Phosphorus Removal from Natural Waters Using Controlled Algal Production

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Abstract

A series of experiments designed to demonstrate the potential of using managed, attached algal production to permanently remove excess phosphorus from agricultural run-off is described. The experiments were carried out on a secondary canal in the New Hope South region of the Florida Everglades Agricultural Area from October, 1991, to May, 1992. Natural algal populations of periphyton, including species of the genera *Cladophora*, *Spirogyra*, *Enteromorpha*, *Stigeoclonium*, and a variety of filamentous diatoms such as *Eunotia* and *Melosira*, were grown on plastic screens in raceways, under a wave surge regime. Considerable biomass production of algae occurred, and the resulting algal canopy also trapped plankton and organic particulates from the water column. A seven- to eight-day harvest interval was determined to be optimal, and both hand harvesting and vacuum harvesting were employed. The vacuum device is applicable to large scale-up. In source water having total phosphorus concentrations of 0.012–0.148 ppm, mean macro-recovery dry biomass production levels of 15–27 g/m^2/day were achieved. The lower rates occurred in the winter, the higher rates in the late spring. Two techniques were employed to reduce losses of fine material at harvest during the March to May period. Gravity sieving increased mean dry production levels to 33–39 g/m^2/day. The mean phosphorus content of harvested biomass ranged from 0.34% to 0.43%. Total phosphorus removal rates during the spring period of average solar intensity and low nutrient supply, by methods demonstrated in this study, ranged from 104 to 139 mgTP/m^2/day (380–507 kgP/ha/year). Over the incoming nutrient range studied, phosphorus removal was independent of concentration and was 16.3% of total phosphorus for 15 m of raceway. Upstream-downstream studies of overflowing water chemistry (total P, total dissolved -P, orthophosphate -P) showed highly significant reductions of all phosphorus species. Total phosphorus reduction closely correlated with phosphorus yield from biomass removal. Yearly, minimum phosphorus removal rates are predicted that are 100–250 times that achieved both experimentally and in long-term, large-area wetland systems. Engineering scale-up to systems of hundreds of acres is being studied.

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In fresh waters, phosphorus is the primary problem element of cultural eutrophication. Much of the excess phosphorus currently derived from human sources comes from agriculture, although poorly-processed human sewage, urban run-off, and food processing are certainly serious problems. Sewage phosphorus is kept under control by chemical precipitation, although this is one of the most expensive elements of sewage treatment. Agricultural phosphorus is considerably more difficult to treat, since it tends to be more diffuse (from nonpoint sources) and provides a more critical economic factor in terms of the cost of removal.

Since at least the early 1930s (Beadle 1932), it has been documented that freshwater wetlands, largely dominated by higher plants, have the ability to improve the quality of waste water that passes through them. Only in the last two decades, however, has emphasis been placed on understanding the functioning of these wetland systems (Clark & Clark 1979). Recent research has demonstrated a highly variable response in phosphorus assimilation for different wetland types (Fetter et al. 1978; Nichols 1983; Richardson & Marshall 1986; Bastian & Benforado 1988; Gilliam et al. 1988; Hammer 1989; Kadlec & Alford 1989). Organic soils held significantly less phosphorus than highly organic peat (Whigham & Bayley 1978; Richardson 1985). Increased quantities of iron, aluminum, and calcium in inorganic soils allow the formation of compounds that attract and hold additional phosphorus. Recent research using radioactive methods to determine peat accumulation rates in the *Cladium jamaicense* (saw grass) wetlands of the Florida Everglades has found a mean phosphorus uptake rate of 4.4 kgTP/ha/yr, approximately 10% of the maximum rates reported for some wetland systems (Richardson et al. 1991). This rate of uptake is based on a peak accumulation of 3.54 mm/yr, much higher than the rate for the Holocene, and assumes that such a peat accumulation rate in the long term will be continued under future weather, atmospheric chemistry, water regulation, and prairie-burning conditions. Based on 10 years of phosphorus retention in over 200,000 ha of the South Florida Water Conservation Areas, an uptake rate of 2 kgTP/ha/yr was reported (South Florida Water Management District 1992). In a more recent analysis (South Florida Water Management District 1992, Appendix F), a mean long-term phosphorus retention rate for Water Conservation Area 2A was found to be about 3 kgTP/ha/yr.

In the context of the phosphorus management needs of South Florida, algal production has been considered to have potential as a "polisher," because of the recognized ability of algae to efficiently sequester nutrients at very low concentrations (South Florida Water Management District 1991). Many algae are opportunists, however known for an extraordinary capability to accomplish short-term, massive productivity when sufficient nutrients are available. Algal solutions to cultural eutrophication have great promise in terms of the needed, greatly-enhanced efficiency of recyclable ecotechnology. A number of successful, large-scale sewage treatment plants using algae have been built (Oswald 1988).

Algal turf scrubbers (ATS) are cultured communities of attached or benthic algae that can be used to manage water quality or to scrub a variety of nutrients or contaminants from marine, estuarine, and fresh waters (Adey 1987; Adey & Goertemiller 1987). In the latter context, they could be called "periphyton scrubbers." Algal scrubbers are complex algal communities and as such do not show the sensitivities and instabilities characteristic of monocultures of algae (Adey & Loveland 1991). Scrubbers have been used over the last decade to achieve and maintain high water quality for research and in aquarium systems (Adey & Loveland 1991). They have been shown to be effective in removing phosphorus, nitrogen, and other micronutrients from sewage to nutrient-poor Caribbean reef waters. Productivity for algae and other plants generally increases with increasing nutrient concentrations and has strong minimum nutrient limitations. Yet ATS productivity has been demonstrated in excess of 15 g (dry weight)/m^2/day in sea water with total phosphorus concentrations of less than 0.05 μMP-PO_4 = (1.5 ppb).

