

## *Trichodesmium* Phenomenon

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*Trichodesmium* phenomenon was studied during the seasons of 1975, 1977 and 1978 in the Arabian Sea (nearshore waters of Goa, west coast of India). This phenomenon occurred in the form of blooms of *T. erythraeum* every year with a marked periodicity from February to April. During this period the sea was calm with little wave action and had high temperature, high salinity and maximum periods of sunshine. High inorganic  $PO_4\text{-P}$ ,  $NH_4\text{-N}$  and  $NO_3\text{-N}$  were found in the sea associated with the blooms. The values of all these nutrients went up with every pulse of the bloom. Each year the bloom occupied many square kilometres of the near-shore water. (It was generally spread out in long bands probably because of convective circulation prevailing in the region during the premonsoon months.) In association with the patches of bloom, 44 different algae were recorded during the 1975 season when the bloom was in great profusion. In the 1977 season, 39 different algae were recorded besides *Trichodesmium* species and these did not attain as high counts as in the 1975 season. During the bloom,  $^{14}C$  uptake was largely contributed by *Trichodesmium*. Similarly, high chl. *a* and particulate organic carbon (POC) coincided with dense bloom. At times, pheophytin was higher than chl. *a* probably because of the presence of a large number of physiologically inactive filaments. During the bloom seasons, other phytoplankton organisms were abundant and some diatoms appeared in profusion in association with the bloom. Zooplankton organisms were fairly abundant in bloom patches as in non-bloom areas. Many zooplankton organisms were found living in patches of dense bloom. Fish catches taken in areas of the bloom were largely composed of 'trash fish' showing no marked dissimilarity from those of the non-bloom areas. *Trichodesmium* is not much favoured as food by the fishes or other animals although the bloom is totally non-toxic. No mortality of fish or any other animal was ever found in association with the bloom. During the 3 seasons, the intensity of the bloom was highly variable not only from year to year but from day to day. Bloom patches kept appearing and disappearing with the state of the sea. (Slightly turbulent conditions made the bloom disappear from the surface and calm conditions made it reappear. The bloom was largely confined to the surface. In its early stages, the bloom had the appearance of sprinkled saw-dust over the sea surface, but as the season advanced, it began to impart reddish brown colour to the water. Laboratory experiment with natural blooms gave a clear evidence that *Trichodesmium* plays a very important role in the enrichment of water by releasing phosphorus and nitrogen. The ability of *Trichodesmium* to fix nitrogen enhances its role in enrichment. With the disintegration and decay of the bloom,  $NH_4\text{-N}$  becomes very high in the water. Growth of unialgal culture is enhanced in lower concentrations of the medium in which the bloom decays. In each season, *Trichodesmium* phenomenon makes a substantial contribution to the total nutrient budget of the sea.

ONE of the most spectacular biological phenomena occurring in tropical oceans every year is the formation of blooms of the blue-green alga, *Trichodesmium erythraeum* (EHR). Many reports are available on the occurrence of *Trichodesmium* blooms from different parts of the world oceans indicating that the phenomenon is very widespread in tropical seas<sup>1,2</sup>. In the Indian Ocean, its occurrence is a regular feature from February to April when large areas of the ocean, particularly in the Arabian Sea, get covered with clumps of saw-dust coloured algae<sup>3,4</sup>. In the early literature, the phenomenon has often been referred to as 'red tide' or 'red water' presumably because of the colour it imparts to the water when it occurs in great profusion. Perhaps for this reason, the 'Red Sea' owes its name, as in early days, sailors passing through this sea in certain seasons observed

blood red colour imparted to the water over long stretches by *Trichodesmium* blooms<sup>1,2</sup>. Even today, the word 'bloom' of any alga has become synonymous with 'red tide' even if the colour of water is yellow, brown, orange or even green. However, it is clear that, apart from the occurrence of *Trichodesmium* blooms from time to time in different geographical regions of the world, no detailed study has ever been undertaken on the phenomenon itself from start to finish.

From the Goa waters, the occurrence of *Trichodesmium* bloom was first reported in 1972<sup>5</sup>. Since then the bloom phenomenon has been observed every year from February to May indicating a well-defined periodicity and annual rhythm in its appearance. In 1975, the first series of investigations were carried out on the bloom from the time it was seen and till it finished, but since many portions of the study

remained incomplete, the observations were repeated more intensively during the season of 1977 and a few studies were undertaken during 1978. This communication presents details of this unique phenomenon occurring in the sea and throws some light on the importance of the bloom in relation to physical, chemical and biological features of the sea. Qasim<sup>4</sup> made the following general remarks on the blooms of *Trichodesmium*. "The interesting feature, which has often puzzled both marine scientists and oceanographers is the suddenness with which the blooms of *Trichodesmium*, an organism which normally constitutes an insignificant proportion of the total biomass in the sea, appear. Even more intriguing is the disappearance of the bloom, which, according to published reports, has been found to be sudden and dramatic".

#### Materials and Methods

Data used in this paper were collected from several different sources. The information on tides and tidal currents, coastal currents and waves of the region where blooms were studied, was taken from the earlier publications of NIO. Data on wind and total sunshine were obtained from the office of the India Meteorological Department in Paraji, Goa.

Studies on this phenomenon were carried out during the 3 seasons of 1975, 1977 and 1978. In 1975, sampling was done from 5 March to 11 June and in 1977 from 19 Feb. to 28 May. In 1978, some studies on the enrichment caused by the bloom and the colour it imparts to the water were carried out in February and March. Time and place of the observation and the stations covered during 1975 and 1977, together with the state of tides are given in Table 1. The choice of the stations during the study was arbitrary. However, it should be noted that station 1 throughout the text refers to the site where bloom was in profusion at the surface and station 2, whenever selected, was in close vicinity of the bloom but almost free from bloom at the surface (Table 1). Nevertheless, during the bloom season, it is impossible to get any adjoining area totally free from *Trichodesmium* filaments. Hence the bloom-free area mentioned here is a relative term to indicate environmental conditions under two rapidly changing situations. Thus the bloom-free area might have had bloom earlier and similarly the bloom area might become free as soon as the bloom has shifted to another location. The area covered, between 5 and 25 m isobaths during the study is shown in Fig. 1.

Samples of sea water containing *Trichodesmium* were collected at or near the surface (within 20 cm depth) for determining the density of the blooms and physical and chemical features of the water containing the bloom. The adhesive nature of *Trichodesmium* clumps posed some problems in sampling, filtration and incubation of samples. The organism sticks to the sides of the buckets, samplers and glasswares. Most of them could be made free by shaking vigorously with sea water or by gently passing a glass rod over the adhering surface. Whatever filaments or clumps could not be removed in this way were neglected. Similarly, for the incubation, sub-sampling was carried out after

TABLE 1 — DATE, TIME AND PLACE OF OBSERVATION OF *Trichodesmium* BLOOM TOGETHER WITH TIDAL PHASE DURING 1975 AND 1977 SEASONS

(Station 1 refers to areas of bloom at the surface and station 2 to those free from bloom)

Date	Time (hrs)	Station	Time (Low water)	Time (High water)	Tidal phase
1975					
AGUADA					
5-3-75	1045	1	1024	1759	F
10-3-75	0930	1	1535	0929	F
18-3-75	0830	1	0740	1433	F
18-3-75	1045	2	0740	1433	F
22-3-75	0830	1	1139	0432	E
22-3-75	1100	2	1139	0432	E
29-3-75	0815	1	0556	1238	F
29-3-75	0930	2	0556	1238	F
2-4-75	0830	1	0851	1557	E
2-4-75	1130	2	0851	1557	F
7-4-75	0845	1	1415	0828	E
16-4-75	0800	1	0716	1419	F
21-4-75	0800	1	1222	0629	E
MORMUGAO HARBOUR					
25-4-75	0815	1	0405	1052	F
DONA PAULA					
29-4-75	0845	1	0653	1353	F
13-5-75	0800	1	0542	1245	F
AGUADA					
24-5-75	0800	1	0343	1045	F
MANDOVI ESTUARY					
5-6-75	0745	1	0125	0818	F
11-6-75	1015	1	0524	1230	F
1977					
AGUADA					
19-2-77	1300	1	1742	1149	E
19-2-77	1115	2	1742	1149	F
4-3-77	0930	1	0404	0942	F
4-3-77	0940	2	0404	0942	F
15-3-77	1300	1	1329	0658	E
15-3-77	1100	2	1329	0658	E
18-3-77	0945	1	0407	1014	F
18-3-77	1015	2	0407	1014	F
23-3-77	1000	1	0651	1325	F
23-3-77	1300	2	0651	1325	F
29-3-77	1245	1	1130	1859	F
29-3-77	1430	2	1130	1859	F
27-4-77	1500	1	1035	1749	F
MORMUGAO					
23-5-77	0820	1	0728	1432	F
CALANGUTE					
26-5-77	0930	1	1208	0654	E
28-5-77	1020	1	1208	0654	E
28-5-77	1045	1	1208	0654	E

E = ebb; F = flood.

thoroughly mixing the sample containing *Trichodesmium*. During the incubation, samples were kept well shaken to ensure that the organisms were not floating at the surface. The adhering *Trichodesmium* clumps or filaments were carefully removed with a fine brush during filtration.

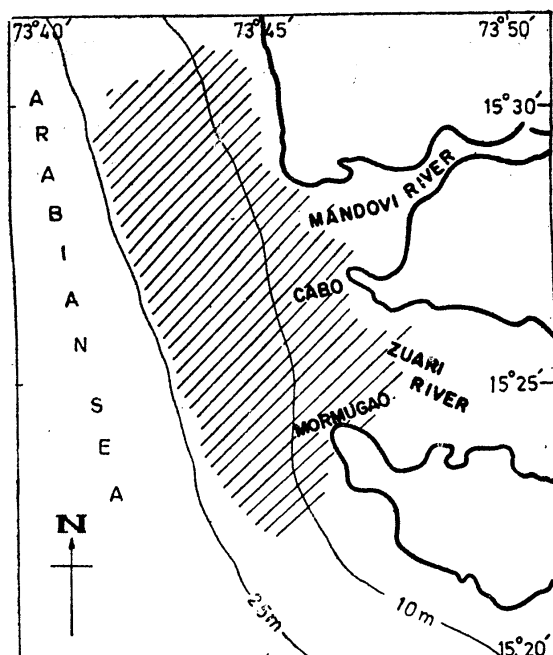


Fig. 1 — Goa coast showing the region (shaded area) where *Trichodesmium* blooms were studied during the seasons of 1975, 1977 and 1978

From both stations 1 and 2, temperature, salinity, dissolved oxygen, inorganic nutrients ( $\text{PO}_4\text{-P}$ ;  $\text{NO}_3\text{-N}$ ;  $\text{NO}_2\text{-N}$  and  $\text{NH}_4\text{-N}$ ) were measured. Similarly,  $^{14}\text{C}$  uptake, phytoplankton cell counts, particulate organic carbon, chlorophyll *a* and pheophytin were determined from both types of water, i.e. those containing *Trichodesmium* and those which were free from the bloom. Salinity and nutrients were measured in water after removing all *Trichodesmium* clumps and filaments.  $^{14}\text{C}$  incubated samples were filtered through membrane filters of  $0.45\ \mu\text{m}$  pore size. The filters were exposed to acid fumes, dried and then transferred to a scintillation vial containing 10 ml of NE 220 liquid scintillator. Counting was done in a liquid scintillation counter (ECIL make) by the channel ratio method.  $^{14}\text{C}$  uptake was then calculated after correcting for dark uptake. Horizontal zooplankton hauls of 5 min duration were taken with an HT net ( $0.22\ \text{mm}$  mesh width) both from the surface and between 3 and 5 m depth. Fish composition in the bloom area was studied by conducting a few trawl operations and the gut contents of the fishes obtained from trawling were examined.

