

Macroalgal farming in the sea: water motion and nitrate uptake

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Abstract

A better understanding of water motion effects on nutrient uptake by marine crop plants should make it possible to farm the sea more effectively. Farms in China, Japan and the Philippines now grow plants on slack lines or nets that move with passing waves and currents. Nutrient uptake rates are increased on *Laminaria* farms in China by adding nitrogen-containing fertilizer. In contrast, forests of the giant kelp, *Macrocystis* grow in California at low nutrient levels without fertilization. The giant kelp, compared as a structure with the slack Chinese farms, has float-supported, spring-like stipes that stretch and recoil as waves pass. This motion seems likely to enhance flow over the thallus surface. In this study we modified flow around kelp blades in a water tunnel in the laboratory by changing orifice plates, and flow around Chinese-style long-line farms in the sea by tightening them under various sea conditions. Our measurements suggest that if marine farms were designed and operated to increase water movement over the plants being grown, their rates of nutrient uptake, and growth would increase.

Introduction

In-the-sea growth and reproduction of giant kelp has been shown to be enhanced by fertilizer (Neushul, 1982; Neushul & Harger, 1985). However the importance of fertilization is best illustrated by the productivity of the vast Chinese *Laminaria* farms, where fertilizer is routinely applied. In the early 1980s, these and other macroalgal farms produced crops worth as much as one billion dollars annually (Tseng, 1981; Doty, 1982). Clearly it is very important to understand how macroalgae take up nutrients from the ambient water.

Some of the first studies of plant-water inter-

actions focused on the strength of macroalgal attachment to the substratum in the sea (Jones, 1959; Jones & Demetropoulos, 1968). Adaptations that enhance nitrate uptake would also be of obvious importance. Given the morphological diversity exhibited by macroalgae, this is not a trivial problem, although studies of form-function relationships of macroalgae as this relates to their cultivation have been undertaken (Hanisak *et al.*, 1990). The fact that light- and nitrate-effects interact further complicates the situation (Shivji, 1984, 1985). The effects of moving water on aquatic organisms have been studied by a number of authors who have examined the uptake of nitrate and other nutrients, as well as the effects

Table 1. Effects of water motion on aquatic organisms.

Effects on:	Authors
Growth/Survival	Conover, 1968; Dayton & Tegner, 1984. Denny, 1982, 1985, 1988. Denny <i>et al.</i> , 1985; Doty 1971a, b, Gerard & Mann, 1979; Haines & Wheeler, 1978; Hay, 1981; Jackson & Winant, 1983; Jones, 1959; Koehl, 1982, 1985; Matsumoto 1959; Neish & Knudson, 1979; Norton <i>et al.</i> 1981; Nowell & Jumars, 1984; Oliger & Santelices, 1981.
Reproduction	Ackerman, 1986; Norton <i>et al.</i> 1981; Riedl 1971a, b; Schwenke 1971; Vogel, 1981; Charters <i>et al.</i> 1973; Fetter & Neushul, 1981; Okuda & Neushul, 1981. Charters <i>et al.</i> , 1972, Delf, 1932, Koehl, 1986; Koehl & Wainwright, 1977; Mann, 1971; Neushul, 1972; O'Neill, 1978; Peterson <i>et al.</i> , 1969, 1976a, b.
Nutrient uptake	Anderson & Chartres, 1982; D'Elia & De Boer, 1978; Gerard, 1982a, b; Gessner, 1940; Koehl & Alberte, 1988; Neish & Knutson, 1979; Schumacher & Whitford, 1965; Westlake, 1967; Pasciak & Gavis, 1975; Whitford & Schumacher, 1961, 1964; Wheeler, 1989.

of moving water on growth, reproduction and distribution (Table 1).

While one cannot directly observe flow around a marine plant without using dye or some other marker in the water, it is possible to measure the movement of an algal thallus as it moves back and forth in the sea. An example of what might be called whole plant flow-visualization was first used in a study of the hydrodynamic responses of the sea palm *Eisenia* (Charters *et al.*, 1969). This showed that the stipe of *Eisenia* acts as a spring, and that the fronds clump as water moves past them, thereby reducing form drag. By using an underwater audio tape recorder and a meter-stick anchored in place, it was possible for the observer to quantitatively describe a 'motion diagram' to show the back and forth excursion of the plant.

