TABLE 2. COMPARISON OF AVERAGE PRODUCTIVITIES AND PHOTOSYNTHETIC EFFICIENCIES IN PHOTOBIOREACTORS

Reactor Configuration	$g/m^2/d$	% PAR
Pond 2, covered 75% contiguously	5.2	4.4
Pond 3, covered 70% Shade Cloth	10.8	9.2
Pond 4, covered 75% intermittently	10.3	8.5
Pond 5, uncovered	20.5	4.6
Flat Plate	7.0	7.1

The pond covered contiguously over 75% of its area produced one-fourth as much algal biomass as the uncovered pond. It received one-fourth the amount of light. The pond covered intermittently over 75% of its area was nearly twice as productive as the 75% contiguously, covered pond, even though they received the same total amount of light. Clearly, the periodicity of light and dark cycles had a very significant influence on productivity. In the contiguously covered pond, the algal suspension was in the dark (or nearly dark) for about 18 s followed by 6 s in the light. In the intermittently covered pond, the suspension cycled in and out of the light faster, alternating about 1.5 s in the dark and 0.5 s in the light.

The pond covered by 70% shade cloth also received nearly the same number of photons per day as the 75% covered ponds. Its productivity was the same as the intermittently covered pond. Both of these were one-half as productive as the uncovered pond. Due to the lower photon input, these ponds had a higher PE than the uncovered pond. Again, the PE were quite high, at least 9% of PAR. The PE of the vertically oriented reactor was also quite high, at 7% during this period.

DISCUSSION

The main objective of these experiments was to compare the different photobioreactors in terms of three characteristics:

1. The practical operation of each, including stability and temperature control;
2. The productivity actually achieved; and
3. The potential of each for attaining maximal productivity, using photosynthetic efficiencies obtained under reduced light as an experimental tool.

Regarding the first objective, even at the small-scale studied here, the open ponds were easier to manage and the cultures were more stable. The other systems studied were vertical in orientation and required aeration to mix. This aeration proved to a destabilizing factor. Inevitably each of these cultures failed through a foaming and air flotation process as batch cultures aged, or early on, in semi-continuous culture. Temperature control was also more difficult in the clear-sided systems. With the thin (4 cm thick optical path) flat plate, temperature on a sunny day rose from 22 ^oC to 37 ^oC in three hours. Misting with water at 22 ^oC effectively controlled temperature, but this is very costly in water usage in large-scale applications. In the large diameter tanks, temperature control was a problem for a different reason. The much larger volume to surface area (333 L/m2 versus 180 L/m2 in for the ponds and versus 25 L/m2 for the flat plate) limited maximal daytime temperatures. But on modestly warm, sunny days, these tanks did not cool down at night below 30 ^oC, even when nighttime air temperature was only 22 ^oC.

There was no inherent advantage of the flat-plate system in producing more biomass. Daily increases in cell densities of batch cultures were, of course, higher. However, they needed to be nearly five times higher since the optical path was a little more than one-fifth of that of the ponds. The large tanks on the other hand, had much lower surface to volume ratios than either the ponds or the flat plate. Productivity from these tanks was similar to that from the ponds.

Photosynthetic efficiencies in the vertically oriented systems were higher than in the ponds. The vertical nature led to lower intensity of light at the surface. However there is no practical way to benefit from the higher photosynthetic efficiencies from these vertical systems, as crowding them together would result in a decrease in productivity, at a high cost. By contrast, ponds scale very well in terms of coverage of ground area. The higher PEs calculated here with partially covered ponds are of great interest in determining potential of algal physiology in solar conversion. The results with shade cloth, which reduces light intensity, are consistent with, and expected from, the well-known phenomenon of light saturation. As the incident irradiance increases above that which saturates the growth rate of the cells in the culture, further increases in irradiance lead to increasing waste of photons. Although the productivity of a dense algal culture still increases, with increasing sunlight intensity above light saturation level for photosynthesis of individual cells (as could be measured in an oxygen electrode), the productivity increases much more slowly than photon input, lowering overall PEs of pond cultures exposed to full sunlight. Thus covering a pond with a 70% shade cloth only reduced productivity by about half, increasing PE by about 70%.

