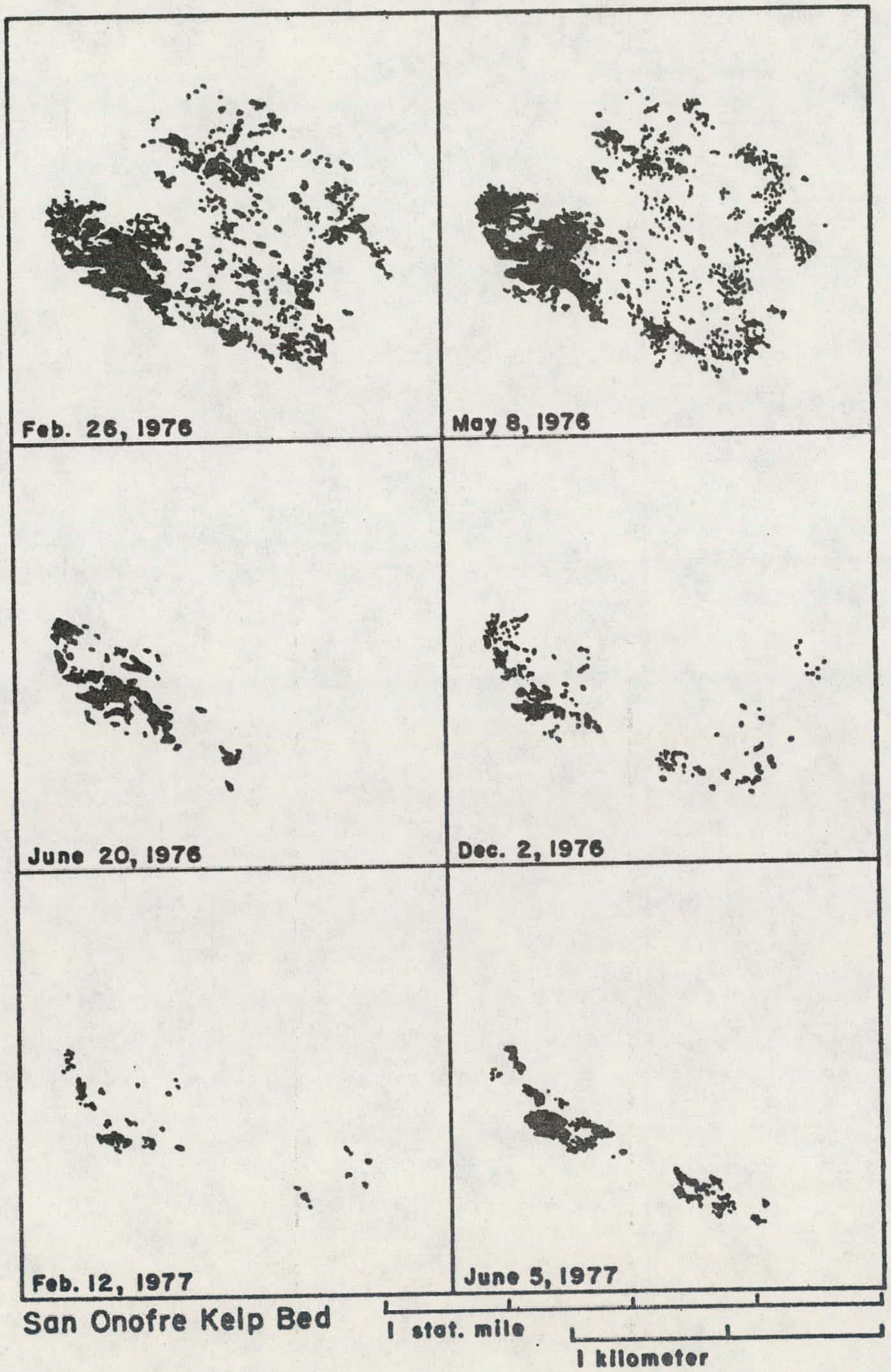

Figure 48. Abnormal pattern of canopy changes that occurred in 1976-77 when canopy did not recover in later fall although surface temperatures were no longer damaging. About 90 percent of the bed was lost, probably because of a reduction in nutrient supply arising from a lack of upwelling at that time.

Grazing and Predation

Many animal species feed on Macrocystis. Most cause only superficial damage to kelp tissues. Grazing by a few species, however, can achieve proportions that pose serious threats to continued existence of plant populations. Two urchins - Strongylocentrotus franciscanus and S. purpuratus - have frequently been implicated as responsible for major losses of Macrocystis and other seaweeds in California waters. The most extensive and persistent urchin populations formerly tended to be associated with large sewer outfalls. These populations have been controlled artificially in recent years (see below). More restricted but nonetheless dense and persistent groups of urchins can occur where currents reliably and continuously supply drift seaweeds for food. Elsewhere, urchins may forage when vegetation becomes scarce, moving from one location to another. As locations are abandoned, vegetative cover can reestablish. Vegetation can develop when density of S. franciscanus is about one per m^2 or at S. purpuratus densities of ten per m^2, provided water is clear so that the bottom is well-illuminated. After a coexistence relationship appears between urchins and seaweeds, the echinoids become crevice dwellers depending primarily on drift for nourishment. Urchins along California's coasts have at least one important natural predator - the Sea Otter, Enhydra lutris. A group of several dozen Sea Otters can control urchins over many hectares of kelp bed so that excessive grazing is prevented. The fur trading industry eliminated Sea Otters from much of their former territory throughout the Northeast Pacific. Strict conservation laws have allowed very significant expansion of the Sea Otter herds during the past two decades. The role of otters in controlling urchin grazing was documented for the Diablo Canyon region in central California when a herd reoccupied the region after an absence of many decades (North, Anderson, and Chapman, In Press). Seaweed biomass increased very substantially after otters returned but numbers of plant species remained fairly constant.

Competition

Competitive seaweeds influence primarily the microscopic and juvenile stages of Macrocystis. Canopies of stalked forms such as Eisenia and Pterygophora may act by shading the smaller specimens of Giant Kelp. Dense mats of turf-forming species often leave no substrate available for settling by spores of kelps. After an adult Macrocystis disappears due to grazing or dislodgement or other accident, bottom illumination usually increases. Frequently the former site of the holdfast becomes populated with many juvenile Macrocystis but not other species. Possibly an antibiotic was produced by the parent plant, preventing or hindering development by other species.

HUMAN INFLUENCES

Municipal Waste Water Disposal

Gradual disappearance of large Macrocystis beds from Point Loma and Palos Verdes in southern California was documented in publication of the State Water Quality Control Board (1964).

Both these beds were situated near major sewage discharges - the City of San Diego near Point Loma and County of Los Angeles at Palos Verdes. Those portions of the beds closest to the discharges tended to disappear first, suggesting an adverse relationship between sewage and kelp. Appropriate dilutions of sewage in seawater, however, stimulated photosynthesis in Macrocystis, suggesting lack of any toxic effects. Examination of sites near these sewer outfalls at the time kelp was disappearing revealed large populations of actively-foraging urchins (North, 1964a). Investigations by Clark (1969) and by Clark et al. (1972) suggested that dissolved organic matter from dispersing sewage effluents could contribute significantly to urchin nutrition. Presumably such a contribution would be greatest near the largest sources of sewage. Small outfalls do not appear to encourage development of persistent urchin populations. When foraging urchins were artificially controlled at Point Loma and Palos Verdes, kelp losses ceased and the Macrocystis population began expanding (Figures 5 and 6). This was followed at Point Loma by restoration of portions of the vanished kelp by natural reproductive processes from existing plants (Leighton et al., 1965). Macrocystis had completely vanished from Palos Verdes by the time an urchin control project was initiated. Hence it was necessary to introduce Macrocystis transplants to serve as sources of reproductive spores (Wilson et al., 1977).

