Spatial distributions of major phytoplankton community components in Narragansett Bay at the peak of the winter-spring bloom

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ABSTRACT

The horizontal distribution of phytoplankton in western Narragansett Bay at the height of the 1978 winter-spring bloom was characterized using data from an airborne fluorosensor to extend *in situ* point measurements of chlorophyll *a* and phytoplankton population composition to linear or area coverage. At the same time, the performance of the remote fluorosensor was evaluated by a comparison of remote and *in situ* measurements of total chlorophyll *a* and phytoplankton population composition at coincident sample points. Three types of phytoplankton patchiness were observed; the winter-spring diatom bloom and two types of smaller features superimposed upon it. Distributions of the two major components of the phytoplankton, the diatoms and the flagellates, indicated a unique pattern of patchiness for each component. These patterns reflected differences in the effects of winds, tides, salinity, light and distribution of nutrients on the two components. Correlation between remote and water column measurements of the same or similar parameters was generally excellent, although remote measurements can presently only grossly characterize phytoplankton population composition. The combination of the remote fluorescence and selected *in situ* measurements was found to be a promising approach to the study of phytoplankton patchiness in estuarine and coastal shelf waters.

1. Introduction

The phytoplankton populations of Narragansett Bay, Rhode Island, have been intensively examined and characterized (e.g., Ferrara, 1953; Smayda, 1957; Pratt, 1959; and Mitchell-Innes, 1973), with particular attention having been paid to the characteristics of the winter-spring diatom bloom (e.g., Pratt, 1965; and Smayda, 1973). Bi-weekly variations in total chlorophyll *a* and nutrients have been measured

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at 13 stations in the bay over the period August 1972 to August 1973 by Nixon and Oviatt (unpublished data, summarized in Kremer and Nixon, 1978). However, these investigations have focused primarily on the temporal changes in the phytoplankton population. Spatial distributions have received much less attention, particularly the spatial distributions of the major components of the phytoplankton population.

During the last quarter-century, there has been increasing interest in the spatial heterogeneity or patchiness of phytoplankton, and the interactions of biological, chemical and physical processes which cause these distributions (Steele, 1978). Two indicators of this increasing interest have been the development of theoretical models (e.g., Kierstead and Slobodkin, 1953; Parsons *et al.*, 1967; and Wroblewski and O'Brien, 1976), and of instrumentation and measurement techniques designed to obtain quasi-synoptic, near sea-surface chlorophyll distributions which can be used as inputs to these models (e.g., Lorenzen, 1966; Clark *et al.*, 1970; and Mumola *et al.*, 1973). Of these methods, the remote laser fluorosensor approach initiated by Mumola *et al.* has the greatest potential for providing the type of data needed for studies of mesoscale and submesoscale phytoplankton patchiness in coastal shelf and estuarine waters. This aircraft-borne system utilizes narrow-band light from multiple dye lasers to excite algal photosynthetic pigments and measures the resultant fluorescence emitted from chlorophyll *a* in the region of 685 nm. The remote fluorescence data are then converted to chlorophyll *a* concentrations utilizing a combination of known algal fluorescence cross-sections and remote fluorescence to *in situ* chlorophyll *a* ratios. The primary advantages of this approach are its capabilities for near-synoptic data and variable data density, and its potential for resolution of 10 m to 100 km scale features. In addition, it has the capability to make a phytoplankton population composition measurement, i.e., the distribution of the phytoplankton species among four color groups (golden-brown, green,[4] blue-green, red), which cannot presently be made by any other type of remote sensor (Mumola *et al.*, 1973; Brown *et al.*, 1977). Although this system and technique had been rigorously tested in laboratory experiments (Brown *et al.*, 1977, 1981) and in field experiments utilizing fixed platforms, extensive flight data had not been obtained prior to the present investigation.

The aim of the present investigation was to characterize the horizontal distributions of phytoplankton in western Narragansett Bay at the height of the winter-spring bloom, utilizing the laser fluorosensor data to extend *in situ* point measurements of chlorophyll *a* and phytoplankton population composition to linear or area coverage, and to evaluate the performance of the laser fluorosensor, utilizing a com-

4. Members of the "green" color group are not limited to the chlorophytes, but include all species which lack both the carotenoid-chlorophyll-protein complexes which are characteristic of the members of the "golden-brown" color group, and the phycobilin pigments which are characteristic of the members of the "red" and "blue-green" color groups.

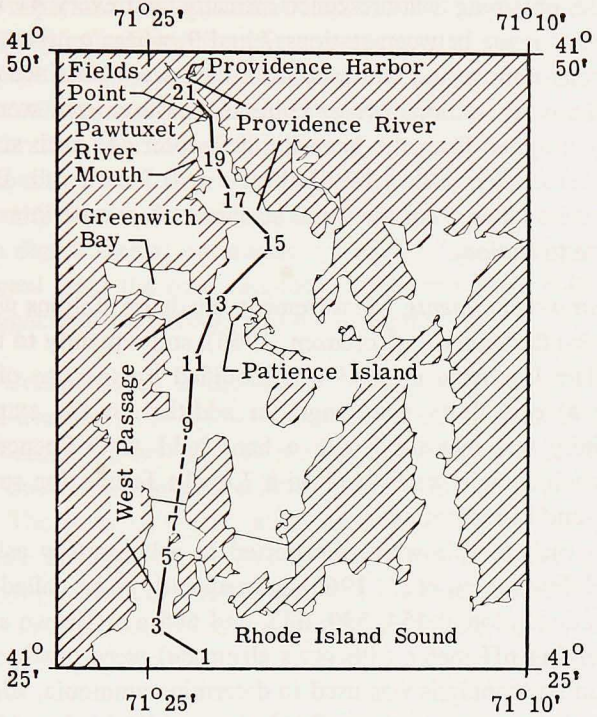

Figure 1. Location of the helicopter flight path and *in situ* sampling stations for the March 16, 1978 Narragansett Bay experiment. – – – indicates area where flight path was at right angles to line between stations.

parison of remote and *in situ* total chlorophyll *a* and phytoplankton population composition measurements at coincident sample points.

2. Materials and methods

The data presented in this paper were obtained on the morning of March 16, 1978, a few days after the winter-spring diatom bloom had reached its maximum. The temporal status of the bloom was determined by twice-weekly chlorophyll *a* measurements taken throughout the winter from a station at 41° 34′ 07″ N, 71° 23′ 31″ W (Smayda, unpublished data).

a. Sampling procedures. Both remote and water column data were obtained at and between 11 stations in western Narragansett Bay (Fig. 1). The helicopter-borne laser fluorosensor started at station 1 and flew up the bay, taking 20 sets (excitation at 454 and 539 nm) of remote fluorescence data at each station while hovering at an altitude of about 25 m. The intervening straight line distance was then flown at

the same altitude, obtaining a fluorescence measurement every 41 m. An exception to this regimen was made between stations 7 and 9, where a criss-cross pattern was used. Simultaneous remote and water column data were obtained at stations 1, 7, 9 and 15. At the other stations, water column measurements were taken at free-floating markers dropped from the hovering helicopter. At each station or marker, a water sample was taken with a Niskin bottle at 0.5 m depth. Between stations, bucket samples were taken from the water surface at 3-minute intervals as the boats went from station to station.

b. Water column measurements. Measurements made on stations were temperature, salinity and *in vivo* fluorescence (Lorenzen, 1966), subsequently to be called "*in situ* fluorescence." The Lorenzen method was modified by the use of a narrow-band excitation filter at each laser wavelength in addition to the standard blue filter (CS 5-60). Salinity was measured with a hand-held A/O Spencer refractometer. Twenty ml of each sample were fixed with Lugol's Iodine for subsequent phytoplankton counts and identifications.