The unexpected finding in these experiments was that the intermittent illumination resulting from the partial covering of the ponds, could, depending on the light:dark periodicity, greatly increase the overall PE. This increase was substantial, to about 10% of PAR, similar to that of the pond covered with 70% shade cloth. The significant difference was that the partially covered pond cultures were exposed to full sunlight intensity 25% of the time. This result cannot be explained in terms of the light saturation effect, nor the classical flashing light effect in which cases the algae cycle in and out of the light with periodicities of a few to a few tens of milliseconds. The explanation that most easily fits these results is that the uncovered pond cultures were significantly photoinhibited, but that a cycling time of 0.5 s L: 1.5 s D is sufficient to overcome most of this inhibition. A substantially longer L:D periodicity did not. An important question is whether the result with the 70% shade cloth reflects more a decrease in the effects of light saturation, as is assumed above, or if photoinhibition could still limit productivity even at such reduced light intensities. Experiments with shade cloth and intermittent illumination could resolve this.

CONCLUSIONS

These results with the partially covered ponds were surprising. The explanation is that the algae in the ponds not only exhibit considerable reduction in productivity due to light saturation but that in addition a significant, indeed similar, decrease can be attributed to photoinhibition. The ponds that received high light intensities in short (0.5 sec) bursts for a quarter of the time had a greatly reduced photoinhibition and thus higher PEs. The main conclusion of these experiments is that there are some light periodicities that result in a large increase in PEs, while other, longer, cycle light fluctuations do not. It should be noted that the "flashing light effect" of Kok (1953) probably does not account for this result. It can be concluded that this is due to photoinhibition of the algae at the longer cycles, but this remains to be more rigorously demonstrated. Experiments are required that explore this phenomenon over a larger range of light : dark cycles. This work is fundamental in that it demonstrates PE's that, if they could be achieved with fully uncovered ponds, would yield the high productivities, well over 100 mt/ha-yr, required for large-scale production of microalgae for commodities and greenhouse gas abatement (Benemann et al., 2003, also, Benemann et al., These Proceedings). Currently, in open ponds, both light saturation and photoinhibition limit productivities.

A method is needed to accomplish both high area productivity and high PE. A doubling of productivity, from 20 g/m2/d at 5% PE, to 40 g/m2/d at 10% PE may be achievable. Such productivities will be required to allow the use of algal mass cultures for energy production and greenhouse gas abatement. Phase I of this project has demonstrated that the algal cultures have the potential for achieving such productivities. Both light saturation and photoinhibition were indicated as major factors in decreasing the productivity. This is the most important conclusion of this study, and forms the basis of the objectives of the Phase II proposed for this project. The approach to be taken is the development of algal strains that have reduced harvesting pigment content (Neidhardt et al., 1998; Nakajima and Ueda, 2000; Polle et al., 2000), which theoretically should lead to higher productivity by reducing both of these factors, light saturation and photoinhibition. Research on increasing the productivity of microalgae mass cultures is central to the objectives of greenhouse gas abatement and could have applications beyond the microalgae to higher plants and biomass production systems generally.

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FIGURES

FIGURE 1a. PONDS WITH NO COVERS (Below) AND LONGITUDINAL COVERS (above)

