TECHNICAL AND ECONOMICAL FEASIBILITY OF INTEGRATED SALMON AND KELP PRODUCTION SYSTEM

By

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ABSTRACT

The purpose of this study was to evaluate the technical and economical feasibility of *Laminaria saccharina* culture near a salmon netpen farm. A computer model was developed to make this assessment. The availability of ammonia nitrogen from the netpens and its diffusion into the kelp were included in the model. *Laminaria* production is based on nitrogen availability, light and water temperature. Light intensity, including its availability and attenuation, was incorporated into a submodel. This submodel could be used to manage the light intensity on a kelp farm (i.e. by changing the depth of kelp ropes).

Based on model predictions, a *Laminaria* farm containing 10 60 m ropes on each end of a salmon netpen farm is technically feasible and is fertilized by the salmon farm. A yearly production of 1600 kg of kelp (dry basis) and a net profit of $20,000 are expected by this size of farm (selling price = $35 per kg dry mass). Kelp production on multiple salmon farms or with more kelp ropes could increase the overall net revenue of the owner. Larger-sized kelp farms may, however, need artificial fertilizer.

The average rate of light radiation for good kelp growth should not exceed 100 $\mu E\ m^{-2}\ s^{-1}$ and should not be less than 30 $\mu E\ m^{-2}\ s^{-1}$. Light intensity for different depths and attenuation coefficients can be predicted by the light submodel, and this information can be used as a kelp farm management tool. Light availability depends on the season of the year and water condition.

By using this submodel, the optimum depth of a kelp raft for growth can be determined. A 47% reduction in light intensity is observed when light travels from a depth of 2 to 7 m (attenuation coefficient = 0.1 m^{-1}). A set of experiments was conducted at the Department of Fisheries and Oceans facilities (July-August 1991) to examine *Laminaria* growth at different salmon-effluent nitrogen concentrations and to validate the *Laminaria* growth model. The experiment was a model of an actual kelp farm near a netpen (i.e. similar water velocity and tidal effects). The model was validated for ammonia nitrogen concentrations of less than 5 μM. A direct relationship between growth rate, and ammonia nitrogen and nitrate availability was found. For a combined nitrogen concentration of ammonia nitrogen and nitrate of 9.7 μM, a specific growth rate of 9% d^{-1} was obtained.

A second set of experiments was conducted to measure the oxygen consumption rate of the kelp. The results were used in the computer model to determine if kelp farms would cause an oxygen deficit for fish in the netpens at night. The consumption rate was found to be 0.024 mg O_2 g $kelp^{-1}$ h^{-1}. This result was used in the model to compare oxygen availability versus oxygen consumption rate. The results from the model were used to show that for a 10 x 60 m rope kelp farm, oxygen consumption at night was less than 1% of the oxygen available to the fish in the netpens. Therefore, oxygen consumption at night by a 10 x 60 m rope farm would not cause significant oxygen depletion for fish.

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I. INTRODUCTION

World demand for fish as a source of food for human consumption has been continuously growing since the end of the second World War. The demand is projected to increase by around 2 to 2.4% per annum (Beveridge, 1987). The British Columbia Salmon Farmers Association projected a farmed salmon harvest of about 16,500 tonnes in 1992. This production generates an environmental nutrient loading (i.e. nitrogen in the form of ammonia nitrogen) and reduces the concentration of the dissolved oxygen around the salmon net pen farm (Phillips et al., 1985).

The cultivation of kelp outside a fish farm could utilize the released nitrogen for tissue growth, increase the dissolved oxygen level through photosynthesis and bring an economical return. Kelp has economic value for its food value (i.e. kombu), chemical content, particularly iodine, and to lesser extent for its vitamin and alginic acid content (Glicksman, 1987; Druehl, 1988a). Alginate has a large application in the food industry, where it is mostly used as a thickener and stabilizer for different frozen, dairy and bakery products. Kelp accounts for 66% of the total cultured seaweed production of Asia and the Pacific in 1988 (FAO, 1990). The total cultured seaweed production globally reached 3.6 million tons in 1988. Kelp has been cultivated for many years in South East Asia and recently in British Columbia (Druehl et al., 1988b).

Kelp cultured on fish culture effluent receives the benefit of free fertilizer. Lobban and Wynne (1981) discuss the need of applying fertilizer to the body of water to enhance kelp growth. The fish farm replaces the need for artificial fertilization. To date, this type of integrated system has not been modelled or tested.

Mathematical models were developed in this thesis in order to determine technical and economical feasibility of kelp culture near a salmon netpen farm. *Laminaria* species was chosen to be studied because it is a cold temperate species, which grows in British Columbia; it can be grown in raft culture in waters beside salmon netpens, and it has a commercial value as kombu. With a few modifications in the model, *Nereocystis* and *Macrocystis* culture feasibility can be substituted.

II. OBJECTIVES

The objectives of this study were :

1) to examine the relationship between growth rate of *Laminaria saccharina* and ammonia nitrogen concentration from salmon effluent through a set of experiments and computer simulations.

2) to examine phosphorus limitation in the integrated salmon and kelp culture.

3) to analyze oxygen consumption by kelp due to respiration at night.

4) to analyze light intensity in different water conditions (i.e. different attenuation coefficients) at different water depths. This would enable farmers to alter the cultivation depth of kelp for maximum growth.

5) to develop a computer model to simulate the following:
   - i) fish growth in netpens
   - ii) ammonia nitrogen production in netpens
   - iii) phosphate production in netpens
   - iv) ammonia nitrogen and phosphate concentration in the kelp raft.

v) kelp growth rate at different ammonia nitrogen concentration with different water temperatures.

vi) mass of kelp produced for different farm sizes.

6) to estimate the economical feasibility of the kelp farm beside a netpen operation (i.e. selling kombu).

III. LITERATURE REVIEW

3.1 Kelp Characteristics

Seaweeds are large marine algae, which can be divided into three major groups: green, brown and red algae. Seaweeds grow in intertidal and subtidal habitats; they vary in form from filamentous, simple to branched blades. Seaweeds require sunlight for photosynthesis. They absorb nutrients directly from the water through cell walls, since they do not have a root system. Seaweeds reproduce either by fragments or by mobile or immobile microscopic spores (Cheney and Mumford, 1986).

Kelp (or brown algae) grow around Vancouver. Different types of kelp, such as *Macrocystis integrifolia* and *Laminaria saccharina*, can be found in coastal waters of British Columbia. The technology for extensive culture of *Laminaria saccharina* has been proven in B.C. (Druehl et al., 1988).

Laminaria is important for its food value (i.e. kombu) as well as its chemical content (e.g. alginate and iodine). *Laminaria* is used to prepare different food dishes. Powdered kelp and kelp strips can be utilized as tea or as the base for various soups, broths and marinades (Druehl, 1988a). Dried kelp (1 m long and 0.40 to 0.50 m wide) were sold to health food stores in Vancouver for $32 per kg dry mass in 1988 (Lloyd, Pers. Comm.).

On the other hand, alginate, extracted from kelp, is used as a stabilizer (e.g. for cream cheese and whipped cream) and as a thickener for bottled salad dressings (Glicksman, 1987). Food demand for edible seaweed is increasing, on the other hand; the alginate market is nearly saturated (Csavas, 1990).

3.2 Kelp Growth Studies

Different environmental parameters such as nutrient availability, irradiance and water temperature influence kelp growth. In nature, seasonal growth patterns, due to different combinations of environmental factors, can be observed. In winter, because of low water temperature, respiration is minimal, therefore; the carbonic compensation point is low and a photosynthetic surplus could be achieved despite low light intensities (Gagne et al., 1982). In summer, growth is nitrogen-limited, so *Laminaria lingicruris* builds up reserves of carbohydrates. In fall, respiration is maximum; light intensity decreases, and growth is minimum (Gagne et al., 1982).

Druehl (1967) mentioned two growth seasons for *Laminaria* grown in British Columbia, namely, the season of rapid growth (January-June) (i.e. due to upwelling) and the season of slow growth (July-December). Gagne et al. (1982) suggested that *Laminaria* did not have a typical seasonal pattern of growth and it responds differently to different environmental factors. When a *Laminaria* population is sufficiently exposed to a particular combination of environmental parameters, it can genetically change and lose the potential to respond to other environmental combinations.

3.3 <u>Nutrients and Water Motion</u>

Nitrogen is a limiting factor in oceanic environment. Harrison et al. (1986) concluded that *Laminaria groenlandica* utilized ammonium as well as nitrate. Subandar (1991) found that ammonium and nitrate contributed equally to nitrogen uptake by *Laminaria saccharina* cultured in tanks receiving salmon culture effluent. The nutrient uptake by a seaweed depends both upon concentration of the nutrient in the surrounding water and the amount of water movement. Dunton (1985) stated that the periods of highest growth in *Laminaria solidungula* and *L. saccharina* occurred during the periods when high concentrations of inorganic nitrogen were available in water.

Phosphorus is one of the nutrients required by kelp. Phosphorus is generally not considered to be a limiting nutrient in the marine environment (Lobban and Wynne 1981). The major form in which algae acquire phosphorus is as orthophosphate ions. A maximum uptake rate (i.e. V_{max}) of 0.47 μmoles g dry mass^{-1} h^{-1} was obtained for the red algal *Agardhiella subulata* (DeBoer, 1981).

Nutrient uptake by marine plants is related to water motion. The effect of water motion on growth and production of *Laminaria* has extensively been studied. Some studies concluded that a positive relationship between water current and growth or production exists (Pace, 1972; Markham, 1973; Kain, 1977; Parker, 1981). Gerard (1987) observed that plants in turbulent habitats grew faster than the plants in still habitats. Dayton (1975) indicated that wave action (i.e. high water current environment) could limit predatory or competitive species.

Gerard (1987) reported that plants subjected to constant longitudinal tension had significantly narrower blades and higher rates of blade elongation than plants with no stress on them. Low flow velocities can limit boundary layer transport of essential dissolved gases and nutrients and thus result in reduced growth and production (Wheeler, 1980; Parker, 1981 and 1982). "The Japanese feel that water motion is an important factor influencing the quality of cultivated kombu (edible kelp)" (Druehl, 1967).

3.4 Temperature

Temperature is one of the environmental parameters affecting kelp growth rate. It is also the single most important factor determining the geographic distribution of benthic marine macroalgae (Gerard and DuBois, 1988). The growth rate of seaweeds is affected by the surrounding temperature. Generally, individual enzyme reactions have a peak above or below the optimum-temperature range. Bolton and Luning (1982) concluded that optimal growth (15 to 18% d^{-1} in length) of *Laminaria saccharina* occurred at a temperature range between 10 to 15°C. They also observed that the specific growth rate of *Laminaria saccharina* was reduced by 50 to 70% when the surrounding temperature reached 20°C, and it was reduced to 60 to 70% of the optimum when the temperature reached 5°C.

3.5 Light

Light intensity is an controlling factor for photosynthesis in seaweeds. Photosynthesis consists of two reactions, namely light and dark reactions. The light reactions consist of energy absorption, energy trapping and ATP generation. In the dark reactions, ATP and NADPH are used to fix inorganic carbon. Boden (1979) concluded that irradiance controlled *Laminaria saccharina* production. The saturation irradiance for *Laminaria* is between 30 to 100 $\mu E\ m^{-2}\ s^{-1}$ (Harrison and Druehl, 1982).

The photosynthetic rates of the kelp also affect oxygen production. King and Schramm (1976a) measured the photosynthetic rate for *Laminaria digitata* to be 1.19-3.97 mg O_2 g dry mass^{-1} h^{-1}. King and Schramm (1976b) concluded that for *Laminaria saccharina* the maximum photosynthetic rate was 2.0 mg 02/g dry mass^{-1} h^{-1} (i.e. for Millipore-filtered (0.22 μm) natural seawater of salinity 15°/oo and, temperature 15°C).

The parameters which affect solar-light intensity are discussed next, because they help explain light-limited growth patterns of seaweed. The intensity of solar radiation at the plant canopy depends on different factors such as time of year, plant spacing, water depth, water clarity (i.e. phytoplankton blooms) and latitude. Dunton (1985) observed very little growth in *Laminaria saccharina* during the dark period. Growth is delayed until light is available, irregardless of nutrient concentrations.

As solar radiation passes through the atmosphere, some energy is scattered and some is absorbed (i.e. transferred to heat)

(Figure 1). The solar radiation reaching the earth's surface is composed of direct and diffuse radiation. Dry-air molecular absorption, scattering and absorption from dust, selective absorption by water vapour and other gases (e.g. CO and CO_2), and reflection and absorption in cloud layers are the parameters given by Kreith and Black (1980) to reduce solar intensity. The availability of solar radiation on the earth depends on latitude, season and weather. The dependency on latitude and season is because of the elliptical path of the earth around the sun.

Light penetration in water depends on the amount of scattering and absorption in the water column. Scattering can be divided into two components, namely, scattering by pure water (molecular scattering) and particle scattering. The attenuation of light in water is a function of water depth and the size and concentration of particulate matter in the sea. Ingmanson and Wallace (1989) defined attenuation as a lessening of the amplitude of a wave with distance from the origin.