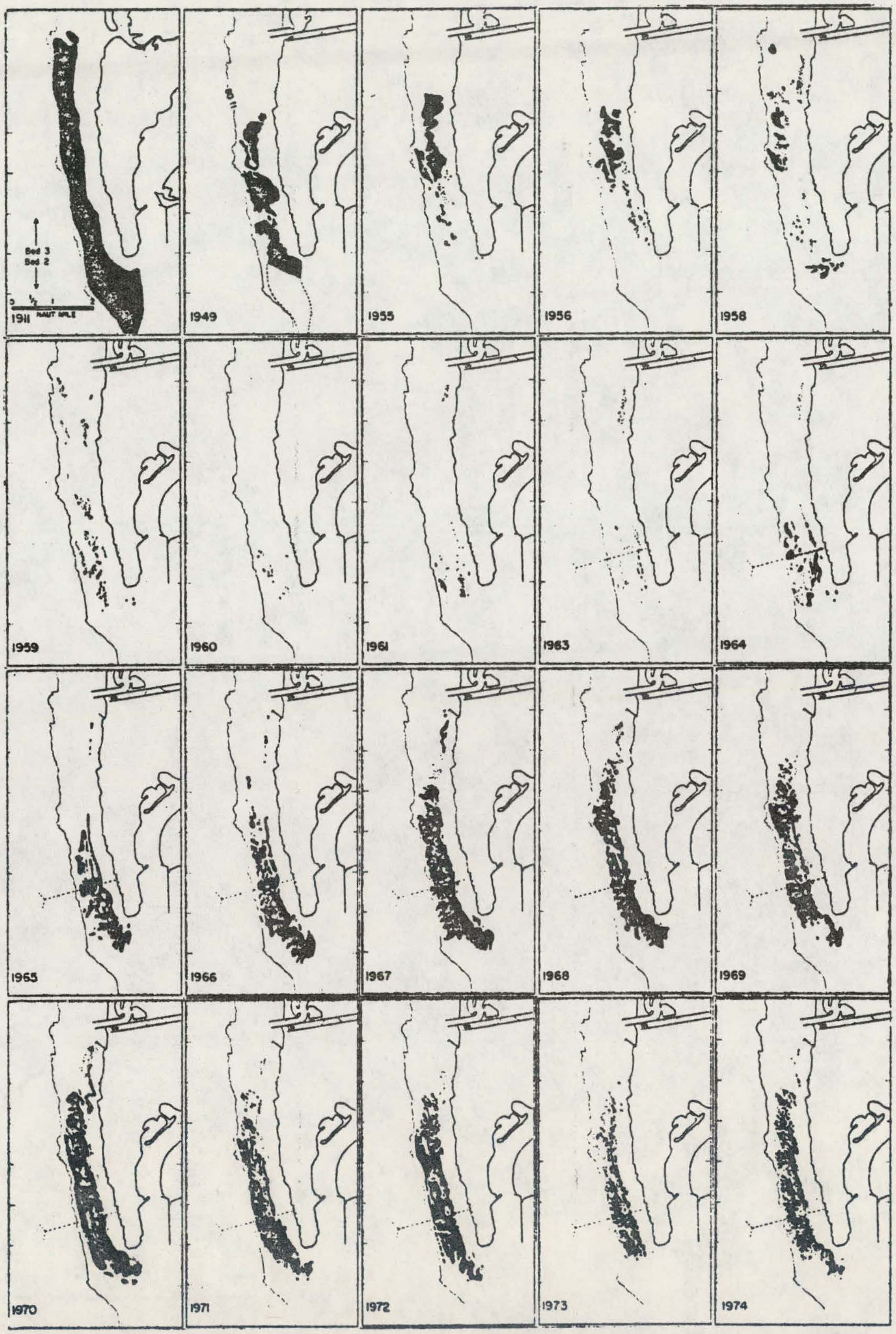

Figure 5. Historical charts illustrating decline of the Point Loma Kelp Bed from 1949 to 1963. Kelp shown as black. Restoration efforts began here in 1963, progressing northward from the southern tip.

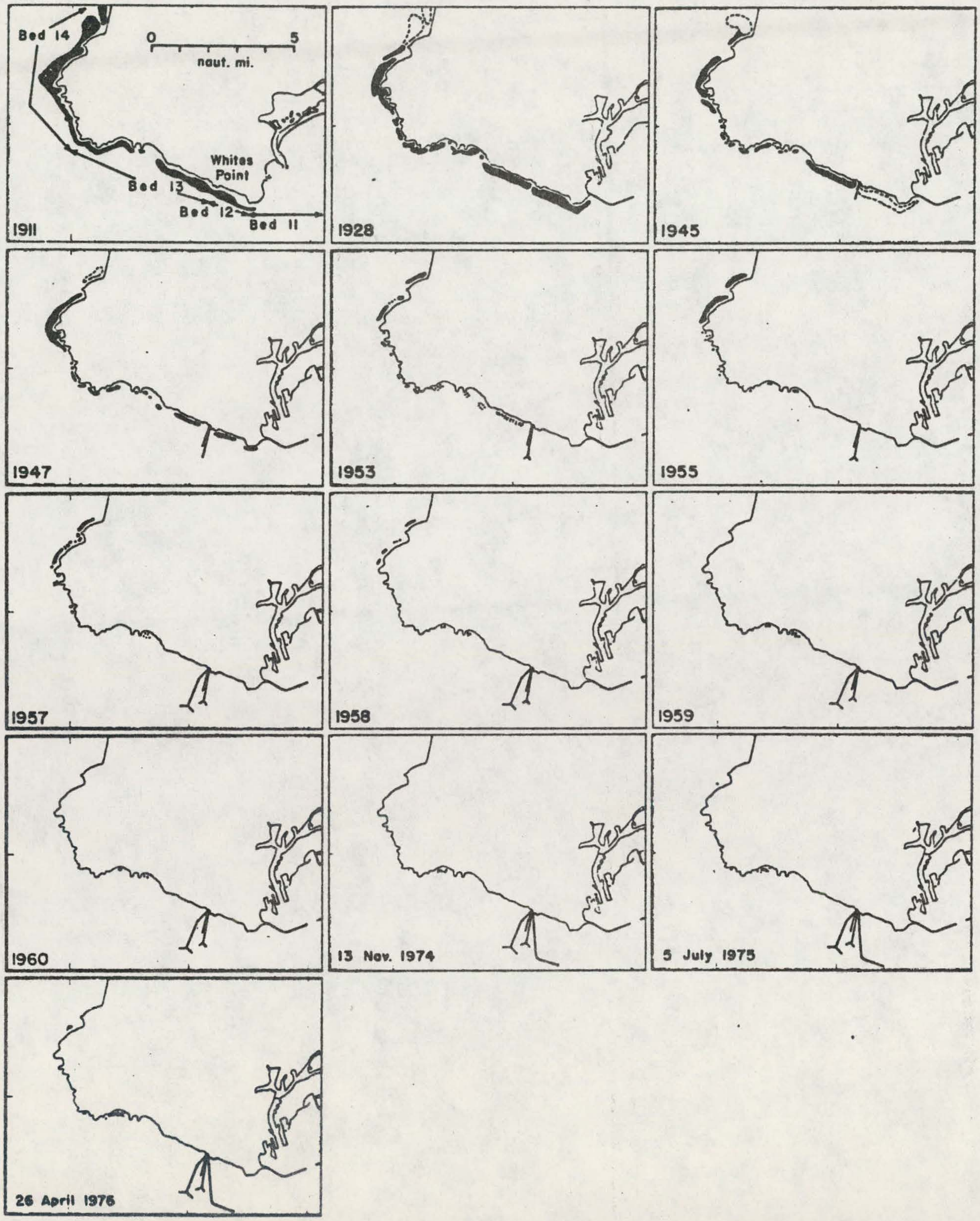

Figure 6. Historical charts illustrating the decline between 1928 and 1960 of Macrocystis beds bordering the Palos Verdes Peninsula. Kelp shown as black. Note succeeding installations of sewage outfalls at Whites Point. By 1974, restoration efforts had created several isolated Macrocystis colonies.

Kelp Harvesting

The University of California's Institute of Marine Resources conducted an extensive seven-year investigation into physiological and ecological effects attributable to kelp harvesting in southern California. No major effects, either adverse or beneficial, were reported (North and Hubb, 1968). Subsequently several studies added to knowledge in this field. ZoBell (1971) found that kelp harvesting, as practiced in southern California, did not contribute significantly to drift seaweeds stranded on beaches. Parker (1971b) reported that removal of the frond apex was followed by an increased rate of downward translocation. Lobban (1976, 1978b) obtained supporting results by showing that upward translocation was absent among fronds lacking the apical meristem. Thus upward translocation presumably ceases among cut fronds after harvesting so that photosynthate is not indefinitely wasted by exuding from the severed seive tubes. Lobban (1976) estimated that upward translocation would terminate within one or two days after cutting. Miller and Geibel (1973) reported that hapteral development in Macrocystis holdfasts was reduced after canopies were artificially removed. These results, however, may not be applicable to plants that are harvested commercially because of severe conditions imposed by their experiments (Barilotti et al., In Press). Rosenthal et al. (1974) found an unexpectedly high number of dislodged plants (i.e. 3 dislodged out of 14 tagged) in a flat-bottom study area off Del Mar after the bed had been cut by a commercial harvesting vessel. This may have been a somewhat localized situation because no such effect was observed by the author from surveillance following a harvesting operation in a test plot at La Jolla where the bottom was irregular.