On a few occasions, observations were made at 3 hr intervals for periods varying from 24 to 48 hr to determine the variation in density and distribution of *Trichodesmium* with time and environmental parameters. Population density of *Trichodesmium* was estimated in terms of individual filaments and not clumps. This was found necessary as the clumps break easily into filaments during handling of samples and their preservation. Since any sample of *Trichodesmium* bloom will contain both clumps and filaments, it will be erroneous to express the density of the bloom as clumps. Therefore, on

each sampling day, after mixing the samples well, 25 clumps were picked out at random. Each clump was placed on a slide with a coverslip. When the coverslip was pressed gently, the filaments became more or less free to be counted. All the filaments thus released were counted, averaged and then pooled to obtain the population density. Whenever the sub-sample contained free filaments these were also counted. Thus, counting in terms of filaments gave a greater accuracy because the number of filaments in each clump varied from 12 to 190.

Water samples containing thick blooms were brought to the laboratory and the bloom was allowed to die and decay in flasks. Continuous measurements of inorganic nutrients were made from the water samples as the bloom disintegrated.

## Results and Discussion.

### Physical Features

**Tides and tidal currents** — Tides in the Goa region are of a mixed, semidiurnal type with a macrotidal range. Tidal currents at the mouth of Mandovi estuary in the premonsoon months, have an average speed of 160 cm/sec during the flood and 110 cm/sec during the ebb. Close to the shore, tidal currents become weak with an average speed of 50 cm/sec during the flood and 40 cm/sec during the ebb<sup>6</sup>. The direction of the currents during the flood is towards upcoast and during the ebb towards down-coast<sup>6</sup>.

**Winds** — The offshore components of the winds recorded at 0830 hrs showed a gradual decrease in their strength from March to May while the onshore components showed an increase at 1730 hrs. The average onshore wind speed in these months at 1730 hrs was about 15-20 km/hr (Fig. 2A).

The windfield at 0830 hrs showed northerly components during April and May. In March, southerly components were somewhat predominant (Fig. 2B). These winds were found to be weak. At 1730 hrs, generally the winds were northerly. During March, however, alternately fluctuating northerly and southerly winds prevailed. Such winds would lead to drift currents which will be directed towards the south and the water will be oscillating onshore and offshore at the surface. The interaction of these currents with those of the existing tidal currents would contribute a great deal to the lateral shift in the bloom patch as was observed during these months.

**Sea currents** — During the premonsoon period (February-May) the coastal circulation of water is counter-clockwise with speeds varying from 10-15 cm/sec. Converging currents are found to be associated with the counter-clockwise circulation, although deviations may take place during periods of strong onshore/offshore winds<sup>7</sup>.

**Waves** — Wave characteristics based on visual estimates from shipboard and shorebased observations published by India Meteorological Department and the wave records obtained by NIO off Goa from time to time indicate that from January to March, the sea state and the swell state present extremely calm conditions. However, in April

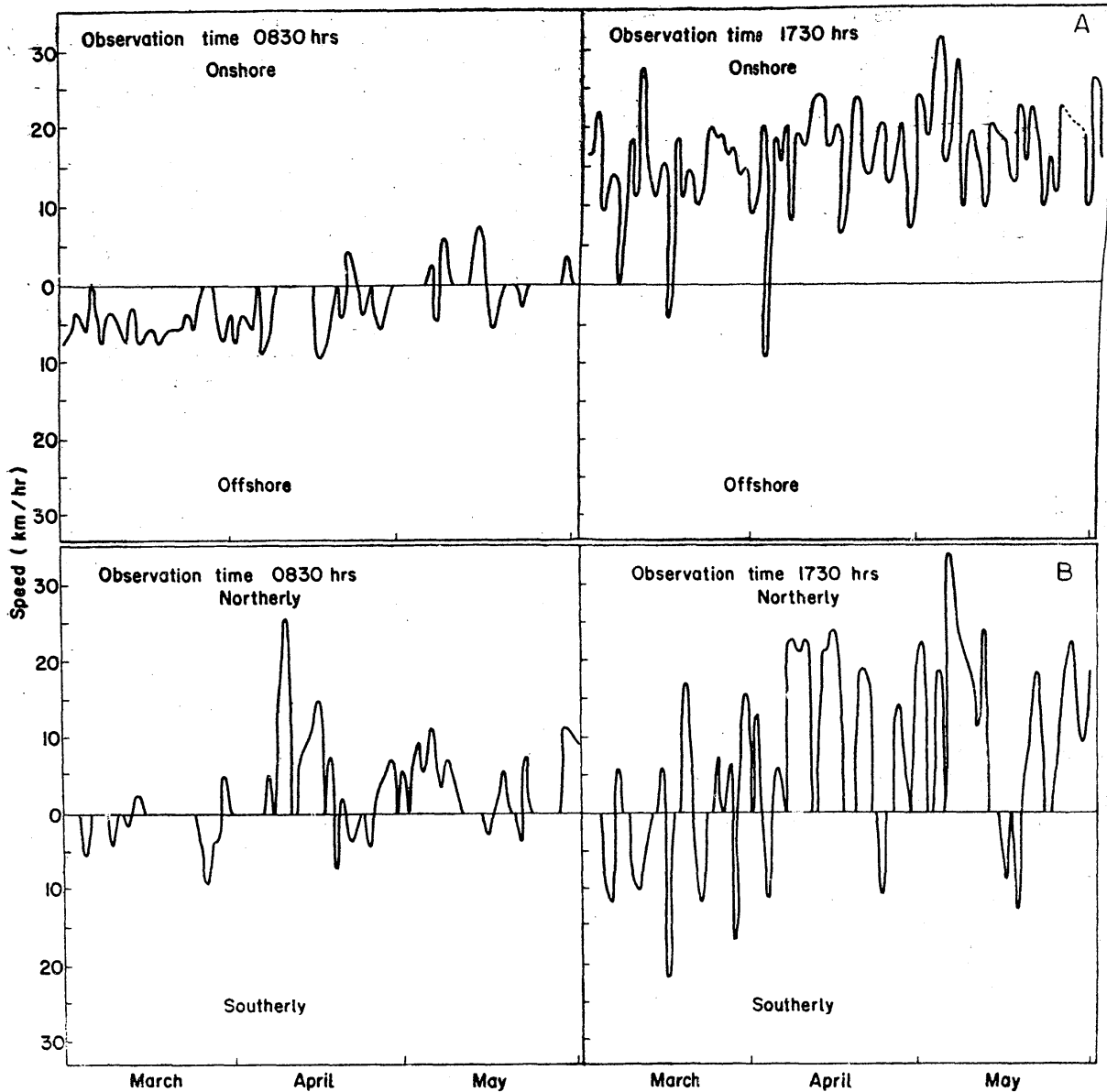


Fig. 2 — Onshore and offshore (A) and northerly and southerly (B) wind components recorded at 0830 and 1730 hrs in Panaji (Goa) during the 1977 season of *Trichodesmium* bloom [Data from Indian Daily Weather Report, India Meteorological Department]

and May a gradual increase in the wave activity becomes evident. Over the entire area, there is a growing phase of swell wave characteristics preceding the actual increase in the wind speed.

**Sunshine** — Daily sunshine hours from February to May 1977 are given in Fig. 3. Sunshine of more than 10 hr/day occurs during February and early March. In late March, daily sunshine is about 8 to 10 hr. In April and May, although on certain days, the sunshine may reach more than 11 hr, the average is lower than that of February and March.

**General oceanographic features of the area** — During the fair weather season (January-April), the shallow nearshore water remains well mixed. The temperature in the area shows diurnal variation while the

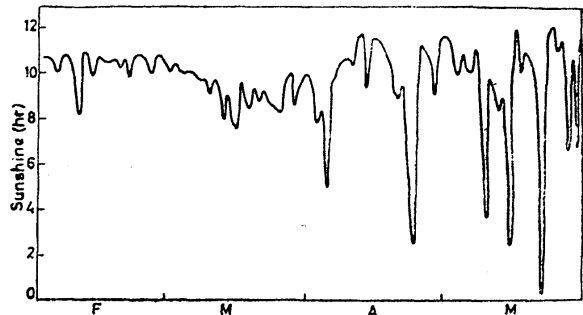


Fig. 3 — Sunshine hours in Panaji, Goa during 1977 season of *Trichodesmium* bloom [Data from India Meteorological Department]

salinity remains more or less uniform ( $\sim 35\%$ ). The water of the area indicates considerable instability in the top layers (0-2 m) because of intense evaporation. The increase in salinity and daily fluctuation in temperature lead to an increase in the density of surface water leading to a reduction in stability. The incoming solar radiation during the day, though compensates for the increase in density by raising the sea temperature at the surface, during the night the continued evaporation leads to an increase in density and results in negative stabilities. This feature persists in the top layers during March and April in spite of convection and mixing by winds and tidal currents.

**Temperature** — In the bloom area, sea temperature, during the 1975 season (February-May) in the top 2 m column, ranged from 27.0° to 31.8°C and during the 1977 season, from 27.1° to 31.7°C.

**Salinity** — During the 1975 season of the bloom (February-May), variation in salinity was from 35.14 to 35.66‰ and during the 1977 season from 35.07 to 36.00‰ in the top 2 m column of water.

**Chemical Features**

**Oxygen** — Fig. 4 gives the dissolved oxygen in areas with bloom and in nearby areas which appeared to be relatively free from blooms during Feb-May 1975 and 1977. Dissolved oxygen in the bloom areas ranged from 4.03 to 5.8 ml/litre in 1975 and from 3.85 to 6.7 ml/litre in 1977. In the adjoining areas which were relatively free from blooms, dissolved oxygen did not show such a wide range of fluctuation and the variation in both the areas probably indicates the combined effect of both decay and photosynthesis of *Trichodesmium*.

**Phosphate-phosphorus** — During the bloom season of 1975, PO<sub>4</sub>-P values ranged from 2.0 to 13.15 µg-at/litre. When the bloom was at its peak, phosphorous values became high, but towards the end of bloom the values declined and by the end of

May, only traces of PO<sub>4</sub>-P were left in the area where the bloom was in profusion earlier (Fig. 5).

In 1977, the PO<sub>4</sub>-P concentration was much higher with maximum values reaching 35.66 µg-at/litre in the area where bloom was in profusion (Fig. 5).

**Nitrate-nitrogen** — In both the seasons, NO<sub>3</sub>-N values were low during the early phase of the bloom (0.57 to 1.73 µg-at/litre). However, when the bloom was at its peak, NO<sub>3</sub>-N values became high in both bloom and non-bloom areas (Fig. 6). When the bloom came to an end, there was a sharp decline in the NO<sub>3</sub>-N values.

**Nitrite-nitrogen** — NO<sub>2</sub>-N values were generally lower than those of NO<sub>3</sub>-N. In the bloom and non-bloom areas, fluctuations in NO<sub>2</sub>-N values were of a similar range. During 1977, NO<sub>2</sub>-N did not show as much fluctuation as in 1975 in the bloom areas. In non-bloom areas, the fluctuations were even greater during both the seasons (Fig. 7).