If the light intensity at different locations and periods are known, the optimum depth for the kelp raft can be determined. The mathematical equations to compute light availability in the water column are described in this section. Daily extraterrestrial

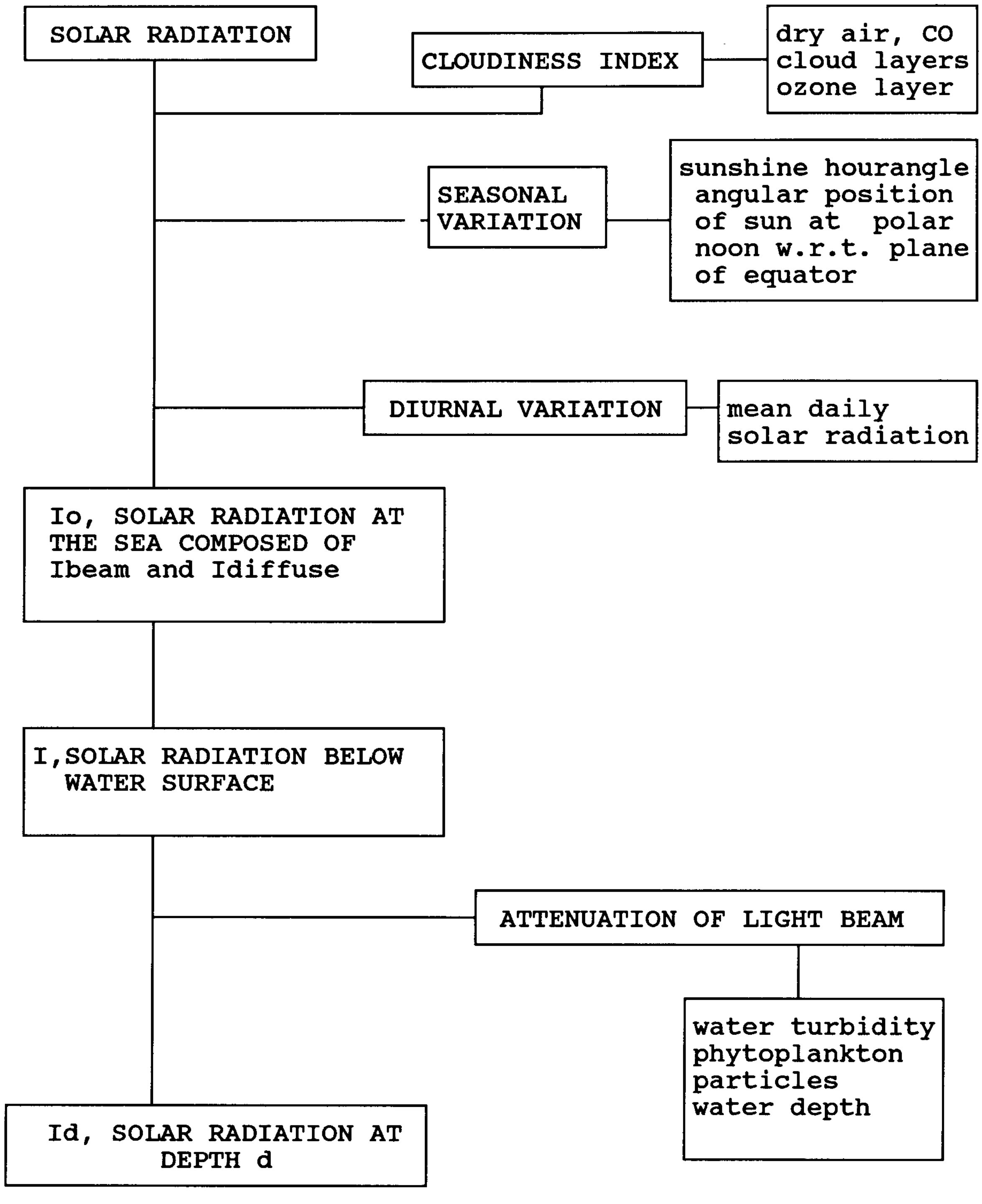

Figure 1. Solar radiation path from the sun to an ocean depth.

radiation on a horizontal surface can be computed using the following equation:

$$H_o = \frac{24}{\pi} I_{sc} E_o \left[\frac{\pi}{180} w_s (\sin\delta \sin\phi) + \cos\delta \cos\phi \sin w_s \right] \qquad (1)$$

where I_{sc} = solar constant = 1367 W/m^2.

Solar constant is the rate of solar energy incident in per unit area exposed normally to sun rays at one AU or mean sun earth distance. Parameter E_o is eccentricity and is mathematically described below:

$$E_o = \left(\frac{r_o}{r}\right)^2 = 1 + 0.033 \left[\cos \frac{2 d_n \pi}{365}\right]) \qquad (2)$$

where r_o = mean sun to earth distance,
r = sun to earth distance on a particular date, and
d_n = day number (e.g. on Jan 1 d_n = 1).

Sunrise hour angle w_s is calculated using the following equation:

$$w_s = \cos^{-1} [-\tan\delta \tan\phi] \qquad (3)$$

Solar declination is defined as follows by Iqbal (1983):

Daily diffuse radiation, H_d, is needed to calculate the hourly

$$\delta = \sin^{-1}\left[0.4 \sin\left(\frac{360}{365}(d_n - 82)\right)\right] \qquad (4)$$

diffuse radiation in Equation 6. Parameter H_d is calculated as follows (Iqbal, 1983):

$$H_d = H\,(0.958 - 0.982\,K_T) \qquad (5)$$

where H is the global daily radiation and is obtained by summing the hourly solar radiations from Canadian Climate Normals. Cloudiness index K_T is the ratio of global to extraterrestrial radiation (Iqbal, 1983).

$$K_T = \frac{H}{H_o} \qquad (6)$$

The hourly diffuse radiation I_d is computed by equation 7. Hourly global radiation (from Canadian Climate Normals) is composed of beam and diffuse radiation. Hourly beam radiation is calculated using Equation 8 (Iqbal, 1983).

$$\frac{I_d}{H_d} = \frac{\pi}{24}\,\frac{\cos w - \cos w_s}{\sin w_s - w_s\left(\frac{\pi}{180}\right)\cos w_s} \qquad (7)$$

$$I_{beam} = I_{global} - I_d \qquad (8)$$

where I_{beam} = hourly beam radiation
I_d = hourly diffuse radiation, and
w = solar hour angle.

Below the water surface, radiant energy decreases exponentially as it penetrates through optically uniform water (Riley and Skirrow, 1975).

$$I_z = I_o e^{-kz} \qquad (9)$$

where I_o = intensity of light crossing the water surface
I_z = intensity at depth z, and
k = vertical attenuation coefficient.

In order to convert the units from watts m^{-2} to $\mu E\ m^{-2}\ s^{-1}$, the following approximation for sunlight for the photosynthetically active range of 400-700 nm can be used (Brock, 1981)

$$1 W m^{-2} = 4.6\ \mu E\ m^{-2} s^{-1} \qquad (10)$$

A summary of the light model algorithm is presented in Chapter 7. This algorithm describes different parameters which affect light intensity from the sun to a point in the water column.

3.6 Kelp Production and Integrated Culture

As competition for coastal waters increases and demand for edible kelp increases, a greater importance will be given to extensive cultivation methods. In Asia and the Pacific regions where the seaweed production was 3.6 million tonnes in 1988, 90% of the harvested seaweeds comes, for instance, from aquacultural practices (Csavas, 1990). At present most of the cultured seaweed production in the world is in Asia and the Pacific regions. In the rest of the world, seaweed production comprises only 1% of the total aquaculture production.

Farming involves the cultivation in the sea of small sporophytes of *Laminaria* until they reach the desired size of approximately 1 m. Floating kelp farms constructed of anchored ropes are buoyed at the surface by floats. In South East Asia two kinds of floating arrangements are used to construct a cultivation raft in offshore areas (Lobban and Wynne, 1981). One type is horizontal where the rope lies parallel to the sea surface and is buoyed by commercial rafts. The second method is the hanging type, where series of ropes lie perpendicular to the sea surface. Clusters of *Laminaria* are inserted in the twist of the ropes every 30 cm. The distance between the ropes is at least 5 m, in order for boats to pass and in order to enhance nutrient availability. Boats are used to spray fertilizer on the farm every few days (Lobban and Wynne, 1981).

Different fertilizer application methods have evolved to enhance the kelp growth. Lobban and Wynne (1981) mentioned the porous container method as well as the spraying method. Both methods are used in China to apply nitrogen to the kelp. In the porous container method, the clay bottles containing nitrogenous fertilizer, usually ammonium sulphate, are hung at certain intervals from the rope. Fertilizer application using the spray method is not very laborious and is more efficient. In either the horizontal or vertical type farming arrangement when the kelp grow to their harvesting age, the ropes are pulled into the boat and transferred to shore. Once on shore, the kelp is dried and sold.

In British Columbia the duration of *Laminaria saccharina* cultivation is approximately 8 months. In a set of experiments conducted by Druehl et al. (1988b) the final wet mass of *Laminaria saccharina* ranged from 192 to 435 g after 8 months of cultivation. In these experiments, production started in February and ended in September. The farming practice was the horizontal cultivation type. Seedlings were inserted in the twist of the ropes approximately every 30 cm. The ropes laid horizontally in the water column. At the harvest time ropes were transferred to the shore by boats, and the clusters were detached from the ropes. In British Columbia, air drying is not permitted, so either green houses or commercial dryers must be used to process the product.

3.7 Netpens and Fish Growth

Netpen or cage culture provides low cost alternatives to conventional land-based grow-out facilities. A cage is a type of rearing unit which is screened on all sides (except the top) by mesh or netting, through which water exchange is facilitated. Netpens are sometimes preferred to land-based structures because of their simple technology, ease of management and lower cost. Netpens are floating structures which are used to grow different marine species. Salmon ranging in size between 10 and 60 g are put in the netpens. Final stocking density is approximately 10 $kg.m^{-3}$ in British Columbia, and the final fish size ranges from 1.8 to 3 kg.

The growout period for Atlantic salmon is up to 18 months (Laird and Needham, 1988). The number of the netpens per farm in British Columbia ranges from 6 to 60 netpens (Tillapaugh, Pers. Comm.). The typical size of the netpens in British Columbia is 2250 m^3 (15 x 15 x 10 m) for Atlantic salmon and 3375 m^3 (15 x 15 x 15 m) for Pacific salmon (Tillapaugh, Pers. Comm.).

Cage finfish aquaculture is the most common method of intensively reared marine fish species (Kuo and Beveridge, 1990). Water quality determines to a great extent the success or failure of a fish production operation. Oxygen requirements of fish depend on species, stage of development and size. At most sites, dissolved oxygen concentrations of surface waters are close to saturation levels (i.e. 8 to 9 mg l^{-1}). As long as cages are maintained free from fouling organisms and current is sufficient, no oxygen depletion should occur (Beveridge, 1987).

Oxygen, being the second most abundant gas in water after nitrogen, is needed by fish for digestion and assimilation of food, maintenance of osmotic balance and their activities. Oxygen uptake by fish occurs by diffusion. The governing parameter in diffusion (gas exchange process) is the oxygen tension gradient between tissues and the external medium (i.e. water). Oxygen diffuses across the gills into the blood down an oxygen gradient of 40 to 100 mm Hg. Stewart et al. (1967) concluded that low concentrations of oxygen would decrease food conversion efficiency. Whitmore et al. (1960) observed that juvenile chinook salmon showed avoidance to oxygen concentrations of 1.5 to 4.5 mg l^{-1} in summer, but showed little avoidance in winter. Randall (1970) mentioned that fish became more active in hypoxic (i.e. low oxygen concentration) water and tried to move away from the low oxygen level zone. Oxygen concentrations below 6.0 mg l^{-1} are not recommended.

The environmental parameters such as water current and water temperature affect oxygen availability in the net pens. Gormican (1989) compared dissolved oxygen values in two different fish cages with the same stocking densities. The cage with slower current had a larger dissolved oxygen value compared to the cage with faster current. He suggested that a faster current speed may necessitate a greater swimming speed, and hence an increase in the metabolic rate. The optimum current speed depends on fish size and stocking density; however, it is assumed that the current velocity should not be lower than 0.10 m s^{-1} in the cages (Aarsens et al., 1990). Braaten and Saerre (1973) suggested that the sites with a tidal current range of 0.1 to 0.6 m s^{-1} were appropriate for cage culture.

The fluctuations of dissolved oxygen level in water column depend on water temperature and water salinity (see Beveridge, 1987). Oxygen solubility declines with increasing salinity. Seawater contains, therefore less dissolved oxygen than fresh water. As water temperature increases, O_2 solubility in water decreases. Fish living in warm water should pump more water to maintain a constant oxygen level.

3.8 Fish Growth Models

There are different approaches to simulate fish growth. Stauffer (1973) developed the following equation to predict coho and chinook salmon growth.

$$W = (W_o^B + ABt)^{1/B}$$

where W = final fish mass (g),
W_o = initial fish mass (g),
t = time (days),
B = 1/3, and
A = a polynomial function of temperature.

Iwama and Fidler (1989) developed a growth equation for salmon based on initial mass and temperature (valid between 4 to 18°C).

$$W_t^{0.33} = W_o^{0.33} + G_c(T/1000)t$$

where W_t = fish mass at time t (g),
W_o = fish mass at t = 0 (g),
t = time (days),
T = temperature (°C), and
G_c = variable growth coefficient.

Austreng et al. (1987) produced tables of fish (salmon and rainbow trout) growth rate in sea cages for different fish sizes and different temperatures.

3.9. Nutrient Loading

Weston (1986) proposed three sources of nutrient loading from the netpens. They include: the dispersion of the soluble end products of the salmonid metabolism, the excretory products of fouling organisms on the nets and the decomposition of the excessive feed and faeces deposited beneath a netpen.

Enell (1982) concluded that nitrogen concentration increased by 0.05 mg l^{-1} in a fish farm with an annual production of 20 to 44 tons per year. He measured the total nitrogen load from the farm to be 86 kg ton^{-1} of fish produced per season (N-content in fish food = 8.45% of dry weight). Enell (1982) found that about 78% of total nitrogen was in the dissolved form.

Phillips et al. (1985) stated that phosphorus and nitrogen were the two important nutrients which cause nutrient loading. Phosphorus, being an important element for fish growth, is added to the fish diet. Beveridge and Muir (1982) reported the dietary phosphorus requirements of fish to be from 0.29% to 0.90% of the mass of the diet. Ackefors and Enell (1990) estimated 2.2 kg dissolved phosphorus and 7.3 kg particulate phosphorus per ton of fish were produced in a cage farm operation. Their estimate was based on a feed containing 0.9% phosphorus and a feed conversion ratio of 1.5. The particulate matters will accumulate beneath the fish netpens. The pattern of sedimentation beneath the netpens depends on current velocity, water depth and total particulate matter output from the fish netpens (Iwama, 1991).

3.10. Uptake and Growth Models

Different growth models have been developed to estimate the nutrient removal rate. Monod equation for bacterial growth is

$$y = \frac{(y_{max} S)}{K_s + S}$$

where y = uptake or growth rate,
y_{max} = maximum uptake or growth rate,
S = limiting substrate concentration (μM), and
K_s = half saturation concentration (μM).

In nature, production depends on growth as well as loss. For kelp this loss could be due to predators and other limiting environmental parameters (i.e. limiting light or nutrient).

The following equation describes the production (Charpa and Reckhow, 1983) :

$$R = R_{growth} - R_{loss}$$

where R = phytoplankton production,
R_{growth} = phytoplankton growth, and
R_{loss} = phytoplankton mass loss.