Wave force was measured simultaneously with an anchored-in-place, fish pole tensiometer, so that wave force and plant motion could be correlated. Subsequent laboratory experiments measured the forces on the plant and its responses in a somewhat more controlled environment. Denny (1988) uses a motion diagram to illustrate how a floating *Nereocystis* plant responds to waves and discusses how the long stipe of this plant also acts as a spring. Thus making the measurements needed to quantify a motion diagram is a simple way to compare the interaction of plant and moving water under both natural and cultivated conditions (Melo *et al.*, 1991).

Matsumoto's (1959) classic study of *Porphyra* cultivation started with laboratory measurements to define the resource needs of the plant. He measured the amounts of water motion, light and nutrients needed for successful growth. Subsequently he grew test crops in the sea in locations where these needs were met, and ultimately these experimental farms were replaced by commercial ones. The standard *Porphyra*-net farm is only one of many types of marine farm now in use for the

Table 2. A classification of marine macroalgal farms modified from Kerr *et al.* (1980), Beveridge (1988), and Melo, Harger and Neushul (1991).

Crop carrier	Anchored non-buoyant farm	Anchored buoyant farm
Nets		
Anchor bags	Anchored chain	Curtain lines
Monofilament	and rope grid for	lift nets for
Lines	<i>Macrocystis</i>	<i>Laminaria</i> and
		<i>Porphyra</i>
	Staked	long lines for
	monofilament	<i>Undaria</i>
	lines	
	for <i>Eucheuma</i>	
	stake and table-	
	supported nets	
	for <i>Porphyra</i>	
Spar buoys and spars made of plastic pipe		Experimental test farms for <i>Gelidium</i> 'I', 'H' and 'Z' test structures

cultivation of macroalgae (Table 2). One of the main objectives of marine farm design has been to dampen the damaging effect of waves, rather than enhancing turbulence over the crop (McKay, 1983).

If large scale commercial cultivation of many different macroalgal crops is to be successful, (Neushul, 1983), we must understand plant-water interactions on marine farms. This paper presents some progress in the search for new generalizations about water flow and nitrate uptake, and shows that flow rates over a crop in the sea can be controlled.

Materials and methods

1. Measuring water motion and nitrate in the sea

Measurements were made of water movement on, and adjacent to long-time farms under different sea conditions with Marsh-McBirney 512 electromagnetic current meters (ECMs). These measured water moving past a spherical 1.5" diameter head, with probes oriented in two orthogonal directions (one plane), so that two appropriately positioned ECMs gave a three dimensional measurement of water motion. In addition an Endeco 949 wavetrack buoy was used to measure sea surface elevation over time. The wave and current data from these instruments was sampled twice per second for 249 s to produce data files. The files were stored on floppy disks at sea for later analysis in the laboratory. Four such files (16.6 min total) were collected for each measurement. Vector addition of the individual magnitudes of water motion past the aligned ECMs allowed calculation of both water speed and direction.

The separate effects of waves and current were calculated by subtracting out the latter. During storms, wave height and period were calculated from the sea surface elevation signal transmitted about two miles to our laboratory by the battery-powered wave-track buoy. When it was calm enough to work from the boat, we also measured water velocities near the crop and on the sea floor using the ECMs. The 'hydrodynamic perfor-

mance' of a given farm configuration and tension is defined here as the percent difference between the velocity measured by ECMs attached to the farm and the velocity measured using ECMs attached to a rigid structure nearby, or predicted for that depth from surface wave measurements. Farm tensions (measured in Newtons with a spring scale) were increased by specific amounts from a slack configuration, with a lever-operated pulley attached to the horizontal line of the farm which stretched between two subsurface buoys, anchored to the sea floor. Tension on the main horizontal line of the farm ranged from 0 to 1600 Newton.

The root mean square (rms) water velocity was calculated from the velocity spectrum for each of the three orthogonal directions. These directional velocities can be compared to one another, or can be used to calculate an overall mean velocity vector. They can also be compared to the ambient rms velocity predicted for that depth using surface elevation measurements and Airy theory. Guza and Thornton (1980), using linear Airy wave theory, predicted sea surface elevation from bottom velocity and pressure measurements and found less than 10% difference between measured and predicted significant wave heights. We measured nitrate concentrations in the sea from 1980 to 1986, using standard methods (Strickland & Parsons, 1972) (Fig. 1). These same methods were used to measure nitrate levels in the laboratory experiments described below.