**Ammonia-nitrogen** — Measurements of NH<sub>4</sub>-N were made only during the 1977 season (February to May). Fig. 8 shows the recorded values of NH<sub>4</sub>-N in bloom and non-bloom areas. There was a considerable difference in NH<sub>4</sub>-N values between the locations. With the commencement of the bloom, NH<sub>4</sub>-N values began to increase, and after every pulse of the bloom, the values increased sharply. Towards the end of the bloom, when *Trichodesmium* was dying and decaying, the concentration of ammonia in both bloom and non-bloom areas became very high (Fig. 8).

**Particulate organic carbon** — Particulate organic carbon (POC) in the water was determined only during the 1977 season and this has been shown in Fig. 9. As can be expected, in the bloom areas, very high values of POC were recorded indicating that *Trichodesmium* largely contributes to POC values. In non-bloom areas, POC was relatively low but filaments of *Trichodesmium* occurring in these areas occasionally gave rise to the fluctuations in POC.

**Biological Features**

**<sup>14</sup>C uptake** — Fig. 10 shows the rate of <sup>14</sup>C uptake in the bloom and non-bloom areas during 1975 and 1977 seasons. In 1975, the appearance and propagation of bloom was late, and hence in early March, low values of <sup>14</sup>C uptake were recorded. In late March and late April, 2 peaks of maximum <sup>14</sup>C uptake, associated with the two pulses of maximum *Trichodesmium* blooms, were recorded. During 1977, the 1st maxima of <sup>14</sup>C uptake was noticed in early March and the later peak towards the middle of March. By the end of May, with the disappearance of bloom, carbon assimilation values reached minimum. In the non-bloom areas also similar rise and fall were noticed during the season indicating that algae, other than *Trichodesmium* also contribute substantially to the carbon assimilation. Towards the end of the bloom, carbon uptake becomes very low (Fig. 10).

**Phytoplankton population** — Total counts of *Trichodesmium* and other algae, both in bloom and non-bloom areas are shown in Fig. 11. The most

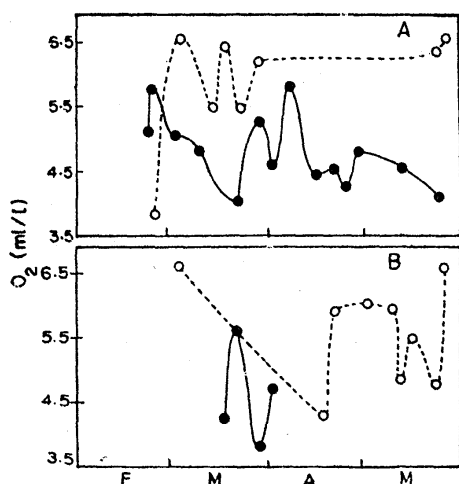
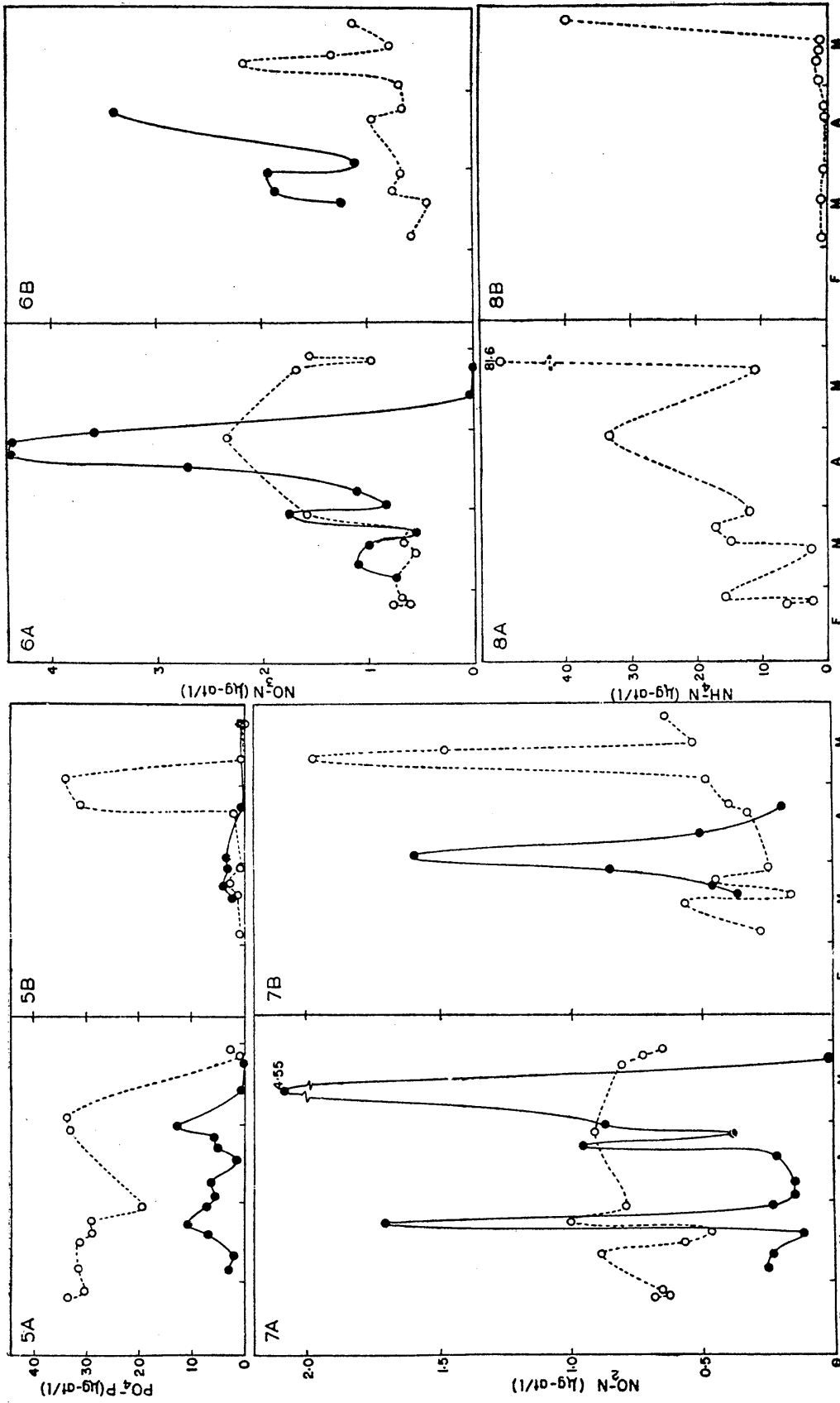


Fig. 4 — Dissolved oxygen in bloom areas (A) and in non-bloom areas (B) [●—●, 1975 season and ○....○, 1977 season]



Figs. 5-8 — Inorganic phosphate-phosphorus (5), nitrate-nitrogen (6), nitrite-nitrogen (7) and ammonia-nitrogen (8) measured in water after removing all *Trichodesmium* clumps and filaments [A, bloom area; B, non-bloom area. —●—, 1975 season and - - -○- - -, 1977 season]

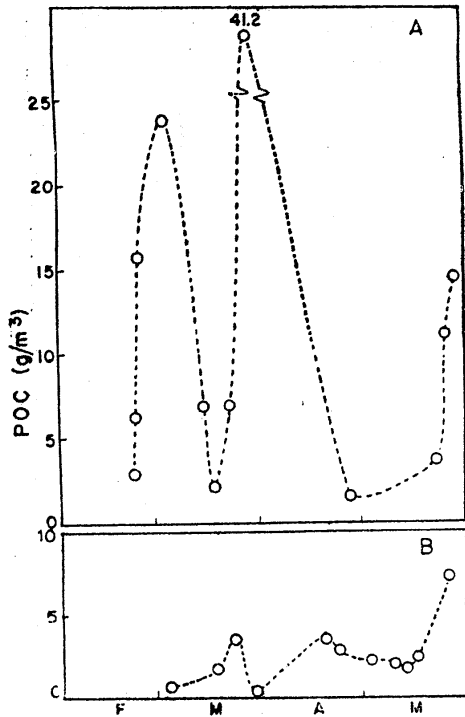


Fig. 9 — Concentration of particulate organic carbon (POC) in bloom area (A) and non-bloom area (B) during 1977 season

abundant alga during the bloom was *Trichodesmium erythraeum*. The other species *T. thiebautii* was also seen in the samples during the bloom but this species did not contribute much to the total phytoplankton counts. During the 1975 season, besides *Trichodesmium*, 44 algae were identified during the bloom. After *Trichodesmium*, *Nitzschia closterium* was most predominant. The population of other algae included 32 diatoms, 6 dinoflagellates, 3 blue-greens and 3 green algae. Table 2 gives a list of dominant organisms in each month.

As can be seen from Table 2 and Fig. 11, besides *Trichodesmium*, other algae were also quite abundant during the bloom. This is true for the non-bloom areas also; and in the month of May, when *Trichodesmium* had almost disappeared, other algae continued to occur in abundance. Immediately after the disappearance of *Trichodesmium*, the diatom, *Asterionella japonica* was seen in abundance, almost occurring in succession (Table 2). During the 1977 season, 39 phytoplankton organisms were recorded. Of these, only the dominant forms are given in Table 3 as averages for different months. The most abundant alga was *Trichodesmium erythraeum* followed by *Nitzschia closterium*, *N. seriata*, *Chaetoceros* spp., *Navicula* spp. and *Rhizosolenia* spp. In the early stages of the bloom, *Trichodesmium thiebautii* was also common in the samples (Table 3). In general, the algal density during this season, including that of *Trichodesmium erythraeum*, was significantly lower than that of the 1975 season. In addition to *Trichodesmium*, 27 diatoms, 6 dinoflagellates, 3 blue-greens and 3

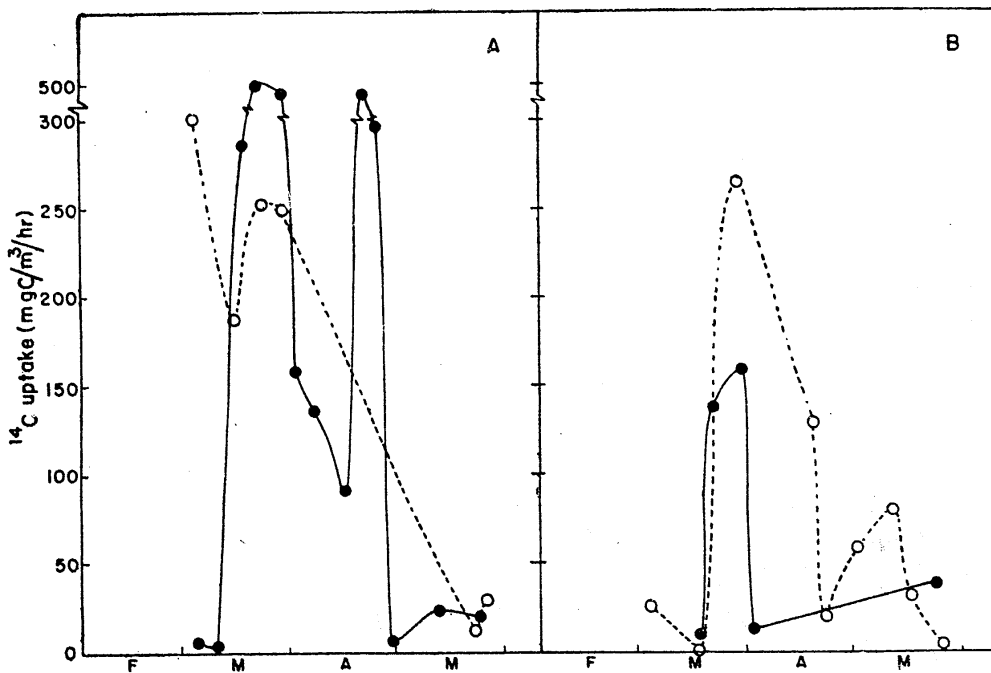


Fig. 10 — Carbon assimilation in bloom area (A) and non-bloom area (B) [●—●, 1975 season and ○....○, 1977 season]