Four liters of each sample were transported to a laboratory ashore where total chlorophyll *a* (Holm-Hansen *et al.*, 1965), subsequently to be called "direct" chlorophyll *a*, optical attenuation at 454, 539, 633, and 685 nm (Brown *et al.*, 1977), and pH (using a Corning pH meter with glass electrode) were measured within a few hours. Technicon Autoanalysis was used to determine ammonia, silicate, phosphate, and nitrate plus nitrite concentrations (Friederich and Whitledge, 1972). Cell counts and identifications for stations 1, 5, 9, 13, 17, and 21 were made using a Sedgewick-Rafter Chamber at 100 and 200× (Guillard, 1973), while those for stations 3, 7, 11, 15, and 19 were done by the settling chamber method of Utermöhl (1931) at 100, 200, and 400×. Since the Sedgewick-Rafter Method had been used in previous studies of Narragansett Bay phytoplankton (e.g., Smayda, 1957, 1973; Durbin *et al.*, 1975), but the Utermöhl Method had been used in earlier developmental studies with the remote fluorosensor, it was decided to use both counting methods in this investigation.

In situ fluorescence was the only measurement made on bucket samples.

c. Laser fluorosensor measurements. Remote fluorescence was measured by the NASA/LaRC Remote Airborne Fluorosensor (RAF, formerly known as ALOPE). This system is designed to excite phytoplankton sequentially with laser light of four different wavelengths (454, 539, 598, and 617 nm) and to measure the returning fluorescence at 685 nm resulting from each excitation. The narrow-band excitation light is produced by a multicavity dye laser, while the returning fluorescence is captured by a 10-inch diameter telescope which focuses it upon the face of a photomultiplier tube. A sequence of narrow-band and high-pass optical filters are placed immediately before the PMT to screen out unwanted wavelengths of light. The excitation bandwidth is 5 nm and the fluorescence bandwidth is 9 nm. The RAF was

modified for this experiment to operate at only two excitation wavelengths (454 and 539 nm) because phytoplankton of only two color groups (green and golden-brown) were expected. This modification doubled the laser power at both wavelengths and substantially lowered the level of detectable chlorophyll *a*. Further details on the system and its operation may be found in Brown *et al.* (1977, 1981).

Remote laser-induced fluorescence plus background radiance at 685 nm, background radiance at 685 nm (no laser fired), laser output energy, and aircraft altitude were recorded in digital format on magnetic tape. Background radiance at 685 nm was later subtracted from the total radiance at 685 nm when a laser was fired to obtain the laser-light induced fluorescence of chlorophyll *a*.

d. Calculations. Computations of the "remote"[5] chlorophyll *a* for each color group of phytoplankton were achieved by the simultaneous solution of two equations, each with two unknowns, using two sets of remote fluorescence data (F_{454}, F_{539}). The derivation of the fluorosensor equation is discussed by Mumola *et al.* (1973) and by Browell (1977). The form of the equation used for these calculations is equation (1). The variables determined for each laser firing were P_o, P_r, α_i, α_f, and R. Values for each attenuation coefficient were determined between stations by a linear interpolation between *in situ* data at the stations. The ratio P_r/P_o for the unfired laser was obtained by averaging the ratio for the previous and subsequent laser firings.

$$n_1 \sigma_{i1} + n_2 \sigma_{i2} = \frac{P_{ri}(\alpha_i + \alpha_f)}{C R^2 P_{oi}} = F_i \qquad i = 1,2 \tag{1}$$

where n_j = number of chlorophyll *a* molecules/m³ in color group *j*.

P_{ri} = energy of fluorescence returned at 685 nm after excitation with laser *i*, in joules.

α_i = attenuation coefficient at wavelength of incident light (454 or 539 nm), m^{-1}.

α_f = attenuation coefficient at wavelength of chlorophyll *a* fluorescence (685 nm), m^{-1}.

C = Optical constant characteristics of the remote fluorosensor, m^{-2}.

σ_{ij} = Fluorescence cross-section at laser light wavelength (454 or 539 nm) of color group *j*, m^2.

P_{oi} = Output energy of the fired laser, joules.

R = Altitude, m.

F_i = "Remote fluorescence" as presented in Figure 2.

The parameter which relates fluorescence at 685 nm to the chlorophyll *a* concentration, the fluorescence cross-section (σ), has been extensively investigated in

5. "remote" is used in quotes because chlorophyll *a* is actually not measured remotely, but instead calculated from a remote measurement of fluorescence using both *in situ* and laboratory-derived parameters.

Table 1. Fluorescence cross-sections (m^2).

	454nm	539nm
Golden-brown species	7.308×10^{-22}	5.389×10^{-22}
Green species	2.775×10^{-22}	0.838×10^{-22}

our laboratories (NASA-Langley Research Center) and mean spectra for the four major color groups have been computed. The fluorescence cross-sections (Table 1) used to compute the "remote" chlorophyll *a* concentrations in this experiment were determined by Brown *et al.* (1981). These cross-sections were multiplied by a single calibration factor (4.37) determined from the ratio of remote fluorescence to *in situ* chlorophyll *a* (see Fig. 8). This calibration was necessary to account for a difference in fluorescence efficiency between laboratory cultures and natural populations at the time the remote data were taken, as the natural populations averaged about one fourth as much fluorescence per μg chlorophyll *a* as did the laboratory cultures.

Depths of 1% light penetration were calculated from our attenuation coefficients at 454, 539, 633, and 685 nm. The four coefficients were averaged to give a "white light" coefficient, which was then converted to "*K*" by multiplying by 0.30 (W. Houghton, personal communication). This "*K*" was then used to calculate the 1% light penetration depth ($Z_{.01}$) using equation (2).

$$Z_{.01} = \frac{4.605}{K} \quad . \tag{2}$$

Table 2a. Water column data for all stations.

Station no.	Chloro-phyll *a* (μg/l)*	Total phyto-plankton**		*In situ* fluorescence†	Optical attenua-tion††	*T* (°C)	Salinity (‰)	$\bar{Z}$ (m)***
1	2.7	682		(0.35)†††	0.97	1.2	31.0	23.7
3	7.1		3608	(1.0)	1.32	2.0	30.0	15.9
5	8.4	2143		(1.1)	1.53	2.2	30.0	13.0
7	15.5		4921	2.0	1.77	—	30.0	12.4
9	22.2	5287		4.4	2.29	—	30.0	8.5
11	29.8		8845	5.1	3.09	2.0	28.5	5.4
13	43.8	6738		9.5	4.43	2.8	26.0	7.2
15	37.0		9980	7.8	4.09	2.6	23.0	7.2
17	31.5	5392		5.1	4.78	3.0	21.0	6.6
19	9.4		3173	2.8	4.87	2.7	—	5.0
21	24.6	3248		4.3	9.15	3.0	9.0	5.2

* Mean of two values.
** cells/ml; Sedgewick-Rafter counts in left column, Utermöhl counts in right column.
*** Mean of 20 closest depths to station, taken from USC&GS Chart 13221.
† In relative terms; excitation filter—CS 5-60.
†† At 632.8nm, m^{-1}.
††† Field data not taken; laboratory measurement normalized to station 7.