For multiple nutrient limitation, the reduction in growth due to all limiting nutrients should be considered (Charpa and Reckhow, 1983):

$$R = R_1 \times R_2 \times R_3 \times \ldots \times R_i$$

where R = fractional limitation for multiple nutrient limitation, and
R_i= fractional limitation for individual nutrients.

3.11. Production Models

This section gives a brief description of two recent production models for kelp. To date all models that were developed were used on natural populations. Different approaches were taken to develop the models. Since a model is a simplification of a system, naturally each model has its own limitations. More powerful models should be developed to enhance our ability to predict the growth of kelp and its sensitivity to variations of environmental parameters.

The models which are discussed are as follows :

1) A stage structured, stochastic population model for the giant kelp *Macrocystis pyrifera* by Burgman and Gerard (1990).

2) Growth and harvest yield of the giant kelp *Macrocystis pyrifera* by Jackson (1987).

The above mentioned models are for kelp growth in the natural state. Computer models of kelp farm production have not been developed.

i) Burgman and Gerard (1990) developed a stage-structured stochastic population model for the giant kelp *Macrocystis pyrifera*. The model predicts monthly changes of population in an area of 1000 m^2. The model is a function of environmental stochasticity. Environmental stochasticity can be defined as the random variation in population parameters due to variability of environmental conditions. Environmental stochasticity is represented in Burgman's model by a coefficient of variation , CV. Environmental parameters include temperature (at sea surface and bottom), irradiance (at the bottom in open water) and gametophyte density. Coefficient of variation for each of these parameters is input data in the model. The model predicts the density of each sporophyte stage (population is divided into 5 life-history stages) monthly for up to 20 years. The model uses temperature to simulate the effects of both temperature and nitrogen supply.

In order to consider mortality, specific monthly survival probabilities for each life-history stage are used. A coefficient of variation CV is specified by the user for each mean survival probability. The output of the model is the mean density for each sporophyte stage as a function of time. Monthly mean values of canopy frond density, irradiance on the bottom (under the kelp canopy), temperature (at sea surface and bottom), as well as extinction probability for the adult sporophyte can also be obtained from the model.

ii) Jackson (1987) introduced a model for growth and harvest yield of *Macrocystis pyrifera*. The model calculates plant biomass and production as a function of environmental parameters. All of the environmental parameters affect the growth by affecting the light flux. The environmental parameters include water clarity, bottom depth, latitude, harvesting activity and photosynthetic response (i.e. P_{max} vs I). Plant growth is obtained using daily net production (i.e. photosynthesis - respiration).

Jackson (1987) compared light limitation versus nutrient limitation for the growth of kelp. Chapman and Craige (1978) observed that winter growth for various seaweeds is light-limited (i.e. high nutrient winter condition) and nutrient-limited during summer conditions. Jackson (1987) suggested that a combination of light and nutrient limited models should be considered.

IV. MODEL DEVELOPMENT

4.0 Conceptual Model.

Few adequate near-shore sites for *Laminaria* exist in British Columbia. *Laminaria saccharina* requires a site with the following characteristics: an optimum water temperature range of 10 to 15 °C and good water clarity. Saturation irradiance range from 30 to 100 $\mu E\ m^{-2}\ s^{-1}$ (Harrison and Druehl, 1982). Sites should be chosen in upwelling zones or any place that nutrients can be added artificially.

Salmon netpen farms meet most of these criteria. The water clarity in terms of water on salmon farms is good, because it ranges from 6.5 m in summer to 11 m in winter (from records of the Fisheries and Oceans Canada). These translate into extinction coefficients of 0.26 and 0.15 m^{-1}. The low values of extinction coefficients indicate that the ropes should be laid deep in water to avoid photoinhibition. The rate of irradiance in British Columbia from January to June ranges from 300 to 1330 $\mu E\ m^{-2}\ s^{-1}$. The depth of cultivation ropes, therefore, should be between 2 to 3 m in winter and 6 to 7 m in summer. As the kelp grow, there would be a self-shading effect of kelp plants, and therefore, they can be brought up closer to the surface.

The conventional kelp mooring system would, however, need to be redesigned, and the drying facilities, if not located on the salmon farm, would have to be remotely located. One advantage of the integrated system is that fertilization costs do not apply here, because the nutrients stemming from the salmon farm fertilize the kelp. In a conventional system, fertilizer is applied to a kelp farm every other day. The fertilizer application requires a great deal of labour, because it is a continuous operation. In an integrated system, labour would be required during the harvesting period to pull out the ropes and to insert the new seedlings in the ropes. Daily inspections lasting 15 to 120 minutes would also be required.

Another advantage to integrated culture is the ability of the kelp to improve water quality for the salmon farm in terms of oxygen and nutrient removal. The salmon farmer may be able to renegotiate lease agreements based on the "on site filtering" system.

One possible concern of kelp production beside a netpen is the ability of the seaweeds to withstand a current velocity of 0.1 m/s. The interaction between hydrodynamic forces in the ocean and the structure of the seaweeds have been studied. The primary hydrodynamic force exerted on macroalgae is drag, which acts in the direction of flow. Carrington (1990) suggested that the survival of intertidal macroalgae (i.e. *Laminaria*) depended on their ability to withstand large hydrodynamic forces generated by breaking waves, an ability that is a function of both morphology and the size of the plants. Jackson and Winant (1983) found that for a tidal current of 0.10 m s^{-1}, the drag force was given as 15.5 N on a typical *Macrocystis* plant. They concluded that the structure of the plant and its holdfast are sufficiently strong to withstand loads of this magnitude.

Another possible concern to integrated culture is the nightly oxygen requirements of kelp. The oxygen production in a kelp farm beside netpens could provide continuous oxygen supply during the daylight hours, but in the dark, kelp consume oxygen. Respiration rates for *Laminaria saccharina* were measured to be between 0.1 to 0.3 μmol cm^{-2} h^{-1} (Gerard, 1988).

The integrated salmon/kelp system was conceptualized to be composed of different components, namely, the fish farm and nutrient availability, kelp farm and productivity, and the economical component (Figure 2). Horizontal-type kelp farms are viewed being located on both ends of a salmon netpen farm. A horizontal type was chosen over the vertical type because it was tested in British Columbia (Druehl et al. 1988b). In the conceptual system, the rope spacing between the ropes is 3 m, whereas in practise, fertilized kelp farms have 5 m rope spacings to facilitate the movement of the boats used for fertilizer application. In the conceptualized integrated system, nutrients are transferred by water current, and hence the spacing between the ropes are reduced. The smallest rope spacings in this integrated system could possibly be as small as 1 m. The spacing could be the smallest before light impedance limits growth.

The fish farm used in the conceptualized model contains 12 (15 m x 15 m x 10 m deep) netpens. The cages are arranged 4 by 3, with the current passing through the side with the largest number of cages. The species chosen for culture is Atlantic Salmon. The final stocking density in the netpens is 10 kg m^{-3}, which is

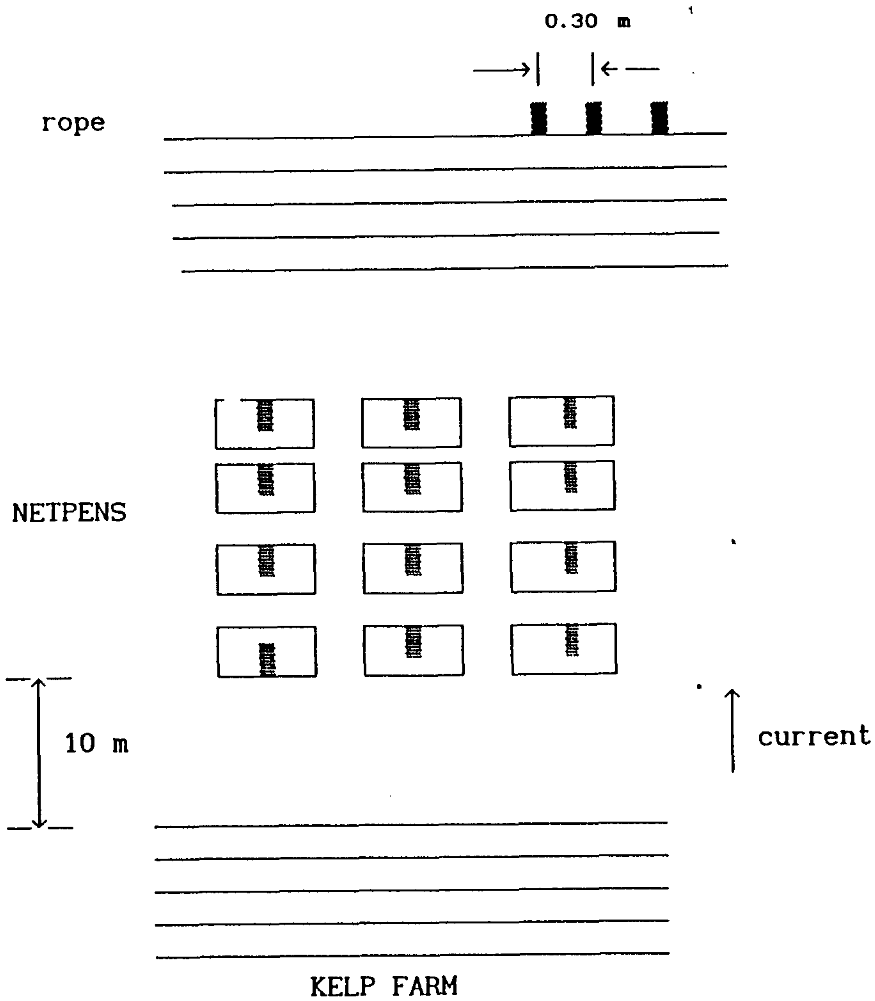

Figure 2. Schematic of the proposed integrated salmon/*Laminaria* farm. Current on the site changes direction with tidal pattern.

currently typical in British Columbia. The initial fish mass in the model is 40 g. The fish production schedule follows a single-year class scheme. A 10% mortality throughout the production cycle is assumed.

Tidal currents would bring waste nutrients to one of the kelp farms, and when the tidal currents change direction, nutrients would bring nutrients to the other farm. A distance of 10 m between the kelp and salmon farms was considered ideal for boat movement.

A mathematical model was developed using mathematical expressions of netpen nutrient release, kelp nutrient uptake and kelp growth. These expressions were interrelated in order to predict seasonal kelp production and economics (Figure 3). The kelp farm size for this study was limited to the size expected to be fertilized by the netpen farm and not expected to be light limited. The payback period of the resulting farm was calculated. The mathematical expressions, interrelations and economical assumptions used to develop the production model are discussed in this Chapter. The model with small changes can be used to study the economics of different netpen clusters, fish species, kelp farming methods, kelp species and kelp farm sizes.

4.1 Fish Farm and Nutrient Availability

A netpen salmon farm produces valuable nutrients for kelp, ammonia, urea, nitrate and phosphate. These nutrients are needed for rapid kelp growth. The nutrient in the system model will be

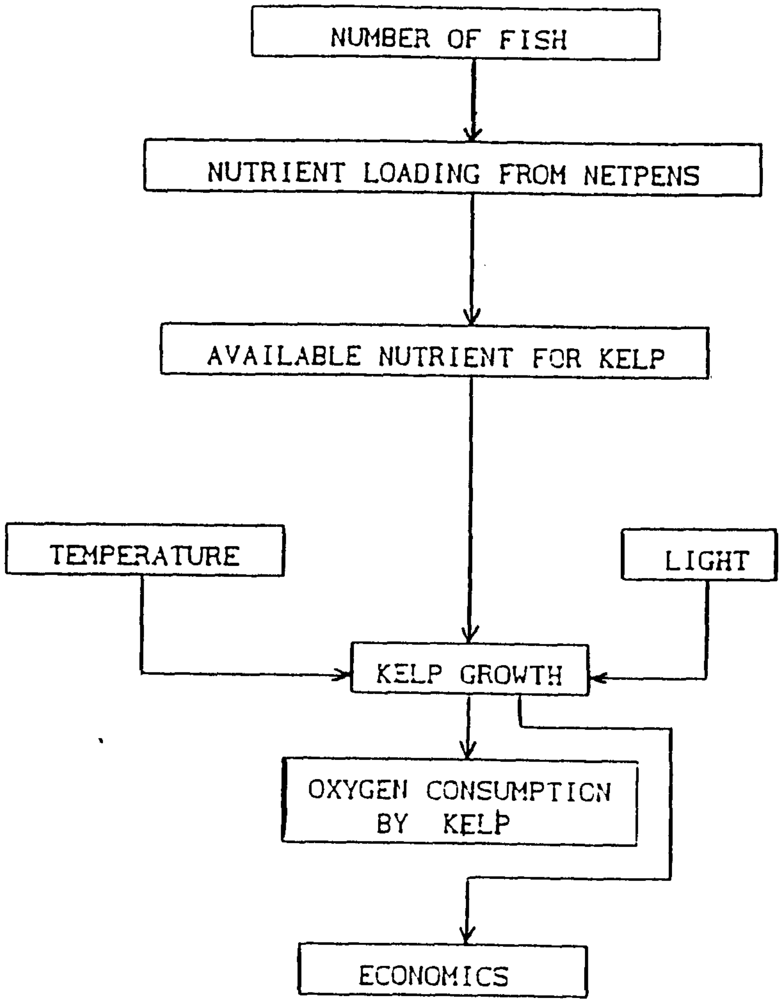

Figure 3. Flow diagram of an integrated salmon/*Laminaria* system representing components and environmental inputs. It includes nutrient loading (ammonia nitrogen + phosphorus) from the netpens, *Laminaria* growth, environmental parameters affecting *Laminaria* growth and economics.

restricted to ammonia nitrogen, because more than 60% of salmon nitrogen waste is found in this form (Fivelstad et al., 1990). In this section, parameters which affect the supply of nutrients to the kelp farm and kelp growth are discussed.

The supply of nutrients depends on the number and size of fish. In order to simulate fish production, the growth rate estimates for cultured Atlantic salmon in sea cages by Austreng et al. (1987) are used (section 3.9). Their approach was preferred over other models, because they have used actual data from sea cages. They produced tables of Atlantic salmon growth rate (% mass day^{-1}) for different fish sizes at different temperatures. Mathematical expressions relating growth to temperature were obtained from this growth data (Table 1). The expressions were obtained with linear correlation.