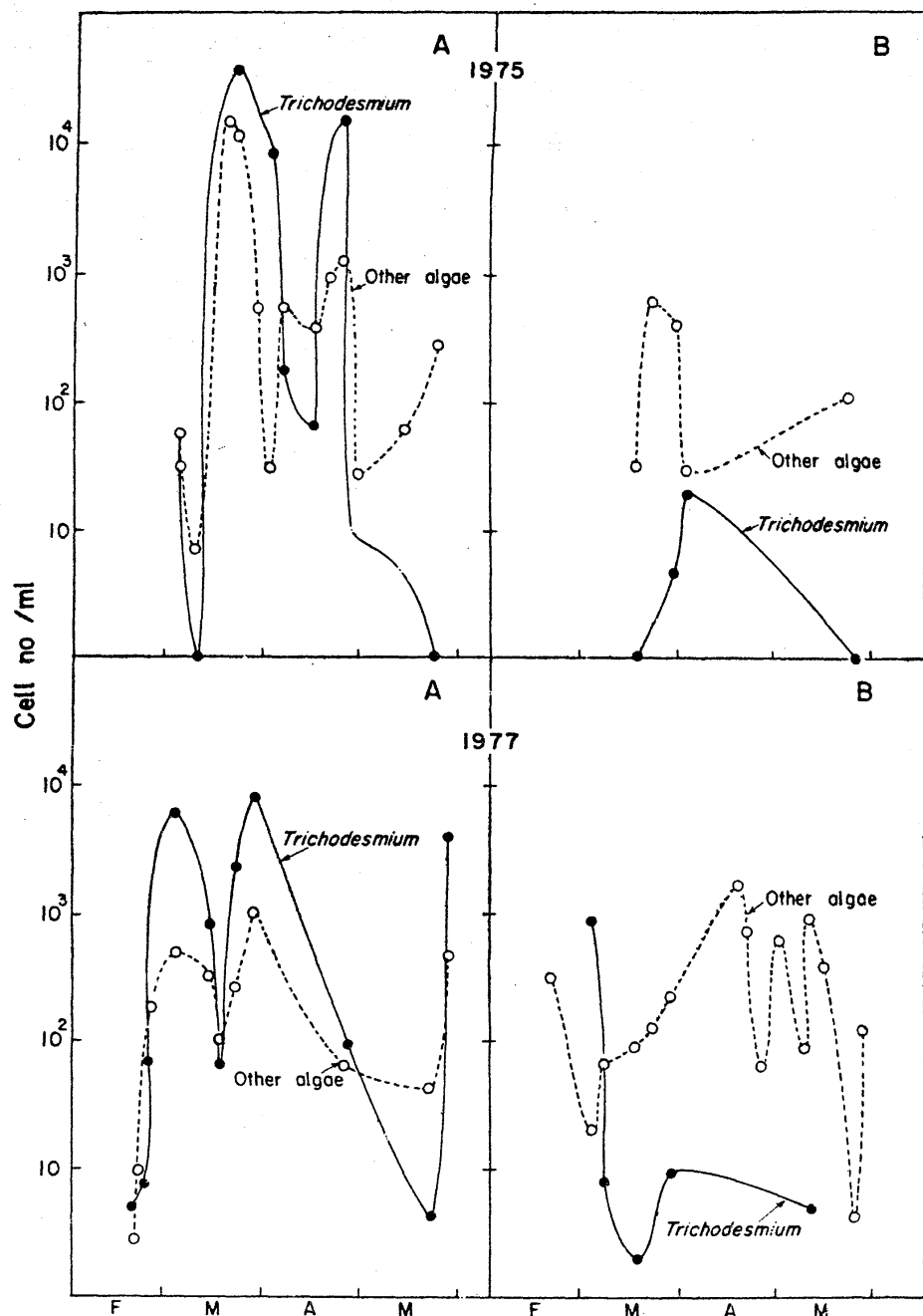


Fig. 11 — Counts of *Trichodesmium* [(filaments/ml) and other algae (cell numbers/ml) from the bloom area (A) and non-bloom area (B) during 1975 and 1977 seasons]

green algae were recorded. Bimodal peaks, like that of the year 1975, were quite distinct in both *Trichodesmium* and other algae in bloom areas. In bloom-free areas also other algae were fairly abundant (Fig. 11).

For the determination of diversity index of species during the bloom of *Trichodesmium*, the formula of Shannon and Weaver<sup>8</sup> was used. During the season of 1975, the index ranged between 0.96 and 0.05 and in the 1977 season, the range in the index was between 0.46 and 0.15. In other seasons when

there is no *Trichodesmium* bloom, the index was  $\geq 2$ . Thus, the diversity index was inversely correlated with the total biomass of the algae. During peak bloom, when *Trichodesmium* is most abundant, diversity index is the lowest.

*Chlorophyll a* and *pheophytin* — During both the seasons, chl. *a* concentrations (Fig. 12) were similar to those of carbon assimilation and cell counts. Two peaks during March and April/May in 1975 coincided with the maximum <sup>14</sup>C uptake and cell counts. The values in the bloom area ranged from



TABLE 2 — DOMINANT PHYTOPLANKTON ORGANISMS FROM MARCH TO JUNE OF 1975 IN BLOOM AND NON-BLOOM AREAS

(All values are average cell numbers/ml)

	Bloom area				Non-bloom area		
	March	April	May	June	March	April	May
DIATOMS							
<i>Asterionella japonica</i>	—	6	80	33	—	—	35
<i>Chaetoceros</i> spp	2	12	7	9	1	—	—
<i>Coscinodiscus</i> spp	3	1	16	22	2	—	1
<i>Fragilaria oceanica</i>	—	—	10	16	2	—	—
<i>Leptocylindrus</i> spp	2	3	2	—	—	—	2
<i>Navicula</i> spp	65	17	23	37	42	1	8
<i>Nitzschia closterium</i>	5835	398	10	11	150	4	—
<i>N. seriata</i>	8	6	5	1	3	—	3
<i>Nitzschia</i> spp	—	—	6	—	3	—	—
<i>Rhizosolenia</i> spp	3	87	1	1	—	—	5
<i>Streptotheca</i> sp.	—	—	4	14	—	—	7
DINOFLAGELLATES							
<i>Gonyaulax</i> sp.	—	14	1	—	1	1	2
<i>Peridinium</i> spp	7	4	3	—	1	—	—
<i>Prorocentrum</i> spp	4	—	—	—	1	—	2
Flagellates	14	55	6	8	21	—	3
BLUE-GREEN ALGAE							
<i>Trichodesmium erythraeum</i>	16509	6170	3	14	185	3	1
<i>T. thiebautii</i>	9	—	—	—	2	44	—

TABLE 3 — DOMINANT PHYTOPLANKTON ORGANISMS FROM FEBRUARY TO MAY 1977 IN BLOOM AND NON-BLOOM AREAS

(All values are average cell numbers/ml)

	Bloom area				Non-bloom area			
	Feb.	March	April	May	Feb.	March	April	May
DIATOMS								
<i>Chaetoceros curviseles</i>	—	—	—	—	—	5	—	—
<i>Chaetoceros</i> spp	41	14	—	22	38	14	—	—
<i>Hemiaulus</i> sp.	—	1	—	—	—	—	—	—
<i>Navicula</i> spp	11	13	7	14	13	9	—	3
<i>Nitzschia closterium</i>	23	129	2	128	4	8	—	—
<i>N. seriata</i>	8	31	—	—	5	16	—	1
<i>Nitzschia</i> spp	4	2	—	—	—	—	—	—
<i>Pleurosigma</i> sp.	1	4	—	—	1	—	—	—
<i>Rhizosolenia</i> sp.	6	7	—	2	1	—	—	—
Flagellates	12	14	5	17	4	14	—	6
DINOFLAGELLATES								
<i>Peridinium</i> spp	5	2	5	2	2	4	—	7
<i>Prorocentrum</i> spp	—	9	—	—	—	1	3	5
BLUE-GREEN ALGAE								
<i>Trichodesmium erythraeum</i>	9	2373	97	1520	—	197	—	15
<i>T. thiebautii</i>	12	156	—	2	—	—	4	—

1.07 to 591.4 mg/m<sup>3</sup> in 1975 and from 1.44 to 540.54 mg/m<sup>3</sup> in 1977. Pheophytin values (not shown in the Figure) were higher than chl. *a* in the 1975 season and ranged from 2.1 to 934.5 mg/m<sup>3</sup>. During the peak bloom season, both chl. *a* and pheophytin were high. During 1977, however, pheophytin values were lower than those of chl. *a*. In the non-bloom area, chl. *a* during the 1977 season was much greater than in 1975 and was largely contributed by other algae (Fig. 12).

In *T. thiebautii*, besides chl. *a*, the characteristic pigment has been reported to be phycoerythrin<sup>9</sup>. This pigment is similar to fucoxanthin of diatoms and peridinin of dinoflagellates. It is the main pigment which absorbs light energy for photosynthesis and has 3 absorption peaks at 495, 547 and 565 nm. In the other blue-green algae, phycoerythrin has a single peak. Excitation of chl. *a* band in *T. thiebautii* at 679 nm produces photosynthetic rate comparable or slightly higher than that produced

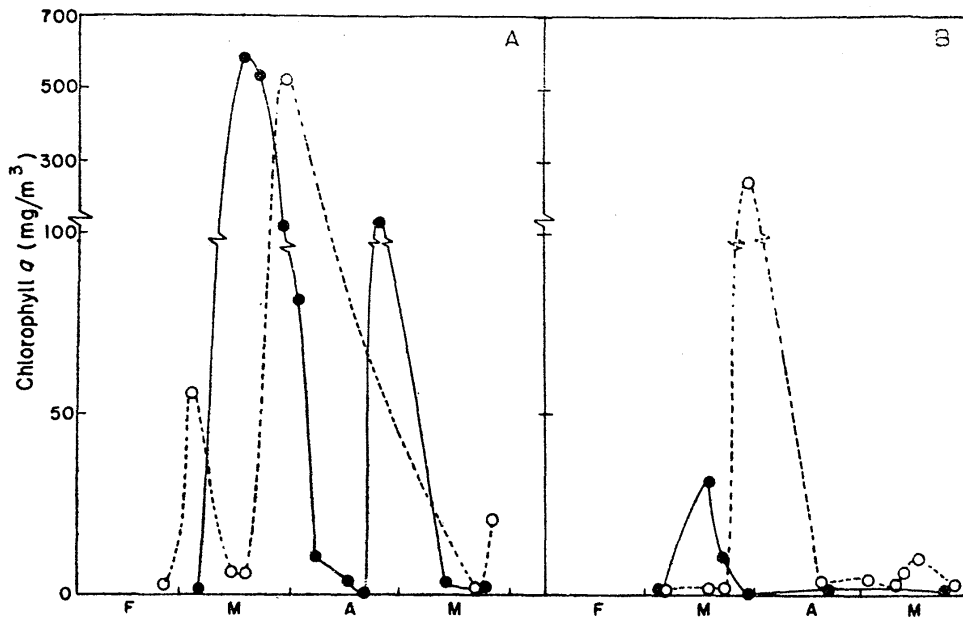


Fig. 12 — Chlorophyll *a* in bloom area (A) and non-bloom area (B) during 1975 (●—●) and 1977 (○...○) seasons

by the excitation of phycoerythrin bands (562 and 543 nm). The triple peaked phycoerythrin functions as a light capturing pigment in *T. thiebautii* similar to the single peaked phycoerythrin of other blue-green algae. In *T. thiebautii* phycoerythrin varies from 0.7 to 0.1 mg/mg chl. *a*<sup>9</sup>. Moreth and Yentsch<sup>10</sup> give the phycoerythrin content as 6% of chl. *a* in a moderate bloom of *T. thiebautii* off Florida coast. In the present investigation, since the measurements were made at 665 nm, the values shown in Fig. 12 refer to chl. *a* only.