A stepwise regression analysis (Hemmerle, 1967) was performed on the primary remote and *in situ* variables related to the production of remote fluorescence to determine if chlorophyll *a* was the variable with which remote fluorescence was best correlated, and if so, if any of the other variables contributed significantly to the variance of the remote fluorescence. Independent variables analyzed were chlorophyll *a* concentration, optical attenuation at 633 nm, background radiance at 685 nm, level of incident sunlight, and cosine of sun angle. Standard error terms were calculated for each step in the analysis.

3. Results

All water column indicators of phytoplankton density (direct chlorophyll *a*, total cell count, and *in situ* fluorescence) show maximum values in the upper West Passage near Greenwich Bay and decreasing values, not only going down the West Passage toward Block Island Sound, but also up the Providence River (Table 2a). Very little additional structure is indicated by the *in situ* data, the only exception being an increase in chlorophyll *a* and *in situ* fluorescence in Providence Harbor (station 21). Linear plots of remote fluorescence and "remote" total chlorophyll *a* follow the same general trend, but indicate much finer structure, particularly in the Providence River (Figs. 2 and 3). Even finer structure is revealed by the hand contoured plot of "remote" total chlorophyll *a* between stations 7 and 9 (Fig. 4). Here several patches of phytoplankton are indicated as well as general gradients.

The diatoms *Skeletonema costatum, Thalassiosira nordenskioeldii,* and *Detonula confervacea* dominated the phytoplankton population in the bloom area, but in the lower West Passage, microflagellates were almost as numerous as diatoms (Table 3). Microflagellates were also numerous in the Providence River, but the pennate diatoms of the genus *Navicula* were dominant in Providence Harbor. Phytoplankton

Table 2b. Water column data (continued).

Station no.	pH	Nutrients (μM) Ammonia	Silicate	Phosphate	Nitrate + Nitrite
1	8.14	—	—	—	—
3	8.17	<0.20	<0.40	0.21	<0.20
5	8.23	—	—	—	—
7	8.36	<0.20	<0.40	0.10	<0.20
9	8.42	<0.20	<0.40	0.12	<0.20
11	8.45	<0.20	0.56	0.24	0.36
13	8.40	2.90	8.47	1.62	4.29
15	8.23	18.7	25.7	2.02	17.4
17	8.14	—	—	—	—
19	—	21.0	21.2	1.92	14.7
21	7.58	—	—	—	—

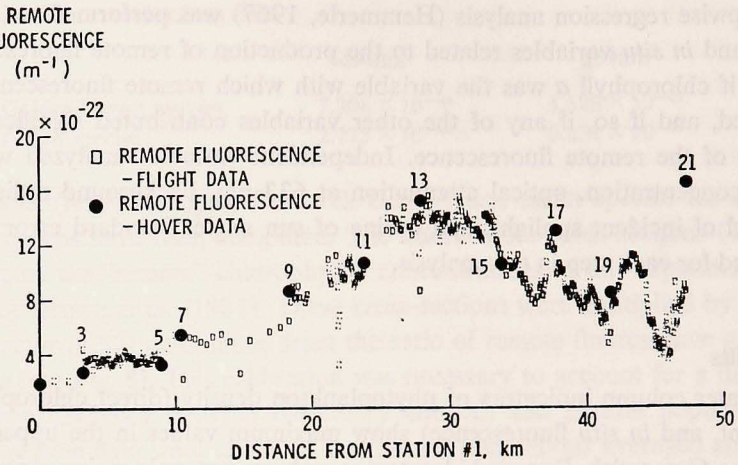

Figure 2. Remote fluorescence resulting from excitation at 454 nm (flight and hover data) along flight path from station 1 to station 21. Points between stations 7 and 9 were where criss-cross pattern intersected a direct line between stations.

population composition data from the 11 stations are summarized in Table 4 to allow easier comparisons with composition calculated from fluorescence, which is based on algal color groups. Although patchiness is indicated by the station data, particularly at the species level, its spatial extent is unknown. Again, the linear plot of "remote" chlorophyll *a* versus distance, this time distributed between the green and golden-brown color groups, indicates gross patchiness of these major phytoplankton components (Fig. 5). Contour plots of these components in the region be-

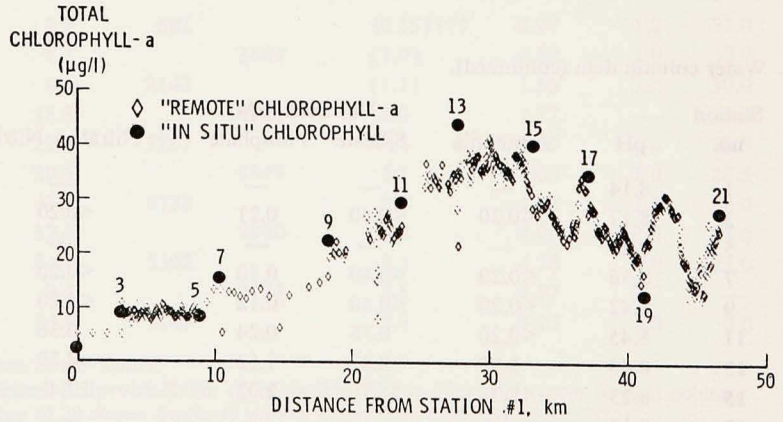

Figure 3. "Remote" chlorophyll *a* along flight path and mean direct chlorophyll *a* measured on samples taken at the 11 stations.

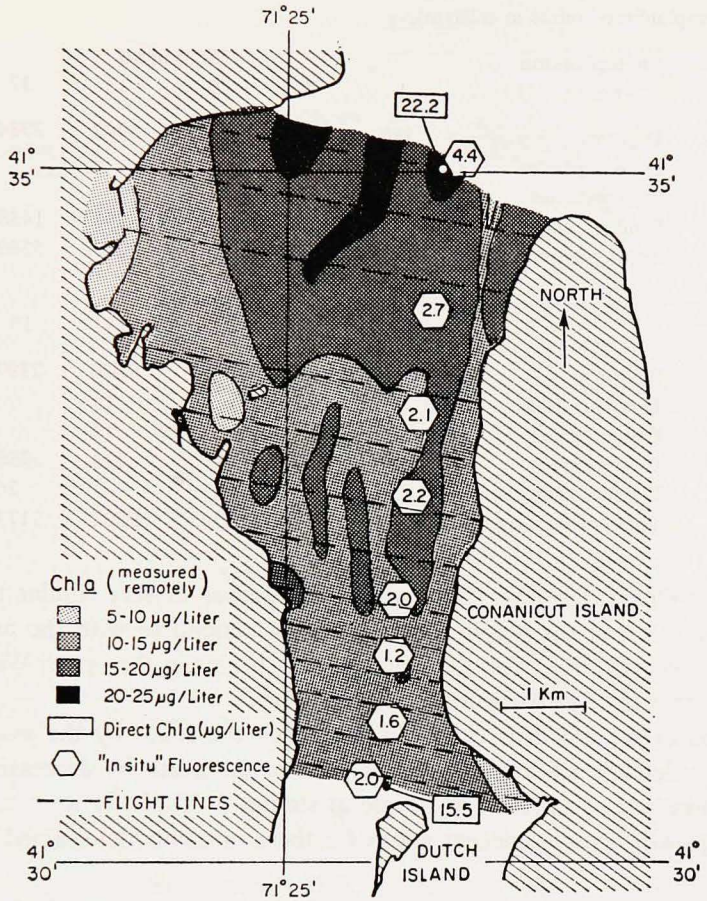

Figure 4. Distribution of total "remote" chlorophyll *a* between stations 7 and 9 in the lower West Passage compared with *in situ* fluorescence along boat tracks and direct chlorophyll *a* at stations 7 and 9.

tween stations 7 and 9 indicate a unique pattern of patchiness for each component (Figs. 6 and 7).