From time to time, there is concern that kelp harvesting might adversely impact fishes, either by removal of food (i.e. kelp tissues and encrusting organisms), or of shelter, or that disturbance by the cutting operation might frighten fishes away. These questions were separately addressed by Limbaugh (1955), Davies (1968), and Quast (1968e). All three investigators concluded that commercial harvesting was not producing any detectable influences among fishes in the Macrocystis beds of southern California.

Miscellaneous Factors

Because Macrocystis appears sensitive to warmer summer surface water temperatures, possibilities might exist for adverse effects on kelp beds from heated effluents such as those discharged from electrical generating stations utilizing seawater in once-through cooling systems. Such systems can raise temperatures of very significant volumes of water by 10°C or more. Direct and continued exposure to seawater 10°C above ambient during summer would unquestionably be damaging to Macrocystis and to many other species in kelp beds. Fortunately a combination of factors can reduce this potential stress to rather minor proportions. The natural processes of dilution, dispersion, and loss of heat to the atmosphere generally prevent expansion of the higher isotherms surrounding a heated water discharge, across more than a few hectares of the sea surface (North and Adams, 1969). Dispersion and dilution can be enhanced by diffuser systems. Heated plumes can be discharged so they are confined to near-surface waters, avoiding contact with lower portions of adult Macrocystis and with juvenile plants. The discharge locus can be kept well away from kelp beds by attention to power plant siting and by use of long outfalls or conduits to convey heated effluents to suitable locations for discharge. Two power plants in southern California at Encina and San Onofre discharge heated effluents within one to two km from Macrocystis beds. Neither discharge appears to have affected the closest kelp stands in any permanent way.

K.A. Clendenning reported adverse effects on photosynthesis by Macrocystis after exposure to various dilutions in seawater of petroleum fuels and oil refinery wastes (cf State Water Quality Control Board, 1964). It was somewhat surprising, therefore, that relatively little damage appeared among canopy blades during studies of two oil spills in kelp beds (Jones et al., 1969; North, Neushul, and Clendenning, 1964). In both cases, oil was easily removed from coated blade surfaces by mild agitation. Possibly the outer mucus layer prevents direct contact between oil and the underlying cells. The author has repeatedly noted completely healthy Macrocystis canopies off Coal Oil Point near Santa Barbara, where natural oil seeps continually discharge substantial quantities of crude oil among kelp plants.

Sedimentation on rocky surfaces or onto Macrocystis pyrifera blades can affect kelp adversely (Rosenthal et al., 1974). Light sedimentary deposits on glass slides killed gametophytes in kelp cultures. Embryonic sporophytes seemed slightly more resistant to such deposits. We have noted that holdfast burial from shifting sand caused damage to young plants at several locations studied in San Diego County. The primary stipes deteriorated after sand packed in around them. In the Santa Barbara regions, however, Macrocystis angustifolia, Northern Hemisphere Phase, seems to tolerate sedimentary deposits. Jetty construction, in one instance, may have altered longshore sediment movements with adverse effects on a bed of M. pyrifera immediately downcurrent. Early charts clearly depicted a dense bed of Macrocystis extending south from the Mission Bay entrance channel (Figure 5). Much of this kelp disappeared after jetties were constructed out from the channel margins. Macrocystis in this region requires rocky substrate for attachment because of wave exposure conditions. Diving surveys just south of the Mission Bay jetties reveal few rocky outcrops. Most of the bottom is now sand and mud. Possibly sediment transport has been diverted seaward by the jetties, causing burial of any low-lying rocks that formerly may have been exposed and supported kelp growth.

KELP CULTURING AND RESTORATION

Combined effects from adverse natural and human-induced factors led to significant deterioration among some kelp beds in southern California during the 1940s and 50s (examples are seen in Figures 5 and 6). Need arose for techniques to halt the recessionary trends and restore at least some of the more valuable *Macrocystis* stands. Funds for research were made available by government, industry, and private organizations. A number of useful discoveries and methods resulted. These have been described at length in various publications (Wilson, Haaker, and Hanan, 1977; North, 1976; Annual Reports of the Kelp Habitat Improvement Project, 1965 to 1975). We will here outline briefly the major successful methods and some of the accomplishments. Methods are conveniently divided into two categories: A. Predator and competitor control, B. Transplanting and culturing.

Control of Predators and Competitors

Sea urchins, as we noted above, caused extensive damage to many *Macrocystis* populations and to associated vegetation. Control of these animals involved reducing densities of *S. franciscanus* to less than one per m^2 and numbers of other urchin species to less than ten per m^2. Where urchins were dispersed, the most effective control technique employed divers who crushed the urchins with hammers. When urchins were concentrated in bands or "fronts" along the margin of kelp beds, destruction with the toxic chemical quicklime (calcium oxide) was possible (Leighton *et al.*, 1965; Inst. Mar. Res., 1963). Quicklime was purchased as lumps 2 to 3 cm in diameter. Lumps were broadcast in the wake of a slowly-moving vessel. The lime quickly settled to the bottom. Contact between quicklime and an urchin caused a severe burn that almost always destroyed the animal. The chemical must be used with discrimination, however, because it affects many other slowly-moving soft-bodied animals such as sea stars, certain mollusks, annelids, etc. Rapidly moving fishes, crustaceans, and the like apparently avoid the lumps with no difficulty. Wilson *et al*. (l.c.) described a diver-held device for dispersing quicklime directly onto groups of urchins. A program of urchin control was initiated off southern Point Loma in 1963. The efforts successfully caused restoration of the southern 2/3 of the *Macrocystis* bed there during the next five years (see Figure 5).

Isolated plants or small groups of *Macrocystis* may succumb to grazing of blade tissues by schools of herbivorous fishes such as Opaleye (*Girella nigricans*) and Halfmoon (*Medialuna californiensis*). Grazing by these fishes has frequently been a serious problem when a relatively small amount of *Macrocystis* biomass is transplanted to an area where the species is absent. Gillnetting the fish populations offers a partial remedy but many harmless but closely associating species may be destroyed in the process. Alternatively, plant productivity may be raised by expanding the transplanting effort till productivity by the plant biomass substantially exceeds demand by grazers. Considerable numbers of transplants may be needed. Thus a transplanting project restored a *Macrocystis* bed to Abalone Cove on the Palos Verdes Peninsula through the combined efforts of Department of Fish and Game personnel and staff of the

California Institute of Technology. More than 4000 plants were introduced during a five-year period before plant productivity stabilized and the bed began expanding without further assistance. Fishes tend to depart from kelp areas where Sea Lions (*Zalophus californianus*) are common. We anchored small rafts in our kelp bed at Abalone Cove to encourage presence of Sea Lions (the rafts were used as haul-out areas by the mammals). Problems from grazing fishes diminished greatly whenever Sea Lions were seen resting on the rafts. Combined transplanting and predator control efforts in recent times have succeeded in reestablishing *Macrocystis* at other sites along the Palos Verdes Peninsula (Figure 6).