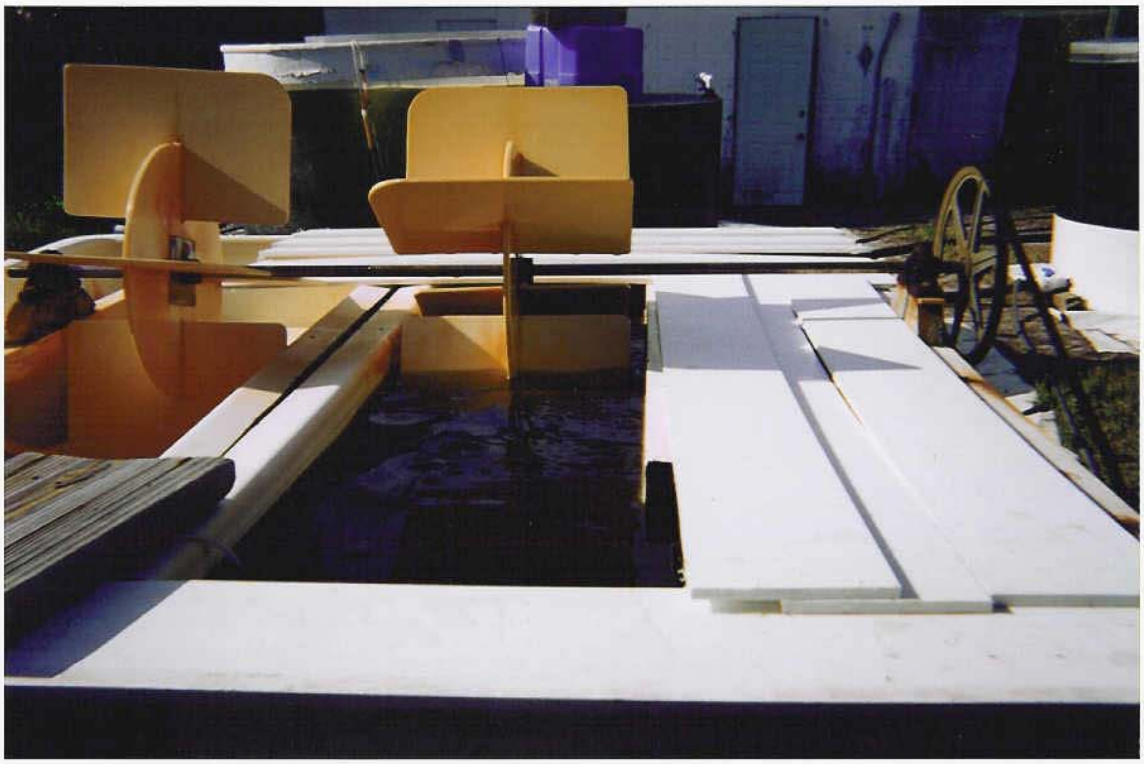


FIGURE 1b. PONDS WITH 70% SHADE CLOTH (above) AND 75%

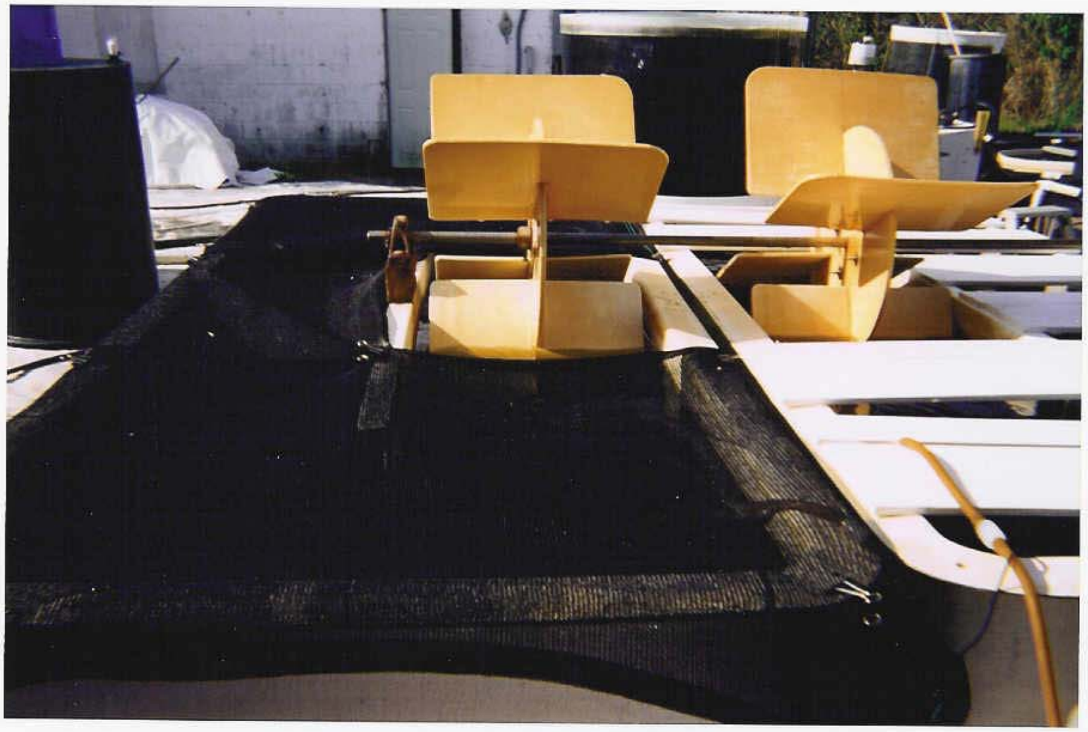


FIGURE 1c. FLAT PLATE PHOTOBIOREACTOR
(Provided by Prof. Mario Tredici, University of Florence)