4. Discussion

a. Analysis of one-dimensional remote data and related water column data. Three types of phytoplankton patches are indicated by the one-dimensional remote data and related water column data: the winter-spring diatom bloom, and two types of smaller scale features superimposed upon it. The primary diatom bloom extended from the area north of Dutch Island in the lower West Passage northward into the upper reaches of the Providence River, with maximum intensity in the upper West

Table 3. Phytoplankton counts in cells/ml.

Technique	Phytoplankton group	Station no. 1	5	9	13	17	21
Sedgewick-Rafter Cell	Diatoms	380	1183	3935	5942	3934	2525
	Dinoflagellates	2	6		3		
	Chrysophytes		23				
	Unident. flagellates	300	932	1352	796	1458	723
	Total phytoplankton	682	2143	5287	6738	5392	3248
		Station no. 3	7	11	15	19	
Utermöhl	Diatoms	2650	4790	8120	9670	2397	
	Dinoflagellates		1		26		
	Cryptophytes		1	78	52		
	Chlorophytes	931	103	492	232	750	
	Unident. flagellates	26	26	155		26	
	Total phytoplankton	3607	4919	8767	9902	3173	

Passage near Greenwich Bay. This type of distribution is very similar to that observed at the peak of the bloom in 1973 and is compatible with the assertion by Kremer and Nixon (1978) that the winter bloom begins in the upper West Passage and then spreads to other parts of Narragansett Bay.

Expansion of the bloom is evidently limited on the south by the availability of nutrients, particularly silicate and nitrate, and on the north by decreasing salinity. The concentrations of silicate and nitrate at station 9 (Table 2) were considerably below the growth limiting concentrations for these nutrients determined for Narra-

Table 4. Phytoplankton population composition indications from remote and *in situ* data.

Station no.	*In situ* data G.B.	(%)*	Green**		Remote data G.B.	(%)*	Green	Remote 454/539	*In situ* 460/540
1	56.0		44.0		75.2		24.8	1.42	—
3		73.5		26.5	—		—	—	—
5	55.2		44.8		74.9		25.1	1.48	—
7		97.4		2.6	86.2		13.8	0.988	0.88
9	74.4		25.6		88.3		11.7	0.910	1.00
11		92.7		7.3	88.8		11.2	0.927	1.13
13	88.2		11.8		90.4		9.6	0.897	1.05
15		97.7		2.3	89.7		10.3	0.914	1.94
17	73.0		27.0		90.5		9.5	0.895	1.91
19		75.5		24.5	83.8		16.2	1.18	1.80
21	77.7		22.3		84.7		15.3	1.15	1.90

* by volume.

** Includes chlorophytes and microflagellates; left column from Sedgewick-Rafter counts, right column from Utermöhl counts.

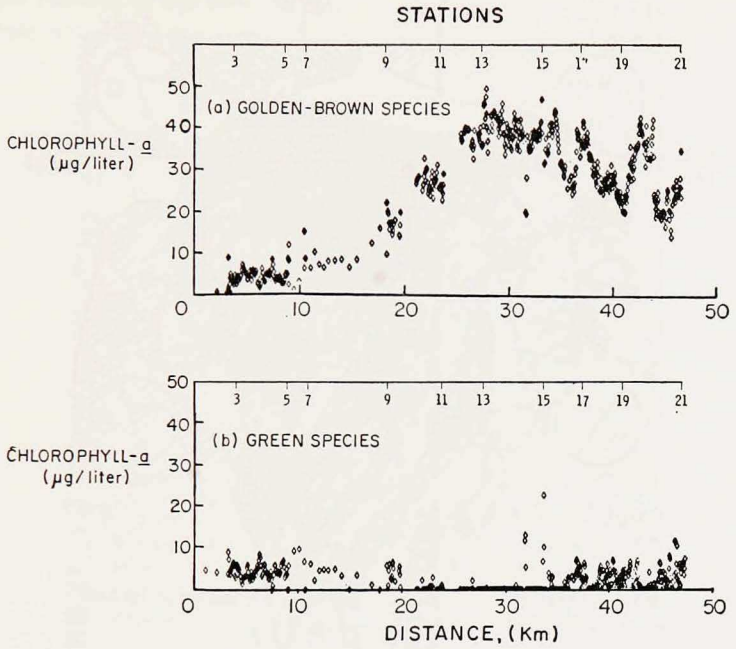

Figure 5. "Remote" chlorophyll *a* concentrations for the green and golden-brown components of the phytoplankton population along flight path from station 1 to 21.

gansett Bay blooms species by Pratt (1965), and by Mitchell-Innes (1973); while the salinity at station 21 (9‰) was well below the "preferred" range of 20 to 24‰ for *Skeletonema costatum* (Droop, 1973), the primary bloom organism, and near the minimum salinity for most of the predominant bloom species (Smayda, 1958). The dimensions of this bloom are of the same order as nutrient enrichment related patches on shelf edges (Bainbridge, 1957; Steele, 1978) and the factors which contribute directly to their establishment are similar (Pratt, 1965; Hitchcock and Smayda, 1977). However, the effects of low salinities and physical boundaries are obviously unique to the estuarine blooms.

The green species (chlorophytes and microflagellates) minimum in the area of the diatom bloom maximum noted in the remote data (Fig. 5) was also noted to a lesser extent in the water column data (Table 3). This minimum is more evident when the two components are presented as a percentage of the total cell number (Table 4). This relationship between these two components of the phytoplankton population is not as evident in the previous studies of the bay, although some indications can be found. In the winter of 1955/56 the diatom and flagellate populations occurred in similar proportions at five stations in the West Passage, but during the winter of 1953/54 the flagellates were a much smaller component of the

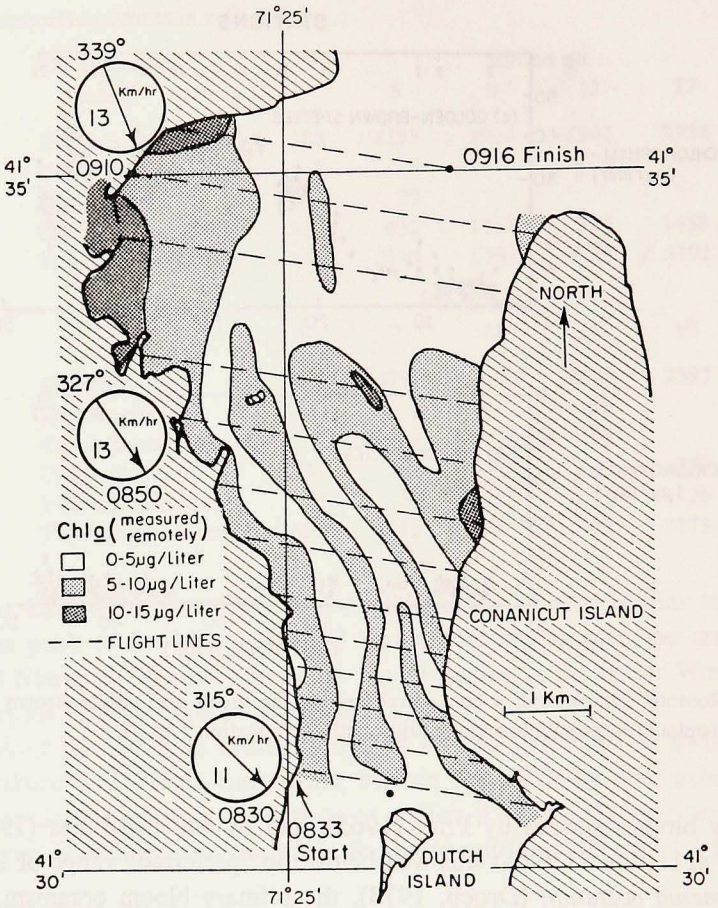

Figure 6. Distribution of "remote" chlorophyll *a* in green species in the lower West Passage between stations 7 and 9. Wind speed and direction at three times during the flight.