2. Measuring water motion and nitrate in the laboratory

A modified version of the water tunnel used by Anderson and Charters (1980) was used to study nitrate uptake by *Macrocystis* blades. The size of the water tunnel working section was increased to accommodate several blades and stipe-segments, and a baffle was introduced into the reservoir below the tunnel to decrease the volume of the whole system to 20 l, so that changes in nitrate levels could be measured more easily. With this apparatus it was possible to control light, water

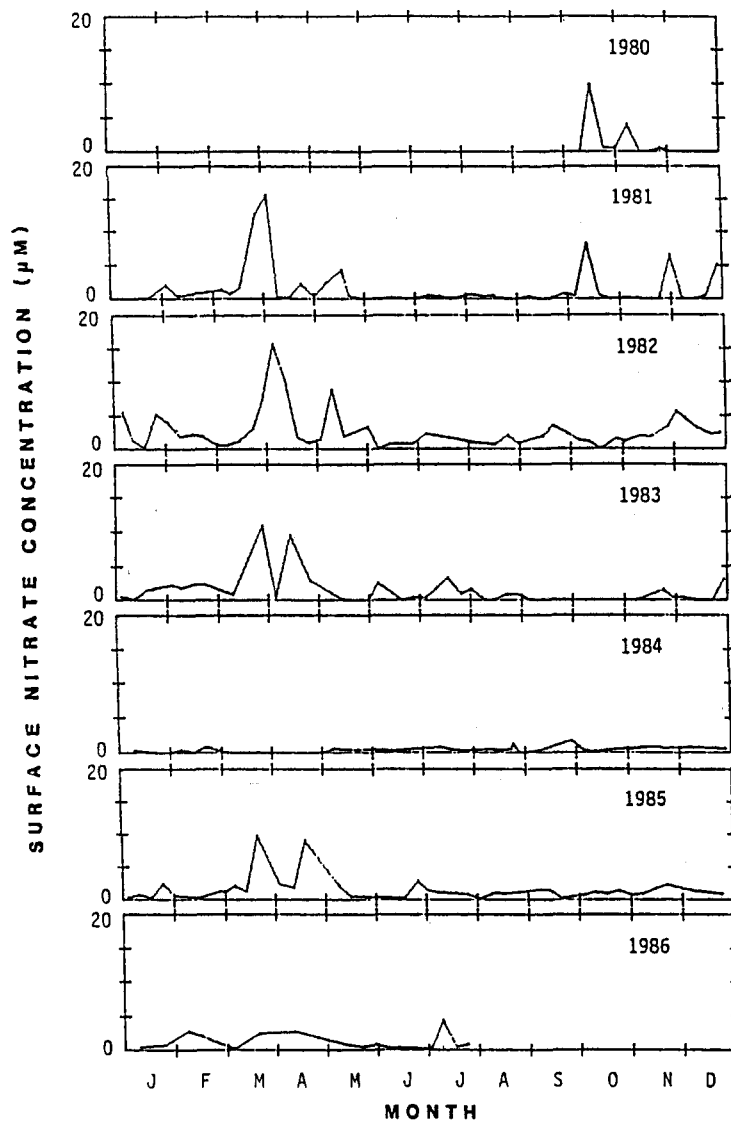


Fig. 1. Surface nitrate levels ($\mu\text{g-at l}^{-1}$), in the sea near Goleta, California, from 1980 to 1986. Major pulses of nutrients were measured in March and April, except for 1984 and the first seven months of 1986. Most of the time nutrients levels were well below $5 \mu\text{g-at l}^{-1}$.

motion, nitrate concentration and temperature. We were able to gain some control over the physiological condition of the blades studied and their prior nitrate exposure, by holding blades in nitrate-poor conditions for a day prior to testing.