The available nutrient in the netpens depends also on the desired final stocking density, mortality, individual fish mass, the volume of each netpen, as well as the number of netpens in operation. Total fish mass in netpens at any time can be calculated using the following equation :

total fish mass = ((initial fish number in netpens) x (fish mass at time t)) x (1 - (% daily mortality x days after start of production) (11)

initial fish number in netpens = netpen volume (m^3) x number of netpens x final stocking density (kg/m^3) / final fish mass / (1 - % mortality)

fish mass at time t = (fish mass at time t = 0) e^{Gt}

where G = specific growth rate, in % day^{-1}, Table 1,
t = time in days.

Table 1. Mathematical expressions relating growth (% day^{-1}) to temperature (°C) were obtained from Austreng et al., 1987.

Fish Size (g)	Growth Equations (% day^{-1})	R^2
30 - 150	Growth = 0.15 * Temp + 0.10	1.0
150 - 600	Growth = 0.12 * Temp - 0.014	0.996
600 - 2000	Growth = 0.079 * Temp + 0.014	0.992
> 2000	Growth = 0.05 * Temp	1.0

Different ammonia nitrogen and Phosphorus production models exist (Liao, 1974 and Fivelstad et al., 1990. Liao (1974) used feeding rate as the parameter determining ammonia nitrogen and phosphate production, whereas Fivelstad et al., (1990) related ammonia nitrogen production to fish growth rate:

1) Fivelstad's model

ammonia produced = 0.1525 * Growth - 0.0078 **(12)**

ammonia produced = mg ammonia / kg fish / min, and
Growth = is obtained from equations (Table 1).

2) Liao's model

ammonia produced = (0.0289)(Feeding rate)(TFM)(0.01) **(13)**

phosphate produced = (.0162)(Feeding rate)(TFM)(0.01) **(14)**

where Feeding rate = kg feed per 100 kg fish,
ammonia produced = kg per day, and
TFM = total fish mass, kg from equation 11.

In order to evaluate which of the two previously mentioned models would be most useful in the production model, they were compared (Figure 4). The comparisons were made assuming a 1% feeding rate. Monthly water temperatures for comparison of models varied from 7.3 to 10.9°C.

Liao's (1974) equation resulted in a higher ammonia nitrogen production rate than Fivelstad et al's. (1990) equation. Liao (1974) based his equation on fish feeding rate, whereas Fivelstad's model is based directly on fish growth rate.

The results of the two models were very close for the first eight months, assuming a 1% feeding rate. The model is simulated

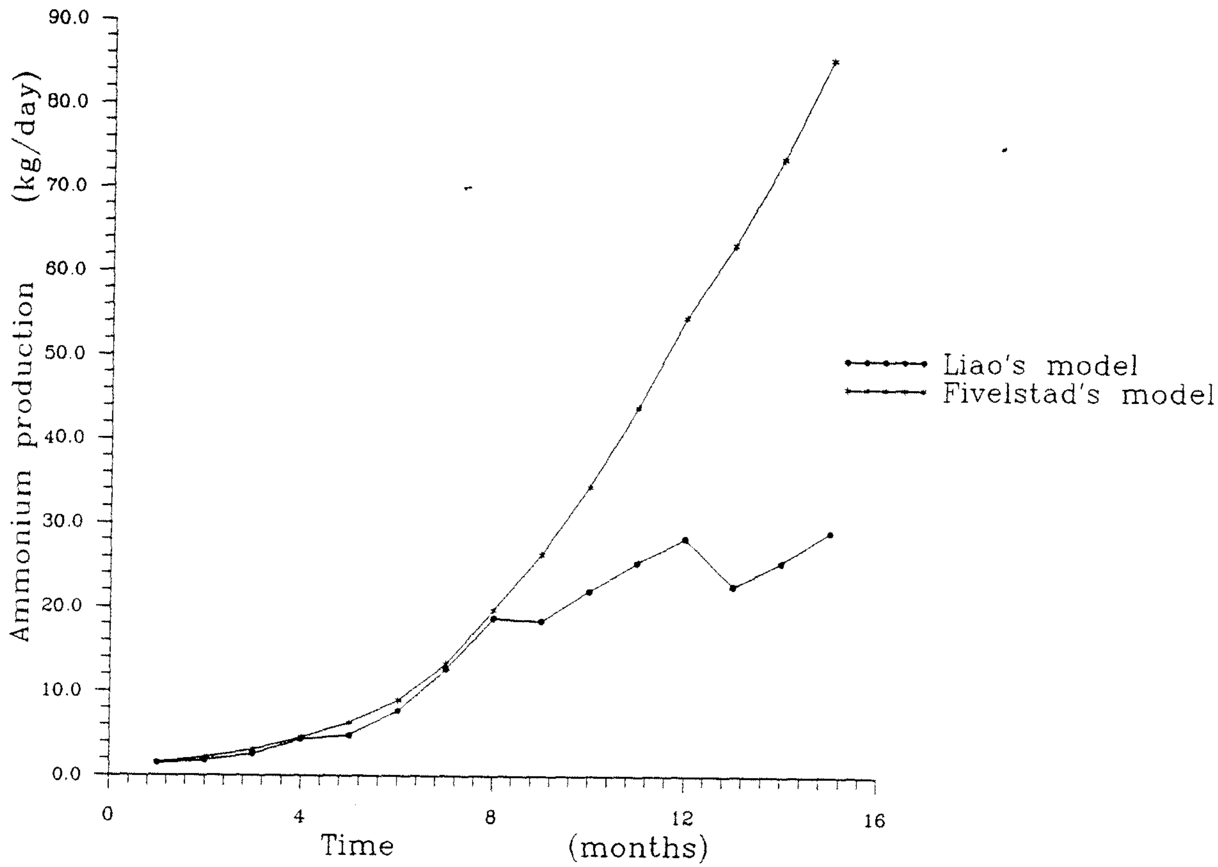

Figure 4. Ammonia nitrogen production rate using two different models. At time = 1, initial mass of fish = 0.040 kg. Final individual fish mass = 3.0 kg.

Based on Fivelstad's model, the increase in ammonia nitrogen production would not exceed 30 kg day^{-1} (Figure 4).

Contrary to Liao's model, which is widely cited in the literature, Fivelstad's model is very recent. No evaluation of its precision has been reported. Therefore, Liao's equation was chosen for the kelp production model.

4.2. Kelp Farm and Productivity

Environmental parameters, such as temperature, light and nutrient availability affect kelp growth (see literature review).

In order to consider kelp mortality in the model, only 5 plants in each cluster are assumed to survive (initially 10 plants). This assumption was based on Druehl et al. (1988b), where they measured the mass of individual plants as well as total mass of each cluster in a kelp production system.

The following three equations for *Laminaria saccharina* growth are used. These equations represent the reduction of kelp growth at extreme temperatures (i.e. 60% reduction at 20°C and 40% reduction at 5°C, from section 3.3). The following equations relate ammonia nitrogen concentration and temperature of water to *Laminaria* growth. The assumptions for equation 16 are as follows:

1) There is a direct relationship between nutrient concentration and *Laminaria saccharina* growth up to 10 μM NH_4^+ (Chapman et al., 1978b).
2) At the optimum temperature (i.e. 10 to 15°C), growth is 1.5 times the available ammonia nitrogen concentration (Gerard et al., 1987).

3) A 60% reduction in growth occurs when temperature increases from 15 to 20°C (see section 3.3).

4) A 40% reduction in growth occurs when water temperature decreases from 10 to 5°C (see section 3.3).

5) Phosphorus is not a limiting nutrient.

6) Light is not considered a limiting factor, because light intensity would be controlled by changing the depth of the ropes, (see chapter 7).

Assumptions concerning growth were partially validated (see Chapters 5) and assumption 5 was validated using computer simulations.

The growth equations, which are used in the production model are as follows (see Appendix 1 for sample calculations):

T = 5 to 10°C $\quad G = 1.5\,[\text{ammonia nitrogen}]\,((0.08\,T) + 0.2)$

T = 10 to 15°C $\quad G = 1.5\,[\text{ammonia nitrogen}]$

T = 15 to 20°C $\quad G = 1.5\,[\text{ammonia nitrogen}]\,((-0.12\,T) + 2.8)$ **(15)**

where T = Temperature in °C, and

[nitrogen] = ammonia nitrogen concentration within the kelp farm in μM.

Ammonia nitrogen and phosphate consumption in the model is calculated by the following equation :

rate of ammonia uptake = 10 μmol g dry mass^{-1} h^{-1} x (m) **(16)**

(Harrison et al., 1986)

mass of phosphorus consumed = 42 g dry mass^{-1} x (m) **(17)**

(Druehl, 1988a)

where m = dry mass of kelp.

4.3. Interrelationships and Formulations

Although kelp farms and fish netpens are two physically separate components, they are interrelated through current and flow conditions. The size of the fertilized kelp farm will depend on the availability of the nutrients, and availability depends on dilution. The fish depend on oxygen-rich water, so oxygen consumption by kelp during dark hours could have a negative impact on them. In this section three interrelationships, namely, nutrient dilution effect, nutrients and oxygen concentrations are described.

Ammonia nitrogen from the fish farm is the main input to the kelp farm. One of the problems in the model was to relate ammonia nitrogen concentration in the netpens to ammonia nitrogen concentration in the kelp farm. Three reports focused on the distribution of nitrogen around netpens. Black (1987) took water samples at a number of depths both in the netpens and at points along a line down current from the pens. Current velocity in the four different sites ranged from 0.0008 to 0.015 m s^{-1}. Black (1987) found no significant difference in ammonia nitrogen concentration with water depth. The average total ammonia nitrogen concentration in the netpens ranged from 0.7 μM (total biomass in 8, 12 m^2 x 6 m deep netpens, was 28,300 kg) to 2.3 μM (total biomass in 13, 36 m^2 x 6 m deep netpens was 12,500 kg). Typical ocean background level for ammonia concentration ranged from 0.6 to 0.9 μM (Black, 1987). Weston (1986) measured ammonia concentration in a netpen (with an approximate biomass of 27,000 kg) to be 1.0 μM, whereas 30 m downcurrent the concentration was 0.7 μM.

On the other hand, Korman (1989) found that ammonia nitrogen concentration decreased with distance from the netpens up to a distance of 10 m. After 10 m and up to 35 m, he found that the concentration fluctuated. The total ammonia nitrogen concentration within the netpens and at the outer stations (i.e. 25 m away) was 2.0 to 5.6 μM (with an annual production of 65 tonnes of salmon) and 1.4 to 3.4 μM (with an annual production of 52 tonnes), respectively.

A River-run mathematical model was initially used to account for the change in the nutrient concentration between fish cage and kelp farm. A River-Run model where both advection and diffusion are important could not be used to model the unsteady and complicated flow pattern around the netpen structure. The flow pattern also varies with site and actual current direction. Instead Korman's data was used to predict the dilution effect.

The dilution effect on ammonia nitrogen concentration was most evident within 10 m of the netpen. A random variation in nitrogen concentration was observed from 10 m to 40 m away from the netpens (i.e. at 35 m away the concentration was higher than 15 m away).

In the conceptualized *Laminaria* production system, a 30 m wide mixing zone after the initial 10 m was assumed to be fertilized. Any portion of a kelp farm extending beyond 40 m from the salmon farm may, therefore, have to be artificially fertilized. The size of one of the kelp production areas (e.g. for one end of a netpen farm, 4 cages wide and 15 m wide per cage) was calculated using the following formula:

Kelp production area per netpen end =

1,800 m^2= 30 m of fertilized distance x 4 cages x 15 m, the number of kelp ropes = 10 = 30 m of fertilized distance/3 m spacing,

number of surviving kelp = 10,000 = number of ropes * 4 cages * 15 m * 5 plants per cluster / 0.3 m.

Mathematical expressions were obtained using Korman's data which related dilution with distance from netpen up to 10 m. Nine data points from Korman's data were used (i.e. 3 concentrations in the netpens, 3 concentrations at 3 m away from the netpens, and 3 concentrations at 10 m away from the netpens) to calculate this dilution rate. Ammonia nitrogen concentration decayed as a linear function of initial ammonia nitrogen concentration and as a function of distance from the netpen (see Equation 18). At 10 m from the netpens, a 48% decrease in concentration was evident.

$$\text{Decay} = 1.02-0.056\ d \qquad r^2 = 0.92 \qquad (18)$$

where decay = Ammonia Nitrogen Concentration Decay (Fraction of initial concentration), and
d = distance from Netpen.

In order to interrelate the two components (i.e. nutrient availability and kelp growth as discussed in sections 4.1.1 and 4.1.2), the ammonia nitrogen production rate is converted to ammonia nitrogen concentration using the current speed and the flow area of the netpens (Inoue, 1972).

Ammonia = Ammonia nitrogen / (area x speed * 1000) (19)

where Ammonia production = kg h^{-1}, equations 13, 18
Ammonia = μM,
area = netpen depth x netpen width m^2,
speed = current velocity m/s.

Ammonia nitrogen is rapidly diluted on a netpen farm (Korman, 1989). Based on Korman's data the ammonia nitrogen concentration decay as a function of distance was obtained.

kelp raft concentration = Ammonia x dilution (20)

where kelp raft concentration = ammonium concentration at the kelp raft in μM,

Ammonia = ammonia nitrogen concentration in the netpens,

and

dilution = dilution effect due to distance from the netpens, obtained from equation (18).

Oxygen is another interrelationship between fish netpen and kelp farm. Oxygen consumption in the kelp farm at night could cause oxygen depletion in the netpens. Oxygen consumption in the kelp farm was calculated by the following equation:

oxygen consumption = uptake rate x mass of kelp **(21)**

where oxygen consumption = kg per day,
mass of kelp = kg, and
uptake rate = mass of oxygen per mass of kelp per time (experimentally obtained, section (5.2.2).

4.4. Economic Considerations

In order to determine the economical feasibility of the operation of the two 10 60 m rope areas, a breakdown of input costs was first established. The cost of the operation includes capital costs, direct costs and indirect costs. Subsequently, the revenue and the break-even point were determined.

