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Laminaria culture for reduction of dissolved inorganic nitrogen in salmon farm effluent

A. Subandar[1], R.J. Petrell[2]* & P.J. Harrison[3]
[1] *BPP Teknolgi, LT.13, Jakarta Pusat 10340, Thamrin 8, Indonesia;* [2] *Department of Bio-Resource Engineering, University of British Columbia, Vancouver, B.C. V6T 1Z4 Canada (* author for correspondence);* [3] *Department of Oceanography and Botany, University of British Columbia, Vancouver, B.C. V6T 1Z4 Canada*

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Abstract

Finfish culture is a growing industry, and it causes a nutrient loading problem. To investigate the feasibility of an integrated culture of kelp and salmon, 15-cm long kelp (*Laminaria saccharina*) was grown in salmon culture effluent. The objectives were to test the effects of flow rate and kelp density on dissolved inorganic nitrogen removal (DIN), and DIN uptake and growth by the kelp. NH_4^+, NO_3^- and DIN ($NH_4^+ + NO_3^-$) loadings were in the ranges 6.2–25.4, 12.9–40.0, 19.7–52.7 μmol l^{-1}, respectively, over the experimental period.

Surplus uptake of nitrogen was not evident, because the C:N ratio (10–11) was constant in all experiments. During light periods, the kelp removed from 170–339 μmol l^{-1} h^{-1}, and approximately 26–40% of the incoming DIN. The DIN uptake rate, based on daylight sampling periods, ranged between 6.1–22.5 μmol g^{-1} dry mass h^{-1}. The highest-flow rate, lowest-density tank had the highest DIN uptake rate. Debris from the fish effluent settling on the kelp thalli in the low-flow rate tanks affected uptake. Mean DIN uptake rate based on 3 days of growth for all flow-density combinations ranged between 5.4–8.3 μmol g^{-1} dry mass h^{-1}. The kelp utilized NH_4^+ and NO_3^- equally.

The growth ranged between 6.5–9% d^{-1}. The biomass production ranged from 1–2 g per sampling period. The highest growth rate and biomass production were achieved by kelp in the highest-flow rate, lowest-density tank. Lower DIN concentrations due to higher DIN removal rates in the other tanks and light limitation due to self-shading in the high-density tanks were probably responsible for the reduced growth rate in these tanks.

Introduction

Finfish aquaculture is a large industry that contributes to a nutrient loading problem in receiving waters. The total loading of N and P from a typical salmon growout farm is 78 and 9.5 kg (t^{-1} fish produced) with 57–86% dissolved inorganic nitrogen (DIN) and 22–46% soluble P (Ackefors & Enell, 1990, Fivelstad *et al.*, 1990). The ratio of soluble DIN:P of salmon effluent waste averages 17:1.

Kelp grown on salmon waste could remove

excess nutrients, gain rapid growth, and through photosynthetic activity, supply oxygen to the usually oxygen-depleted fish effluent water. The N:P atomic ratio of benthic marine macroalgae was found to be 30:1 (Atkinson & Smith, 1983). Fish effluent is P rich compared to kelp requirements, and it supplies DIN to generally N-limited marine waters. Markovtsev and Krupnova (1988) reported that the culture of *Laminaria* around the discharge of a fish-processing plant at southern Maritime Kray area (Soviet Union), purified the effluent containing up to 120 mg total N l^{-1}. In an integrated (land-based) culture with salmon, red macroalgae removed 30–50% of the NH_4^- (initial concentration 12.8 μmol l^{-1}) in the salmon culture effluent (Fujita *et al.*, 1990). *Ulva lactuca* biofilter systems were tested on marine fishpond effluent, and 40 to 90% of the incoming ammonia was removed (Cohen & Neori, 1991; Neori *et al.*, 1991).

Integrated fish/kelp culture, where the kelp is grown on fish culture effluent, could also mean an economical utilization of the fertilizer stemming from the fish culture. Kelp has economic value for its chemical content, mainly iodine, alginate, laminaran and mannitol (Druehl, 1988) and its use as a food source (Saito, 1976). In Asia over 2 million tons of kelp per year were produced in 1988, and 90% of the total seaweed production came from aquaculture growout operations which use an increasing amount of fertilizer (Csavas, 1990). The world market for edible seaweed appears to be increasing along with the increasing demand for Japanese food and health foods, while the seaweed market for raw material for extraction industries appears to be saturated (Csavas, 1990). Although Asia and the Pacific regions are traditional sites for cultured seaweed, sites closer to western markets can be developed provided they meet basic biological, technical and economical criteria.