After each experiment the blades used were removed from the tunnel, placed on white paper and sprayed with paint, producing a spray-print that was then measured with a planimeter to give total blade area. Several such blades, collectively

weighing 55 to 100 g, were mounted in the tunnel. Prior to mounting the blades dye streamer tests were used to confirm that the flow in the working section of the tunnel was laminar. Water samples were taken from the tunnel before and after each experimental run and nitrate levels at the $1 \mu\text{g-at l}^{-1}$ range measured. Samples taken from the empty tunnel run for one hour both before and after plants were tested in it, showed no changes in nitrate levels in the absence of plants. In order

to reduce possible microbial effects on nitrate levels, the filter used on the tunnel was replaced prior to each experiment, and the apparatus was carefully cleaned after use. Water velocity was controlled by placing orifice plates in the tunnel that produced velocities of 1.18, 3.22 and 4.96 $\text{cm}\cdot\text{sec}^{-1}$. For each series of speeds tested the nitrate concentration was first readjusted to a specific value between 2.1 and 5.1 $\mu\text{g}\cdot\text{at l}^{-1}$.

Results and discussion

1. Laboratory studies

In all 13 one-hour sampling periods in four experiments with blades in the water tunnel, the nitrate concentration in the tunnel decreased over time as expected, since the blades removed nitrate from the water passing over them (Table 3). Our experiments, like those of Wheeler (1980), show that water flow, either as a defined unidirectional current in a water tunnel, or as general turbulence in stirred jars, enhances the nitrate uptake by kelp blades or blade segments. Wheeler (1980) showed that nitrate uptake rates could be increased from 9 to 44 $\text{nM cm}^{-2}\text{ h}^{-1}$ (at a 15 $\mu\text{g}\cdot\text{at}$ concentration), which was an enhancement of 488% as the

water motion increased from 0 to 6 cm s^{-1} . Our experiments at lower nutrient concentrations like those in the sea (Fig. 1) (2.1–5.1 $\mu\text{g at l}^{-1}$) also show substantial increases in uptake as the flow rate was increased from 1 to 5 cm s^{-1} (2.1 to 4.3 $\text{nM cm}^{-2}\text{ h}^{-1}$).

It seems logical to assume that with more turbulence there would be more nitrate uptake; however, unlike turbulence in a jar, a blade in a water tunnel is exposed to a stream of water. Observations of dye markers suggest that the blade, stipe and vesicle 'plough' or 'stir' the passing water in a specific way. The efficiency of nitrate removal can be expressed in terms of the percentage of reduction in nitrate level produced by a single passage of water over the blades, or as a percentage of reduction produced by the total residence time in moving water, with multiple passes over the blades (Table 4). It is interesting that the single pass calculations suggest that blades are more efficient at taking up the nitrate at the lowest velocity, whereas the greatest multiple-pass efficiency is with a long residence time at a high velocity. Obviously this preliminary observation is in need of further study. The maximum uptake rate measured in this study was 0.229 $\mu\text{M N g}^{-1}$ fresh wt h^{-1} (for nitrogen 1 $\mu\text{M} = 1 \mu\text{g at.}$)

Table 3. Nitrate uptake by *Macrocystis** blades at three different current speeds.

Date	Tissue weight (g)	Area (cm^2)*	Current speed (cm s^{-1})	Starting concentration ($\mu\text{mol l}^{-1}$)	Uptake rate ($\mu\text{mol g}^{-1}$ fresh weight h^{-1})
12/17/80	55	5500	3.22	5.1	0.103
12/27/80	118	4937	1.18	3.5	0.084
			3.22	3.2	0.118
			4.96	2.9	0.139
			1.18	3.1	0.025
12/29/80	100	3864	1.18	4.1	0.119
			3.22	3.8	0.182
			4.96	3.4	0.153
			1.18	3.2	0.047
12/31/80	80	3325	1.18	3.0	0.190
			3.22	2.5	0.184
			54.96	2.2	0.229
			1.18	2.5	0.051

* Experimental conditions: The kelp blades used had an average surface area (both sides) of about 50 $\text{cm}^2\text{ g}^{-1}$ fresh weight; the water tunnel diameter was 10.16 cm; and it had a cross sectional area of 81 cm^2 ; tunnel volume was 20 liters; plant length = 76 cm; plant weight = 90 g; time of each run = ca 1 h.

Table 4. Nutrient uptake efficiency of *Macrocystis* blades at three different speeds in a water tunnel with experimental conditions as in Table 3.