total population at the station of the diatom maximum than at the other stations (Pratt, 1959). Since there were few dinoflagellates in the winter samples, these data are comparable with our results. This effect has also been noted in temporal studies. During a nine month period in 1954, flagellate minima usually coincided with diatom maxima at three stations in the lower bay (Smayda, 1957), a pattern which was also noted during the period of July 1968 to June 1969 at three different stations (Mitchell-Innes, 1973). For five of these six stations the winter-spring diatom bloom maximum occurred within two weeks of the annual or nine-month flagellate minimum.

Although the March 16, 1978 golden-brown species (diatom) maximum, for both cell counts and remote and direct chlorophyll *a*, and the concurrent green

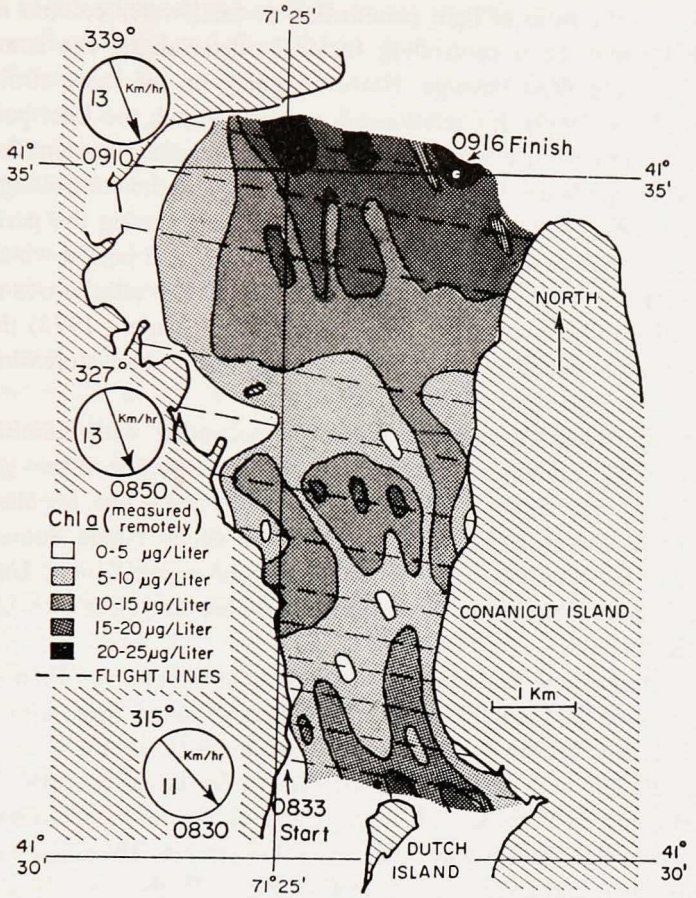

Figure 7. Distribution of "remote" chlorophyll *a* in golden-brown species in the lower West Passage between stations 7 and 9. Wind speed and direction at three times during the flight.

species (chlorophytes and microflagellates) minimum were accompanied by an optical attenuation maximum (Table 2a), there is no evidence which indicates that shading selectively inhibits the microflagellate population. In most cases where the maximum/minimum effect has been observed, the Secci depth has shown no consistent trends (Smayda, 1957; Mitchell-Innes, 1973). However, Schnitzer (1979) observed in Long Island Sound that in well-mixed waters microflagellates predominated when the ratio of 1% light penetration depth to water column depth was less than 0.5, while diatoms predominated in shallow, well-mixed waters when the ratio was higher than 0.5. This same relationship apparently existed in the West Passage, as the transition from microflagellate/diatom equivalence in the lower Passage to diatom predominance in the upper Passage was accompanied by a sharp increase

(0.55 to 0.80) in the ratio of light penetration to total water column depth. Thus light availability may be a controlling factor in determining the composition of phytoplankton in the West Passage. However, going up the more stratified Providence River (Hicks, 1959) this relationship was not noted; the light penetration to total depth ratio remained constant while the microflagellate content increased. In this region the sharp change in salinity (Table 2a) may be the controlling parameter. Mitchell-Innes (1973) found sharp decreases in salinity during the period just before the observed diatom maxima/microflagellate minima, a period which coincided with maximum river runoff. Although no temporal study of salinity was made in the present study, it can be inferred from river runoff data (Anon., 1978) that our data were taken during a period of rapidly decreasing salinity, and increasing stratification in the upper bay and Providence River.

The green/microflagellate species minimum coincided with salinities between 23.0 and 28.5‰. This minimum may result from the existence of two green/microflagellate species populations in the Narragansett Bay area, one hypohaline (Providence River) and one hyperhaline (lower bay and Block Island Sound), with the salinity range in between not being optimum for either population. Unfortunately, this hypothesis cannot presently be tested because we are unable to identify most of the microflagellates.

The three intermediate scale patches of phytoplankton in the Providence River noted in the remote data (Fig. 3) all had diameters of about three kilometers along their flight line axis. However, the bases for their existence are varied, related to localized stimulation and/or inhibition of growth by environmental factors. The northernmost patch, in Providence Harbor, was a bloom of *Navicula* species, which were not found in significant numbers at any other station. The unique combination of low salinity (9‰) and high nutrients in Providence Harbor may be related to the limited distribution of these species. The other two patches had a species composition very similar to the main diatom bloom, except for their higher content of microflagellates. These were evidently semi-detached portions of the main bloom, separated from it by areas where growth of phytoplankton may be inhibited, areas whose lengths were about one tidal excursion (3.5 km). One of these areas, in which station 19 was located, was directly opposite the mouth of the Pawtuxet River channel. This river is one of two major natural sources of fresh water which empty into the Providence River estuary. The effect of the Pawtuxet River water is indicated by the lower temperature at station 19 than at 17 and 21. The channel also carries the effluent from the Cranston, R.I. secondary treatment sewerage plant. At station 19, the major inorganic nutrients were adequate for rapid growth (Table 2b), but phytoplankton growth may have been limited by other factors. Potential inhibitors of the growth of bloom species in this area include low salinity, residual chlorine, heavy metals (Phelps *et al.*, 1975; and Ryther *et al.*, 1972), and hydrocarbons (Farrington and Quinn, 1973). A similar condition exists at the chlorophyll *a* minimum opposite

Fields Point (2 km south of end of flight track), where the main Providence sewerage treatment plant discharged about 0.16×10^6 m^3/day.