**Zooplankton population** — During the 1975 season, zooplankton collected from the bloom patches showed that copepods were the most dominant group. However, from time to time, other organisms such as chaetognaths, salps, fish eggs etc., were also abundant and some of these exceeded copepods in terms of biomass (Table 4). The pteropods *Cavolinia* and *Creseis acicula* and the cladoceran *Evadne* sp. were also common in the samples. On one occasion, salps alone contributed almost to the entire biomass. Zooplankton hauls taken from the bloom and non-bloom areas in 1975 clearly show the dominance of several organisms in the bloom area also (Table 4). Therefore, the earlier view that zooplankton organisms avoid *Trichodesmium* blooms does not appear to be valid. Collections made with a hand net in the top-most layer of the surface water within the bloom revealed the following organisms in the order of abundance: pontellids, nematodes, medusae, chaetognaths, polychaete larvae, lucifers, isopods, *Alima* larvae, *Porpita* and bivalve veligers.

The floating mass of *Trichodesmium*, when examined, revealed a host of animals such as small crabs, isopods, *Alima* larvae, lucifers (sergestids), veligers of bivalves and prosobranchiate gastropods, pteropods, polychaetes, amphipods, siphonophores, medusae and fish eggs. *Pontella* sp. was found jumping within the bloom throughout the observation.

Many specimens of *Therapon jarbua*, carangids and fish larvae were found swimming actively in patches of dense bloom. Thus the bloom becomes a complex community of plants and animals. During the 1977 season, copepods dominated the samples followed by siphonophores, fish eggs, chaetognaths, medusae and *Creseis acicula* (Table 4). In the 1978 season of the bloom, apart from copepods, gelatinous forms were also abundant.

It has been reported earlier that phytoplankton, zooplankton and other animals become sparse in Goa waters during *Trichodesmium* blooms<sup>5</sup>. However, as noted above, the present studies indicate that zooplankton organisms are fairly well represented and their total biomass in bloom areas is not very different from that of the other (bloom-free) seasons. Sakthivel and Haridas<sup>11</sup> recorded swarms of a pteropod (*Creseis acicula*) and a cladoceran (*Penilia avirostris*) in association with *Trichodesmium* bloom. They also noted that larger animals (nekton) were relatively sparse but some zooplankton organisms were fairly abundant during the bloom. Bowman and Lancaster<sup>12</sup> found that calanoid copepods (mostly *Paracalanus* and *Acartia* spp) and chaetognaths were abundant in *Trichodesmium* bloom samples collected from Tonga Islands. Verlekar<sup>13</sup> noted swarms of *Physalia* in association with *Trichodesmium* bloom. Marumo<sup>14</sup> found that *T. thiebautii* bloom usually occurs in association with other organisms such as *Oscillatoria*, diatoms and copepods forming a complicated plankton community.

**Fish population** — Trawl operations in the areas of dense bloom showed fish catches similar in size and composition as in non-bloom areas. The bulk of the catch was composed of less-valued trash fish. Gut contents of the following fishes from the catch were examined: *Sardinella albella*, *Therapon jarbua*, *Caranx* spp, *Ambassis* sp, *Trichiurus* sp, *Otolithus ruber*, *Stromateus niger* and *Leognathus* spp. In

TABLE 4 — BIOMASS AND DOMINANT ZOOPLANKTON ORGANISMS OCCURRING IN BLOOM AND NON-BLOOM AREAS

Date	Bloom area*			Non-bloom area		
	Isobath (m)	Biomass (ml/m <sup>3</sup> )	Dominant organisms	Isobath (m)	Biomass (ml/m <sup>3</sup> )	Dominant organisms
5-3-75	20	0.049	Copepods and chaetognaths	—	—	—
10-3-75	20	0.374	Salps, chaetognaths and copepods	—	—	—
18-3-75	14	0.028	Copepods, <i>Acartia</i> , <i>Labidocera</i> , <i>Eucalanus</i> sp. and <i>Sergestid</i> larvae	18	0.008	Copepods and Lucifers
22-3-75	10	0.024	Copepods and Lucifers	—	—	—
22-3-75	12	0.049†	Copepods, crab zoea, proto-zoea and non-penaeids	18	0.033	Copepods, protozoa, zoea, juveniles of crab and Lucifers
29-3-75	18	0.028	Copepods, fish eggs, cladocera and crab zoea	—	—	—
29-3-75	18	0.049†	Mainly copepods	11	0.004	Copepods and fish eggs
2-4-75	20	0.089†	Copepods, <i>Evadne</i> and siphonophores	10	0.081	Copepods and <i>Evadne</i>
7-4-75	18	0.020†	Mainly copepods	—	—	—
7-4-75	15	0.008	do	—	—	—
16-4-75	12	0.163	Copepods, salps, <i>Cavolinia</i> and <i>Creseis acicula</i>	—	—	—
16-4-75	16	1.472 (Salps alone 1.341)	Salps, isopods, copepods, <i>Creseis acicula</i> and <i>Cavolinia</i>	20	0.106	Salps, copepods, chaetognaths and cladocerans
21-4-75	10	0.020	Mainly copepods	15	10 (Salps alone 9.959)	Salps, copepods and chaetognaths
25-4-75	20	0.024	do	15	4.472 (Salps alone 4.390)	Salps and copepods
29-4-75	20	1.220	Chaetognaths, salps and copepods	10	0.024	Chaetognaths and copepods
13-5-75	10	0.051	Copepods and chaetognaths	—	—	—
24-2-77	10	0.101	Copepods, siphonophores, fish eggs and chaetognaths	15	0.020	Copepods, chaetognaths, <i>Creseis acicula</i> and <i>Cavolinia</i>
4-3-77	12	0.024	Copepods and medusae	—	—	—

\*Biomass including *Trichodesmium* filaments and clumps.

†Samples collected between 3 and 5 m depth.

*S. albella*, the gut contents included fairly large quantities of *Trichodesmium* filaments, whereas *Therapon*, *Caranx* and *Trichiurus* contained only a few filaments. Besides fishes, the gut contents of *Squilla* also contained filaments of *Trichodesmium*.

#### Characteristics of Blooms

**Shape and formation of bloom** — The bloom was found floating at the surface and it largely occupied a layer of few centimetres from the top. At times, the bloom had a semicircular shape over an area of 3-5 km where the depth of water was 10-20 m. On other occasions (April), it was seen drifting in irregular patches. These patches are probably formed because of changing sea state associated with mixing of water. Very often, the bloom was spread out in the form of long bands or lanes. This could be because of circulation induced by convection prevailing in the top-most layers as a result of intense evaporation. Mixing and convective circulation under the influence of tidal currents probably lead to the distribution of bloom in the form of long bands.

Defant<sup>15</sup> made the following remarks on the long bands of foam often seen in the sea 'the long lines of foam frequently observed on the sea surface can be regarded as "convective rolls" formed by a combination of strong current in a single direction and circulations in convection cells'. Presumably,

like the foam, the convective circulation prevailing in these waters helps in concentrating the filaments into dense patch and its subsequent spreading into linear bands. At times, thick patches of bloom were mixed with foam. Thus the continued formation of blooms as bands is because the filaments become highly buoyant and remain afloat for a long time, possibly for several weeks. The sudden disappearance of the bloom from the surface may be due to dispersion of filaments as a result of wave action. They reappear and congregate at the surface when calm weather recurs. This phenomenon goes on intermittently throughout the season. In the bloom areas, the temperature of water was relatively higher than in the non-bloom areas. This may be due to higher viscosity of water in bloom patches.

The bloom, as noted earlier, was largely confined to the surface (<5 cm). At depths >5 cm, the contribution of *Trichodesmium* was almost negligible even when dense bloom persisted at the surface. This feature of *Trichodesmium* is unlike any other algae because during the bloom they normally get well distributed within a few metres below the surface. Platt and Subba Rao<sup>16</sup>, while working on a mixed diatom bloom, observed that the density of algae remained very high in the water column between 1 and 10 m. Towards the end of the bloom,

most of the patches of *Trichodesmium* got concentrated in the form of slicks.

The appearance and congregation of *Trichodesmium* filaments may be related to stability and stratification of coastal waters. From February to April, the surface temperature showed a progressive increase while the salinity did not show any significant change. Depthwise temperature showed quasi-isothermal conditions with marked diurnal fluctuations. As a result of intense radiation (heating), surface temperature reached maximum at about 1400 hrs. During the night, surface temperature became low because of evaporative cooling and the stabilities computed showed unstable conditions. Presumably because of such day and night changes in temperature and stability, the filaments and clumps keep coming up to the surface.

Clumps of *Trichodesmium* were found to have highly variable numbers of filaments. The filaments of *Trichodesmium* during the bloom are long and resemble *Oscillatoria* (Plate I, Fig. 1). However, from the literature it is not clear whether *Trichodesmium* is another phase of *Oscillatoria* — probably its bloom phase — or *Trichodesmium* is an organism quite different from *Oscillatoria*. These filaments get aggregated and form bundles or clumps. The total

number of filaments in each clump was highly variable (Plate I, Fig. 2) and a large clump is somewhat oval-shaped and may have nearly 150-190 filaments (Plate I, Fig. 3). The number of filaments in the clumps varied from day to day as the following table will indicate:

Sampling date	Range in number of filaments in 25 clumps	Av. No. of filaments/clump	Sampling date	Range in number of filaments in 25 clumps	Av. No. of filaments/clump
18-3-75	30-100	69	4-3-77	15-76	52
22-3-75	28-190	102	15-3-77	44-72	57
29-3-75	20-55	36	23-3-77	21-110	56
2-4-75	35-110	67	29-3-77	33-72	51
21-4-75	12-68	44	28-5-77	28-96	68
25-4-75	16-140	54	—	—	—

The density and profusion of the bloom vary from year to year. The bloom studied in 1975 with a maximum density of 38640 filaments/ml was far more massive and dense than that of 1977 when the maximum density was 8750 filaments/ml. However, the most puzzling feature of *Trichodesmium* appears to be its insignificant presence in the phytoplankton during its pre-bloom phase. In the entire euphotic zone, very small numbers of *Trichodesmium* were