Variable	Unit	Current speed		
		Low	Intermediate	High
current speed	(cm s^{-1})			
Water flow		1.18	3.22	4.96
Nitrate	l h^{-1}	344	939	1446
Nitrogen flux	$\mu\text{mol l}^{-1}$	3.23	3.17	2.80
Nitrate uptake	$\mu\text{mol h}^{-1}$	1111	2977	4409
Rate	$\mu\text{mol h}^{-1} \text{ fresh weight}^{-1} \text{ h}^{-1}$	0.10	0.17	0.17
Uptake rate	$\mu\text{mol h}^{-1}$ for a mean 90 g plant	9	15.3	15.3
Efficiency of uptake per pass		0.81%	0.51%	0.38%
Efficiency of uptake for whole period of flow		13.9%	24.1%	27.3%

2. In situ studies

In the sea, when there is a steady current with no wave action, conditions are similar to those in a water tunnel. However this is rare in an unsheltered coastal habitat, since both surge and current influence the plants, and both are modified by proximity to the bottom. A simplistic description of hydrodynamic habitats (Neushul, 1972) describes current and surge zones in the water column, giving estimated rates of water motion. A more realistic description would consider the combined wave (oscillatory) and current effects. For example a root mean square (rms) velocity of $6\text{--}7 \text{ cm s}^{-1}$ in the sea measures the wave-induced, back-and-forth and up-and-down movement of water, which is qualitatively very different from a steady flow of $6\text{--}7 \text{ cm s}^{-1}$ in the laboratory. Nonetheless, just as laboratory water tunnel flow rates can be experimentally changed, so can rms velocities be changed on farms in the sea.

In situ measurements of water movement over marine farms showed that tensioned, Chinese style long-line farms produced a greater root mean square water velocity than untensioned, slack ones under both moderate and calm conditions (Fig. 2). Consequently, just as in the laboratory water tunnel experiments where different flow rates were achieved by changing orifice plates, one can compare the root mean square ambient water motion on a loose farm ($\text{rms } 1.62 \text{ cm s}^{-1}$)

with that achieved when the same farm was tightened ($\text{rms } 3.72 \text{ cm s}^{-1}$). An 85% increase in water movement was achieved by tightening under calm conditions. Only a 35% increase was obtained under moderate sea conditions. In calm and rough seas the highest water motion was measured at farm line tensions of 800 and 1010 newton, respectively. In most of these first tests water motion on the farm was less than, or at best equal to, ambient levels. However, in four cases water movement was greater than ambient (Fig. 2).

The measurements of nitrate in the sea showed that nitrate levels at Goleta, California varied in a similar way every year, increasing in March and April, except during the El Nino year (1983), and a very calm year (1986) (Fig. 1). The usual seasonal cycle was for nitrate levels to increase in spring, declining to undetectable levels during the summer, with an occasional peak in the fall or winter. Except for trace amounts, there is little nitrate available after June. Consequently, for almost 8 months of the year, *Macrocystis* plants either use stored nitrate or obtain nitrate from transient local mixing, land runoff, or local nutrient regeneration, which is important when seeking to understand these undersea forests (Foster & Schiel, 1985). Harger (1979) has calculated that half of the natural variability in kelp harvests is due to nitrate availability (regulated by seasonally-variable upwelling) and surface irradiance.