4.4.1. Fixed Capital costs

The fixed costs are the equipment costs and initial working money needed to begin an operation up to first harvest. Capital cost includes the cost of all materials needed to construct a kelp farm. Initial working money is the total amount needed until first sale. Initial capital costs include costs of rope, steel cable, galvanized chain, thimbles, buoys, floats, cement bags and shackles. Druehl (1980) outlined the material costs for one 60 m long cultivation rope (Table 2). An industry price index of 4.7% per year was used to inflate the 1980 costs to 1992 costs

Table 2. Cost of materials for one 60 m long cultivation rope (Druehl, 1980).

MATERIALS	COST
125 m, 0.5" polyprop rope	$ 47.00
6 m, 0.5" cable (steel)	13.60
4 m, 3/8" chain (galvanized)	20.68
6 thimbles (galvanized)	9.60
2 #40 buoys	41.30
3, 6600-20 floats	8.85
1.4 bags cement for anchors	10.00
2, 7/16" shackles (galvanized)	4.20
TOTAL	155.23

(Anonymous, 1992). The adjusted material cost due to inflation (i.e. from 1980 to 1992) is $270 for a 60 m long rope. A life expectancy of 3 years is assumed for each rope. A life expectancy of 5 years and a salvage cost of $20 is assumed for other materials needed to put up each rope (e.g. buoys, floats). A complete list of initial fixed capital costs is shown in Table 3.

4.4.1.1 Storage Shed

A small shed is needed for the storage of the kelp. The shed has to be dark and dry. The price of a storage shed is highly variable depending on material. A price of $2500 for a 3 x 5 m shed (i.e. wood framing) is assumed.

A greenhouse is needed to dry the kelp. A price of $2900 for a 6 x 10 x 3 m^3 plastic greenhouse is assumed. A heater ($ 700) is needed in the greenhouse to maintain high temperature (25 to 30°C) throughout the year. The salvage value and life expectancy of the greenhouse and the heater are $400 and 10 years.

4.4.1.2 Boat

A boat is needed to perform routine operations in the kelp farm. The boat is needed mainly for planting and harvesting periods, which usually takes 4 to 6 weeks a year for the farm. The cost of a 4 m aluminum boat is set at $2,433. The salvage value and expected life expectancy of the boat are $300 and 10 years.

Table 3. Breakdown of initial capital investment. This includes the capital investment, initial construction capital, and initial operating capital.

		Price
1. Fixed investment		
1.1	cost of 20 x 60 m ropes (see table 10 for itemized list)	$ 5400
1.2	cost of boat for transportation	$ 2433
1.3	cost of storage shed	$ 2500
1.4	cost of greenhouse	$ 2900
1.5	cost of heater	$ 700
1.6	cost of light sensor	$ 3400
1.7	cost of mooring system installation	$ 1150
1.8	land lease (for 3 months, before first harvest)	$ 1500
2. Initial construction capital		
2.1	interest payment during installation period (compound interest rate = 11%)	$ 9590
2.2	insurance policies (10% of material cost)	$ 1340
3. Initial operating capital		
3.1	labour for seedling production and planting	$ 4147
3.2	management of the operation	$ 18000
3.3	cost of seedling production	$ 600
3.4	overhead (60% of total labour cost)	$ 2488
3.5	cost of gas and oil for boat	$ 200
3.6	cost of transportation to the site	$ 800
3.7	cost of marketing (5% of fixed cost)	$ 1040
3.8	contingency (10% of initial operating cost)	$ 2728

4.4.1.3 Light Sensor

A light sensor is needed to measure light intensity at different depths. The cost of a light sensor with underwater probes is $3400.

4.4.2 Operating Costs

The factors which contribute to direct operating cost are the cost of seedling, labour cost and management costs.

4.4.2.1 Seedling Costs

In order to produce the seedling, space has to be rented for 4 months at a Marine Station (Lloyd, Pers. Comm.). The rental cost is approximately $600 for four months. Eight hour weekly labour is

needed to look after the seedling production (Lloyd, Pers. Comm.). The labour cost (i.e. $12 h^{-1} + 20% benefits) is $1843 (i.e. 128 working hours).

4.4.2.2 Labour Cost for Planting and Harvesting

Two workers are needed for four weeks annually for harvesting and insertion of seedlings in the ropes. The annual labour cost ($12 h^{-1} + 20% benefits) totals $4608 (a total of 320 working hours is assumed).

4.4.2.3 Management Cost

A monthly salary of $1500 is chosen for the manager of the kelp farm. Therefore, $18,000 annual salary is assumed for the manager. The duties of the manager include daily inspections of the farm and marketing for the products.

4.4.2.4 Light Control and Maintenance Costs

The depth of kelp ropes in water can be varied monthly to obtain the optimum light intensity (Chapter 7). A labour cost is associated with the operation. An annual cost of $1150 is estimated for light control operation (i.e. eight hours every month, $12 h^{-1} + benefits).

An annual maintenance cost of $100 is assumed for the boat (i.e. gas and oil). This assumption is based on the fact that the boat travels 600 km annually (i.e. a distance of 10 km to the shore, four weeks a year for transportation of seedlings and harvested material). An annual maintenance cost of $100 is assumed for the heater in the greenhouse.

4.4.2.5 Land Cost

Land to put the greenhouse and storage shed is needed. On some fish farms, space may be available, but for this study land is included. A yearly rent of $5000 is assumed for a quarter acre land (a minimum of 5 year lease).

4.4.2.6 Transportation Cost

The product (after being dried) should be brought to the market. A yearly transportation cost of $400 is considered.

4.4.3 Indirect Operating Costs

Indirect costs arise from work that is beneficial to the farm and include: taxes, administrative and financing costs. Since the operation is small (i.e. less than $200,000 income), and is for production purposes a 18% tax is used in the calculations. A 10% annual rate (10% of equipment cost) is assumed for the insurance of the equipment.

4.4.3.1 Depreciation

Depreciation cost is used for tax purposes. Depreciation cost depends on the lifespan of the equipment as well as the salvage value (Lee, 1988):

Linear Depreciation = (initial cost - Salvage value) / Life span

4.4.3.2 Financing

Interest rate will accrue on the capital cost, at an annual rate that can be set by the user. It is assumed that 50% of the required fixed cost is paid by the owner (Chapter 8). For this study a the compounded interest rate is set at 11% per annum.

4.4.4 Revenue

Revenue depends on the mass of kelp produced annually as well as the selling price of kelp. The selling price of kombu (edible kelp) in Vancouver Health Food Stores is between $4.50 to $5.00 per 2 ounce (i.e. $79 to $88 per kg). A selling price of $35 per kg is assumed for the dry mass of kelp. This assumption is based on a selling price of $32 per kg in Vancouver in 1988 (Lloyd, pers. comm.).

4.4.5 Pay-Back Period

This point is reached when a surplus of cash is established (i.e. total initial cost is equal to total net revenue). The following procedure is used to determine the break-even point :

1) Calculation of total annual revenue (TAR) (i.e. mass of harvested product x price of product).
2) Tax = (TAR - operating cost - depreciation - interest payment) x 0.18

   After Tax Revenue (ATR) = Total Revenue - Tax - operating cost - total bank payment
3) The pay-back period is when the sum of annual profits is equal to the initial cost of the operation (i.e. the cost to start the operation).

4.5 Kelp Production and Economical Model Formulation

A computer model was written using Turbo-C language (Appendix 3). It related the mathematical expressions of netpen nutrient release, kelp nutrient uptake and kelp growth in order to estimate kelp production, kelp oxygen uptake and nutrient removal. The payback period of the resulting production was calculated. The following parameters can be changed, depending on environmental conditions, to determine the feasibility of the operation. A summary of the necessary inputs and the typical outputs is given below.

Typical Inputs:

1) initial fish mass : The mass of fish as they are put in the netpens (unit : g)
2) pH : The pH of seawater is 8.2 (Equation 14)
3) number of netpens
4) the final stocking density (unit : kg m^{-3}).
5) volume of each netpen (unit : m^3).
6) % annual mortality.
7) current velocity : The current speed at the end of the netpens (unit : m s^{-1}).
8) flow area : Netpen flow area (i.e. width x depth) (unit : m^2).
9) plant number : number of clusters of kelp in each m of rope (one cluster every 30 cm).
10) Cluster : average number of surviving plants on each cluster (5 plants per each cluster).
11) kelp mass : initial kelp mass on the rope. (unit : g).
12) salinity : (unit : $^0/_{00}$).
13) temperature : Average monthly water temperature
14) oxygen concentration : The dissolved oxygen concentration of the surrounding water is an input. This concentration can be used to compare the available oxygen to the netpens with the amount of oxygen consumed by the kelp farm at night (unit mg l^{-1}).
15) feeding rate : mass of feed (in kg) per 100 kg of fish.

16) phosphorus uptake : The consumption of phosphorus by the kelp is 42 mg per 100 g dry mass (Druehl 1988a).

4.6. <u>Calculation and Outputs of Kelp Production Model</u>

1) fish mass : fish mass increases with time and temperature (Table 1).

2) Total fish mass : Total fish mass (i.e. kg) in the netpens at any period of time (Table 1, equation 11).

3) ammonia nitrogen produced : Mass (i.e. kg) of ammonia produced in the netpens per day (equation 13).

4) ammonia nitrogen consumed : Mass (i.e. kg) of ammonia nitrogen taken up by the kelps in the kelp farm per day (equations 16).

5) kelp growth : The specific growth rate of kelp (unit : % per day) (equation 15).

6) harvest : Number of harvests during one fish production period. The kelps are harvested when the final kelp mass reaches 400 g.

7) kelp raft concentration : The ammonia nitrogen concentration at the kelp farm (unit : mg/l) (equation 20).

8) phosphate production : The rate of phosphate production in the netpens is simulated in the model (unit : kg per day) (equation 14).

9) phosphorus uptake : The phosphorus uptake rate of kelp is calculated in the model (unit : kg per day) (equation 17).

10) Oxygen consumption : Oxygen uptake by the kelp is measured (unit : kg per day) (equation 21).

V. MODEL VALIDATION AND PARAMETER ESTIMATION

5.1. Materials and Methods

Two sets of experiments were conducted at the Department of Fisheries and Oceans at West Vancouver from June 16 to August 7, 1991. *Laminaria saccharina* was collected at Stanley Park on June 14 and 15 (during the low tide). Kelp were put in a styrofoam cooler covered with seawater, and were transferred to the experimental site immediately.

5.1.1 GROWTH EXPERIMENT

A set of growth experiments was conducted to relate kelp growth to salmon-effluent nitrogen concentration and temperature. In order to measure the growth rate of kelp, they were put in three parallel, 2 m raceways (Figure 5). Effluent water from a salmon tank was siphoned through three hoses to the three raceways. Another three hoses delivered fresh seawater into the raceways, in order to dilute the effluent from the fish tank. Seven kelp, with different coloured pins in their holdfast, were trimmed to 0.15 m and were put into the raceways. In order to simulate the actual current condition around fish netpens, the height of water in the raceways was set so that the water velocity was 0.08 m s^{-1}. The kelp was kept in place with small stones on their holdfast.

Green meshes were laid on top of the raceways in order to maintain the light intensity below 100 $\mu E\ m^{-2}\ s^{-1}$ and to reduce photoinhibition in the kelp. Irradiance was measured (Licor Li 185B, Li 190 SA quantum sensor) and recorded on a portable computer (IBM 286) every

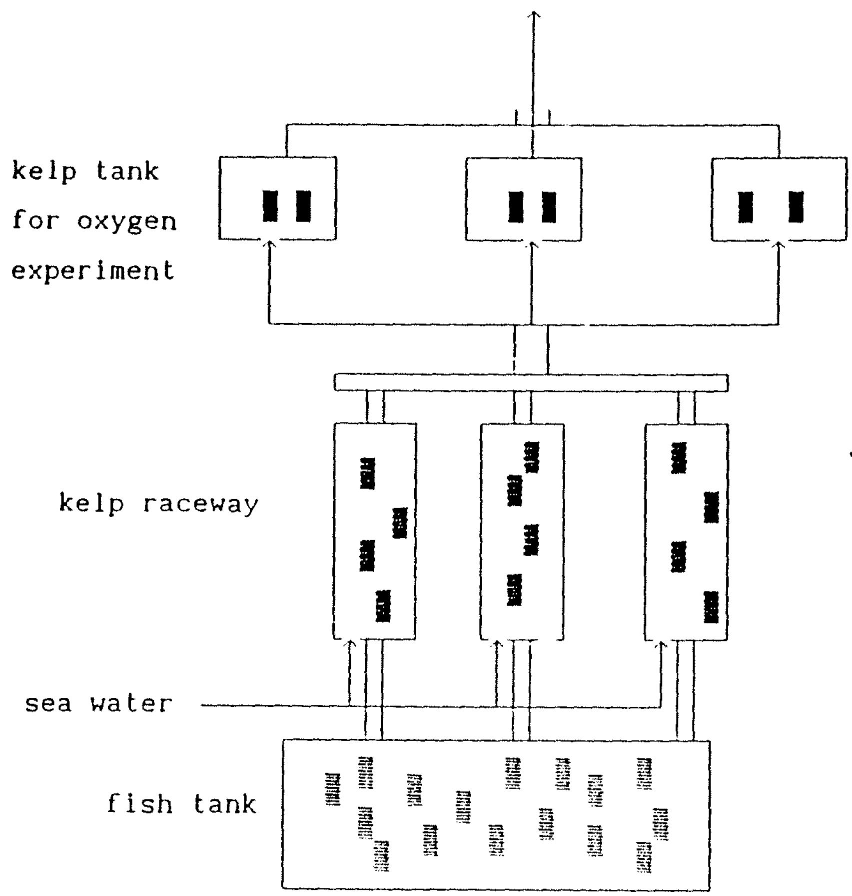

Figure 5. Description of the experimental layout. It includes salmon culture tank, 3 *Laminaria* raceways, 3 *Laminaria* tanks for oxygen experiment.

0.5 h. The kelp was conditioned to the effluent from the salmon tank for two weeks before the start of experiment.

A set of measurements was done (24 samples during a 24 h period) to estimate nitrogen (ammonia + nitrate) concentration in the fish tank. The average total nitrogen concentration from the fish tank (nitrate + ammonia nitrogen) was 38.6 μM; standard deviation was 28.4. A preliminary set of growth experiments were conducted from June 28 to July 12. The results showed no variation in kelp growth in three raceways; therefore, the dilution rates were changed for the second set of experiments.