Kelp growth is affected by many variables, some of which are controllable. Lapointe and Tenore (1981) found that specific growth rate of *Ulva fasciata* decreased by 94% as its density increased 18 times. Gerard and Mann (1979) reported that nutrient uptake of *Laminaria longicruris* was enhanced by increasing water movement. Whitford and Schumacher (1961, 1964) suggested that current produced a steep diffusion gradient, which could increase exchange of materials between macroalgae and surrounding waters. Lapointe and Ryther (1979) showed that nitrogen availability was a function of both concentration and flow rate near the thallus of macroalgae. In nature, seaweed populations have been described as more luxuriant in turbulent waters than in stagnant water (Conover, 1968).

Winter growth of *L. longicruris* correlated significantly with an increase in ambient dissolve N O_3^- (Chapman & Cragie, 1977; Asare & Harlin, 1983). In British Columbia, *L. groenlandica* growth was positively correlated with nutrient concentration (Druehl *et al.*, 1988). Penniman (1988) reported that the lamina growth rate of juvenile *L. longicruris* increased by approximately 10% when background N concentrations increased from 9 to 20 μmol l^{-1}. Chapman *et al.* (1978) observed a linear relationship between the growth of *L. saccharina* and NO_3^- concentration up to 10 μmol l^{-1} and a luxury consumption of NO_3^- above 10 μmol l^{-1}. A variable C:N tissue ratio has been associated with kelp response to nitrogen storage and indicates possible nitrogen limitation to specific growth rate (Atkinson & Smith, 1983).

Nutrient species could affect uptake rate and growth of kelp. The maximum NO_3^- uptake of *L. longicruris* was 7–10 μmol h^{-1} g^{-1} dry mass, and this rate was not affected by the presence of NH_4^+ (Harlin & Craigie, 1978). *L. groenlandica* simultaneously took up NH_4^+ and NO_3^-, and the uptake rates were identical and equal when only NH_4^+ or NO_3^- was present in the medium (Harrison *et al.*, 1986).

In this investigation, kelp was cultured in salmon effluent to study the effects of kelp density and flow rate on DIN (ammonium and nitrate) uptake and kelp growth. This information can be used to develop criteria required to design suitable effluent treatment systems for salmon culture. *Laminaria* was studied, because it can be cultivated in a tank or on ropes near a salmon netpen farm and its market, especially as a food

source, is expanding beyond Japan to the rest of the world (Csavas, 1990).

Materials and methods

Three consecutive experiments were conducted on kelp (*Laminaria saccharina*) receiving waste water from a salmon culture tank for 9 days. Tests were conducted at the outdoor facility of the Marine Ecosystem Programme, West Vancouver, British Columbia. Combinations of kelp density and flow rate were tested. The density treatments consisted of 4 levels (0, 10, 15, 20 kelp/tank or 0, 370, 555, 740 kelp m^{-3}), and the flow treatments consisted of 3 levels (8–24, 25–44, 65–84 $l\,h^{-1}$).

First year age class kelp were collected from Brockton Point, Stanley Park, Vancouver, B.C. The kelp was covered with seawater, placed in styrofoam coolers and brought to the laboratory. The kelp was attached to stones used as weights. They were conditioned to salmon culture effluent for 2 months prior to the initiation of the experiments. Then they were placed in 9 Plexiglas tanks (0.45 m long × 0.45 m deep × 0.20 m wide), whose inlets and outlets were positioned in such a way as to increase water mixing. The kelp was positioned vertically in the tanks. Three other tanks were used as controls, and they contained no kelp. Tanks were randomly reallocated before each experiment. To minimize water temperature increases, tanks were placed in raceways containing flowing seawater. Tanks continuously received salmon culture effluent water from a header tank. The header and kelp tanks were cleaned every 2 days. The fish at a stocking density of approximately 8 kg m^{-3} were fed daily until satiation at approximately 09:00.