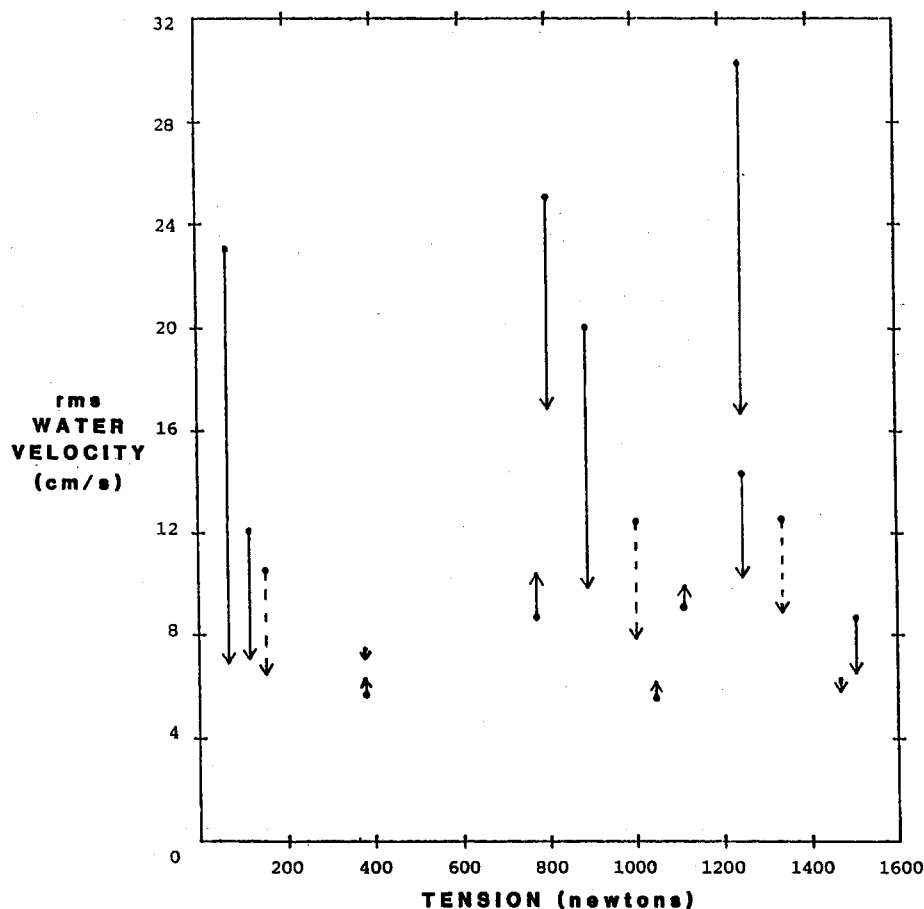


Fig. 2. Farm tension experiments. The arrows allow one to compare water motion on a farm (arrow head) with ambient water motion nearby, for different farm tensions, most of which show a decrease in water motion on the farm relative to ambient levels. Long-line farms parallel (—) and perpendicular (-----) to the direction of wave movement can be compared as well. At four tensions, (between 400 and 110 Newton), there was more water movement on the tensioned farm than in the water around it. The largest increase was about rms 2 cm s^{-1} .

3. Conclusions

Given the laboratory and field results discussed above it seems logical to suggest that nitrate uptake by a crop in the sea can be increased by either fertilization or by increasing water flow. This is illustrated in an idealized example (Fig. 3), which can be compared with actual flow and uptake measurements (Table 3) plotted in a similar way (Fig. 4). If the flow-nitrate uptake relationships postulated in Fig. 3 are correct, then at concentrations less than $5 \mu\text{mol l}^{-1}$ of nitrate (like those commonly measured in the sea during this study), increased water motion achieved by ten-

sioning a farm, or by the tensions in a spring-like kelp stipe, could enhance nitrate uptake from 2 to 15 times. Another way to interpret Fig. 3 is to say that a given nutrient uptake rate can be achieved either by fertilizing or by increasing farm tensions and hence water motion. It would be interesting to compare the costs of *in situ* fertilization with those of adding tensioning devices to farms.

The nitrate-uptake-flow relationship for giant kelp, or any other alga, illustrated in Fig. 4, should be viewed as a first approximation for several reasons. One is that blades we studied were held in a fixed position in the water tunnel. In nature they are not fixed in position, but are structurally