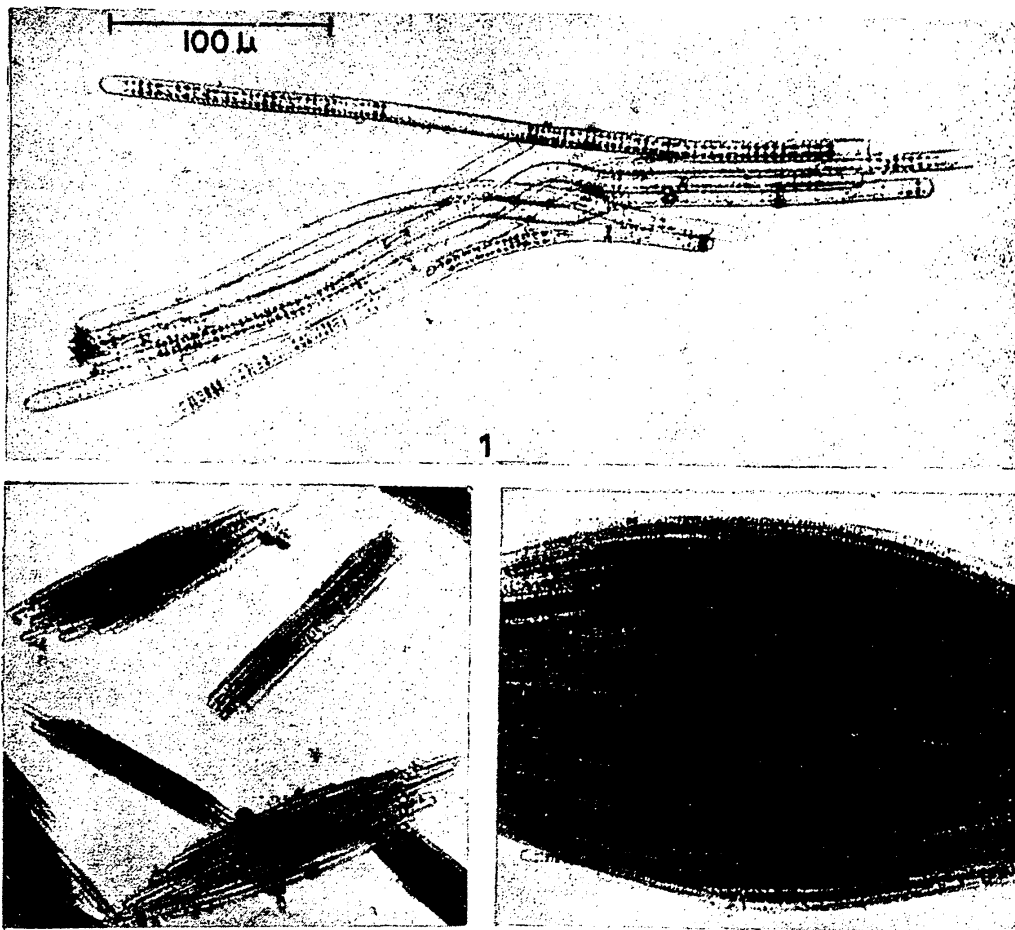


Plate I—Shape and formation of *Trichodesmium* clumps [(1) Filaments of *Trichodesmium* during bloom. (2) *Trichodesmium* clumps showing variable numbers of filaments during bloom. (3) A single large *Trichodesmium* clump]

recorded a few days before the bloom. The sudden explosion of filaments all over the sea surface in the form of bloom suggests that possibly the organism occurs in some other form in the sea, probably as small spores which remain unnoticed. With the return of favourable conditions, the spores quickly grow into filaments. The other possibility could be that the organism in the non-bloom season remains distributed throughout the water column of the illuminated zone and hence, sampling in the non-bloom season will show only a few filaments here and there. With the commencement of the bloom, the filaments probably develop vacuoles, become buoyant and come to the surface, and the prevailing convective circulation makes the filaments congregate in the form of blooms. The intensity and profusion of the bloom noticed in Goa water was never as high as the bloom noticed in Lakshadweep earlier<sup>3,4</sup>.

*Occurrence of blooms in other regions*—Many authors have recorded blooms of *Trichodesmium* from other parts of the Arabian Sea and Bay of Bengal. These records are summarized in Table 5. In the Arabian Sea and Bay of Bengal, blooms of *Trichodesmium* occur from February to May, although some reports suggest that they may appear in other months also. Besides the Indian Ocean, blooms of *Trichodesmium* have been reported from other parts of the world oceans. Baas-Becking<sup>17</sup> recorded *Trichodesmium* bloom spreading over an area of 40000 sq. km in the Great Barrier Reef region.

The earliest authentic record of *Trichodesmium* bloom is difficult to obtain from the literature. Darwin<sup>18</sup> recorded *Trichodesmium* bloom during the Voyage of the Beagle. Subsequently, towards the end of the last century, many explorers recorded the blooms. Some of the earlier reports from other geographical region are given in Table 5 as footnote.

*Colour of the bloom*—When the bloom starts appearing, needle-shaped filaments are seen like dust sprinkled over the sea surface (Plate II, Fig. 1).

The bloom does not impart any colour to the water at this stage. However, after a few days, large patches begin to appear giving them the appearance of sprinkled saw-dust (Plate II, Fig. 2). At this stage, the colour of the bloom is grey. As the bloom gets older, it begins to impart shades of reddish brown colour and in bright sunlight it makes the sea look reddish in wavy lines (Plate II, Fig. 3). After some days, the bloom gets more and more concentrated and gives distinct reddish brown colouration to the water. At this stage, the floating mass of the bloom gets mixed with foam and begins to drift. Its colour becomes greyish brown indicating the decaying phase (Plate II, Figs. 4-6).

On the colour of the bloom, Wimpenny<sup>19</sup> made the following observations:

“The red colour of this species is due to a pigment called ‘phycoerythrin’, although the characteristic colour of the blue-green algae is brought about by a blue pigment called ‘phycocyanin’, present in addition to the usual green and yellow pigments and the occasional red one”.

Very often, the reddish brown colour of the bloom continues to remain even when the bloom has reached its decaying phase. In Plate III, Figs. 1 to 3 show decay and disintegration of the bloom and its eventual disappearance.

When the sea water containing the bloom is filtered in the laboratory, a pink filtrate is obtained which becomes blood red after some time (Plate III, Fig. 5a). The colour begins to fade with time and the filtrate looks brown first and finally it becomes colourless. The chemical characteristics of the pink and blood red solution are not known.

*Time and periodicity of bloom in Goa waters*—In 1975, the bloom was first seen on 27th February, and in the 2nd week of March the bloom was almost at its peak. Throughout April, the bloom continued to appear intermittently and it was at various stages of profusion. In early May, the bloom began to decline and by the middle of May, the bloom

TABLE 5 — PLACE AND TIME OF OCCURRENCE OF *Trichodesmium* BLOOM IN THE ARABIAN SEA AND BAY OF BENGAL AS RECORDED BY DIFFERENT AUTHORS

Place	Month	Place	Month
ARABIAN SEA			
Mangalore <sup>23</sup>	March	Mormugao*	February-June 1975
Cochin <sup>24</sup>	do	do	March-April 1976
Mimicoy <sup>22</sup>	—	do	February-May 1977
Lakshadweep <sup>3,4</sup>	April	do	January-March 1978
Vengurla, Mormugao and Karwar <sup>5</sup>	March-April	Cape Comerin <sup>25</sup>	December
Cochin <sup>11</sup>	March	Mangalore <sup>26</sup>	March
Mormugao†	March-April 1973	Vengurla-Malwan <sup>27</sup>	May
BAY OF BENGAL			
Palk Bay <sup>28</sup>	—	Gulf of Mannar <sup>28</sup>	May
Krusadai Island <sup>29,40</sup> (Gulf of Mannar)	April, May, July, October and November	Porto Novo <sup>41</sup>	March

Some reports of *Trichodesmium* blooms in other parts of the world are: Bay of Tor (Gulf of Suez)<sup>41</sup>, East Indies<sup>42</sup>, Atlantic<sup>18,43</sup>, Arafura sea<sup>44,45</sup>, Pacific (Low Isles)<sup>46</sup>, Java Sea<sup>47</sup>, East coast of Borneo<sup>48</sup>, West coast of Florida<sup>49</sup>, Pacific<sup>17</sup>, Red Sea<sup>1,2</sup> and Pacific Ocean (Tonga Islands)<sup>12</sup>.

\*Present authors.

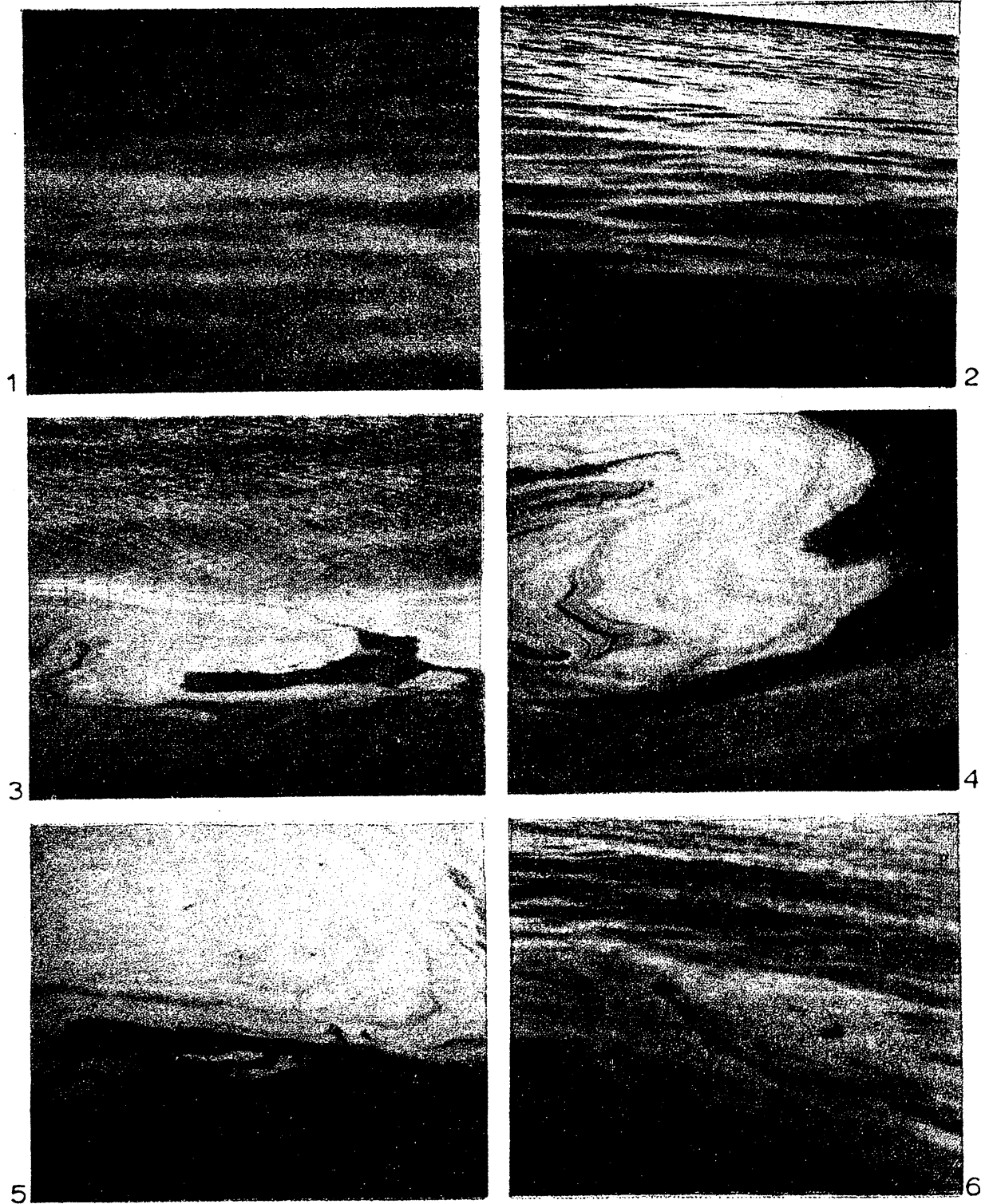


Plate II — Colour characteristics of *Trichodesmium* bloom [(1) Beginning of bloom in the sea when filaments look like sprinkled saw-dust over the sea surface. (2) Reddish brown shades imparted by *Trichodesmium* bloom in bright sunlight. (3-6) *Trichodesmium* bloom as a floating mass and progressively approaching decaying phase]