Algae have considerably less cellulose and carbon in their cell walls than most higher plants and therefore tend to have lower C/P ratios. They are also well known to exhibit "luxury consumption" of phosphorus (Swift & Nicholas 1987) and to store well in excess of immediate needs for growth. In addition, almost all cells of an aquatic algal thallus, particularly in filamentous and unicellular algae, are photosynthetic and participate in storage and growth, with few cells devoted to specialized functions. Adey (1987), for example, was able to demonstrate over twice as much phosphorus in filamentous and unicellular algae than in large macroalgae living in the same oligotrophic environment. Thus, filamentous and trapped unicellular algae in an easily managed and harvestable system would be expected to remove phosphorus more efficiently than macroalgae or vascular plants. The relationships are not simple, however. For example, the mean phosphorus content of 18 wetland macrophytes, including floating, submergent, and emergent forms, was 0.19% (Boyd 1978), while the maximum level was 0.40%. Marine algae growing in highly oligotrophic tropical seas can show high growth rates with tissue phosphorus percentages of less than 0.02%. Adey (1987) and Swift (1981) documented similar levels for periphyton in highly oligotrophic Florida Everglades waters. Nevertheless, growth and phosphorus content in algal periphyton can adjust rapidly to increased phosphorus availability. Abundant data for the Everglades demonstrate a consistent algal tissue concentration for phosphorus that saturates between 0.35% and 0.42%, given a high level of availability in ambient water (Swift 1981). We will describe similar tissue concentrations in algal scrubbers operating at about 50 ppb.

In this paper we describe an attached algal process for phosphorus removal that has been tested, in prototype, in the Everglades Agricultural Area (EAA). It has demonstrated a phosphorus removal efficiency of 380–507 kg/ha/year, or 100–250 times greater than that demonstrated by the proposed macrophyte systems, depending upon what uptake rates would actually be achieved in practice by those systems. In addition, algal scrubbing (or periphyton scrubbing) captures phosphorus in algal tissue. It can be easily harvested, transported, documented, and used as a fertilizer or source of valuable biochemicals, allowing potential recycling. The algal biomass is rich in protein and may be suitable for development as an animal or a human food supplement. This is the kind of ecotechnology that will allow us to buy time in our quest to reduce our load on the biosphere.

Methods

Apparatus. Installation of an ATS experimental system was begun on October 24, 1991, in the middle of the primarily sugar-cane region of the EAA, about 25 km south of Lake Okeechobee, Florida. Plastic "scrubber screens" were installed and allowed to "seed" naturally with local algae. Regular harvests of the algae growing on the screens were initiated on November 22, 1991. The study was continued through May 15, 1992. The scrubbers in this test facility drew water from a secondary drainage canal that is routinely used to drain fertilized cane fields.

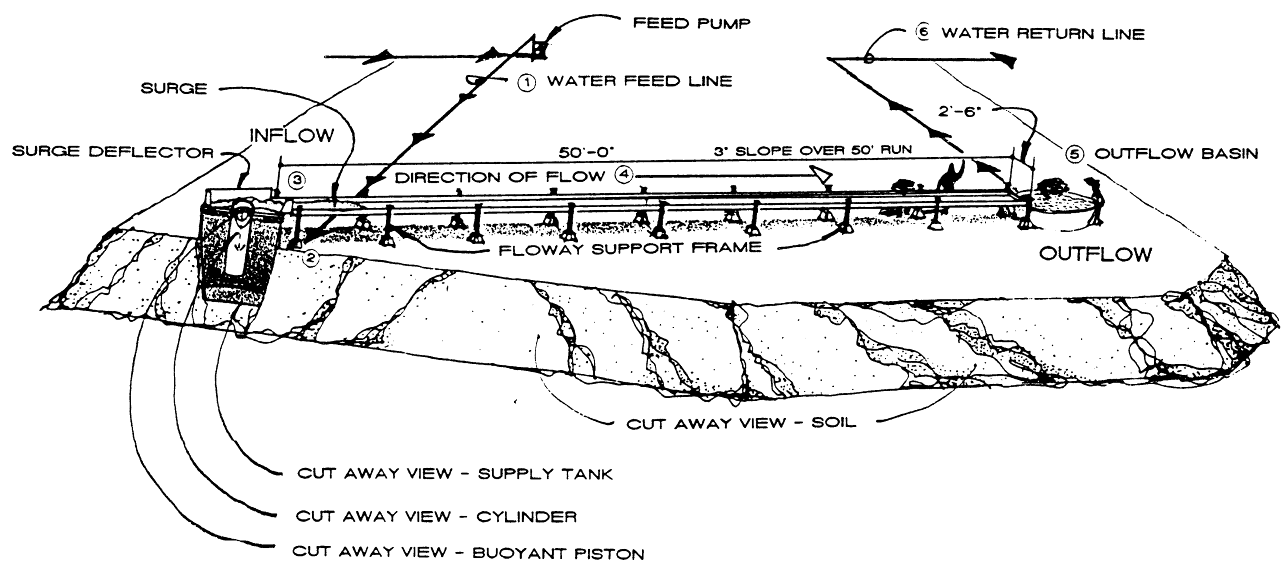

Figure 1. Perspective drawing of "floway" algal scrubber. Dimensions in feet; 1 ft = 0.305 m.

The overall chemistry of input water in this experiment was typical for much of the water standing in the numerous EAA canals during the fall through spring months. The average total phosphorus concentration over the study period was 0.047 mg/l (range: 0.012–0.148; $s = 0.025$; $n = 98$). As the range and standard deviation indicate, total phosphorus levels were quite variable; they peaked during the first week in December and again in the first week of January, then gradually rose through early spring. This value would be considered low during the summer. The pH ranged from 7.6 to 7.7.

Weather conditions were mild throughout the study. Skies were partly to mostly sunny and evaporation greatly exceeded rainfall. Air temperature ranged from 0.5°C to 32.2°C (daily mean was 19.0°C), and water temperature ranged from 18.1°C to 27.2°C during the course of the investigation.