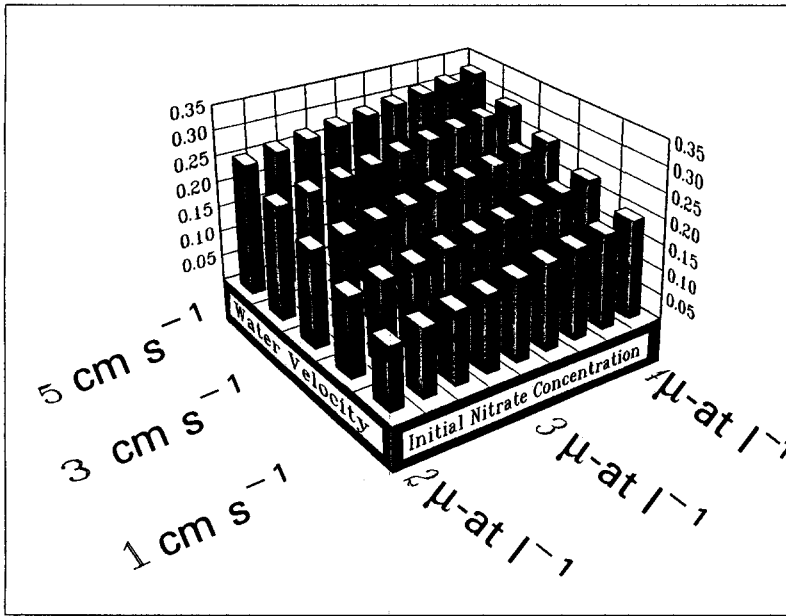


Fig. 3. Estimated relationships between nutrient levels, water flow and uptake rates for *Macrocytis* in moving water. Uptake rates, in μg at sq cm² h would be the highest (over 3.0) at the highest concentration of nitrate (4 μ-at l⁻¹) and water speed (5 cm s⁻¹), and lowest at lowest and lowest speed and concentration. If one wished to increase uptake, this could be done either by increasing speed or adding nitrate. Uptake are (J) can be calculated from the following relationship:

$$J = (0.33 \times U) + (0.69 \times Co/Co + 13),$$

where U = water velocity (cm s⁻¹) and Co is the initial concentration (μg-at l⁻¹).

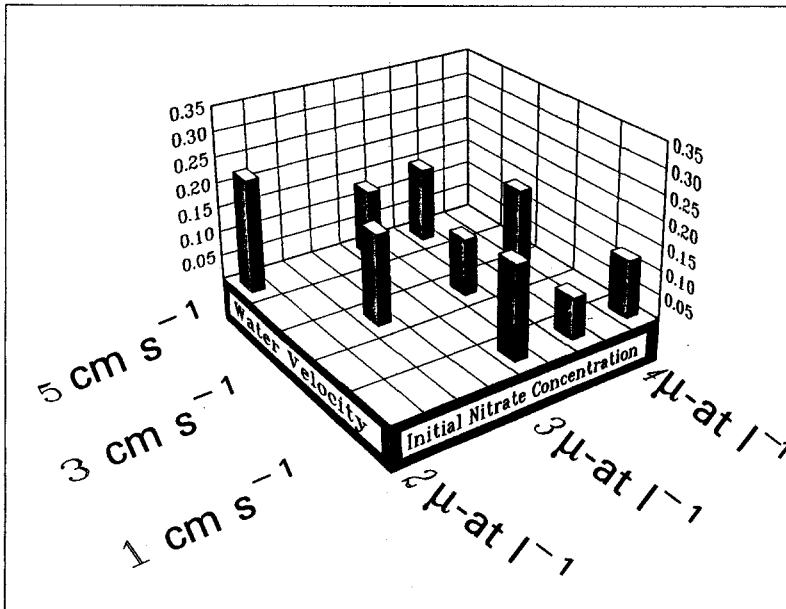


Fig. 4. Measured nutrient levels, water flow and uptake rates for *Macrocytis*. Measured uptake rates are shown relative to current speed and nitrate concentration assuming an empty nitrogen storage pool. The values can be compared with those estimated in Fig. 3.

displaced as each wave surge moves them, because they are attached to stipes that respond in a spring-like fashion. The stirring produced by this elastic deformation and recoil of stipes has not yet been studied, but may well account for additional vortex generation and increased nitrate uptake rates.

A second reason to view the flow-nitrate-uptake-relationships in Fig. 4 as preliminary is because macroalgae are able to store nitrogen, and uptake rate can be influenced by the amounts stored in the plant. Chapman and Craigie (1977) showed that *Laminaria longicuris* could store nitrogen at concentrations 28 000 times that in the sea, and that the plants retained this nitrogen for as long as two months. Our experiments show that while the rate of nitrate uptake by *Macrocystis* increases with increased water flow, in a series of measurements the first uptake rate at 1.2 cm s^{-1} and the last at the same velocity were not the same, suggesting that the plants might be filling a nitrogen 'pool' within them.

We tend to think of macroalgae as plants that capture energy photosynthetically, rather than using the kinetic energy in the water surrounding them, even though in some habitats more energy can reach the plant from the waves, than from the sun (Leigh *et al.*, 1987). It might be useful to think of algae, and also of marine farm structures, as combinations of anchors, lines, floats, springs, and flexible fins. It seems clear that on both the farms and the plants grown on them, these structures can 'use' the kinetic energy in waves and currents to enhance nitrate uptake.

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