Water sampling at the outlet of each experimental tank was conducted every 3 days in the morning (before the fish were fed) and again in the afternoon (approximately 5–6 h after the fish were fed). Water samples were obtained from the header tank twice daily in the morning and the afternoon. Salinity (YSI model 33), pH (Hanna Instrument model HI 8521) and flow rate (manually with stopwatch and graduated cylinder) were measured daily. Irradiance (Licor Li 185B) was measured in one of the highest kelp density tanks, and water temperature was measured in 3 other kelp tanks. Irradiance and water temperature were recorded every 0.5 h using an automatic data logger specially built for use in saltwater experiments (Petrell & Savage, 1990).

Initial length and mass of a single kelp were approximately 0.15 m and 0.009 kg respectively. Kelp length and mass were measured on 60% of the kelp every third day. The kelp were trimmed when lamina length was >0.15 m in order to maintain a fairly constant biomass. The kelp trimmings were used to estimate production.

All the water samples were frozen for chemical analysis later. Ammonium and nitrate analyses were done on filtered samples with a Technicon Auto Analyzer II using standard techniques (Harrison *et al.*, 1986). Tissue C and N were measured using a Carlo Erba Analyzer N2A1500 at the Oceanography Department of U.B.C. Each sample of both water and C and N consisted replicate samples.

Nitrogen uptake V (μmol N g^{-1} dry mass h^{-1}) was calculated according to the following formula (Rosenberg *et al.*, 1984):

$$V = \frac{Q(S_i - S)}{w}, \tag{1}$$

where Q = flow rate (l h −), S_i = inflow DIN concentration (μMol l^{-1} N), S = residual inorganic nitrogen concentrations (μMol l^{-1} N), and w = kelp dry mass.

The punched hole method (Parker, 1947 as quoted by Chapman, 1973) was applied to estimate growth rate. The formula was (Brinkhuis, 1985):

$$U = \frac{(100\,(\ln L_t - \ln L))}{t}, \tag{2}$$

where U = specific growth rate (% d^{-1}), L_t = distance stipe junction at time t, and L = initial distance.

Mean N uptake rate V_{mean} (μmol g^{-1} dry mass d^{-1}) based on 3 days growth which occurred be-

tween water samplings was calculated using

$$V_{mean} = \frac{N_{tissue} U}{100}, \quad (3)$$

where N_{tissue} = total tissue N (μmol g^{-1} dry mass).

Results

Environmental parameters

The mean daily daylight irradiances of experiments I, II and III were 106, 99 and 179 μmol photon m^{-2} s^{-1}, respectively. The irradiances ranged from 0 to 1000 μmol photon m^{-2} s^{-1}. In both the first and third experiments, irradiance was higher than 100 μmol photon m^{-2} s^{-1} for approximately 9 h. The mean water temperatures of experiments I, II and III were 15.6, 13.6 and 14.6 °C, respectively. Water temperature ranged from 10.2 to 23 °C.

Salinity throughout the experimental period ranged from 27–29 ‰. The pH in the tanks ranged between 6.9 and 7.9. The pH in the control tanks was consistently lower than in the kelp tanks. The ranges of NH_4^+, NO_3^- and DIN ($NH_4^+ + NO_3^-$) in the header tank were 6.2–25.4, 12.9–40.0, 19.7–52.7 μmol l^{-1}, respectively. The DIN concentration was usually lower in the morning before the salmon were fed, and it varied daily.

Nitrogen removal and uptake

C:N ratios of the kelp ranged between 10–11 in every flow-density combination and every experiment.

During the daylight period, tanks with kelp demonstrated higher DIN removal rates (μmol l^{-1} h^{-1}) than controls (no kelp) ($p < 0.05$, Table 1). The DIN removal rate in the control tanks ranged between 32.9–54.4 μmol l^{-1} h^{-1}, whereas uptake in the kelp tanks ranged from 170 to 339 μmol l^{-1} h^{-1}. The removal of NH_4^+ and of DIN averaged from 30–45% and 26–40% of the incoming respective concentrations. The highest removal of incoming NH_4^+ (45%) and incoming DIN (40%) were in the lowest flow rate – highest density tank, whereas the lowest removal of incoming NH_4^+ (30%) and incoming DIN (26%) were in the highest flow rate – lowest density tank.