Juvenile *Macrocystis* can be shaded out by dense stands of several seaweed species that form canopies one or two meters off the bottom. Furthermore, the lateral oscillatory movements imparted by wave surge to algae having tough blades with sharp edges (e.g. *Laminaria farlowii*) can slice through the relatively delicate stipes and blades of juvenile *Macrocystis* developing nearby (McPeak, personal communication). Thus competitive seaweeds must usually be removed by divers from areas of several square meters before small *Macrocystis* can develop and survive. If there are no adult Giant Kelp plants in the vicinity to provide spores for "seeding" a cleared area, either juvenile or adult *Macrocystis* must be introduced. The likelihood of obtaining juvenile *Macrocystis* from sporulation by a nearby adult decreases rapidly with distance from a plant. Thus an isolated adult plant yielded juveniles only for a distance of 5 m away (Anderson and North, 1966). Juvenile recruitment decreases markedly 100 m away from even a large kelp bed. McPeak et al. (1973) described a method for using the stubs and holdfasts remaining after competitive weeds are cleared, as substrate for fastening juvenile Macrocystis transplants to the bottom. McPeak and his associates transplanted approximately 30,000 juvenile Macrocystis plants to the northern portion of the La Jolla Kelp Bed from 1973 to 1976 (McPeak, 1975, and personal communication). Macrocystis disappeared from this region during the warm water years of 1957 to 1959 (Figure 7). Competitive weeds dominated the bottom thereafter until removal by McPeak and associates in their experimental areas.

Transplanting and Culturing Macrocystis

We have noted above that the primary purpose of the Macrocystis holdfast is anchoring the plant. Nutrients are absorbed across all exposed surfaces, not just the holdfast. Consequently it is only necessary to restore the mooring function of the holdfast when transplanting (North, 1964b). If there is no movement between substrate and the haptera, transplanted holdfasts will reattach in about two weeks (if there is movement, haptera will not attach). The holdfast must be tied or otherwise fastened very securely to the proposed substrate to eliminate movement caused by wave surge. Substantial labor is involved in fastening large holdfasts so that no movement occurs. In most cases, the effort is not worth the results. It is much simpler to fasten large holdfasts loosely to a

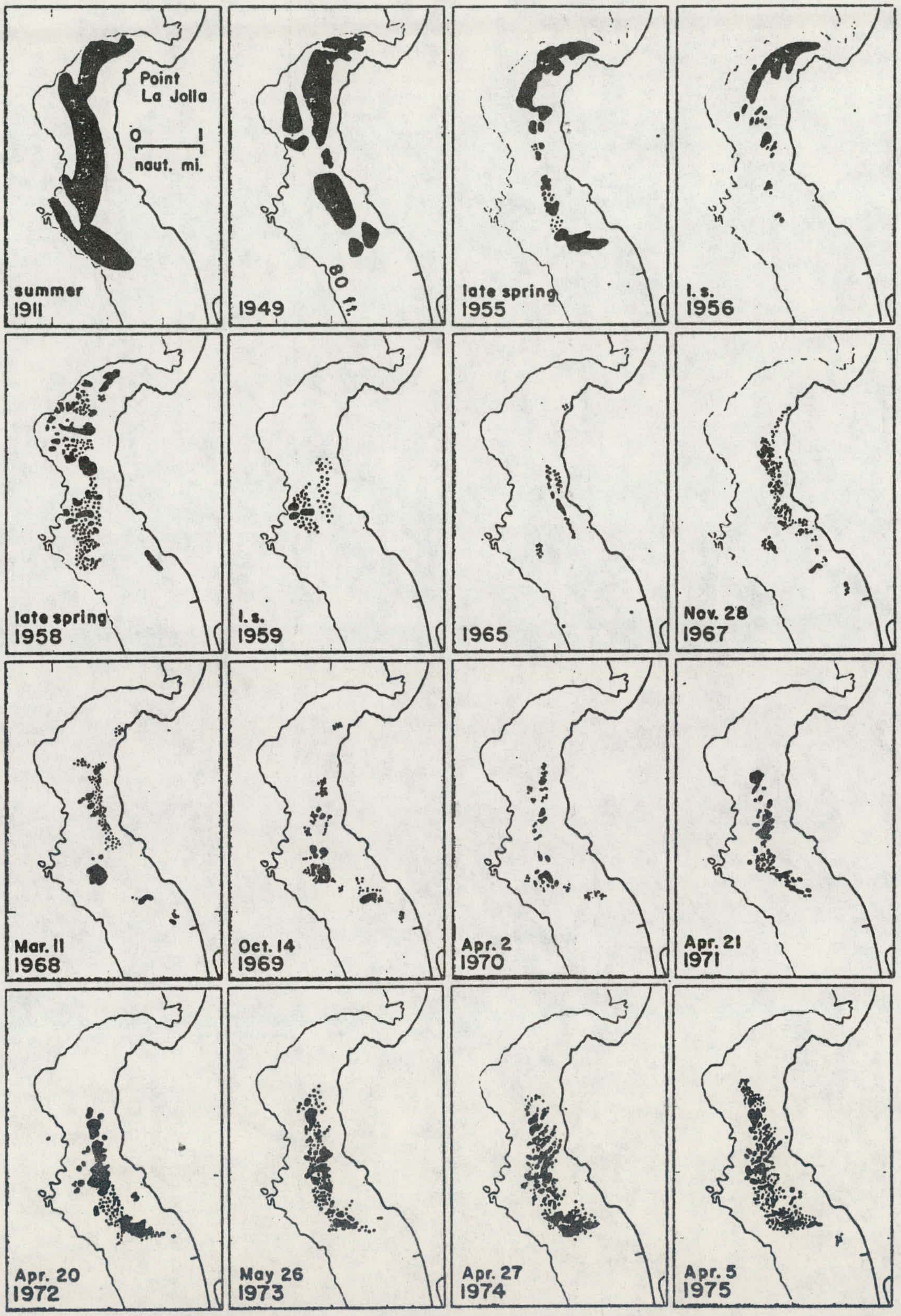

Figure 7. Historical charts illustrating changes in the La Jolla Kelp Bed. Kelp shown as black. Restoration work was initiated here in 1964. Staff of Kelco Co. introduced about 30,000 small transplants here from 1973 to 1976 at the north end of the bed. Expansion at the north end became manifest in 1975.

small buoy which in turn may be moored to the bottom by a tether 50 to 100 cm long. Whether the holdfast ever attaches to the buoy is of no consequence. The buoy keeps the holdfast off the bottom, preventing erosion of the haptera by grinding against rocks during movement caused by wave surge. Small holdfasts can be easily fastened to solid projections on the bottom by rubber bands wound around the haptera and the projection. The rubber band should not contact the primary stipe, however, because stipe tissues deteriorate when tightly covered by inert material.

Alternatively, plants may be cultured on moveable substrates in the laboratory and then transplanted into the field. We have used nylon lines and PVC rings (cut by slicing PVC pipe of 2.5 cm diameter) as culturing substrates for material destined to be transplanted into the field. Young plants 10 to 100 cm tall can be collected in the field and moved to critical areas where restoration work is underway.

Care must be taken when moving transplants to avoid desiccation. Small plants can be kept in seawater in containers rather easily but such water must not be allowed to become warm. Adult plants can either be towed while in the water or hoisted aboard, covered with damp sacks, and sprayed frequently with cool saltwater. Towing becomes difficult for distances greater than a few km because plants tear loose at towing speeds greater than about 1.5 km/hr. Methods for preparing and transplanting adult <u>Macrocystis</u> were described in detail by North (1968b). In brief, stout nylon line is first threaded through the attached holdfast using a large steel needle (Figure 8A). The holdfast is then gently separated from the bottom with a knife or tire iron. A number of transplants may be fastened at one time to a single towing chain (Figure 8B). The chain with its attached transplants is then moved by surface vessel to the new site. A vessel with a 150 hp engine can tow about 50 plants successfully.

Techniques for culturing Macrocystis gametophytes were described by Delf and Levyns (1926), (Cole, 1968) Papenfuss (1942). No unusual procedures were involved and the methods described for almost any of the Laminariales appear to work well with Macrocystis. Kelp spores attach easily to any solid surface that is not toxic. We have successfully produced gametophyte cultures on substrates of glass, paper, wood, nylon, PVC, and plexiglass, as well as on particles of lead and iron.