Smaller, 0.5 to 1.0 km scale, patches were also noted in the remote data. Examples of these patches were located at 23, 32, 34, and 39 km from station 1 (Fig. 3). The origin of these patches is more difficult to assess, particularly in light of the possibility that their peak magnitudes may be within the error band of the sensor. If two-dimensional data were available for these patches, it would lend itself to easier interpretation. As it is, the most that can be said about them is that they probably result from horizontal turbulent diffusion (Platt and Denman, 1974).

b. Analysis of two-dimensional remote data. In the middle West Passage, between stations 7 and 9, the green and golden-brown species evidenced very different distribution patterns (Figs. 6 and 7). While both of these major phytoplankton population components showed orientations related to wind effects, the green species were evidently more strongly influenced. The long narrow windrows of green species noted in the remotely sensed data were very similar to those often noted in many other estuaries and ocean waters (Bainbridge, 1957). Bainbridge noted that these bands usually consist of flagellates and are more superficial than other types of distributions, occurring within a few meters of the surface. Since the small flagellates have lower sinking rates than most diatoms, particularly when the latter are senescent (Smayda, 1970), they would be nearer the surface and thus be more affected by water movements caused by winds. While the bands of green species shown in Figure 6 were 250 to 400 m wide and separated by areas of lower concentration of about the same width, the actual concentration maxima were separated by an average distance of 160 m; a distance well within the range observed by Langmuir (1938), but considerably greater than the expected for convection cell diameters at the local wind speed of 11-13 km/hr (Faller and Woodcock, 1964). However, since the remote data were taken at 40 m intervals, there could be undetected maxima between those observed. It is likely that the combination of the effects of wind, tidal circulation and random turbulence would result in distributions which would not fit a purely wind-driven model, even if the wind was the primary factor in creating those distributions. Also, conditions during the period immediately prior to the time of data acquisition can have significant impact on phytoplankton distributions. An example of these effects was recently reported by Abbott *et al.* (1980) in Lake Tahoe, where spacings of about 200 m between bands were calculated from fluorometry data acquired on a calm day immediately following a period of strong winds.

Of particular interest in the present data was the apparent change in orientation of the bands of green species as wind direction changed with time (Fig. 6). During the 43 minutes it took to fly the criss-cross pattern, the wind direction changed from 45° west of north to less than 20° west of north. During this same period the orien-

tation of the bands appeared to follow the same general trend, placing additional credence in their wind-driven nature.

The golden-brown species distribution shows less orientation to the prevailing winds than demonstrated by the green species. Even this effect may be over emphasized by the remote sensing data, as the maximum sensing depth for this technique was about 2-3 m in these waters, while the photic depth was about 6-7 m. The patchiness of the golden-brown component was predominantly the result of dispersion of the main diatom bloom by tidally-driven mixing. Tidal currents can distribute nutrient and phytoplankton in a manner which would support the observed golden-brown patches; a mechanism which could also apply to the generation of some of the intermediate scale patches in the Providence River. These tide-driven distributions generally have distances between maxima on the order of a tidal excursion (Lekan, 1976). For the West Passage and the Providence River these distances were equivalent, being about 3 to 4 km in both cases. This type of patchiness is comparable to that observed by Platt *et al.* (1970) in St. Margaret's Bay, Nova Scotia and by Lekan (1976) in Long Island Sound.

c. Comparison of remote and direct measurements. Correlation between remote and water column measurements of the same or similar parameters was generally excellent. A comparison between remote fluorescence (excited by the blue laser) and direct chlorophyll *a* is made in Figure 8. Linear regression analysis of these two sets of data produced a correlation coefficient (r) of 0.932 ($n = 176$) for all data taken from hover position. Even better correlations were obtained if data sets within more limited areas were used. In the lower West Passage data, the correlation was 0.958 (stations 1, 5, and 7; $n = 55$), while in the upper bay data it was 0.975 (stations 11, 13, 15, and 17; $n = 78$). "Remote" total chlorophyll *a* also agreed well with direct chlorophyll *a* (Fig. 3). The match between remote and water column measurements is perhaps best illustrated in Figure 4, where "remote" total chlorophyll *a* concentrations can be compared to both direct chlorophyll *a* concentrations at stations 7 and 9 and *in situ* fluorescence along the boat track between stations.

The stepwise regression analysis showed that in all cases, remote fluorescence gave the best correlation with chlorophyll *a* concentration of any single parameter but the inclusion of optical attenuation as a second component always significantly increased the correlation and decreased the standard error. The addition of third and fourth best correlating parameters, usually backscatter or background light level, to the regression analysis never significantly increased the correlation or decreased the standard error. This indicated to us that the effects of attenuation of both laser light and fluorescence in the water column are not fully accounted for in the present fluorosensor equation, and that variables such as background light level or sun elevation angle do not significantly affect the variance of remote fluorescence data. To better account for the effect of attenuation, we are presently investigating

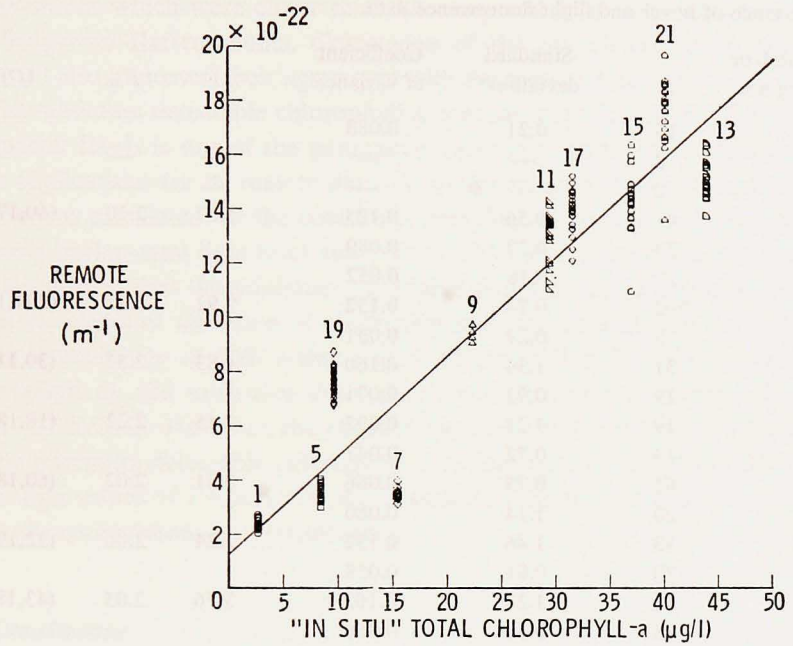

Figure 8. Relationship between remote fluorescence at 685 nm resulting from excitation at 454 nm (hover data) and the mean chlorophyll *a* concentration measured on samples taken at 10 stations. Line is regression of x against y.

a remote technique of attenuation measurement which would use the same laser light which is used for the fluorescence excitation. This technique would utilize either the depolarization of a polarized laser output or Raman scattering of the laser light as an indicator of light attenuation (Bristow *et al.*, 1979).