A second set of growth experiments started on June 18 and ended on August 3. Diurnal samples were taken on June 19, 24, 29 and August 3 (i.e. 32 samples throughout each day). Kelp in three raceways received effluent with different dilution ratios (i.e. seawater : effluent) (raceway one, 3 : 1; raceway two, 8 : 1 and raceway three, 20 : 1) for 12 h daily. The dilution rate were chosen so that nitrogen concentration (ammonium + nitrate) would be below 10 μM. The purpose of introducing fish effluent for 12 h daily was to simulate the tidal effect. The effluent hose was turned on at 8 A.M. and was disconnected at 8 P.M. The temperature was recorded by two copper constant thermocouple (i.e. at the beginning and the end of the raceway) using a computerized data acquisition system. The mass of the kelp was measured weekly, before they were trimmed to 0.15 m.

Water samples were collected from the inlet of the kelp raceways. Each sample was taken with a 60 ml syringe, and then it was injected into a 30 ml bottle through a 934 AH Whatman filter held by a Swinnex 25 mm Millipore filter holder. The first 10 ml was always discarded, and the next 10 ml was used for rinsing the bottle; 25 ml of the sample was injected to the bottle, and the remaining 15 ml was discarded. All the bottles were washed in 10% HCl solution before sampling. Ammonia nitrogen, nitrate and phosphorus analyses were done at the Oceanography Department, U.B.C. using a Technicon Auto Analyzer II using the standard procedure as described in Harrison et al. (1986).

5.1.2. Oxygen Experiment

A set of experiments was conducted to measure the oxygen consumption rate (i.e. mass of oxygen consumed per mass of kelp per time) of the *Laminaria* at night. Three different kelp densities were put into three 25 l buckets. A fourth bucket was used as the control (i.e. no kelp). The kelp densities were as follows : bucket 1, 9.1 kg m^{-3}; bucket 2, 8.0 kg/m^{-3}; and bucket 3, 5.4 kg m^{-3}.

A set of preliminary experiments was conducted from July 6 to 14 to ensure that the oxygen drop would be more than the error of the dissolved oxygen meter. From July 12 to 25 the drop in the dissolved oxygen concentration from 2130 to 0530 was measured using a YSI 50 D.O. meter. The probe was calibrated before each measurement. The temperature and the salinity (YSI model 57) of each bucket were also measured. Samples were taken at the beginning and end of the dark period (i.e. 8 h interval).

Oxygen consumption has been expressed in the literature both in terms of mass as well as surface area. In order to have this flexibility in this study, mass and surface area were determined. The outline of the kelp was traced on a piece of paper (using Autocad software). The wet mass of the kelp (i.e. the kelp in the tanks) was measured at the beginning and at the end of the experiment.

5.2. Results and Discussion

5.2.1 Results of Nutrient Experiment

The growth rate of the kelp varied proportionally with the nitrogen concentration (Table 4). Total nitrogen concentration varied between 3.3 to 9.7 μM in the raceways, while the specific growth rate varied from 3.3 to 8.9 μM.

Nitrate concentration varied between 5.5 to 10.7 μM and ammonium concentration varied between 5 to 16 μM during the experiment in the salmon culture tank (Table 5). Nitrate concentration was relatively constant (i.e. compared to ammonium concentration) (Figure 6). Phosphorus concentration varied between 2.8 and 4.5 μM in the fish tank (Figure 7).

The average temperature in the tanks was less than 10°C (Figure 8). The maximum water temperature during the experiment was 11.5°C, and the minimum water temperature was 6.8°C. The shades on the raceways prevented water temperatures from rising higher on sunny days.

Light intensity was reduced because of the shading panels (Figure 9). The average daily light intensity did not exceed 58 $\mu E\ m^{-2}\ s^{-1}$ (Figure 9). The average light intensity (from June 19 to August 3) before 7 A.M. and after 7 P.M. was less than 20 $\mu E\ m^{-2}\ s^{-1}$.

Table 4. Observed and calculated specific growth rates of kelp (*L. saccharina*) grown in different nitrogen concentrations from July 18 to August 3. The different nitrogen concentrations were made by the dilution of effluent from a salmon culture with seawater. (Error represents 1 standard deviation, sample size = 128).

	RACEWAY 1	RACEWAY 2	RACEWAY 3
INITIAL MASS (g) (July 18)	44	44	59
FINAL MASS (g) (August 3)	161	120	93
OBSERVED SPECIFIC GROWTH RATE % PER DAY	9	7	3
DILUTION RATE effluent:seawater	1 : 3	1 : 8	1 : 20
AVERAGE TOTAL NITROGEN (ammonium + nitrate) CONCENTRATION (July 18 - August 3) μM	9.7 ± 1.1	5.3 ± 0.8	3.2 ± 0.6
CALCULATED SPECIFIC GROWTH RATE % PER DAY USING Eqn. 15	12.1	6.5	4.0

Table 5. Average daily nitrate, ammonia nitrogen, and phosphate concentrations in the fish tank. Samples were taken over a 24 hour period (day and night). (Error represents 1 standard deviation, sample size = 32).

	Nitrate μM	Ammonium μM	Phosphate μM	Sample size
JULY 18	25.9 ± 2.2	8.2 ± 2.0	4.5 ± 0.5	32
JULY 23	25.8 ± 0.3	16.4 ± 3.2	3.6 ± 0.04	32
JULY 28	21.4 ± 0.2	5.2 ± 2.4	2.8 ± 0.04	32
AUGUST 2	21.2 ± 0.6	11.4 ± 0.7	4.9 ± 0.5	32

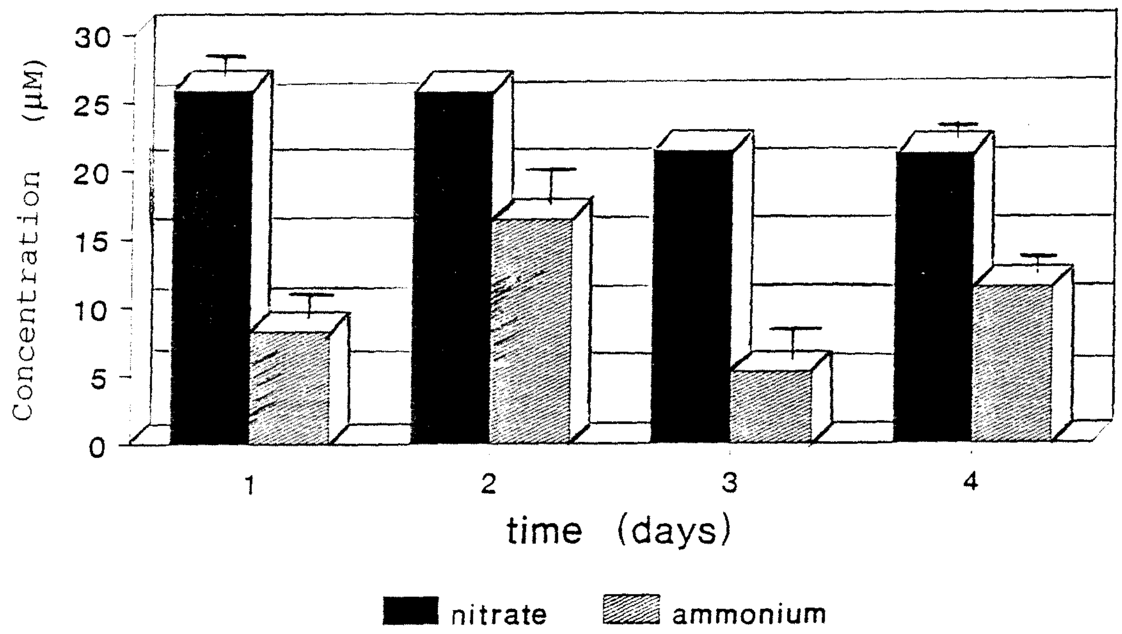

Figure 6. Average daily ammonia and nitrate concentrations in the fish tank. The error bars represent 1 standard deviation with n = 32. Days 1, 2, 3 and 4 represent the days that the samples were taken (July 18, 23, 28 and August 2).

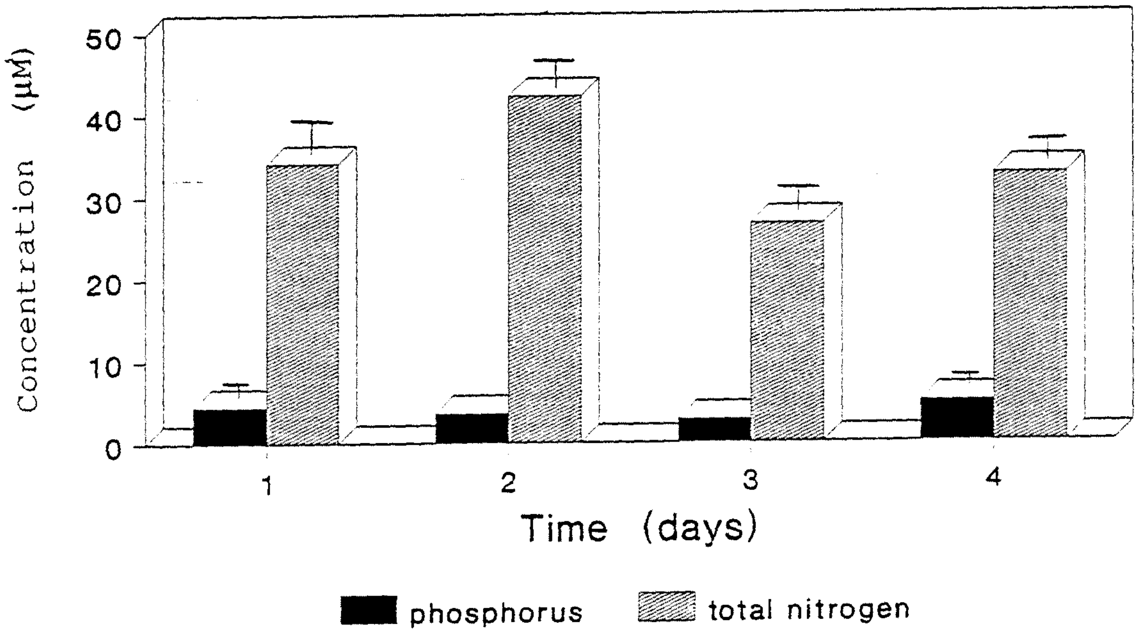

Figure 7. Average daily total nitrogen and phosphorus concentrations in the fish tank. The error bars represent 1 standard deviation with n = 32. Days 1, 2, 3 and 4 represent the days that the samples were taken (July 18, 23, 28 and August 2).

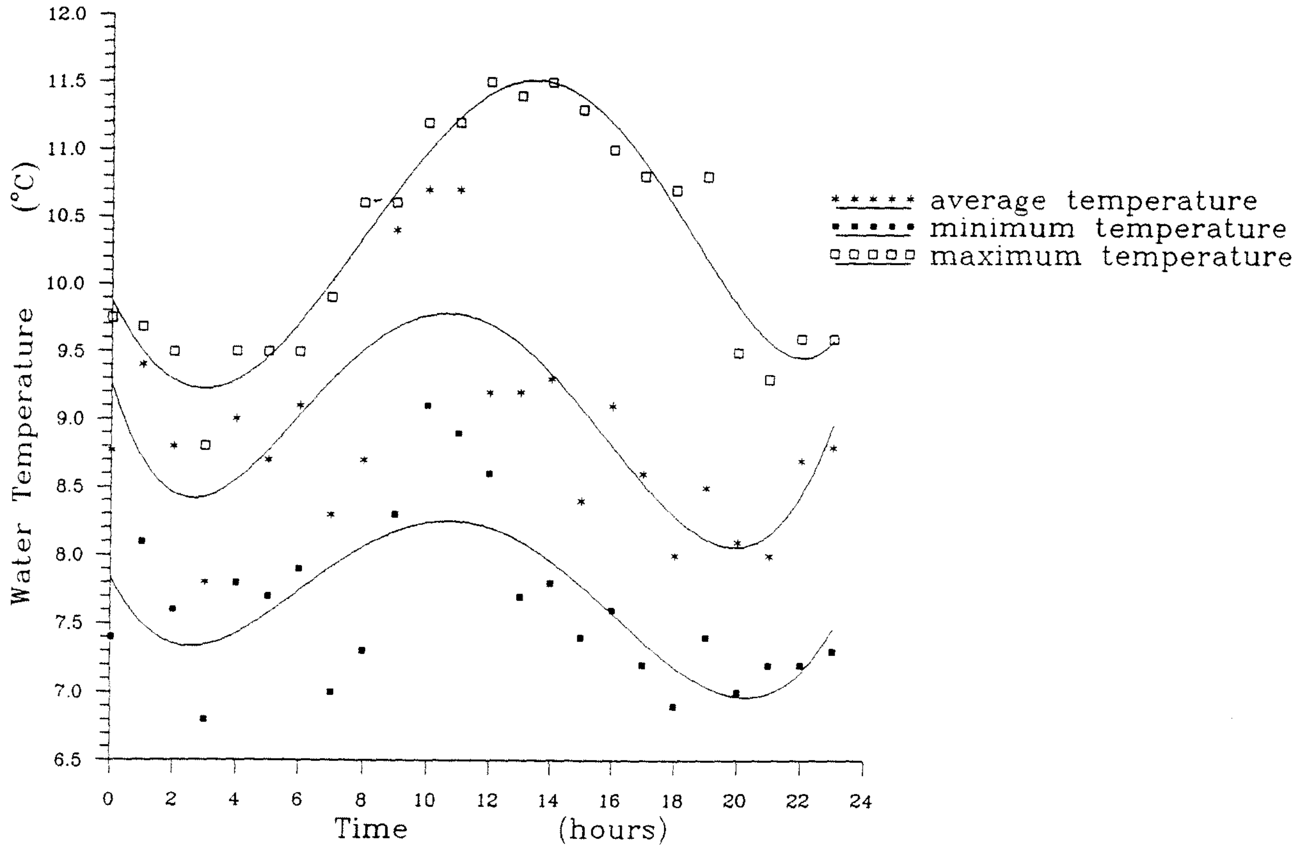

Figure 8. Daily water temperature in the *Laminaria* raceways during the *Laminaria* growth experiment (July 18 - August 3)