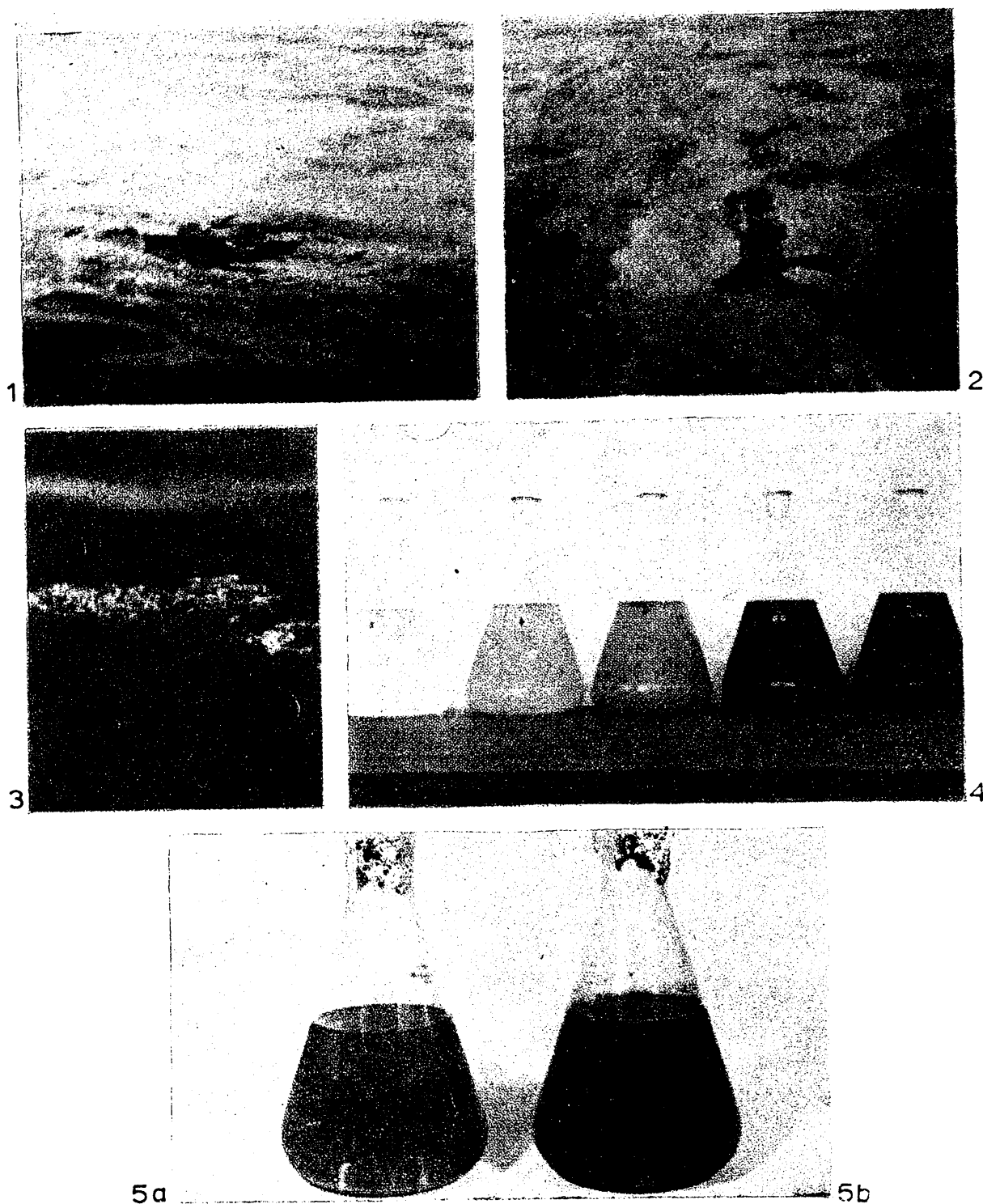


Plate III — Colour characteristics of decaying *Trichodesmium* bloom [(1 and 2) Decaying phases of *Trichodesmium* bloom when pinkish brown colour continues to persist. (3) Decaying slick of bloom. (4) Different grades of colour imparted by bloom (first flask from the left has no *Trichodesmium*, the other 4 have different stages of decay of bloom). (5a) Colour of sea water after filtering *Trichodesmium* clumps. (5b) Colour of sea water with *Trichodesmium* bloom in it]

disappeared completely. In 1976, although no studies were made on the bloom, it was seen in profusion in the nearshore waters of Goa in the 3rd week of March. In 1977, the bloom was first seen on 19th February when the observations began and towards the end of February the bloom was widespread. The bloom continued intermittently till the middle of April and disappeared towards the end of April. In 1978, the bloom was first seen on 20th January and on 27th January, the bloom was fairly widespread giving it the appearance of sprinkled sawdust. On 31st January, thick patches of bloom were noticed. From this account it is clear that there is a marked periodicity in the appearance and disappearance of *Trichodesmium* bloom. The exact time of appearance and disappearance, however, may vary with the state of the sea. In the Arabian Sea (off Goa), blooms last from February to April, and if the conditions are favourable, they may start appearing even towards the end of January and may continue till the early part of May. The striking feature of the bloom is the regularity with which it appears and disappears during the year.

*Other algae and bloom* — During the pre-bloom period, both  $^{14}\text{C}$  uptake and chl. *a* were low. Soon after the bloom becomes widespread, the values of both these parameters suddenly become very high. These are largely contributed by *Trichodesmium erythraeum*, *Nitzschia closterium* and *Chaetoceros* spp, and indicate that the bloom of *Trichodesmium* is followed by the growth and succession of other algae. In 1975, carbon assimilation during the season varied from 2.9 to 517.7 mg C/m<sup>3</sup>/hr and during 1977 from 13.51 to 326.32 mg C/m<sup>3</sup>/hr. Chl. *a*, pheophytin and particulate organic carbon gave a positive correlation with carbon assimilation. However, during laboratory experiments with the natural bloom (Fig. 13), it was noticed that after an initial increase, chlorophyll *a* showed a decline. In the bloom areas also, pheophytin concentration increases rapidly providing an evidence that as the bloom advances, *Trichodesmium* becomes physiologically inactive.

The important feature observed, however, during both the seasons of investigation is the abundance of other algae during the bloom period. As can be seen from Table 2, in 1975, there was also a bloom of *Nitzschia closterium* in March and April in association with the bloom of *Trichodesmium*, and immediately after the bloom in May and June, several other diatoms became very abundant. Most of these diatoms were not so abundant in non-bloom areas (Table 2). During the 1977 season, again *Nitzschia closterium* occurred in large numbers, practically throughout the season of bloom (February-May) along with the other diatoms in both bloom and non-bloom areas (Table 3). The other interesting feature noticed during the 2 seasons was the abundance of *T. thiebautii* along with *T. erythraeum*, but the former species never formed blooms comparable with the latter.

*Bloom and mortality of animals* — No mortality of fish or any other animal was ever seen in association with the blooms of *Trichodesmium* and hence it can be inferred that these blooms are totally non-toxic in nature. Similarly, no irritation or

ill-effect was ever felt after handling the bloom. An indirect effect leading to mortality of animals could possibly be as a result of depletion of oxygen during the decay of the bloom. However, this can only happen in sheltered bays or lagoons and not in the open sea. Similarly, fish mortality can also take place due to choking of gills by *Trichodesmium* filaments<sup>20</sup>. Baas-Becking<sup>17</sup> recorded mass mortality of corals by the decomposition of thick mats of *Trichodesmium* in the Great Barrier Reef region.

*Trichodesmium as food of animals* — Analysis of the gut contents of fishes and other animals collected from the bloom areas indicates that *Trichodesmium* is not much favoured as food. Of all the animals examined, only *Sardinella albella* was found to ingest appreciable quantities of *Trichodesmium* filaments. In all other animals, only a few filaments of *Trichodesmium* were seen in the guts and these were probably ingested accidentally. Noble<sup>21</sup> reported small quantities of *Trichodesmium* in the gut of the mackerel (*Rastrelliger kanagurta*) during April-May and November-December. Nagabhushanam<sup>22</sup> observed that the tuna shoals avoided the blooms of *Trichodesmium* in Minicoy. Some earlier authors have reported that *Trichodesmium* formed an important item of food of fishes<sup>23,24</sup>. From our observations, it is evident that *Trichodesmium* is ingested only accidentally while the fish is probably negotiating the bloom.

*Trichodesmium and nitrogen fixation* — The ability of *Trichodesmium* to fix nitrogen appears to be well established. Several earlier authors suspected the possibility of nitrogen fixation in *Trichodesmium*<sup>3,4,25</sup>. The first positive evidence of nitrogen fixation in *Trichodesmium* was obtained by Dugdale *et al.*<sup>26</sup> using  $^{15}\text{N}$  technique. Goering *et al.*<sup>27</sup> provided further proof of nitrogen fixation in *Trichodesmium*. However, in the blue-green algae, the ability to fix nitrogen is largely confined to those which possess heterocysts<sup>28</sup>. Since *Trichodesmium* lacks heterocyst, Fogg *et al.*<sup>29</sup> suggested the possibility of potential nitrogen-fixing microbes being associated with the cells and these were probably responsible for fixing nitrogen. Carpenter and McCarthy<sup>30</sup>, however, found that the bacteria isolated from *Oscillatoria thiebautii* did not fix nitrogen. Recently, Carpenter and Price<sup>31</sup> provided a clear proof for aerobic nitrogen fixation in *Trichodesmium*. This fixation is associated with centrally located cells present in the filaments of *Trichodesmium* which act like heterocysts of the other blue-green algae. These cells do not incorporate  $\text{CO}_2$  as determined from autoradiographic studies and, therefore, they do not probably produce oxygen which deactivates nitrogenase<sup>31</sup>.