Finally, interpretation of the variance of remote fluorescence and the chlorophyll *a* concentrations derived from it requires an understanding of how much this variance is system generated, i.e., inherent, and how much is due to the variance of the parameter being sensed, in this case chlorophyll *a*. To provide such a guide for data interpretation, standard deviations were calculated for all hover and flight data sets. Since the average chlorophyll *a* concentration at the hover points should have remained constant during the period remote data were taken (about 1 minute), the standard deviation of the remote fluorescence taken from the hover position was taken as an indication of the inherent variance of the technique. The standard deviation of the flight data was tested against this to determine if the variance observed was significantly greater at the 95 percent confidence level. In all but three cases the flight data variance was found to be significantly greater, with the largest relative variance being observed on Flight Leg 8, where the criss-cross flight pattern was flown to give two-dimensional data (Table 5). Thus it is felt that, with those three

Table 5. Variance of hover and flight fluorescence data.

Station and/or flight leg no.	N	Standard deviation*	Coefficient of variance	F	$F_{.05}$	(Df)
1	15	0.21	0.088			
2	2	—	—	—	—	
3	0	—	—	—	—	
4	41	0.56	0.125	5.02	2.10	(40,17)
5	20	0.29	0.080			
7	20	0.18	0.052			
8	202	0.74	0.132	9.92	2.32	(201,12)
9	5	0.29	0.031			
10	31	1.34	0.160	4.83	2.57	(30,11)
11	19	0.93	0.071			
12	19	1.21	0.097	2.15	2.22	(18,18)
13	19	0.72	0.047			
14	61	0.75	0.066	0.61	2.02	(60,18)
15	20	1.14	0.080			
16	33	1.46	0.132	2.24	2.06	(32,19)
17	20	0.81	0.058			
18	44	1.28	0.163	3.76	2.05	(43,18)
19	18	0.51	0.066			
20	56	1.36	0.297	2.01	2.03	(55,18)
21	20	1.41	0.079			

* $\times 10^{22}$.

exceptions, the variance in the flight data between stations primarily reflected variance in chlorophyll *a* concentration.

Analysis of the correlation between the *in situ* and remotely determined composition data is always difficult. The remote measurement is based on the fluorescence excitation characteristics of phytoplankton, similar to those reported by Yentsch and Yentsch (1979), and the assumption that only two major components of the phytoplankton population were present. These two components have well-defined spectral characteristics, particularly in the region of the RAF excitation wavelengths (454 and 539 nm). If the predominant species present in each component have these characteristics, then the remote and *in situ* composition measurements are usually well correlated. In this case, the predominant species in the golden-brown component did have spectral characteristics very similar to those used to represent the group, but the green component species evidently did not. However, by combining the true chlorophytes and the microflagellates (whose spectral characteristics and taxonomic identities are largely unknown), a composite group was obtained which produced *in situ* composition ratios which were comparable with the remote data (Table 5). A linear regression analysis showed good correlations (.8-.9) between these two data sets. The counts using the Utermöhl method gave percent

compositions which were closer to those computed from the remote data than did the Sedgewick-Rafter counts. Conversion of the *in situ* counts to volume terms ($\mu m^3/1$) also improved their agreement with the remote data.

The minimum detectable chlorophyll *a* concentration for the RAF at present output power levels is one of the parameters of interest to those researchers who may have applications for its remote data. A minimum detectable chlorophyll *a* concentration was calculated for the conditions prevalent at station 1 on March 16th, particularly background light level and water turbidity. This computation was based on the assumption that the minimum detectable signal could be approximated by three times the standard deviation of the background radiance at 685 nm (52.5 counts). Using a sensitivity of 108 counts/μg of chlorophyll *a*/1, (293 counts/2.7 μg/1. chlorophyll *a*), the minimum detectable concentration was computed to be 0.48 μg/1 (52.5/108). However, the effect of increased ambient light and water turbidity on the minimum detectable chlorophyll *a*, as indicated by minimum detectable concentration values of 2.8 and 3.8 μg/1 calculated for stations 5 and 13, respectively, must always be taken into consideration.

5. Conclusions

At its peak, the 1978 winter-spring diatom bloom in western Narragansett Bay extended from just north of Dutch Island in the lower West Passage to east of Fields' Point on the upper Providence River estuary; with maximum intensity occurring in the upper West Passage, between Greenwich Bay and Patience Island. This bloom consisted primarily of the diatoms *Skeltonema costatum, Thalassiosira nordenskioeldii* and *Detonula confervacea.* The expansion of the main bloom was evidently limited on the south by the availability of nutrients, primarily nitrate and silicate, and on the north by decreasing salinity. Superimposed upon the main bloom were two types of small-scale (3-4 and 0.5-1 km in one dimension) features or patches, consisting primarily of bloom species, but having a higher content of microflagellates than the main bloom. These patches were evidently created primarily by the action of tides and winds on the main bloom, although toxic materials and low salinity water from tributaries and sewerage treatment plants may have contributed to their establishment in the Providence River.

Associated with the diatom bloom were two populations of chlorophytes/microflagellates; one in low salinity/high nutrient water to the north (Providence River); one in high salinity/low nutrient water to the south (Rhode Island Sound and lower West Passage). In the West Passage, the transition from chlorophyte/microflagellate-diatom equivalence to diatom dominance was accompanied by a sharp increase in the ratio of 1% light penetration depth to total water column depth, indicating that light availability may also be an important controlling factor in determining the phytoplankton population composition in that area. In this transition area, the two

major components of the population were found to have very different distribution patterns. The chlorophyte/microflagellate component appeared to be more wind affected, occurring in long windrows whose axes were approximately parallel to the prevailing winds. The diatom component showed some wind influence, but tidal mixing was evidently the primary factor effecting its fine-scale distribution. This difference in the effect of winds is attributed primarily to differences in sinking rates of these two phytoplankton types. The small, motile, flagellates have lower sinking rates than the prevalent diatoms, particularly when the latter are senescent, and thus stay nearer the surface where they are more likely to be affected by water movements caused by winds.

In general, the correlations were excellent between remotely measured fluorescence and all *in situ* indicators of phytoplankton biomass. Quantitative estimates of chlorophyll *a* concentration were successfully calculated from remote fluorescence values by using *in situ* data to account for variations in the ratio of fluorescence to chlorophyll *a*. However, the variance in optical attenuation by the water column, both at the excitation and fluorescence wavelengths, was found to have a significant effect on the remote fluorescence values which could not be completely corrected for using the present fluorescence excitation/emission model. This effect on remote fluorescence was also evident in calculations of the minimum detectable "remote" chlorophyll *a* concentration, which was determined to be about 0.5 μg/1 in the clear waters of Rhode Island Sound, but only about 4 μg/1 in the turbid waters of the upper West Passage. Good correlations between *in situ* and remote estimates of phytoplankton population composition were obtained by including the microflagellate population in the green species component. This indication of homology between the fluorescence excitation characteristics of many microflagellates and the chlorophytes has recently been supported by laboratory studies of these organisms (Farmer, 1981).

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REFERENCES

Abbott, M. R., T. M. Powell and P. J. Richerson. 1980. The effects of transect direction on observed spatial patterns of chlorophyll in Lake Tahoe. Limnol. Oceanogr., *25*, 534–537.

Anonymous. 1978. Water resources data for Massachusetts and Rhode Island; water year 1978. U.S. Dept. Interior Geological Survey data report. Rockville, Md. MA-RI-78-1, 299 pp.

Bainbridge, R. 1957. The size, shape and density of marine phytoplankton concentrations. Biol. Rev., *32,* 91–115.

Bristow, M., D. Nielsen, D. Bundy, R. Furtek and J. Baker. 1979. Airborne laser fluorosensing of surface water chlorophyll *a*. EPA-600/4-79-048.