Gametophytes held in nutrient-deficient water in static cultures may require two or more months to produce gametes or they may become filamentous and never reproduce. Maturation time can be reduced to 10 to 14 days under continuous illumination by maintaining cultures in running seawater. Presumably supplies of critical nutrients become more available in running water. Spores, however, attach poorly when there is much movement between water and the substrate. Thus it is best to provide quiet water during spore settling, then transfer

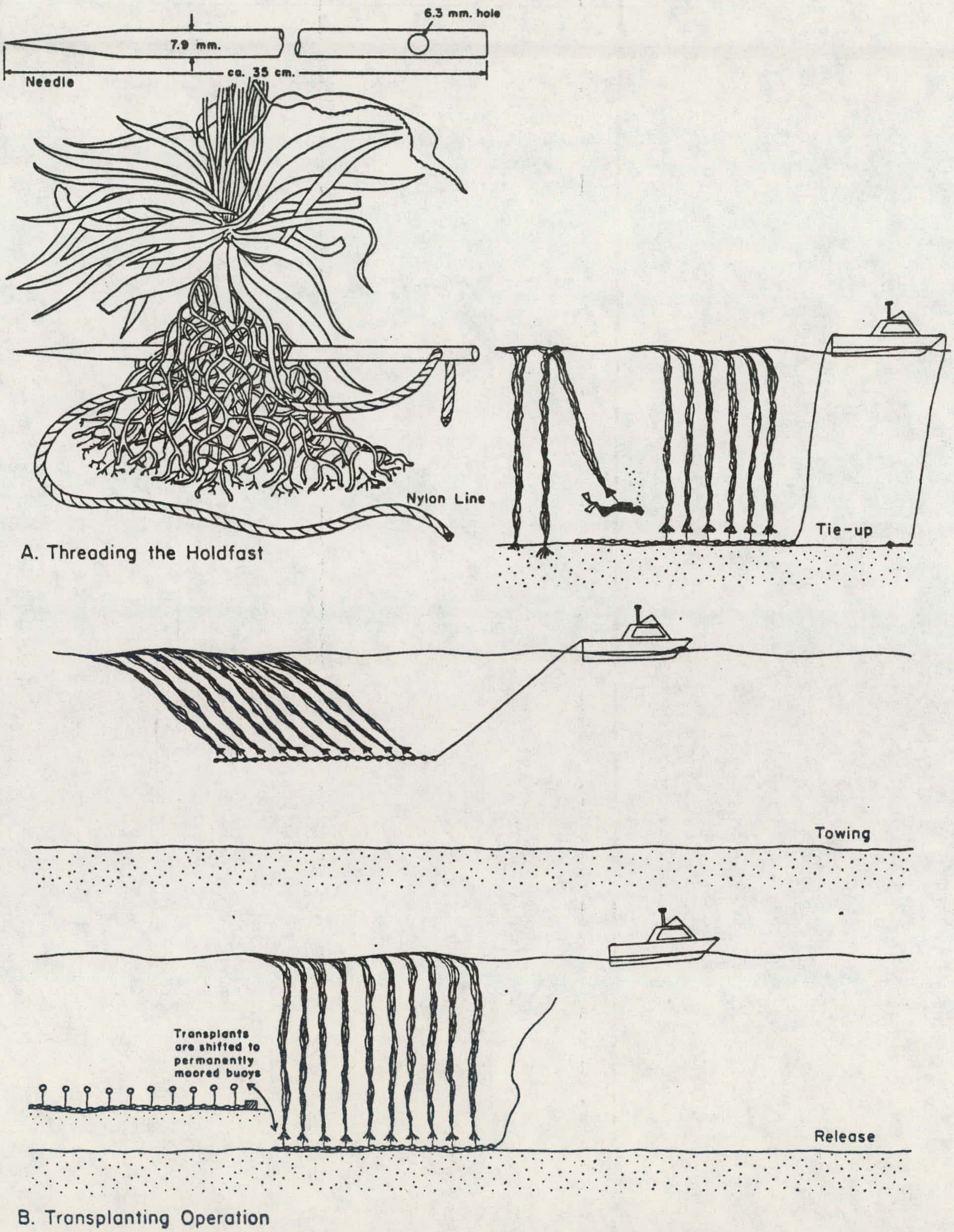

Figure 8. Technique for transplanting adult Macrocystis.

A. Details of kelp needle and its use to thread holdfast with nylon rope.

B. Operation involving tieup, towing, release, and transferring plants to permanent moorings.

the resulting gametophytes several days later to running water. Gentle flows of 5 to 20 cm/sec across the culturing substrate provide for good nutrient exchange between the water and gametophytes. More rapid flows can dislodge and remove many of the attached cells.

Gametophyte cultures often suffer from competitors such as diatoms. A few mg of germanium dioxide per liter of medium inhibits diatom development without affecting gametophytes (Lewin, 1966). Periodic spraying of gametophyte cultures with seawater from a nozzle tends to remove competitors but some gametophytes will also be sacrificed (J. Devinny and J. Leventhal, personal communication).

Newly-formed Macrocystis sporophytes in our cultures typically display sticky external surfaces. When scraped from their native substrates, they are quickly able to reattach and develop normally (North, 1969). This capability suggested that embryonic sporophytes might be dispersed in the sea to introduce Macrocystis to new areas or to aid juvenile recruitment processes in deteriorating kelp beds. Loss rates from sporophytes settling on unfavorable substrates would undoubtedly be high in such an operation. It would thus be necessary to disperse large numbers of tiny sporophytes to ensure success. The concept has been tested by a number of experiments conducted by staff of the California Institute of Technology.

A culturing facility was constructed and operated that produced large numbers of embryonic sporophytes on a weekly basis (North, 1976). In brief, spores were allowed to attach to 0.5 X 8 m strips of polyethylene film in an aquarium (Figure 9). After a few days, the film strips were transferred to running seawater in an inclined tray. Embryonic sporophytes usually appeared one to two weeks later. The sporophytes were either scraped off in the laboratory and dispersed near the ocean bottom through a garden hose or they were scraped off by divers underwater at the experimental site.

Appearance of juvenile Macrocystis plants occurred several months after most of our dispersal operations but numbers of survivors were quite variable. Some experiments were very successful, others were disappointing. Turbid environments where fine sediments accumulated on the rocky surfaces during calm periods appeared to be quite unfavorable for the embryonic sporophytes. It was usually not possible to determine whether a given juvenile plant arose in situ from natural processes or resulted from one of our dispersal operations. In one experimental series, we dispersed embryos cultured from spores derived from a strain of Macrocystis that grows in Bahia Tortugas, Mexico and was morphologically easily distinguished from the variety populating the dispersal site (San Mateo Point in southern California). Large numbers of juveniles of both varieties subsequently appeared at the dispersal site for several months. This experiment clearly demonstrated feasibility of dispersing embryonic sporophytes.

Six major dispersal experiments were undertaken with positive results at Abalone Cove, Whites Point, Newport Harbor,