Two types of algal scrubbers were used in this experiment (Figs. 1 & 2). The floway is a 15.2 m by 0.79 m inclined plastic table. It holds 11.49 square meters of screen surface area. The total surface area is divided into eight removable, heavy plastic screens of 2 × 3 mm mesh, each approximately 1.8 m long. It is supplied with an average flow rate of about 100 l/min of canal water in surges at 13–15-second intervals by a Buoyant Piston Pump (BPP). The BPP is a water lifting device consisting of a large lightweight piston that is slowly pulled into the water column and suddenly released. The highly efficient BPP is very gentle on the planktonic larval and spore components of the treated water. The average water depth in the floway ranges from 1 cm at its upstream end to 3 cm toward the downstream end (due to a small weir at the downstream end).

The serial system scrubbers consist of four sets of four in-series scrubbers, each about 1.2 m long and 0.61 m wide. Each of the 16 scrubbers holds its own wave-generating device or "wave bucket." Each scrubber has a screen with a surface area of 0.67 m^2. The total surface area of a serial plant is 2.67 m^2. Each serial scrubber receives an average flow of about 39 l/min of canal water supplied by a 400 l/min feed pump.

Water Chemistry. Input and output water samples for the floway were taken 11 times in replicates of 5 to 10, giving a total of 60 pairs of input/output data. Floway

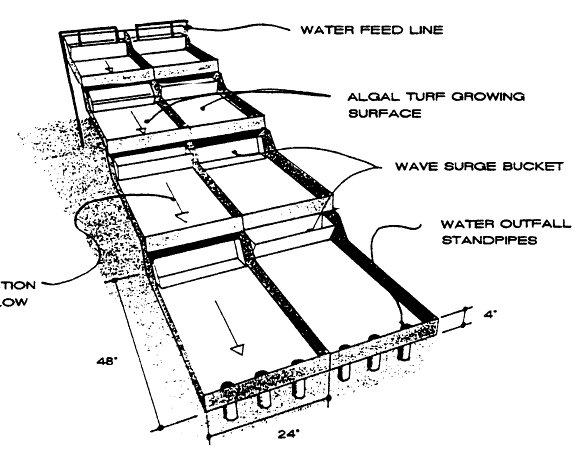

Figure 2. Perspective drawing of serial plant algal scrubber. Dimensions in inches, 1 in = 2.54 cm.

sampling was carried out with an average standing crop of algae at about 4.75 days growth (range = 1–8 days). Input and output water samples for the serial plant were taken seven times in replicates of 3 to 10, typically 5, giving a total of 38 pairs of input/output data for the serial plant. The time of average standing crop for the serial plant was 12.9 days. This number is high, given that algae were usually harvested within 10 days. Some water chemistry data (13 points) were taken in November, when screens were first developing and had over 20 days growth. These samples elevated the mean standing crop from the 7.2-day average that occurred during most of the harvest period.

Chemical analyses were performed by A & L Southern Agricultural Laboratories (ALSAL). Three analyses were carried out on each sample using EPA method number 365.2: total phosphorus (TP); phosphorus as total dissolved phosphorus (TDP) (total phosphorus on a filtered sample [0.45-μ filter]); and phosphorus as orthophosphate on a filtered sample. Floway input samples were taken in the full piston chamber of the Buoyant Piston Pump. Serial input samples were taken from the full wave bucket at the top of each serial plant. Output samples were taken from water after it spilled out of the scrubbers but before it mixed with water in the pools, which return water to the canal. Water flow through the scrubbers was timed so that the output samples were likely taken from the same surge of water that the input samples came from. The residence time for water based on surface flow ranged between one and two minutes. Calculations of the flow prism for the length of the floway in relation to measured pumping rate suggest a somewhat longer residence time (2.5–3.0 minutes). Flow rates were measured during sampling time and recorded.

The 250-ml Nalgene sample bottles were cleaned using 1N HCl. Bottles were filled to the top to prevent air spaces and were put on ice or in a refrigerator within five minutes. They were kept refrigerated until they were filtered and/or prepared for analysis.

Water samples were initially taken in the same bottle in which they were transported to the laboratory. Each bottle was rinsed three times with sample water before the sample was taken. The sample water remained unfiltered until just before being analyzed one to three weeks later. This procedure applied to the first one-fourth of collected samples. The remaining three-quarters of the samples were taken differently to maximize their shelf life. For these, Florida Department of Environmental Regulation guidelines for preparing samples were followed (Florida Department for Environmental Regulations 1990). The samples were taken in a rinsed, clean, one-liter Nalgene bottle. The portion of the 250-ml sample to be analyzed unfiltered was taken first to prevent sedimentation in the one-liter bottle. These samples were acidified with 10 drops of 1:1 H_2SO_4 to a pH below 2. The portion of the sample to be analyzed filtered was prefiltered with a sample rinsed plastic syringe through a disposable 1.0-μ microglass filter. The analytical laboratory (ALSAL) then filtered these samples to 0.45 μ before analysis, which typically occurred one week later. There was no recognizable difference in results between the first sampling method and the second.

Biomass and Productivity. Algal biomass was harvested from floway screens one through eight, one being closest to the BPP. This allowed productivity to be monitored as a function of distance from the water supply. Biomass was also harvested from individual serial plant scrubbers and labeled A, B, C, or D, A being the most upstream screen, "D" the most downstream. Algae were dried and weighed to constant weight (0% moisture) to calculate productivity. Several samples were retested at ALSAL to insure adequate field drying.

Screens were initially harvested by removing the screen from the scrubber and placing it on an inclined easel. Biomass was removed from the screen by scraping with a moderately sharp piece of hard polystyrene plastic. The scraped biomass was collected in a paint strainer of about 0.5 mm mesh size. Biomass was dewatered to between 90 and 97% water by squeezing the strainer. This process is referred to as the "pressure sieve" method. The water that came out of the pressure sieve is called "brown water." An average of 7.66 liters of brown water was generated for every square meter of biomass dewatered. Seventy-four samples of brown water were filtered (0.45 μ), and the solids were weighed and analyzed for total phosphorus content by ALSAL (hydrogen peroxide digestion and method #EPA 365.2) to determine approximately what percentage of potential phosphorus yield was being discarded by this method. Dewatered algae in the form of a patty were then placed in a labeled aluminum pie tin and dried in a drying oven between 50°C and 60°C for two to four days.