Figure 2a. Growth in Vertical Tubes and Ponds

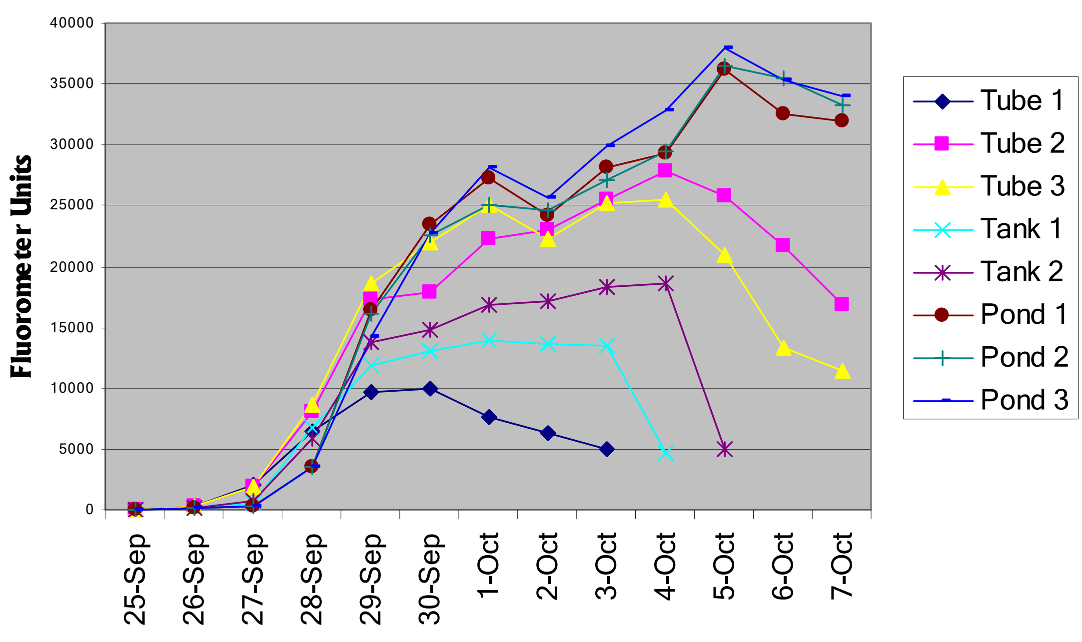


FIGURE 2b. CULTURE DENSITIES AFTER START OF 25% PER DAY DILUTION
(Note that only one of each type of culture was followed in these experiments).