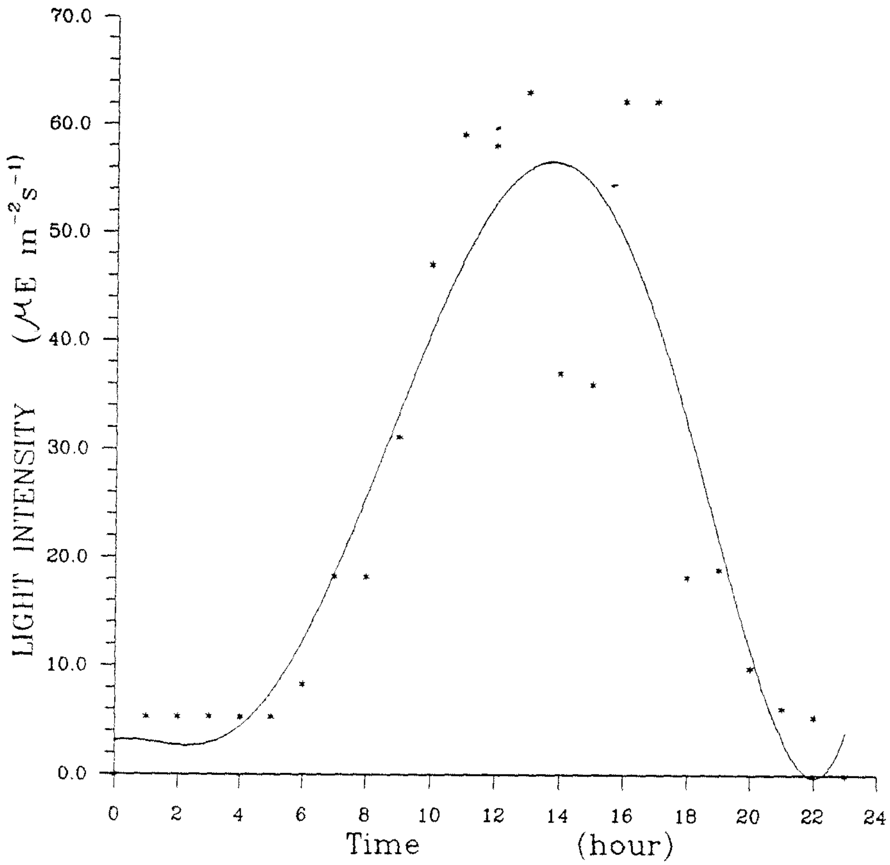

Figure 9. Average daily light intensity reaching the *Laminaria* throughout the growth experiment (July 18 - August 3).

5.2.2 Discussion of Nutrient Experiment

The results of the nutrient experiment confirmed the linear relationship between kelp growth rate and the available nitrogen. The average water temperature was between 8.3 to 9.5°C, which was lower than the optimum range of 10 to 15°C (Bolton and Luning, 1982). The experimental results were compared with the expected values using Eq.20 (Table 5). The experimental and empirical results were tested for a significant difference using the t-test (null hypothesis : no significant difference between the actual and estimated growth). Number of samples (plants) in each raceway was seven (n=7, in Table 5). In raceway 1 (i.e. highest ammonia nitrogen concentration) the null hypothesis was rejected (Table 6). In raceways 2 and 3 the null hypothesis was not rejected (Table 6). Therefore, the developed equation (i.e. equation 16) is valid for low (i.e. less than 7 μM) nitrogen (ammonia nitrogen + nitrate) concentrations.

Since the raceways were covered by the shades, the maximum light intensity did not reach more than 60 $\mu E\ m^{-2}\ s^{-1}$ (Figure 9), which was lower than the expected 80 to 90 $\mu E\ m^{-2}\ s^{-1}$. The low irradiance could be a possible explanation for low growth of kelp in the raceways. The relationship between light intensity and kelp growth rate was not considered directly in the model (Chapter 7).

During the experiments the phosphorus concentration was between 2.8 and 4.9 μM. The calculations (Appendix 1) show that the kelp were not phosphorus limited throughout the experiment

Table 6. The theoretical specific growth rate of *Laminaria* (Eq. 15) is compared with the actual kelp growth in the three raceways. A t-test (95% confidence level) was used. Sample size or number of plants in each raceway = 7, S = standard deviation of samples in each raceway.

Raceway	S	t	$t_{0.05(2),6}$	Actual Growth % /day	Theor. Growth % /day	significant difference
1	2.1	3.8	2.45	9	12	Yes
2	1.1	1.3	2.45	7	6.5	No
3	1.3	2.0	2.45	3.3	4	No

This was expected, because in the marine environment phosphorus is not considered to be a limiting nutrient (Lobban and Wynne, 1981).

5.2.3 Results of Oxygen Experiment

The oxygen drop in the three tanks was different (Table 7). The maximum oxygen drop was 2.2 mg l^{-1} in the tank with the largest mass (i.e. Tank 1). The results of the experiment showed that the oxygen drop was proportional to the kelp mass in the tanks (Table 8). The oxygen drop in tank 1 varied between 1.6 and 2.2 mg l^{-1}. The oxygen drop in tank 2 was between 1.4 and 1.8 mg l^{-1}. Tank 3, having the lowest mass, had an average oxygen drop of 1.10 mg l^{-1}. The salinity of water was between 20 and 26 o/oo with an average value of 24 o/oo. The water temperature was always lower at the beginning of the experiment than at the end. Maximum and minimum increase in water temperature in one night was 3 and 1.5 ^{o}C respectively.

The oxygen drop per unit mass of kelp was 0.026, 0.024, and 0.026 mg O_2 per wet gram kelp per hour in tanks 1, 2, and 3 respectively (Table 8). The summary of the results from the oxygen experiment is presented in Tables 7 and 8.

The surface area for *Laminaria* used in the experiment (Figure 10) was found to be relative to wet mass (in the range of 0.008 to 0.023 kg) by the following equation :

$$\text{Area} = 1.37\ \text{mass} - 0.0004 \qquad r^2 = 0.91 \qquad (22)$$

where Area : kelp surface area in m^2, and
mass : kelp mass in kg.

Table 7. Oxygen drop (mg l^{-1}) in different kelp *Laminaria* during night (8 h). Average kelp mass in tank 1 = 0.20 kg; tank 2 = 0.18 kg ; tank 3 = 0.13 kg.

	TANK 1	TANK 2	TANK 3	CONTROL
JULY 12	1.99	1.82	1.21	0.13
JULY 13	1.56	1.47	0.86	-0.27
JULY 14	1.90	1.64	1.21	-0.01
JULY 15	1.62	1.36	1.02	0.15
JULY 16	1.77	1.42	1.07	0.13
JULY 17	2.09	1.67	1.41	0.13
JULY 18	1.78	1.35	1.17	-0.03
JULY 19	1.77	1.43	1.08	0.13
JULY 20	1.86	1.43	1.01	0.13
JULY 21	2.11	1.51	1.01	-0.04
JULY 22	2.20	1.69	1.17	-0.03
JULY 23	1.93	1.59	1.01	0.04
JULY 24	2.12	1.52	1.17	0.22
JULY 25	1.95	1.35	1.09	0.24

Table 8. Oxygen uptake rate in different Laminaria tanks over experimental period (July 12 to July 25). Cumulative oxygen drop is the total (i.e. 14 nights) in each 22 l bucket.

TANK	CUMULATIVE OXYGEN DROP mg	INITIAL MASS (g)	FINAL MASS (g)	Average Mass (g)	O_2 drop per gram wet mass mg g^{-1} h^{-1}
1	42	188	210	199	0.026
2	33	158	193	176	0.024
3	24	107	130	119	0.026

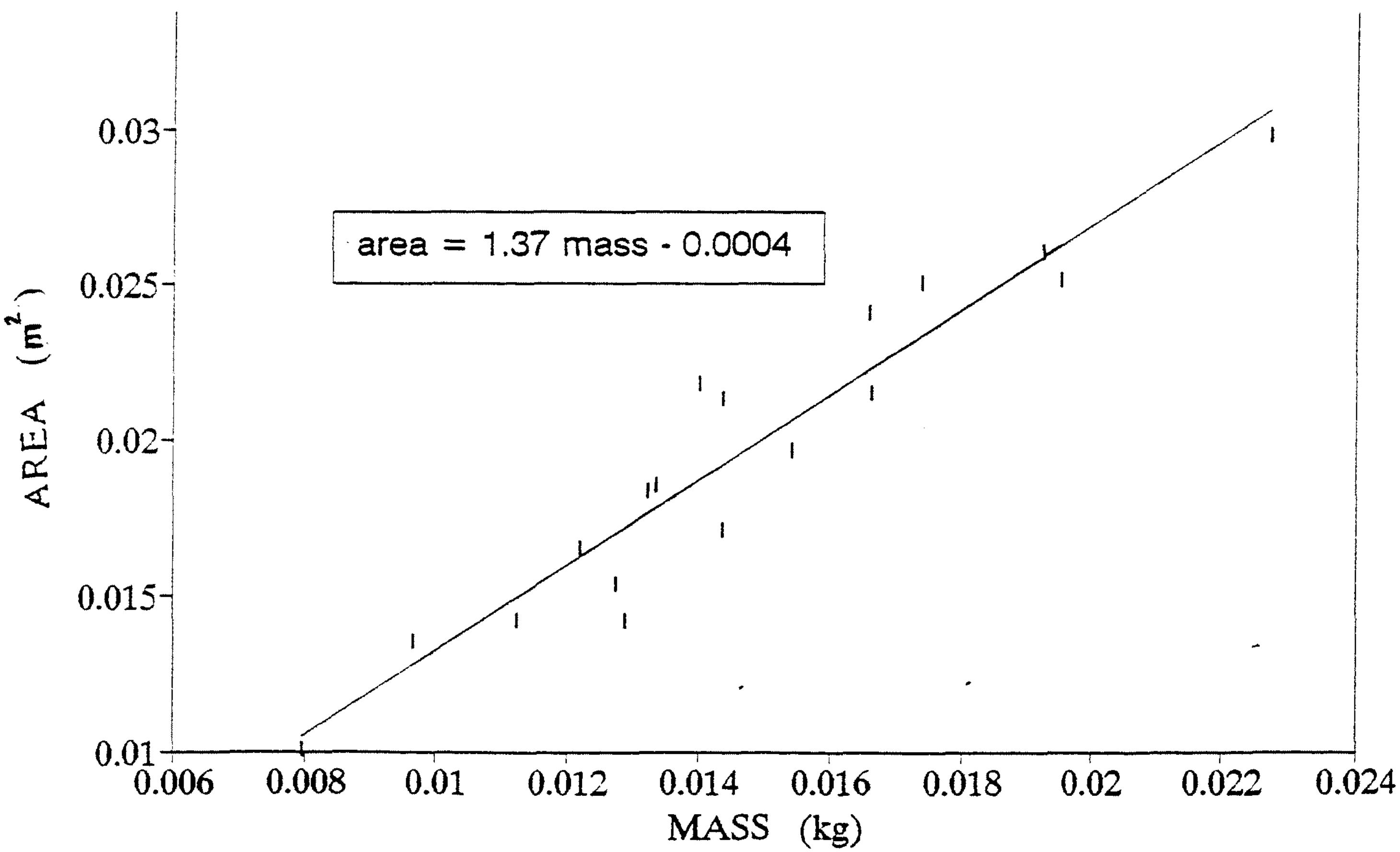

Figure 10. Relationship between mass and surface area of the *Laminaria*.

5.2.4. Discussion of Oxygen Experiment

Oxygen concentration is essential for fish farms. The introduction of the kelp farm near sea cages could cause oxygen concentration depletion in the sea cages at night. In the oxygen experiment, the rate of oxygen consumption at night was measured to be 0.026 mg O_2 g wet mass kelp^{-1} h^{-1}. The oxygen consumption can also be expressed as 0.81 μM O_2 cm^{-2} h^{-1}.

King and Schramm (1976b) calculate the maximum photosynthetic rate for *Laminaria saccharina* to be 2.0 mg O_2 g db^{-1} h^{-1}. Druehl (1967) obtained an average ratio for photosynthesis to dark respiration ratio of 13.36. Assuming a 10% dry mass/ wet mass ratio for the kelp, King and Schramm's (1976b) results can be converted to a respiration rate of 0.015 mg O_2 g db^{-1} h^{-1}.

The two respiration rates, 0.015 and 0.026 O_2 g db^{-1} h^{-1}, were very close. Basically two assumptions were used to convert King and Schramm's (1976b) photosynthetic rate to respiration rate. First, a 10% wet to dry kelp mass ratio was used, and secondly the photosynthesis to respiration rate ratios of Druehl (1967) were used.

Gerard (1988a) measured dark respiration rates for *Laminaria saccharina* to be between 0.1 to 0.3 μmol cm^{-2} h^{-1}, which is lower than this experiment (i.e. 0.8 μmol cm^{-2} h^{-1}). Higher oxygen consumption in the experiment could be partially explained by Biochemical Oxygen Demand (i.e. BOD). The bacteria in water could consume oxygen.

The uniqueness of the oxygen experiment, beside measuring the oxygen consumption, was the method of the experiment. In all the above mentioned references, the oxygen consumption was measured using small portions of kelp, whereas in this experiment the oxygen consumption of the whole seaweed was measured.

VI. PRODUCTION MODEL ANALYSIS

A number of computer simulations were run. They were run in order 1) to test if the kelp could be Phosphorus limiting, 2) to predict the ammonia nitrogen removal by the kelp, 3) to predict the number and amount of kelp harvests with a comparison to a no fertilized situation, and 4) to predict the amount of oxygen consumed by kelp. A summary of typical kelp production model input values used is given (Table 9). The schematic of the proposed integrated salmon/kelp farm is shown in Figure 2. One 10 60 m rope kelp farm lies on each side of the fish farm (Figure 2). Based on empirical data this size of farm would be fertilized and it is assumed and not to be light limited.

6.1. Fish and Kelp Production

Total mass of fish in the 12 netpens after 16 months is 250,000 kg. Ammonium concentration from the fish farm after 16 months was about 1.5 μM. An ambient nitrogen concentration of 1 to 2 μM is assumed. Three kelp harvests were expected within 16 months of operation. A wet mass of 8000 kg was expected at each harvest from each 10 60 m rope kelp farms. The dried mass of kelp from each harvest is 800 kg. A minimum of 2 annual harvests with a yield of 16000 kg of kelp is expected. According to the model, during the same period, a non-fertilized farm would produce 8000 kg of kelp (one half of a fertilized farm).