Table 1. DIN removed as % of incoming concentrations and DIN (ammonium and nitrate) removal rates (μmol l^{-1} h^{-1}) by control (no kelp) and kelp (*L. saccharina*) grown in different flow rate-density combinations. Error estimate represents one standard deviation, and $n = 22$.

Flow rate-Density	% removal	Removal rate
High-Control	5	54 ± 22
High-Low	26	263 ± 170
High-Medium	28	303 ± 270
High-High	29	339 ± 230
Medium-Control	7	48 ± 33
Medium-Low	30	202 ± 83
Medium-Medium	34	234 ± 140
Medium-High	33	225 ± 130
Low-Control	7	33 ± 12
Low-Low	34	170 ± 15
Low-Medium	35	193 ± 89
Low-High	40	204 ± 75

No significant difference between DIN uptake (μmol g^{-1} dry mass h^{-1}) in the morning and afternoon was evident in the kelp tanks. Consequently, the morning and afternoon data of each flow-density combination were pooled (Table 2). After pooling the data, a Tukey test was conducted to determine if any treatment affected uptake. Significant differences in uptake rates were seen among all flow rate – density combinations when the data from first water sampling of each experiment was excluded. Uptake was determined for first sampling using untrimmed kelp, while it was determined for the other samplings with kelp that had been trimmed to 0.15 cm. The higher biomass condition in the first sampling of every experiment logically led to higher uptake values, which were usually 2–3 times higher than the uptake values of the following samplings. By omitting extreme values of the first sampling of every experiment, a distinct pattern of uptake became evident.

Table 2. DIN (ammonium and nitrate) uptake rates measured twice daily and every 3 days (μmol g^{-1} dry mass h^{-1}) of kelp (*L. saccharina*) grown in different flow rate-density combinations. Error bars represent 1 standard deviation, and *n* is in brackets.

Flow rate-Density	Mean morning uptake	Mean afternoon uptake	Mean uptake morning and afternoon	Mean uptake for 3-d period
High-Low	20.9 ± 10.2 (9)	23.6 ± 10.6 (12)	2.5 ± 10.3 (21)	8.3 ± 2.9 (9)
High-Med	17.9 ± 7.9 (10)	16.3 ± 7.6 (12)	17.0 ± 7.6 (22)	6.9 ± 2.5 (9)
High-High	13.9 ± 6.5 (9)	12.9 ± 9.3 (12)	13.3 ± 8.1 (21)	6.7 ± 2.5 (9)
Med-Low	14.5 ± 5.9 (10)	15.1 ± 5.8 (12)	14.8 ± 5.7 (22)	6.9 ± 1.3 (9)
Med-Med	8.9 ± 5.4 (10)	6.7 ± 2.4 (12)	7.7 ± 3.9 (22)	6.5 ± 1.9 (9)
Med-High	9.4 ± 3.5 (9)	7.7 ± 5.4 (12)	8.5 ± 4.6 (21)	5.5 ± 1.9 (9)
Low-Low	9.5 ± 5.1 (10)	8.9 ± 6.7 (12)	9.2 ± 5.7 (22)	6.9 ± 2.9 (9)
Low-Med	7.7 ± 4.2 (10)	8.5 ± 4.2 (11)	8.1 ± 4.1 (21)	6.7 ± 2.2 (9)
Low-High	6.4 ± 3.8 (9)	5.9 ± 2.8 (12)	6.1 ± 3.2 (21)	5.4 ± 1.9 (9)

The effect of kelp density on uptake depended on the flow condition. At the highest and medium flow rates, daily uptake rate of the lowest density kelp was higher than the medium and highest densities of kelp ($p < 0.05$, Table 2). At the lowest flow rate level, however, no difference was found among all kelp density levels. Regardless of kelp density, uptake values in the medium and lowest flow tanks were not significantly different. At the lowest and medium kelp densities, the uptake in the highest-flow rate tanks was higher than the uptake in the medium and lowest-flow rate tanks ($p < 0.05$). At the highest kelp density, the uptake in the highest-flow rate tank was only higher tan the uptake in the lowest-flow rate tank ($p < 0.006$). The highest uptake rate (22.6 ± 10.5 μmol g^{-1} dry mass h^{-1}) was found in the highest flow-lowest density combination.