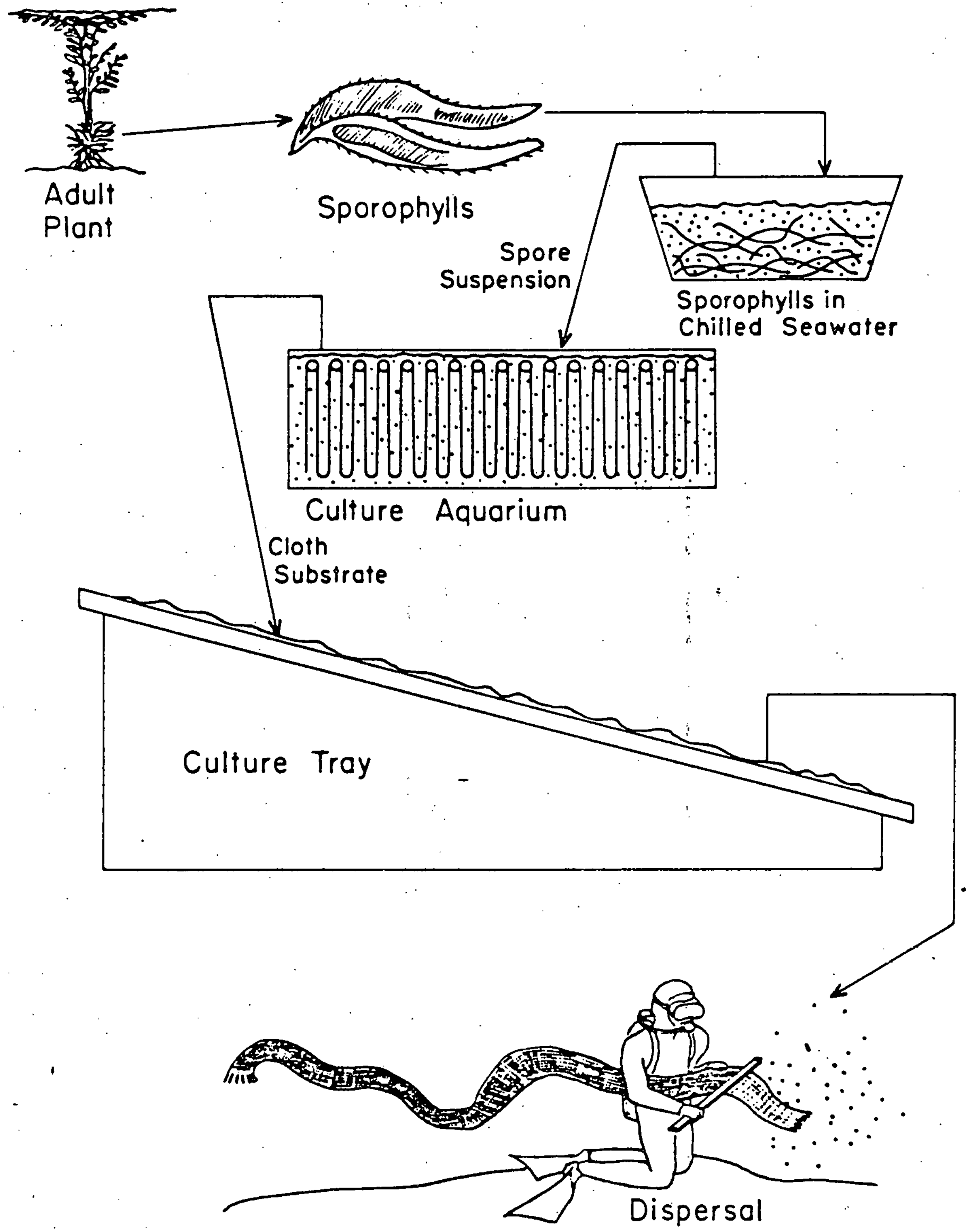

Figure 9. System for mass culturing Macrocystis gametophytes and for dispersing the resulting embryonic sporophytes on the sea floor.

Cameo Shores, Dana Point, and San Mateo Point. Smaller scale operations at North La Jolla and Imperial Beach produced a few juvenile plants but resulted in no permanent development of kelp. After we ceased dispersing embryonic sporophytes, varying degrees of regression occurred at Whites Point, Newport Harbor, Cameo Shores, and Dana Point. We concluded that embryonic sporophytes must be dispersed continuously and intensively for periods of a year or more in the more difficult situations before significant success can be achieved. The mass culturing technique requires skill to operate and the equipment is costly. Consequently the method has not been adopted by either the harvesting industry or by governmental management agencies in California for their kelp restoration activites.

Costs of kelp bed restoration work are related closely to the field efforts involved. A summary of labor and equipment requirements provides a useful basis for estimating costs. A diver can collect and transplant from 50 to 200 juvenile plants per day, depending on the ease with which the young plants can be collected as well as the depths and sea conditions accompanying the operation. Similar comparisons for adult kelp plants give a range of from 2 to 10 plants per diver per day. As noted above, transplantations of hundreds to thousands of adult plants may be needed for very difficult sites to establish Macrocystis populations. Numbers of juveniles required may be greater by an order of magnitude. In addition to labor costs, kelp transplanting programs must budget for diving equipment, suitable boats, adequate shore-based facilities, and maintenance costs.

A single diver can destroy between 500 and 2000 urchins per day by hammering. One individual can set, retrieve, and clean between 3 and 10 gill nets 20 m long, per day in kelp areas where grazing by fishes is a problem.

Culturing activities (including production of mass cultures) require the full attention of two individuals about one day per week and the half-time attention of one individual for the remaining time, including weekends. Necessary major equipment for culturing includes a high-quality microscope, aquaria, refrigeration and air conditioning during warm weather, salt water system and trays, adequate lighting, sterilizing apparatus, as well as minor items such as glassware and chemicals. An appropriate laboratory or other housing is mandatory. Culturing also necessitates occasional diving support for collecting sporophylls when cultures are started and when the products of culturing are returned to the sea.

These considerations show that kelp restoration programs entail substantial expense, particularly when large areas of sea floor are involved. It is usually cheaper to maintain a surveillance program that monitors condition of the resource adequately so that corrective action can be taken during the early phases of problems such as intrusions by urchins or competitive seaweeds. Nonetheless it is comforting that aquacultural technology is now tested and available for managing kelp beds in support of harvesting and fishing industries that may depend on the productivity of this very useful seaweed.

MACROCYSTIS BIOMASS AS AN ENERGY SOURCE

Two scientists in the late 1960s, Edward Hall and Howard Wilcox, independently concluded that a great need would arise during the next several decades for tremendous quantities of plant biomass to serve as an alternative energy source. Much of the terrestrial arable land has been committed to agricultural food production. Wilcox and Hall envisioned using the huge expanse of the ocean for capturing solar energy by growing seaweeds. Other advantages of the ocean included abundances of plant nutrients in the depths and environmental energy in waves and currents near the surface. An investigation known as the Marine Farm Project arose from these concepts. The Project is currently managed by General Electric Co. under funding by the Gas Research Institute and the U.S. Department of Energy (DOE). Participating organizations include: Global Marine Development, Inc. (engineering), U.S. Department of Agriculture (kelp processing), and the Institute of Gas Technology (methane production from kelp). The California Institute of Technology is involved in related kelp production studies under separate DOE funding. Macrocystis is presently receiving primary attention as the test crop, but other seaweed species might also be utilized if the concept can be shown to be technically and economically feasible. DOE-funded studies of growth of other aquatic plants and methane production therefrom are under investigation at Woods Hole Oceanographic Institution, University of California Berkeley, and Dynatech R. & D. Corp.

The initial kelp production studies were conducted in close association with the U.S. Navy. We measured growth rates and other physiological parameters among *Macrocystis* transplants moored to artificial structures located two or more km from shore (i.e. approximating an oceanic environment). The transplants grew quite slowly and displayed low nitrogen contents (North, In Press, B). Similar results were obtained among plants occurring naturally around certain offshore islands. Concentrations of nutrients such as nitrate, ammonium, and phosphate were typically very low in the top 10 to 20 m of these oceanic waters (i.e. at depths where our experimental plants were situated). We concluded that kelp growth would usually be severely limited by lack of nutrients in oceanic surface layers. Some kind of fertilizing operation seemed necessary on an oceanic farm.

Use of artificial fertilizers appeared impractical because of economic and technical reasons. The most promising approach has been employment of nutrient-rich seawater raised from 200 m or deeper. We conducted many experiments assessing growth by both juvenile and adult *Macrocystis* plants held in water pumped up from depths of 300 m. Kelp has grown extremely well in this deep water, although substantial fluctuations in growth rates occur. Thus mean specific growth rates from groups of two to nine juvenile plants held in non-enriched 300 m water ranged from 7.5 to 18.4 percent daily gains in wet weight (Figure 10). These data represented 48 separate experiments, each lasting about a week, extending from August 1, 1977, to September 10, 1978. Unenriched 300 m water always supported more rapid growth when compared to surface water enriched with nitrate and phosphate (North, In Press, C). Presumably surface water was deficient in elements other than N and P.

Some of these observed variations in the mean growth rates of Figure 10 were undoubtedly influenced by plant-to-plant differences because relatively few specimens were used per experiment. Variations in concentrations of micronutrients also played a role. Thus from time to time, enriching deep water with manganese or iron or both proved stimulatory. Periods when supplementation with Mn caused stimulation coincided with instances when Mn concentrations were below detection limits in the 300 m water (North, In Press, C). No stimulation, or even mild inhibition, occurred when this element was added to deep water whose Mn concentrations were above one nM.