After the first month of harvests, a vacuum harvesting system was devised for the floway to speed up the slow manual harvesting process; this system consisted of two "shop vacs" attached to a 200-liter reservoir. Harvesting with a vacuum entailed turning off the water supply, leaving floway screens in place, and vacuuming biomass directly from the screen. When each of the screens had been vacuumed, the biomass removed was then dewatered with a pressure sieve as before.

Both harvest methods were employed with the intention to remove the bulk of the standing crop but to leave behind the algal attachment tissue. This provided "holdfasts" or bases that allowed rapid regrowth of the algae on the screens. Both methods were successful in providing for rapid regrowth of the algae. Since the vacuum method was considerably faster and would allow upscaling without excessive labor cost, most of the floway data reported here were taken by vacuum harvest of in-place screens.

The sum of the weights for dried filtered brown water solids and the pressure-sieved biomass patty represents all the biomass produced that is recoverable by the described experimental technique.

Screens were suspended under the outfall of each serial plant and the floway to catch the algae that sloughed off the screens during their regrowth period. These algae were dewatered and dried in the same way as the other biomass. The days during the harvest period in which the slough was collected were recorded, along with location and dry weight. These data were used to determine when the amount of algae sloughing from the screens reached exponential levels, approaching and eventually reaching the total daily productivity of the system. It is most efficient to harvest at the inflexion point.

A second method was employed to estimate total recoverable dry mass. Eighty-three alternating harvest samples were dewatered by draining/evaporation on 75-μ cloth, retaining nearly all the recoverable solid mass in single samples. When the evaporated samples were dry enough to handle in a single mass, they were then placed in a drying oven as described earlier. This process, called the gravity-sieve method, eliminated the need to analyze brown water by concentrating all solids in a single mass.

Twenty-six pressure-sieve samples, along with their extracted brown water, and thirteen gravity-sieve samples from the floway were analyzed for total tissue phosphorus. The equivalent sample numbers for the serial plant were 10 and 5, respectively. Tissue reduction was carried out by hydrogen peroxide digestion. The percent total phosphorus of the dry mass was then used to calculate phosphorus yield as a function of dry weight productivity.

Results

Community Structure. The algal turf community of both the floway and the serial plant is a natural selection of species from the local periphyton. These elements of the local flora are more adapted to flowing waters. The structure of the community (Fig. 3) is basically that described by Adey and Hackney (1989) and Adey and Loveland (1991), except that the blue-green component is relatively unimportant and the filamentous diatoms more important.

Within a few days after harvesting, the basal algal elements, the attachments or holdfasts, that remain on the screen develop into the essential structure-creating components of the community. These are principally the greens *Cladophora crispata* and *Enteromorpha micrococca*, though at times *Stigeoclonium tenue* and other *Cladophora* species are also present. The second, low "bushy" *Cladophora* could not be securely identified from the literature and may be a small phase of *Cladophora crispata*. For the first few days after harvest, the screens are green, as these species rapidly regrow and additional greens such as *Spirogyra rivularis* and *Dichotomosiphon tuberosus* develop abundantly and ephiphytically among the branches. After several days, the rapidly building algal mass turns golden brown, as diatoms, especially the filamentous species *Eunotia pectinalis* and *Melosira varians*, festoon the primary green algal structure. In limited areas, blue-green mats dominated by *Oscillatoria subbrevis* also occur. Finally, scattered across the screens, branched filaments of the relatively complex red alga *Comosopogon coeruleus*, with the basal cells mostly attached beneath the screen or within the meshwork, work their way up into the algal mass and contribute to both structure and biomass.

The primary difference between algal turf communities previously described for algal scrubbers and the community studied in this experimental investigation is the abundance of filamentous diatoms in the canopy of the mature turf. These diatoms are mostly epiphytically attached to the filamentous green algae. Considering the quantity of phosphorus taken up on particles of less than 0.45 μ in dimension, as we discuss below, it seems likely that after about the fourth or fifth day the turf community begins to act as a filter, abundantly trapping organic particulates and plankters.

A species list for the dominant algal turf components in the test raceways appears in the Appendix. The sampling covered all of the obvious environments of the experimental set-up, and three sample sets were taken, on January 29, 1992, February 24, 1992, and March 6, 1992. The list represents a minimum, however, and is likely to change seasonally.

The faunal or macro-invertebrate community is relatively diverse for such a frequently disturbed (harvested) community. During the study period, eight macro-invertebrates were identified. The bryozoan *Plumatella repens* was common on the underside of screens. Other species only occasionally observed on both floway and serial screens included *Physella cubensis* (snail); *Hyalella azteca* (amphipod); unidentified Cladoceran; and the insects *Trichocorixa* sp. (water boatman), *Baetis* sp. (mayfly larva), *Hydrometra* sp. (marsh treader), and Chironmid larvae.

No herbivorous forms significantly affected algal productivity. Potential grazers of freshwater algal turfs