Browell, E. V. 1977. Analysis of laser fluorosensor systems for remote algae detection and quantification. NASA TN D-8447.

Brown, C. A., Jr., F. H. Farmer, O. Jarrett, Jr. and W. L. Staton. 1977. Laboratory studies of *in vivo* fluorescence of phytoplankton. Proc. Fourth Joint Conf. Sens. Environ. Pollutants, 782–788.

Brown, C. A., Jr., O. Jarrett, Jr. and F. H. Farmer. 1981. Laboratory tank studies of single species of phytoplankton using a remote fluorosensor. NASA TP-1821.

Clarke, G. L., G. C. Ewing and C. J. Lorenzen. 1970. Spectra of backscattered light from the sea obtained from aircraft as a measure of chlorophyll concentration. Science, *167,* 1119–1121.

Droop, M. R. 1973. Some thoughts on nutrient limitation in algae. J. Phycol., *9,* 264–272.

Durbin, E. G., R. W. Krawiec and T. J. Smayda. 1975. Seasonal studies on the relative importance of different size fractions of phytoplankton in Narragansett Bay. Mar. Biol., *32,* 272–287.

Faller, A. J. and A. H. Woodcock. 1964. The spacing of windrows of *Sargassum* in the ocean. J. Mar. Res., *22,* 22–29.

Farmer, F. H. 1981. Interpretation of an index of phytoplankton population composition calculated from Remote Airborne Fluorosensor (RAF) data. Chesapeake Bay Plume Study/ Superflux 1980. NASA Conference Publication 2188, 429–437.

Farrington, J. W. and J. G. Quinn. 1973. Petroleum hydrocarbons and fatty acids in waste water effluents. J. Water Pollution Cont. Fed., *45,* 704–712.

Ferrara, R. 1953. Phytoplankton studies in upper Narragansett Bay. M.S. thesis, Univ. of Rhode Island. 62 pp.

Friederich, G. O. and T. E. Whitledge. 1972. Autoanalyzer procedures for nutrients, *in* Chemostat Methodology and Chemical Analysis, S. P. Pavlou, ed., Spec. Rep. 52, Dept. Oceanogr., Univ. Wash., Seattle.

Gordon, H. R. 1979. Estimation of the depth of sunlight penetration in natural waters for the remote sensing of chlorophyll *a* via *in vivo* fluorescence. Appl. Opt., *18,* 1883–1884.

Guillard, R. R. L. 1973. Division rates, *in* Handbook of Phycological Methods, J. R. Stein, ed., Cambridge Univ. Press, 448 pp.

Hemmerle, W. J. 1967. Statistical computations on a digital computer. Blaisdell Pub. Co., Waltham, Massachusetts, 230 pp.

Hicks, S. D. 1959. The physical oceanography of Narragansett Bay. Limnol. Oceanogr., *4,* 316–327.

Hitchcock, G. L. and T. J. Smayda. 1977. The importance of light in the initiation of the 1972-1973 winter-spring diatom bloom in Narragansett Bay. Limnol. Oceanogr., *22,* 126–131.

Holm-Hansen, O., C. J. Lorenzen, R. W. Holmes and J. D. H. Strickland. 1965. Fluorometric determination of chlorophyll. J. Cons. Perm. Int. Explor. Mer., *30,* 3–15.

Kierstead, H. and L. B. Slobodkin. 1953. The size of water masses containing plankton blooms. J. Mar. Res., *12,* 141–147.

Kremer, J. N. and S. W. Nixon. 1978. A Coastal Marine Ecosystem. Springer-Verlag, New York, 217 pp.

Langmuir, I. 1938. Surface motion of water induced by wind. Science, *87,* 119–123.

Lekan, J. F. 1976. Spatial variability of phytoplankton biomass in the surface waters of Long Island. M.S. thesis, State Univ. of New York, Stony Brook, 32 pp.

Lorenzen, C. J. 1966. A method for the continuous measurement of *in vivo* chlorophyll concentrations. Deep-Sea Res., *13,* 223–227.

Mitchell-Innes, B. A. 1973. Ecology of the phytoplankton of Narragansett Bay and the uptake of silica by natural populations and the diatoms *Skeletonema costatum* and *Detonula confervacea.* Ph.D. thesis, Univ. of Rhode Island, 212 pp.

Mumola, P. B., O. Jarrett, Jr. and C. A. Brown, Jr. 1973. Multi-wavelength laser induced fluorescence of algae *in vivo*: a new remote sensing technique. Proc. Second Joint Conf. Sens. Environ. Pollutants, 53–62.

Parsons, T. R., R. J. Brasseur and J. D. Fulton. 1967. Some observations on the dependence of zooplankton grazing on the cell size and concentration of phytoplankton blooms. J. Oceanogr. Soc. Japan, *23,* 10–17.

Phelps, D. K., G. Telek and R. L. Lapan, Jr. 1975. Assessment of heavy metal distribution within the food web, *in* Progress in Waste Technology, Supplement: Marine Pollution and Marine Waste Disposal, E. A. Pearson *et al.*, eds., Pergamon Press, Elmsford, New York, 341–348.

Platt, T. and K. L. Denman. 1974. A general equation for the mesoscale distribution of phytoplankton in the sea, *in* Sixth Liege Colloquium on Ocean Hydrodynamics, J. Nihoul, ed., Memoires de la Societe Royal des Sciences de Liege, 6° serie, tome VIII, 31–42.

Platt, T., L. M. Dickie and R. W. Trites. 1970. Spatial heterogeneity of phytoplankton in a near-shore environment. J. Fish. Res. Bd. Canada, *27,* 1453–1473.

Pratt, D. M. 1959. The phytoplankton of Narragansett Bay. Limnol. Oceanogr., *4,* 425–440.

—— 1965. The winter-spring diatom flowering in Narragansett Bay. Limnol. Oceanogr., *10,* 173–184.

Ryther, J. H., W. M. Dunstan, K. R. Tenore and J. E. Huguenin. 1972. Controlled eutrophication—increasing food production from the sea by recycling human wastes. Biosci., *22,* 144–151.

Schnitzer, M. B. 1979. Vertical stability and the distribution of phytoplankton in Long Island Sound. M.S. thesis, State Univ. of New York, Stony Brook, 108 pp.

Smayda, T. J. 1957. Phytoplankton studies in lower Narragansett Bay. Limnol. Oceanogr., *2,* 342–359.

—— 1958. Biogeographical studies of marine phytoplankton. Oikos, *9,* 158–191.

—— 1970. The suspension and sinking of phytoplankton in the sea. Oceanogr. Mar. Biol. Ann. Rev., *8,* 353–414.

—— 1973. The growth of *Skeletonema costatum* during a winter-spring bloom in Narragansett Bay, Rhode Island. Norw. J. Bot., *20,* 219–247.

Steele, J. H. 1978. Some comments on plankton patches, *in* Spatial Pattern in Plankton Communities, J. H. Steele, ed., Plenum Press, New York, 470 pp.

Utermöhl, H. 1931. Neue wege in der quantiativen erfassung des planktons. Verhandl. Internat. Ver. Linol., *5,* 567–596.

Wroblewski, J. S. and J. J. O'Brien. 1976. A spatial model of phytoplankton patchiness. Mar. Biol., *35,* 161–175.

Yentsch, C. S. and C. M. Yentsch. 1979. Fluorescence spectral signatures: the characterization of phytoplankton populations by the use of excitation and emission spectra. J. Mar. Res., *37,* 471–483.

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