*Release of nutrients by bloom* — With the progression of the bloom, the concentrations of  $\text{PO}_4\text{-P}$ ,  $\text{NO}_3\text{-N}$  and  $\text{NH}_4\text{-N}$  increase in the water. Thus there is a clear ecological evidence to suggest that both phosphorus and nitrogen are released by the filaments during decay as extracellular products. That the blue-green algae have the ability to liberate nitrogen as extracellular products, has clearly been demonstrated by Stewart<sup>32</sup>. Large differences in the nutrient concentrations between bloom and non-bloom areas (Figs. 5-8) indicate that the mere



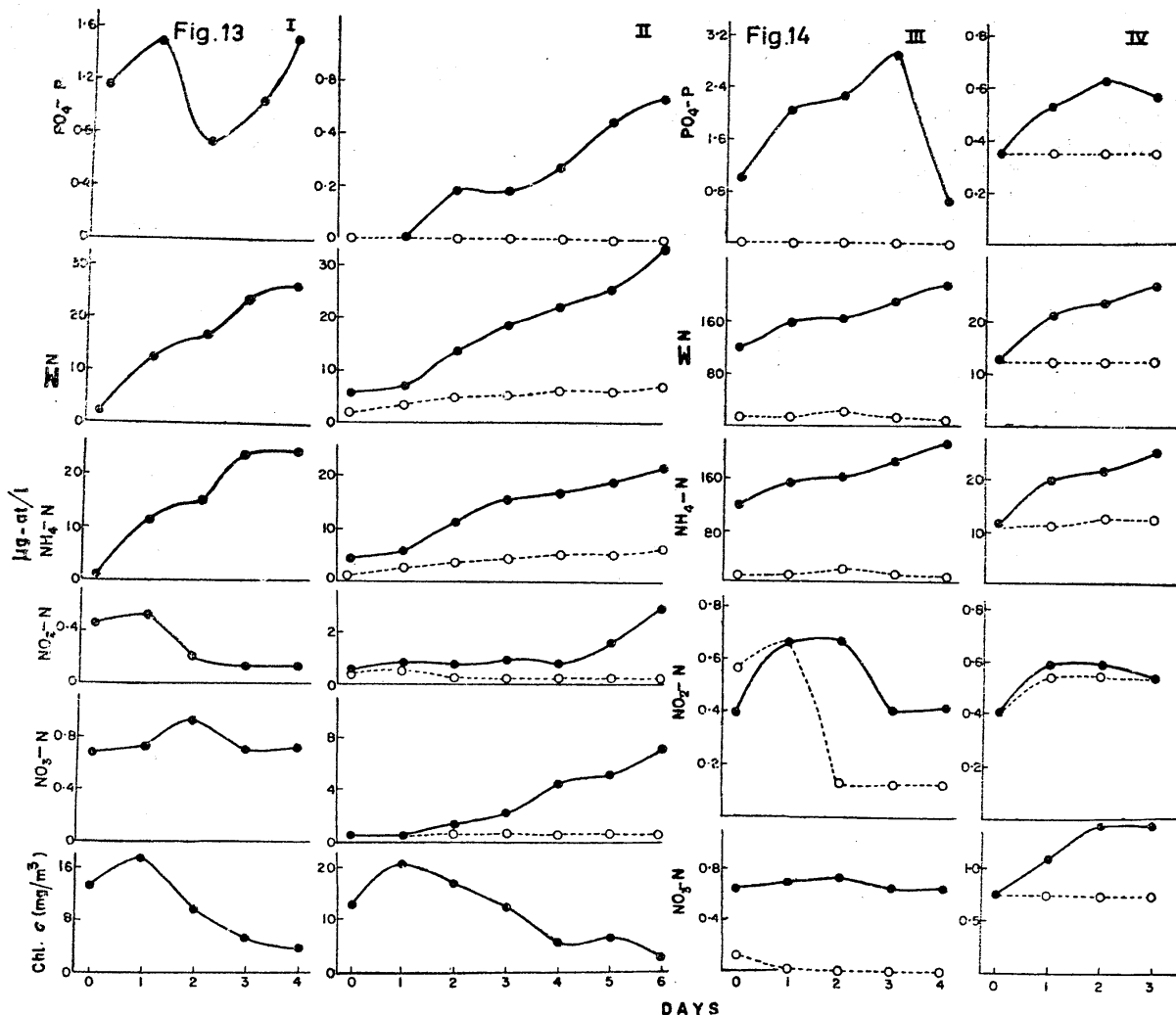


Fig. 13—Two sets of laboratory experiments (I and II) showing the release of nutrients and chlorophyll *a* in the medium on death and decay of *Trichodesmium* [●—●, flasks with *Trichodesmium* (experimental) and ○...○, flasks with sea water only (control)]. Each curve is based on two replicate experiments conducted during 1977 season]

Fig. 14—Release of nutrients in the medium on death and decay of *Trichodesmium* [●—●, flasks with *Trichodesmium* (experimental) and ○...○, flasks with sea water only (control)]. Each curve is based on 4 replicate experiments. Set III was conducted during 1977 season and set IV during 1978 season]

presence of bloom in an area, even if it is intermittent, leads to release of nutrients. This is followed by growth of other phytoplankton organisms in the bloom area (Fig. 11). Further evidence towards the release of nutrients by *Trichodesmium* was obtained experimentally as follows:

Three sets of experiments were conducted with *Trichodesmium* bloom in May 1977 and one set in February 1978. Natural blooms collected from the sea were brought to the laboratory and kept in several flasks containing sea water. Controls had only filtered sea water. Each set had 4 experimental flasks. In the 1st experiment,  $PO_4-P$ , total nitrogen,  $NH_4-N$ ,  $NO_2-N$ ,  $NO_3-N$ , and chl. *a* were measured daily for 5 days. In the 2nd experiment, measurements were continued for 6 days and in the 3rd and 4th sets for 4 and 3 days respectively. The results of these 4 experiments are shown in Figs. 13

and 14. In the 1st experiment (Fig. 13), almost all nutrients and chl. *a* increased substantially. However, the total nitrogen and  $NH_4-N$  continued to increase till the 6th day but chl. *a*,  $PO_4-P$ ,  $NO_2-N$  and  $NO_3-N$  declined after the 2nd or 3rd day. In the 2nd experiment, all nutrients recorded an increase up to the 6th day. Chl. *a*, however, started declining after the 2nd day. The difference between the experimental flasks and controls was very pronounced (Fig. 13).

In the 3rd and 4th experiments also, the overall picture obtained was almost similar. Most of the nutrients increased first and then they either became steady or recorded a decline till the last day of the experiment (Fig. 14).

In the Lakshadweep area, where *Trichodesmium* blooms occur in great profusion Qasim<sup>3,4</sup> reported  $PO_4-P$  concentration from the bloom area, higher

than that of normal oceanic water. However, from the same site,  $\text{NO}_3\text{-N}$  was found to be extremely low. Lakshadweep waters being oceanic in nature, are known to have low concentrations of nutrients and hence the data from that area are not comparable with those of the coastal waters of Goa. In the Goa waters, during the 1977 season,  $\text{PO}_4\text{-P}$  concentration remained very high throughout the bloom. However, the values of phosphorus were not so high during the 1975 season.  $\text{NO}_3\text{-N}$ , on the other hand, remained high during both the seasons, and in 1977,  $\text{NH}_4\text{-N}$  remained high even after the bloom had disappeared.

**Growth of algae in decayed bloom**—To determine the enrichment effect caused by *Trichodesmium* bloom on the algae, the following experiment was conducted:

Four different concentrations of medium containing nutrients released from the decayed *Trichodesmium* bloom were taken in large test tubes and used for the experiment (Fig. 15).  $\text{NO}_3\text{-N}$  and  $\text{PO}_4\text{-P}$  concentrations in each tube at the start of the experiment were measured and equal quantities of the culture of *Tetraselmis gracilis* (5 ml) were added to all the test tubes. Control test tubes had only sea water and the same volume of the culture. Cell counts in each test tube were made after 4 days and the experiment was continued for 12 days. At the start of the experiments, all experimental tubes had pink-coloured medium. With the

increasing concentrations of the bloom, the growth of *Tetraselmis* increased, but at the highest concentration in which the 2 nutrients were maximum, growth declined (Fig. 15). This indicates that the nutrients released by the bloom promote growth of other algae at low concentrations. In the sea, because of dilution, very high concentrations of nutrients would seldom occur (Figs. 5 and 6).

**Contribution of *Trichodesmium* towards enrichment during blooms**—From the studies noted above it is possible to calculate as follows the contribution of  $\text{PO}_4\text{-P}$  and total nitrogen made by *Trichodesmium* during the blooms to the total nutrient budget of the sea:

No. of *Trichodesmium* filaments per gram =  $2.2 \times 10^6$ . Release of  $\text{PO}_4\text{-P}$  per gram of *Trichodesmium* =  $6.8 \mu\text{g-at}$ . Release of total nitrogen per gram of *Trichodesmium* =  $1.5 \mu\text{g-at}$ .

Assuming the thickness of the bloom as 1 cm, in both 1975 and 1977 seasons and taking the maximum density of blooms as 38640 filaments/ml and 8750 filaments/ml respectively, the release of  $\text{PO}_4\text{-P}$  during the 1975 bloom would be  $1200 \mu\text{g-at/m}^2$  and total nitrogen  $260 \mu\text{g-at/m}^2$ . During the 1977 season, the contributions of  $\text{PO}_4\text{-P}$  and total nitrogen would be 270 and  $60 \mu\text{g-at/m}^2$  respectively. The massive *Trichodesmium* blooms such as those recorded in the Lakshadweep<sup>3,4</sup> or in the Great Barrier Reef<sup>17</sup> would make a substantial contribution to the nutrient budget of the sea.

The estimation of both phosphorus and total nitrogen made above might be an underestimate for the simple reason that no estimation has been made of organic phosphorus or urea nitrogen or amino acids which may also be released by the filaments.

The foregoing account clearly indicates that the ecological implications of the *Trichodesmium* phenomenon go far beyond its mere occurrence in the sea. The blooms are definitely a source of enrichment to tropical oceans. Each pulse of the bloom is destined to decay and disintegrate and hence the process of enrichment goes on intermittently for several months. In the light of this, the role of *Trichodesmium* blooms becomes very interesting because besides the two well known mechanisms of enrichment of tropical seas which are upwelling and biodegradation of organic matter, a third phenomenon, which is of *Trichodesmium* bloom and which the sea produces on a massive scale each year, becomes just as important. In the Arabian Sea, *Trichodesmium* phenomenon occurs during the premonsoon season (February-April) which is a period of thermal stratification and nutrient impoverishment of the euphotic zone<sup>3</sup>. The enrichment, therefore, through massive blooms of *Trichodesmium* becomes most timely because this period precedes upwelling and possibly any other process of enrichment at this time of the year is also at its minimum.

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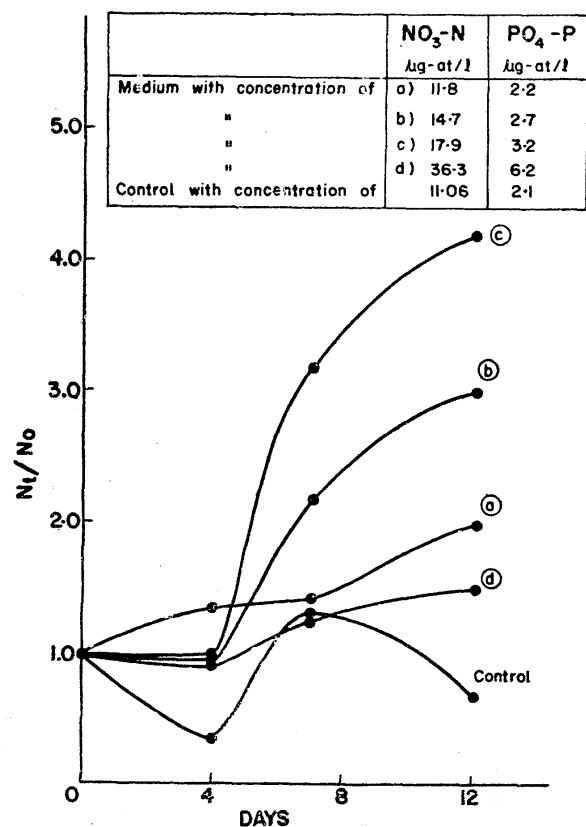


Fig. 15—Growth of unialgal culture of *Tetraselmis gracilis* in different concentrations of the medium containing nutrients released from decayed *Trichodesmium* bloom [ $N_t/N_0$  is the ratio of cell counts at time  $t$  and  $0$ ]

## Note added in proof

While the paper was in press, a publication on *Oscillatoria (Trichodesmium)* has appeared [BORSTAD, G. A. & BORSTAD, L. E., *The Oscillatoria erythroa (Cyanophyta) community of associates. Papers on fisheries, aquaculture and marine biology*, edited by H. B. Stewart (Jr), FAO, Fisheries Report No. 200, December 1977, pp. 51-57]. The observations made in this paper on *Oscillatoria* forming complex micro-communities are in full agreement with the details given by the present authors on *Trichodesmium*.

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