The 3-d mean N uptake based on growth rate and nitrogen content (Eq. 2) ranged between 5 and 8 μmol g^{-1} dry mass h^{-1}. Values varied with growth rate, but no significant difference were found among all flow-density treatments. Mean uptake was up to 40% lower than the mean daily uptake rates (Eq. 1) determined in the highest flow treatments (Table 2).

The kelp utilized NH_4^+ and NO_3^- equally throughout the experiments (Table 3).

Growth and production

In terms of lamina increment, the range of growth varied between 6.5–9% d^{-1}. The growth recorded at the different flow rate levels was not significantly different for all levels of kelp density (Table 4), whereas the growth rate in the lowest density kelp treatment was significantly higher than the growth in the highest density kelp treatment at all flow levels ($p < 0.05$), but it was not

Table 3. Ammonium and nitrate uptake rates (μmol g dry mass^{-1} h^{-1}) of kelp (*L. saccharina*) grown in different flow rate-density combinations. Error bar represents one standard deviation, and *n* is in brackets.

Flow-Density	Ammonium uptake	Nitrate uptake
High-Low	12.1 ± 7.3 (21)	10.4 ± 9.3 (21)
High-Medium	8.4 ± 5.6 (22)	8.6 ± 9.8 (22)
High-High	6.5 ± 4.5 (21)	6.8 ± 7.5 (21)
Medium-Low	7.5 ± 4.1 (22)	7.3 ± 4.4 (22)
Medium-Medium	3.9 ± 2.8 (22)	3.8 ± 5.1 (22)
Medium-High	4.2 ± 2.2 (21)	4.3 ± 4.2 (21)
Low-Low	4.6 ± 3.4 (22)	4.6 ± 4.5 (22)
Low-Medium	4.3 ± 4.1 (21)	3.3 ± 3.7 (21)
Low-High	2.9 ± 1.8 (21)	3.2 ± 2.4 (21)

Table 4. The specific growth rates (% d^{-1}) and 3 day production (g) of kelp (*L. saccharina*) grown in different flow rate-density combinations. Error bar represents one standard deviation. *N* is in brackets and is the same for growth and production.

Flow rate-Density	Growth rate	Production
High-Low	9.0 ± 2.8 (54)	2.1 ± 1.0
High-Med	8.7 ± 2.9 (80)	2.0 ± 1.0
High-High	7.7 ± 2.4 (108)	1.9 ± 0.9
Med-Low	8.6 ± 2.9 (54)	2.1 ± 0.8
Med-Med	7.8 ± 2.4 (80)	1.8 ± 0.9
Med-High	7.1 ± 2.8 (106)	1.6 ± 0.9
Low-Low	8.1 ± 2.4 (54)	1.8 ± 0.9
Low-Med	7.7 ± 2.8 (80)	1.8 ± 0.9
Low-High	6.5 ± 2.4 (107)	1.3 ± 0.8

different from the growth rate in the medium density kelp treatment (Fig. 1).

Biomass production determined over a three day period averaged approximately 25–50 g (db) m^{-3} (Table 4). The biomass production of the lowest density kelp tank was significantly greater than the biomass production of the highest density kelp tank at medium and low flow levels ($p<0.10$). At the highest kelp densities tested, biomass production in the highest-flow rate tank was only significantly different from the production in the lowest flow tank ($p<0.025$).

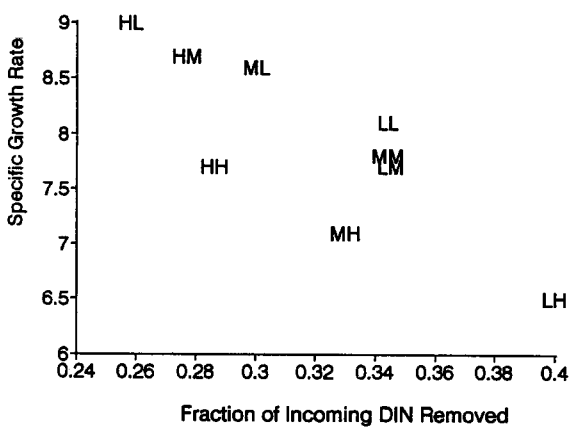

Fig. 1. Specific growth rate decreased as removal rates increased. The symbols represent the different flow-density conditions tested. H, high; M, medium; L, low.