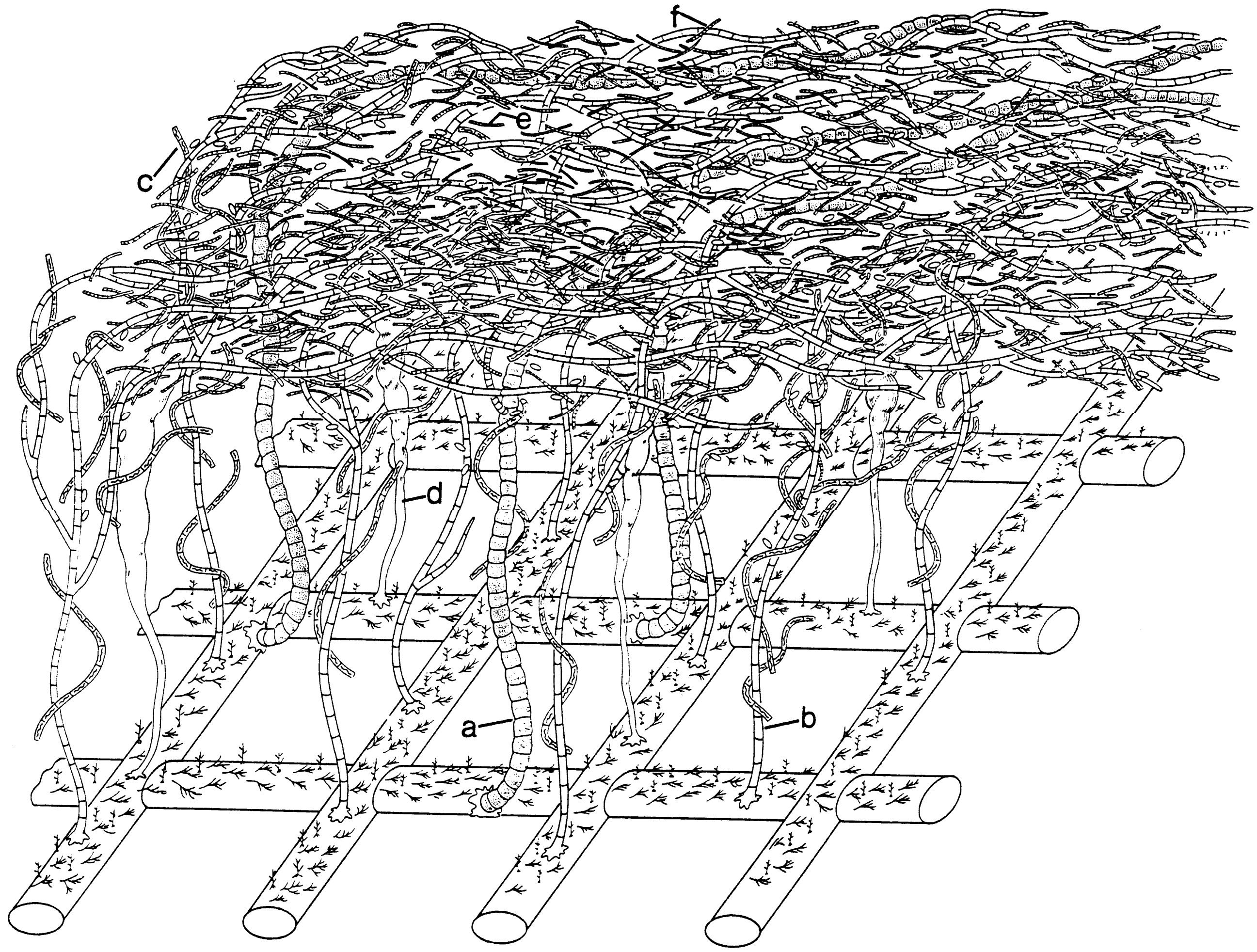

Figure 3. Schematic drawing of primary algal turf species growing on the plastic screen used in the investigation: (a) *Compsopogon coeruleus*, (b) *Cladophora crispata*, (c) *Spirogyra rivularis*, (d) *Enteromorpha micrococca*, (e) *Eunotia pectinalis*, (f) *Melosira varians*. The very small branched alga attached directly to the screen is *Stigeoclonium tenue*, while the numerous small ovoid shapes in the algal canopy represent several small pennolean diatoms, particularly *Amphora* and *Cocconeis* spp. Drawing by Alice Tangerini, Department of Botany, National Museum of Natural History.

(snails, midge larvae, amphipods) were ineffectual at reducing algal biomass. Because of the short harvest interval and the constant disturbance, grazer populations are not able to build to significant levels (Adey & Loveland 1991).

Productivity. The harvest production of algal biomass, taken by the several methodologies described above, is plotted against time in Figure 4. The average productivity of serial plant scrubbers following maturation (beginning at day 22, and not including the sieved or brown water capture) was 21.61 $g/m^2/day$ of direct dry weight biomass ($n = 248$, $s = \pm 6.42$). The average productivity of the floway following maturation (beginning at day 22) was 21.16 $g/m^2/day$ of dry weight biomass ($n = 111$, $s = \pm 7.75$). These estimates of actual biomass production represent minimums, due to the presence of sloughing, minimal grazing, and the loss of particulates in the brown water passing through the sieve. We will call this minimum estimate of algal productivity "macrorecovery." Algal productivity with time, as indicated by macrorecovery, consistently increased from the winter period to late spring (at least until 150–160 days, or April). Although a regression of tested slope has not been performed, a one-way analysis of variance showed productivity to be significantly different each month, with April and May being significantly higher than any other month. Temporary drops in individual harvests are mostly related to forced de-

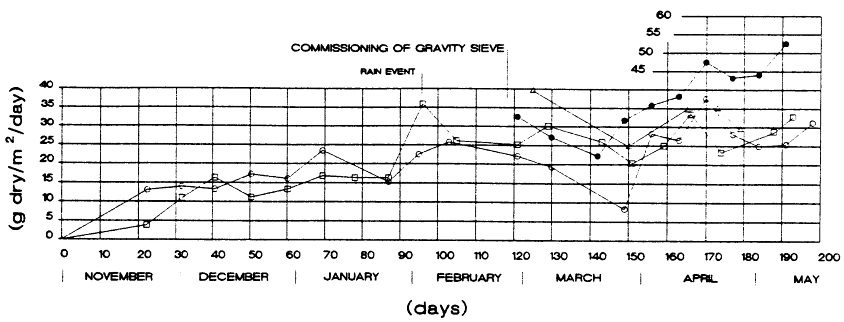

Figure 4. Biomass production from floway and serial systems as a function of time. Squares = serial plant, pressure sieve, brown water not included; open circles = floway, pressure sieve, brown water not included; triangles = serial plant, gravity sieve; solid circles = floway, gravity sieve.

lays in harvest resulting from the unavailability of personnel.