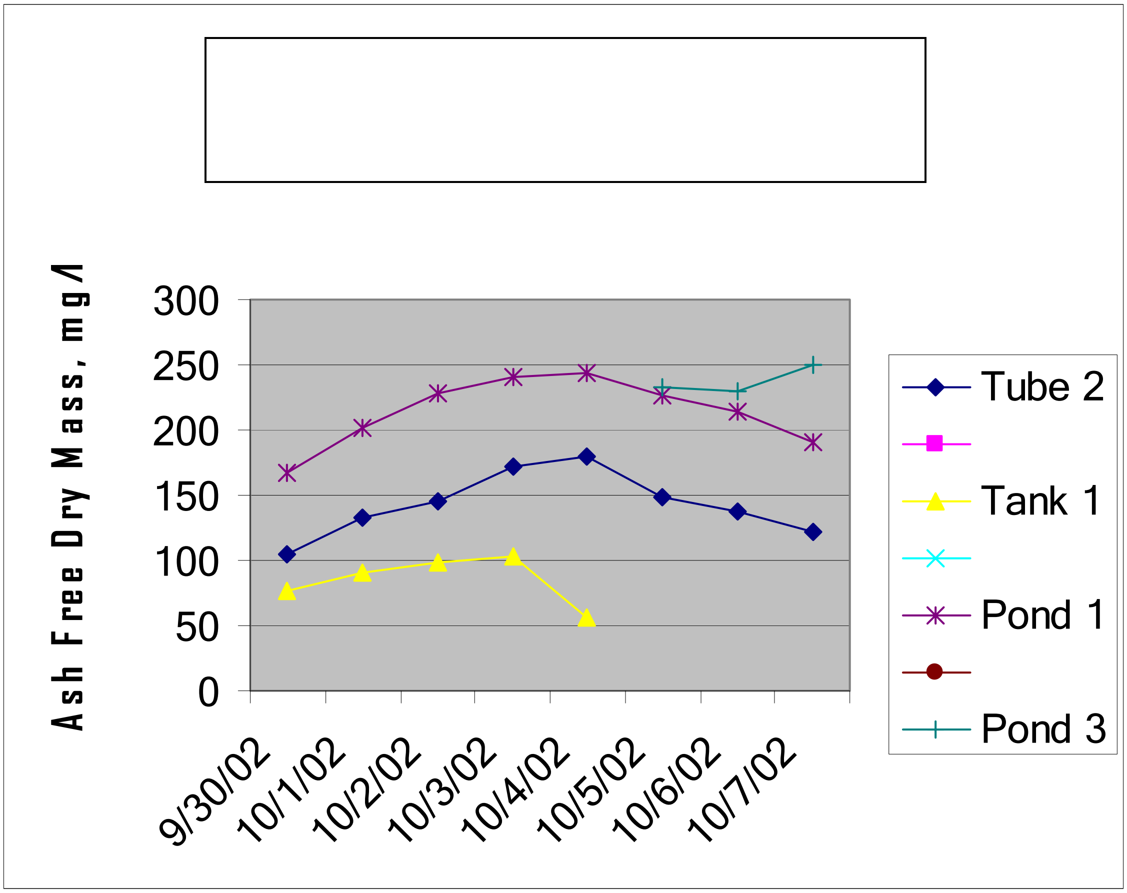


FIGURE 3. COVERED Vs. UNCOVERED PONDS

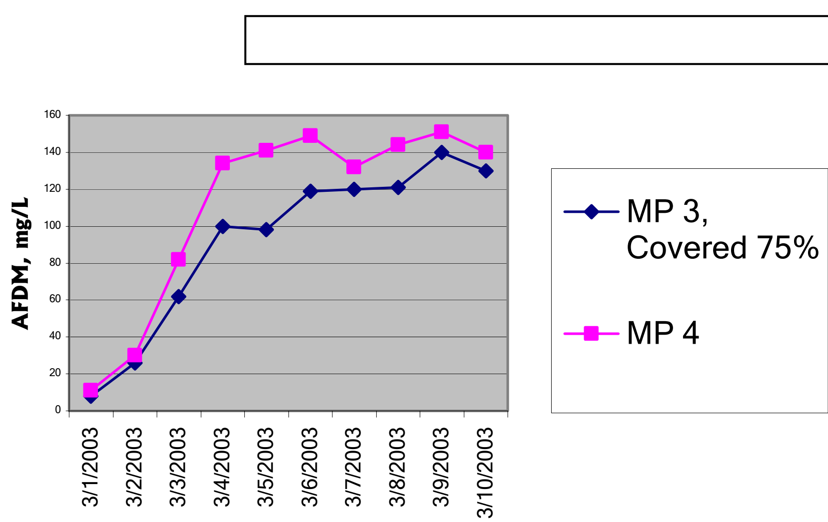
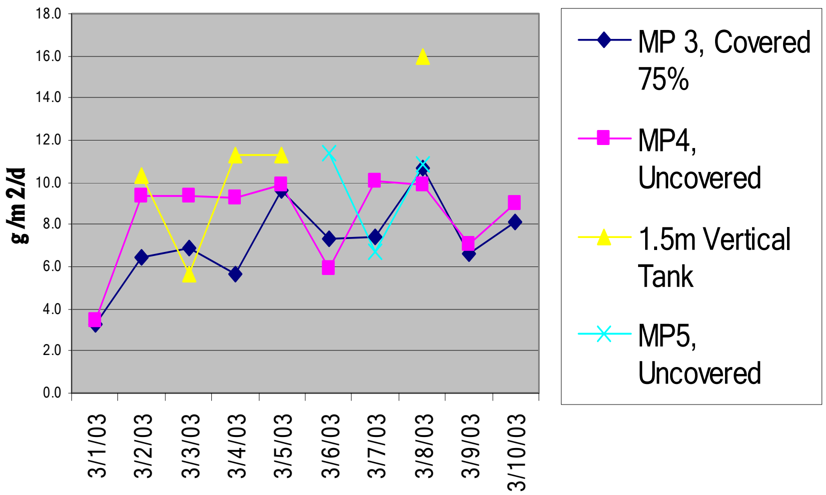


FIGURE 4. PRODUCTIVITY OF PARTIALLY COVERED PONDS



Average Productivity, g/m2/d

MP3	7.9
MP4	8.7
MP5	9.7
TanK	9.7