Discussion

Nitrogen removal and uptake

The constant C:N ratios obtained in this study indicated that the kelp were not storing nitrogen, nor were they N-limited. The low removal rates in the control tanks without kelp were not surprising due to high flushing rate of 1–3 times h^{-1} and regular tank cleaning, which prevented bacteria, phytoplankton and periphyton from utilizing available N.

Ammonium removal in our study fell within the range found for other seaweeds. Working with different seaweeds and fish effluent, Fujita *et al.* (1989) found 30–50% of the incoming NH_4^+ was removed, whereas Cohen & Neori (1991) found 90% of the incoming NH_4^+ was removed when the nutrient flux rate was low. Decreasing the ammonia flux rate from 40 to 10 $\mu mol\, l^{-1}\, h^{-1}$ provided a 225% increase in the percent removal (Cohen & Neori, 1991). In our study, a similar change in DIN flux provided a 173% increase in removal.

In general, uptake was controlled by nutrient-exchange conditions. Uptake was the lowest in the lowest flow and highest kelp density conditions. Debris (mainly fish faeces) accumulated in the low flow conditions, and it covered laminae. The coating on the laminae probably decreased the light received by the thallus and lowered photosynthesis and nutrient uptake. The kelp density that gave the best uptake rate ranged between 2.5–4.0 $g\, l^{-1}$, which was below the suggested growth level of 5 $g\, l^{-1}$ (Harrison & Druehl, 1982). The medium density kelp ranged between 4.5–5.9 l^{-1}, and the highest kelp density ranged between 6.3–8.2 $g\, l^{-1}$. Amat and Braud (1990) found that an increase in density of *C. crispus* from 1.48 to 4.28 g dry mass l^{-1} decreased uptake from 26.8 to 17.2 μg N g dry mass $^{-1}$ min^{-1}.

Uptake values obtained in this experiment (DIN, NH_4^+, NO_3^-) were generally higher than results reported in literature. For instance, Harrison *et al.* (1986) reported than DIN, NH_4^+ and NO_3^- uptake rate of first year *L. groenlandica* were 16.8, 9.75 and 7.05 $\mu mol\, g^{-1}$ dry mass h^{-1}, re-

spectively. The results of total N, NH_4^+ and NO_3^- uptake rate of the highest flow-lowest density combination in our experiment were 22.5, 12.1 and 10.4 μmol g^{-1} dry mass h^{-1}, respectively (Table 3). Differences in experimental techniques may explain the differences in uptakes. Firstly, most of the other reported investigations on uptake involved a batch culture system, whereas this experiment used a continuous-flow culture system. Secondly, DIN supply in this experiment was higher than concentrations used in other reported experiments. Thirdly, this experiment used first-year kelp, which could have a higher N uptake than older kelp. Harrison *et al.* (1986) observed that NH_4^+ and NO_3^- uptake rate of first year *L. groenlandica* was three times higher than older (second and third year) kelp.

Based on an ANCOVA model of the pooled data, incoming DIN concentration, which varied from 19.7–52.7 μmol l^{-1} through the course of the experiments, was found to be an important covariate. N uptake increased as average daily N concentration increased. According to the Michaelis-Menten expression, V_{max} was not achieved, because DIN supply from the fish tank was probably not saturating. Harrison *et al.* (1986) observed that N uptake of *L. groenlandica* increased linearly with either NH_4^+ or NO_3^- up to a concentration of 60 μmol l^{-1}. Amat and Braud (1990) reported that an increasing supply of N enhanced uptake rate of *Chondrus crispus*. Lapointe and Tenore (1981) found that NO_3^- uptake of *U. fasciata* depended mostly on daily N supply of that nutrient.