Macrorecovery, or direct manually dewatered harvests, during the period of early March to mid-May, yielded average biomass productivities of 26.78 g/m²/day ($n = 98$, $s = \pm 7.44$) for the serial plant and 25.10 g/m²/day ($n = 40$, $s = \pm 8.77$) for the floway. The dry weight yield for brown water solids (pressure-sieve method) from the serial plant for this period was 5.96 g/m²/day ($n = 39$, $s = \pm 3.77$), and the dry weight yield for brown water solids from the floway was 22.67 g/m²/day ($n = 35$, $s = \pm 14.04$). The mean total reclaimed algal biomass using the pressure-sieve method during the spring period was 47.77 g/m²/day for the floway and 32.74 g/m²/day for the serial plant. Thus, capturing the solids in the brown water of the pressure-sieve results in a highly significant increase (t-test; 0.0001) of total productivity (compared to simple macrorecovery in the same period).

The average productivity of the serial plant using the gravity-sieve method was 33.48 g/m²/day of dry weight biomass ($n = 48$, $s = \pm 7.49$). The average productivity of floway harvests using the gravity-sieve method was 39.01 g/m²/day of dry weight biomass ($n = 35$, $s = \pm 11.01$). Thus, gravity sieving increases recovered biomass by 25–55% compared to macrorecovery. Table 1 summarizes these results.

Phosphorus Content in Biomass. The mean phosphorus content of dry macrorecovery biomass from the floway was 0.374% ($n = 26$, $s = \pm 0.097$), and the mean phosphorus content of dry, macrorecovery biomass from the serial plant was 0.425% ($n = 10$, $s = \pm 0.106$). Examination of the brown water collected by the pressure-sieve method from the floway showed a mean phosphorus content of 0.210% of dry filtrate ($n = 35$, $s = \pm 0.048$), while the mean phosphorus content of brown water collected by the same method from the serial plant was 0.183% of dry filtrate ($n = 39$, $s = \pm 0.057$).

In the gravity-sieve method, where all recoverable biomass was combined, the mean phosphorus content of dry biomass from the serial plant was 0.336% ($n = 5$, $s = \pm 0.062$). The mean phosphorus content of dry biomass taken by the gravity-sieve method from the floway was 0.355% ($n = 13$, $s = \pm 0.045$).

The algal turf scrubbing process, as in a wetlands

Table 1. Dry productivity of algae harvested from the Everglades scrubbers.

Location/Treatment	*Mean Productivity (g/dry/m²/day)*	*N*	*Days Average Harvest Period*
Floway #1 non-evaporated	21.64 ± 9.58	14	8.5 ± 1.99
Floway #2 non-evaporated	23.12 ± 7.13	13	8.38 ± 1.94
Floway #3 non-evaporated	23.60 ± 10.28	16	8.25 ± 1.82
Floway #4 non-evaporated	18.69 ± 6.05	13	8.53 ± 1.82
Floway #5 non-evaporated	20.87 ± 6.77	13	8.46 ± 1.86
Floway #6 non-evaporated	18.78 ± 5.26	14	8.14 ± 1.92
Floway #7 non-evaporated	21.61 ± 6.42	15	8.2 ± 1.87
Floway #8 non-evaporated	19.43 ± 6.55	13	8.23 ± 1.97
Floway 1-8 non-evaporated	21.16 ± 7.75	111	8.33 ± 1.90
Serial all non-evaporated	21.61 ± 9.31	248	8.85 ± 1.64
Floway 1-8 evaporated after 2-26-92	39.01 ± 11.01	35	7.4 ± 1.29
Serial all evaporated after 2-26-92	33.48 ± 7.49	48	8.0 ± 1.66
Floway non-evaporated after 2-26-92	25.10 ± 8.77	40	7.18 ± 0.74
Serial non-evaporated after 2-26-92	26.78 ± 7.44	98	7.81 ± 1.26
Floway brown water reclaimed	22.67 ± 14.04	35	7.14 ± 0.91
Serial brown water reclaimed	5.96 ± 3.77	39	9.0 ± 1.97

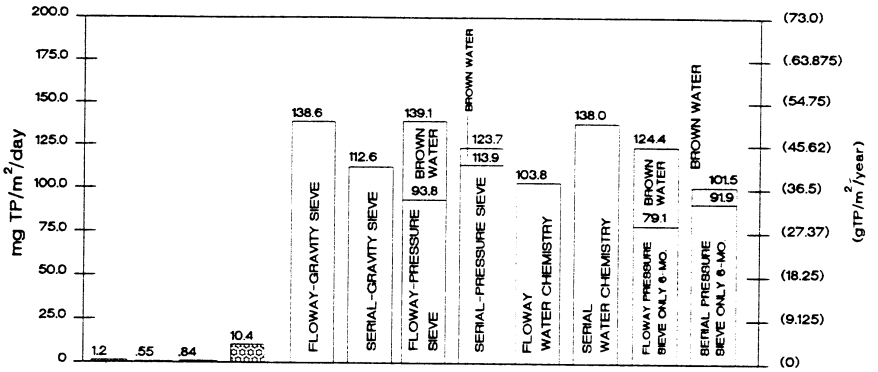

Figure 5. Phosphorus yield of algal turf, grown in the Everglades Agricultural Area, as measured by various methods and compared to sugar cane removal and marsh sequestration. Sources for the comparison bars on the left are (from left to right): Florida Everglades Marsh (Richardson 1991), Florida Everglades Marsh (high and low) (South Florida Water Management District, 1992); sugar cane with tops (Cole, personal communication).

system, removes phosphorus in several ways. Direct phosphorus removal via bioassimilation within the algal structuring elements and the larger epiphytic filaments occurs, and, to a large extent, this appears as the phosphorus in macrorecovery biomass. Algal turfs also remove phosphorus by trapping organic particulates, along with their microbial flora and fauna. This removal, in part, appears in the brown water and the increased yields in the gravity-sieve method, as discussed above. It also appears in the removal of total phosphorus as measured by water chemistry in samples taken upstream and downstream on the raceways. This measurement of yield we discuss later.

The brown water discarded in the early harvesting process contains phosphorus from broken algal filaments, diatoms, and organic sediment. This phosphorus can be reclaimed efficiently by either filtration or settling as we have done in this study.