The vertical distribution of Mn in the ocean is somewhat unusual because surface waters may yield higher concentrations than deep waters (Bender _et al_., 1977). Hence appropriate mixtures of surface and deep water might yield a better growth medium than either administered separately. Such was the case

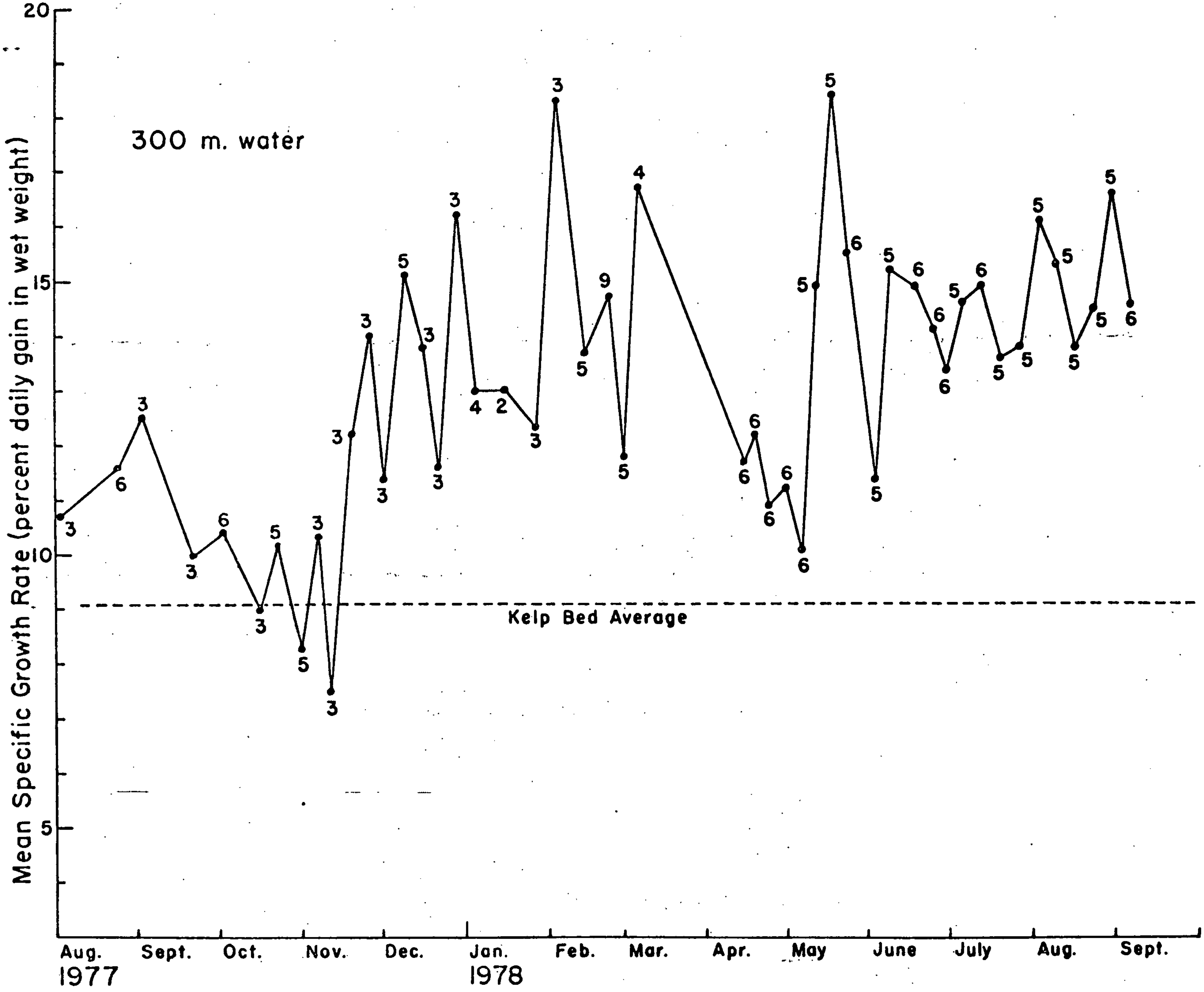

Figure 10. Fluctuations in mean specific growth rates derived from groups of juvenile *Macrocystis* sporophytes held in 40 liters of unenriched seawater from 300 m deep, under batch culturing conditions.

in an experimental series employing flowing sources of surface and 870 m Atlantic Ocean water at St. Croix, U.S. Virgin Islands. An equal parts mixture of the two waters yielded the highest growth rate (Table 5). Mn was present in the surface water but was undetectable in the 870 m source (Table 6). Thus an optimal fertilizing strategy appears to involve both surface and deep water.

The Marine Farm Project is presently assessing harvest yields obtainable from adult plants fertilized by water pumped from depths of about 450 m. Yields from coastal kelp beds (i.e. a mean value of ca. 1.1 metric tons/ha/yr) are probably less than the true potential because such stands are almost certainly nutrient-limited for significant periods each year. Economic assessments of open ocean farms to date have lacked yield data for kelp beds supplied with adequate nutrients. General Electric Co. and associates on September 14, 1978, deployed an experimental structure designed to support adult Macrocystis transplants, fertilize them continuously with deep water, allowing periodic cutting for estimating yields. Responsibility for supplying kelp transplants to the test farm structure and monitoring biological aspects of the experiment has been given to staff of the California Institute of Technology.

The test farm structure consists in part of a central spar buoy (2.7 m diameter) containing the diesel-powered upwelling pumps, other machinery, and instrumentation (Figure 11). This machinery buoy supports a radiating, hexagonally-arranged,

Table 5

Specific growth rates (percent daily gain in wet weight) shown by juvenile <u>Macrocystis</u> sporophytes held in flowing systems either of seawater artificially upwelled from 870 m deep, or in mixtures of deep and surface water, or in pure surface water. Experiment conducted at the St. Croix facility of the University of Texas from September 5 to 9, 1976. Modified from North (1977c). Flow rates: 100% deep = 18 l/min, rest 3 l/min.

Plant No.	Composition of Medium		Wet Weight, Gms		Specific Growth Rate Percent/Day	
	% surface	% deep	Init.	Final	Indiv.	Mean
21	0	100	0.413	0.919	16.0	15.1
22	"	"	0.480	1.040	15.4	
23	"	"	0.720	1.445	14.0	
24	50	50	1.047	2.754	19.3	19.3
25	"	"	0.333	0.884	19.5	
8	"	"	1.721	4.505	19.2	
26	90	10	0.489	0.625	4.5*	17.5*
27	"	"	0.634	1.597	18.5	
7	"	"	2.495	5.680	16.5	
28	95	5	0.585	1.112	12.9	12.2
29	"	"	0.781	1.369	11.2	
10	"	"	2.532	4.723	12.6	
30	100	0	0.954	1.523	9.4	9.5
31	"	"	1.608	2.345	7.5	
9	"	"	4.406	7.929	11.7	

*Plant No. 26 identified later as <u>Eisenia</u> and ignored for computing mean

Table 6

Concentrations of five trace metals assayed by atomic absorption spectroscopy by Sylvia Garcia (Calif. Inst. Tech.) on samples of seawater collected August 19, 1978, in the vicinity of the artificial upwelling station of the University of Texas at St. Croix, U.S. Virgin Islands. Surface water taken approximately 30 m from shore. Deep water sampled from a PVC valve at the pumphouse. ND = Not Detected (less than 1 ng-at/l for Co and Mn). Samples collected in ultra-clean Teflon containers.

Source Depth m	Concentration ng-at/l				
	Co	Cu	Fe	Zn	Mn
0.5	ND	11	12	17	7
870	ND	8	13	18	ND