The mean uptake averaged over 3 days was lower than the day-light uptake, because the mean averaged values were affected by dark periods as well as light periods. The uptake rate at night has been found to be lower than the daylight uptake rate (Chapman, 1987). Harrison *et al.* (1986) reported that NO_3^- uptake rate of first year *L. groenlandica* at night was half of NO_3^- uptake rate during daylight, while NH_4^+ uptake rate of the same kelp at night was one-third of NH_4^+ uptake rate during daylight.

The NH_4^+ and the NO_3^- uptake rates were similar for the *Laminaria saccharina* in this work, and comparable results were reported for other *Laminaria* species in other studies (Harrison *et al.*, 1986; Harlin & Craigie, 1978).

Growth and production

Light limitation due to self-shading and high removal rates negatively affected growth. The highest kelp density (6.3–8.2 g l^{-1}) was higher than the suggested density of 5 g l^{-1} (Harrison and Druehl, 1982). The specific growth rate decreased as DIN removal (%) increased and uptake rate decreased (Fig. 1). This result can be attributed to available or ambient DIN concentrations and its effect on growth. As the removal rate increases in a well-mixed culture system like our experimental tanks, ambient or available DIN decreases in the culture tank. Growth was affected, because a direct relationship exists between DIN and *Laminaria* growth (Chapman *et al.*, 1978).

Our results were generally higher than for unfertilized kelp reported in the literature. For example, Gerard *et al.* (1987) reported that the growth rate of *L. saccharina* in nature (ambient N was 0.1–16 μmol l^{-1}) was 1.6–6% d^{-1}. The growth rate of *L. saccharina* in the highest flow-lowest density combination was 9% d^{-1}. The high specific growth rate of *L. saccharina* (5–19% d^{-1}) reported by Bolton and Lüning (1982) was obtained in optimal conditions of enriched seawater and temperature (range 10–15 °C), whereas in our experiment the kelp showed symptoms of photoinhibition and had an unfavourable temperature range during part of the experiment.

In general, biomass production in this study was controlled by light limitation due to self-shading and nutrient-exchange conditions. High densities yield the same biomass as lower densities if flow is adequate.

Applications

If N removal is the purpose of an integrated kelp/salmon system, a kelp treatment system that can remove N quickly and most economically should be considered. An uptake rate V_{mean} of 6.5 μmol

N (g^{-1} dry mass h^{-1}) determined from average daily conditions should be used, because this number would ensure good N removal potential even during the dark periods. Kelp density above 6 kg (wb) m^{-3} negatively affected both N uptake and growth potential, but positively affected DIN removal provided flow rate was below 24 l h^{-1}. If the system had a mixing apparatus so that the light would be evenly distributed, a higher kelp density could be technically, although, perhaps not economically practical. A plugflow type system where background DIN concentration decreases as water passes through the system, may not be effective for biomass production, because in this study kelp DIN uptake and growth decreased with decreasing DIN concentration and increasing removal efficiency. Flow rate in the tank should be adequate to ensure that organic particles do not settle on the kelp blades.

Uptake rates, flow rates and residence times obtained or used in this work can be used to design kelp production and nutrient removal systems that would be effective for similar environmental conditions. A formula derived from considerations of mass balance and required in order to calculate the volume of a kelp land base DIN removal system is

$$\text{Vol} = \frac{10\,EKQ}{VS}, \qquad (4)$$

where Vol = kelp tank volume = QT, T = time required to replace one tank volume (s), Q = flow rate (l h^{-1}), K = DIN loading concentration (μmol l^{-1}), E = desired DIN removal efficiency (fraction), S = kelp stocking density (g m^{-3} db). In nutrient mixed systems, residence time or the time for one complete water exchange can be calculated using simple formulae (Kraul *et al.*, 1985), and it should not be confused with T. Using Eq. 4 with $V = 6.25$ μmol N (g^{-1} dry mass h^{-1}), $Q = 24$ l h^{-1}, $S = 6$ kg m^{-3}, $K = 50$ μmol l^{-1} and $E = 90\%$, Vol = 228 l. If E were reduced to 40%, then Vol = 128 l. Biomass production would be higher in the 40% removal system, because DIN concentrations in the culture tank would be higher.

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