Phosphorus Yield. The mean phosphorus yield calculated directly from macrorecovery biomass taken in the floway, using the pressure sieve for separation, over the entire period of study was 79 mgTP/m^2/day (n = 26, 111), while the mean phosphorus yield from macrorecovery biomass for the serial plant for the same period was 92 mmTP/m^2/day (n = 10, 248). The mean phosphorus yield for brown water from the floway for the entire period was 45 mgTP/m^2/day (n = 35). The equivalent for serial plant was 10 mgTP/m^2/day (n = 39). Thus, total phosphorus yields using the pressure-sieve method and reclaiming brown water for the entire period of study were 124 mgTP/m^2/day for the floway and 102 mgTP/m^2/day for the serial plant.

The mean phosphorus yield from the floway using the gravity-sieve method during the spring period was 139 mgTP/m^2/day (n = 35, 13). The mean phosphorus yield for the same time and method from the serial plant was 113 mgTP/m^2/day (n = 48, 5). The mean phosphorus yield from macrorecovery biomass plus the accompanying brown water during the spring period, when some samples were alternately being evaporated, was higher than the yield for the whole six-month period. This is to be expected because of the greater light availability. During this time the total phosphorus yield from the floway was 139 mgTP/m^2/day (n = 40, 26 + 35), or 12% higher than the six-month average, and the same as that from the gravity-sieve method. During the spring period, the total phosphorus yield from the serial plant was 124 mgTP/m^2/day (n = 98, 10), or 24% higher than the six-month average and 10% higher than that found by gravity sieve. Figure 5 compares phosphorus yield results for methods of brown water reclamation and compares them to other phosphorus yields.

Water Chemistry. A consistent and significant reduction in phosphorus was measured between input and output water samples in both the floway and serial plants. Table 2 shows average input and output concentrations for unfiltered total phosphorus, filtered total phosphorus (phosphorus in all dissolved forms), and filtered orthophosphate (phosphorus as orthophosphate). Each reduction pair was analyzed using paired comparison totals, and the resultant differences were significant at the 0.01 level. With a one-way repeated measure analysis of variance (ANOVA), reductions were significant at the 0.0001 level on a monthly basis.

All input and output concentrations for each analysis were combined to generate the averages in Table 3. This was done to summarize data taken over a 150-day period where the concentrations of phosphorus in input water varied widely. A plot of phosphorus removed against input concentration for the 15.2-m-long floway showed a consistent removal rate of 16.3% of total phosphorus over the range of 0.025–0.125 mg/l.

Discussion

We found few similarities between this work and previous work on the community structure of the periphyton of the Water Conservation Area carried out

Table 2. Phosphorus removal by Everglades algal scrubbers (floway and serial systems) as demonstrated by upstream/downstream water chemistry.

Floway (n = 60)	*Total P (mg/l)*	*Dissolved P (mg/l)*	*Ortho P (mg/l)*	*Flowrate (l/m)*	*Growing Interval at Sampling/Days*
Input	0.053 ± 0.026	0.038 ± 0.021	0.018 ± 0.014	89.12 ± 21.25	4.75 ± 2.58
Output	0.044 ± 0.028	0.033 ± 0.020	0.0013 ± 0.008	—	—
Reduction	0.009	0.005	0.005	—	—
Serial (n = 38)	*Total P (mg/l)*	*Dissolved P (mg/l)*	*Ortho P (mg/l)*	*Flowrate (l/m)*	*Growing Interval at Sampling/Days*
Input	0.038 ± 0.019	0.021 ± 0.015	0.011 ± 0.013	26.12 ± 8.62	12.86 ± 7.99
Output	0.028 ± 0.015	0.015 ± 0.008	0.007 ± 0.004	—	—
Reduction	0.010	0.006	0.004	—	—

by Swift (1981) and Swift and Nicholas (1987). Even recognizing the difficulties of blue-green systematics, it is clear that the ubiquitous and eutrophic-indicating species *Microcoleus lyngbyaceous* was not present in significant quantity. The typically abundant *Schizothrix calcicola*, an indicator of hard water in the Florida Everglades, was also not found. Indeed, blue-green algae were a very minor component of turf in the test system as a whole. Another major component of less eutrophic areas identified by Swift and by Swift and Nicholas, the desmid group, was also not seen on the experimental unit. It seems likely that desmids were not abundant in the canal waters during the experiment or they certainly would have been trapped in the turf meshwork.

The structural framework of the abundantly branching green *Cladophora*, the large, complex *Compsopogon*, and the saccate *Enteromorpha* lying in the well-lit, nutrient-rich, flowing and surging waters of the scrubber raceways provides an ideal attachment and growing environment for the "cottony" masses of *Spirogyra*, *Eunotia*, and *Melosira*. Development of this algal network creates a natural filtration system that, in addition to direct metabolic uptake, also adsorbs organic particulates and probably plankters from the canal water column. The production and trapping capability of these scrubbers is primarily limited by the structural strength of the basal branching filaments, since after about seven to eight days loss by sloughing rapidly increases.

The biomass of algae developed, as well as total organic mass produced and trapped in this experiment, may seem extraordinarily high. However, given the optimization factors (moderately eutrophic waters; constant return to the colonial "log phase" state, a harvest regime that prevents the development of grazing animal populations, constant flow and low-level disturbance of the water column, a physical and community structure that enhances trapping of the organic particulates rich in phosphorus in the ambient incoming water, and the fully photosynthetic nature of the biomass), this level of production is to be expected and will probably increase during the long days and higher nutrient levels of summer. It should be noted that the potential maximum of primary production in the oceans has long been accepted to be about 25 g(dry-weight)/m^2/day. This has been exceeded by rates in culture of over 30 g(dry weight)/m^2/day (Adey 1987). Furthermore, laboratory-optimized rates of primary production for wheat have exceeded 120 g(dry weight)/m^2/day (Bugbee & Salisbury 1988). The unique aspect of primary production described in this paper is its field nature, the use of natural light, the inexpensive form of the apparatus, and the ease of routine harvest.