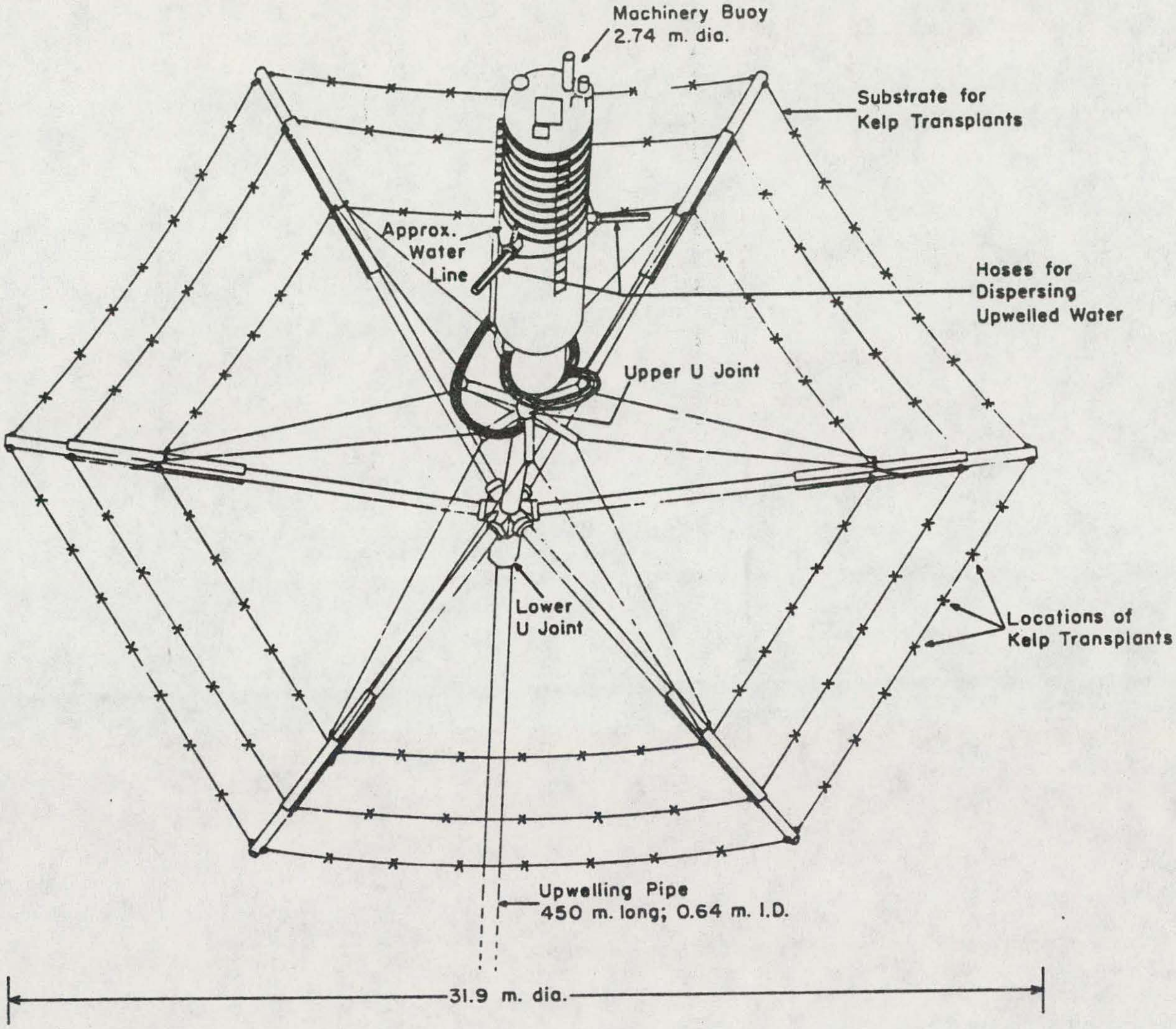

Figure 11. Diagram of the test farm structure used for supporting 100 adult Macrocystis transplants and fertilizing them with water artificially upwelled from depths of about 450 m.

set of arms that spread out at a depth of about 15 m. Cables are positioned circumferentially near the outer ends of the arms to serve as substrate for the 100 Macrocystis transplants used in the experiment. A 64 cm ID polyethylene pipe lies below the radiating arms and supplies water from about 450 m depth at a flow of about 30,000 l/min. The study was only in the initial phases of operation as of this writing, so we are not yet able to comment on results.

POSSIBILITIES FOR FERTILIZING MACROCYSTIS BEDS

Kelco Company, a San Diego-based kelp harvesting and processing firm, and staff of the California Institute of Technology have undertaken a cooperative study examining fertilizing effects from dispersing compounds of nitrogen and phosphorus among Macrocystis canopies. The project has involved a combination of theoretical, laboratory, and field studies. Research is incomplete at this time and conclusions are tentative. We wish merely to describe current status of the project.

Objective of the theoretical work was to develop a fertilizing strategy involving a reasonable likelihood of success. The studies involved modeling events following releases of nutrient compounds such as nitrate and ammonium under a variety of circumstances. Sometimes critical factual information was lacking. Laboratory and field studies were conducted to supply the necessary data. For example, several dye release experiments were performed to determine flow patterns and residence times of water within and near kelp beds. The theoretical studies indicated that water exchange between the interior and exterior of large kelp beds was sufficiently slow to permit capture of the major portions of rapidly-accumulated nutrients such as ammonium when these are released centrally within dense kelp beds. Fates of nutrients introduced to small kelp beds was uncertain. The material might be captured or it, might escape, depending on the rapidity with which water was exchanged with the surrounding ocean. Water within canopy interstices appears to exchange much more slowly than water lying in open channels penetrating into kelp beds.

Two fertilizing experiments were undertaken, timed to occur during periods when upwelling was minimal. Presumably effects from the fertilizing would be distinguished most easily at such times. The first experiment involved fertilizer dispersals lasting from October 3 to November 23, 1977, and from December 29, 1977, through January 12, 1978, at Point Loma (McPeak, 1978). Kelco personnel dispersed a total of about 3320 kg of nitrogen-and-phosphorus-containing compounds during these two periods. The fertilizer was a commercial pelletized and encapsulated form called Osmocote (Sierra Chemical Co., Milpitas, California) allowing steady slow diffusion. Each week about 140 kg of pellets were placed in three plastic cannisters moored in a triangular pattern, 30 m apart, centrally within the Point Loma Kelp Bed (one of California's largest beds).

The cannisters remained about 3 m below the surface as they dispersed their charges of ammonium, nitrate, and phosphate. Six parameters were monitored at the dispersal site and at a control station about two km northward (canopy coverage in aerial photos, N-contents of fronds, dissolved nitrate and phosphate, elongation rates of juvenile and of adult fronds). Most of the parameters failed to provide consistent indications of effects from the fertilizer dispersal. Elongation rates, for example, increased during the early phases of fertilizing but declined after a week of strong ground swells caused substantial damage to the bed. We continued monitoring the bed by aerial photography during months following the experiment because of massive canopy development extending for about one km immediately north of the dispersal site. This development began during the fertilizing operation and persisted until May 1978, in spite of repeated harvestings. No such striking flourishing of canopies occurred among adjacent areas in other directions from the dispersal site. Consequently one would need to postulate that currents moved most of the fertilizer northward, if the observed pattern of development was related to the dispersal operation. Unfortunately, current measurements were not conducted during this experiment. Furthermore, our dye dispersal studies had monitored only movements of near-surface water, perhaps not reflecting accurately any flows occurring beneath the usual canopy depths.

We performed a second fertilizing experiment from January 24 to February 7, 1978, to determine whether significant fluorishing by a kelp canopy would again develop in conjunction with such a dispersal operation. The second study was conducted at a small Macrocystis bed off Crystal Cove, California. Because of the reduced size of the bed, we attempted to introduce the fertilizer directly into the slowly-exchanging interstitial waters of the canopy, to minimize losses of the nutrients. We accordingly sprayed concentrated solutions of ammonium sulfate across the canopies from a moving vessel. About 910 kg of ammonium sulfate were dispersed during ten operating days. Aerial photos were taken before, during, and after the study and fronds were collected and N-contents analyzed from the experimental site and from a control bed at Laguna Beach, about 6 km southeasterly. During early phases, the fertilizing vessel was easily able to maneuver throughout the bed, passing along the channels lying between the sparsely-distributed patches of canopy. Two weeks later, it was necessary to spray the fertilizing solution primarily from the periphery of the bed because the channels were obliterated by dense canopy development. These observations by the vessel operators were confirmed by our aerial photographs which indicated very significant appearances of surface fronds similar to our observations off Point Loma. Fronds were sampled February 16, 1978, for chemical analysis. They yielded N-contents ranging from 3.1 to 4.8 percent of the dry weight for the experimental site and 2.1 to 2.6 percent N for the control station. Values for the experimental frond were the highest ever measured by our staff during four years of investigating nitrogen metabolism in Macrocystis. It appears very likely that spraying fertilizer solutions directly onto kelp canopies was considerably more efficient than slow dispersal from cannisters beneath the canopy. We were unable to follow the subsequent canopy development at Crystal Cove as we had at Point Loma because storms almost obliterated the kelp population here during latter February and March.

In summary, our first two fertilizing studies indicated that Macrocystis is able to accumulate significant amounts of nitrogen from fertilizer dispersals and perhaps this stimulates canopy development. Spraying concentrated fertilizer solutions directly onto kelp canopies may be the most effective method of application because nutrients are thereby introduced directly into interstitial waters within the canopy. We wish to repeat our preliminary experiments, however, and as yet our data are insufficient to permit assessments of any economic benefits accruing from fertilizing operations.

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