As discussed in the introduction, phosphorus content in Everglades periphyton is a function of ambient dissolved phosphorus (Swift 1981). With increasing dissolved phosphorus in the water column, phosphorus content in algae increases, reaching saturation levels at about 0.35–0.42%. Thus, the values of phosphorus content found in scrubber algae in this study seem quite reasonable. In the Swift study, however, those levels were achieved at total ambient dissolved phosphorus concentrations of over 0.10 mg/l. In this investigation, phosphorus concentrations in the harvested biomass remained near saturation level down to water concentrations of 0.025 mg/l total phosphorus. There is energy input into this system that does not typically occur in the wild environment. Water flow in the raceways is obvious. In general, however, algal scrubbing is an optimization process that enhances water-cell contact, as discussed below. The input of wave or surge/riffle energy typically doubles algal productivity (Adey & Loveland 1991). In addition, the harvest clearly consists of abundant plankton and organic particulates. Phosphorus removal rates based on upstream-downstream chemistry on the algal

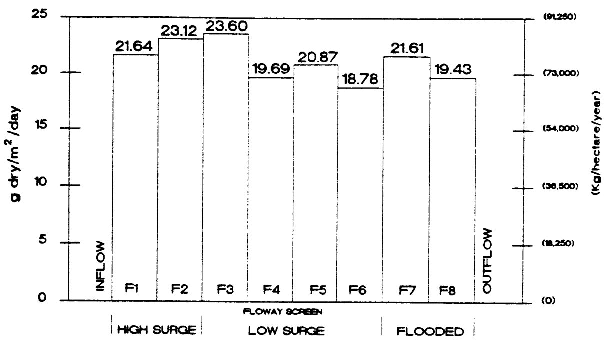

Figure 6. Mean biomass production with distance from water source in the 15.2-m-long floway. Pressure sieve, not including brown water. November 29, 1991, to May 6, 1992.

scrubbers indicate removal rates equivalent to those obtained by harvest techniques.

This study found a mean total phosphorus removal rate of approximately 120 mgTP/m^2/day based on upstream-downstream water chemistry. This compares with 125 mgTP/m^2/day that can be attributed to the phosphorus in biomass and other quantifiable losses. At 140 mgTP/m^2/day, floway phosphorus removal as calculated from algal harvests is consistently higher than that of the serial plant, while water chemistry would seem to indicate the reverse. Considering the short raceways and the normal difficulties of water quality analysis, however, direct phosphorus removal values are likely considerably more accurate than those provided by water chemistry.

The average harvest interval for both systems was about 8.5 days. A low loss or slough rate of about 8 g/day occurred for the first seven days on the floway, with 35–40 g/day characterizing days seven to eight. Thus, sloughing during the harvest interval accounts for a loss of approximately 4 mgTP/m^2. While some of this loss is inevitable, almost 80% of it occurred during the last three days and could be limited by collecting or trapping the slough. Slough rates rise rapidly after eight days, and further delay of harvest significantly reduces yield. Since this study was primarily carried out during the minimum nutrient season and over a period of less-than-average light availability, it seems likely that a routine, year-round uptake and storage rate using this methodology would be somewhat higher than 140 mg/m^2/day (511 kg/ha/year). This minimum value is 100–250 times the wetland phosphorus removal rates documented for this environment, as discussed earlier (Fig. 6).

There does not seem to be anything intrinsic to the floway design that would caution against further scale-up of the system. Recent studies during the summer period of high temperatures and high nutrient levels have shown a shift in algal community structure toward blue-green dominance, but with continued high productivity levels. Also, productivity of the floway remained high along the run from the water source, as shown in Figure 6 (n = 111). Although it is necessary to study phosphorus removal using methodology on considerably longer raceways, our previous experience with algal scrubbing in other environments indicates a capability for removal in the environment of an algal scrubber or its wild equivalent to concentrations below 2 ppb, (0.002 mg/l).

The potential for harvest removal and documentation for phosphorus, and the possibility for food, feed, fertilizer and biochemical use of the algal product, have great potential value in their own right. This is a recycling process using solar energy. Nevertheless, the large scale use of controlled algal turf or periphyton production for phosphorus management in the restoration of the Everglades would necessarily be determined by cost factors. It is not the purpose of this discussion to enter into cost factors, though the high rate of efficiency of the algal method suggests that careful cost comparisons are warranted. Investigation of the potential for laying a plastic screen on top of the peat are underway and appear quite promising. Also, in the Florida Everglades Agricultural Area, a relatively flat-lying limestone with a caliche capstone lies at shallow depth under the peat. If this surface can be adapted to the algal scrubber process, or if an acceptable algal growing surface can be established on the peat, there is little question that algal scrubbing will provide a phosphorus removal process that is highly competitive with a managed marsh system.

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Appendix

Algal species identified from Everglades Agricultural Area scrubbers used for phosphorus removal analysis.

Cyanophycota (Cyanobacteria) Blue-Green Algae
- Oscillatoriaceae
  - Oscillatoria subbrevis
  - Oscillatoria princeps

Chlorophycota (Green Algae)
- Chlorococcales
  - Pediastrum duplex
- Ulothrichales
  - Ulothix aegualis
  - †Enteromorpha micrococca
- Zygenematales
  - *Spirogyra rivularis
- Chaetophorales
  - Stigeoclonium tenue
- Cladophorales
  - *Cladophora crispata
  - Cladophora sp.
- Siphohocladales
  - †Dichotomosiphon tuberosus

Chromophycota
- Bacillariophyta (Diatoms)
  - Coscinodiscophyceae (centrales)
  - *Melosira varians
  - Melosira indica
- Fragilariophyceae (pennales-araphid)
  - Ctenophora sp.
  - Asterionella sp.
- Bacillariophyceae (pennales-raphid)
  - Amphipleura pellucida
  - *Eunotia pectinalis
  - Cocconeis sp.
  - †Amphora sp.
  - Placoneis sp.
  - Rhoikoneis sp.
  - Bacillaria sp.

Rhodophycota
- Bangiophycidae
  - †Compsopogon coeruleus

*Dominant species that appeared in every observation on every slide.
†Common species that appeared on every slide at least once.
Other species appeared at least on two slides.