Table 9. Summary of typical kelp production model input values. Average monthly water temperatures (1921-1991) of Race Rocks (latitude = 48.18°N, longitude = 123.32°W, water depth = 1 m) was used in this model.

number of netpens = 12 ,	final stocking density = 10 kg m^{-3}
netpen volume = 2250 m^3,	fish mortality = 10% per year
final fish mass = 3.0 kg,	current velocity = 0.1 m s^{-1}
feeding rate = 1% of fish mass,	initial fish mass = 40 g
kelp farm = 10 60 m ropes,	final kelp mass = 400 g/plant
monthly water Temperature = 7.3, 7.3, 7.6, 8.4, 9.4, 10.2, 10.8, 10.9, 10.6, 9.7, 8.7, 8.0 °C	
# kelps per cluster = 5,	flow area = 300 m^2

6.2. Ammonia Nitrogen

Ammonia nitrogen production in the netpens as well as ammonia nitrogen consumption in the *Laminaria* farm was simulated by the model. A mass balance was used to estimate the production and consumption values. The consumption rate was computed by two different approaches. In the first method, the nitrogen uptake was based on the nitrogen content of *Laminaria* (Figure 11). This value has been estimated to be about 2% dry mass (Harrison et al. 1986, Asare and Harlin, 1983). In the second method, an uptake rate of 10 μmol h^{-1} dry mass g^{-1} (i.e. based on Harrison et al. 1986) was assumed (Figure 12). The results indicate that for a 10 60 m rope kelp farm, the ratio of consumed ammonia nitrogen to the total (i.e. particulate and dissolved) ammonia nitrogen was never more than 0.5%. For a 100 x 60 m rope farm the above ratio could reach as high as 5.4%. If the dissolved ammonia nitrogen produced is considered, the above ratio could reach 9.6% for a 100 x 60 m rope farm (Figure 14). The results indicate that throughout the production cycle no nitrogen limitation exists. The results also suggest that a larger kelp farm operation could bring down the nutrient loading significantly. Ammonia nitrogen production rate ranged between 6.6 and 13.2 kg day^{-1} for 1 and 2 netpens respectively (Figures 11 and 13) and the nitrogen consumption rate reached 0.2 and 1.0 kg day^{-1} for a 40 and 100 rope kelp farm respectively.

In order to observe the efficiency of kelp farms to decrease the nutrient loading from the sea cages, the ratio of total and

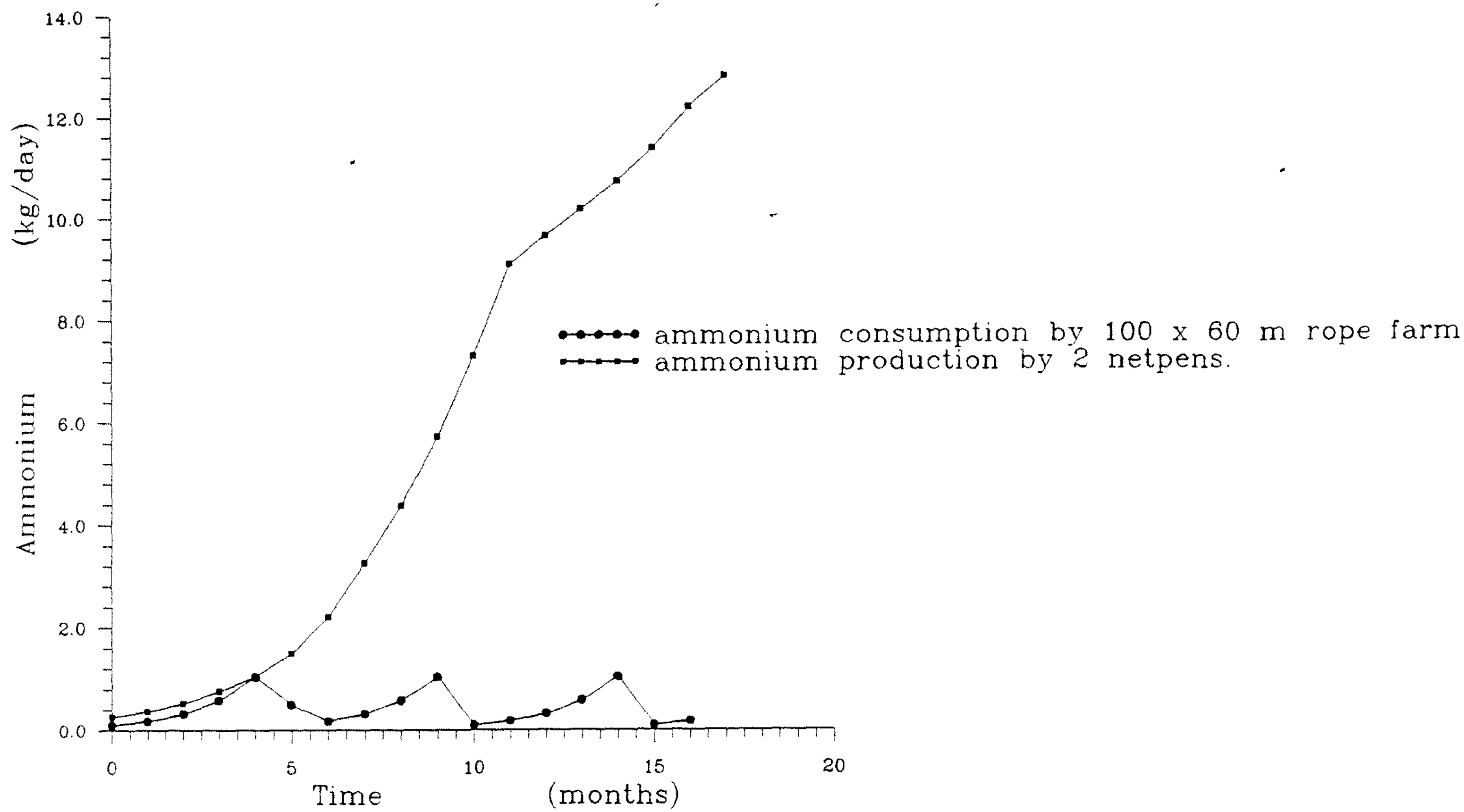

Figure 11. Ammonia nitrogen availability for an integrated Salmon/*Laminaria* farm (netpens = 2, 50 ropes *Laminaria* farm).

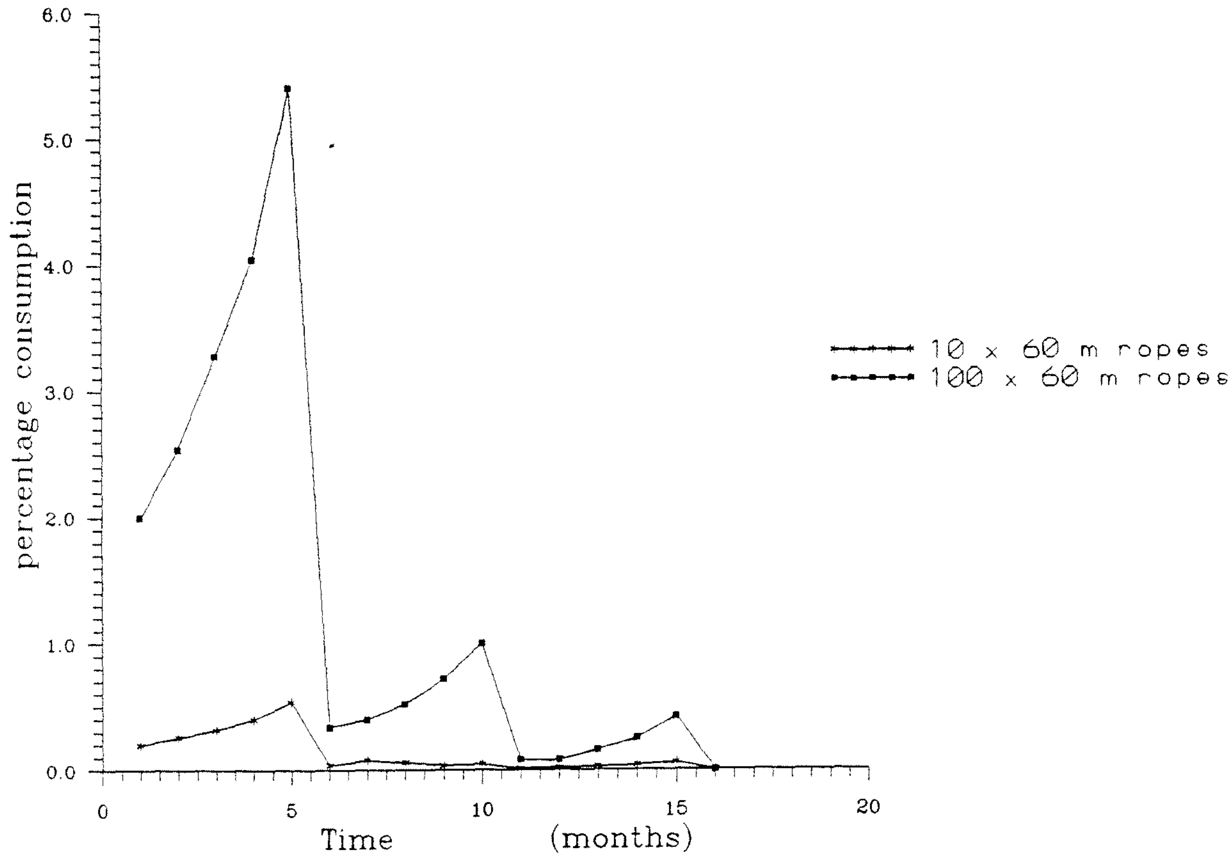

Figure 12. Ratio of total ammonia nitrogen consumed by the *Laminaria* to ammonia nitrogen produced by salmon farm. The drops represent the harvesting periods in the *Laminaria* farms.

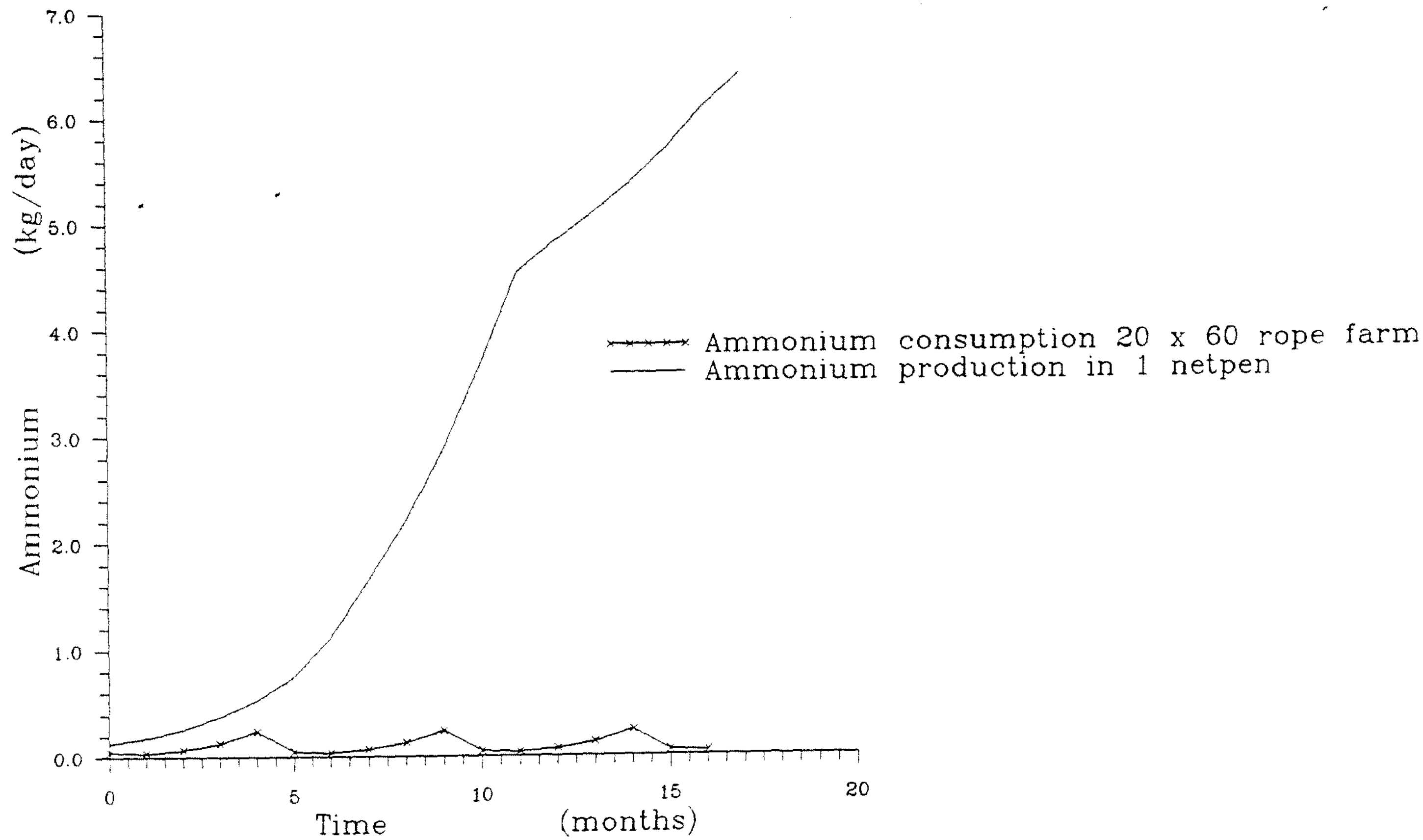

Figure 13. Ammonia nitrogen availability for an integrated Salmon/*Laminaria* farm (netpens = 1, 20 ropes *Laminaria* farm).

dissolved ammonia nitrogen loading (from 12 netpens) to ammonia nitrogen consumption by kelp was obtained (Figures 12, 14). For the 10 60 m rope farm, the percentage consumption did not reach more than 1.0%. On the other hand, for a 100 60 m rope farm this rate could reach up to 9.4% (Figure 14).

6.3. Phosphorus

Phosphorus production and consumption were analyzed in the kelp production model using equation 14. The model predicted a maximum phosphate production of 4.8 kg per day (Figure 15), whereas the maximum phosphorus consumption by kelp would be 0.0026 kg per day for a 10 60 m rope kelp farm (Figure 16).

On one hand the phosphate production rate by fish was high, and on the other hand the phosphorus content of kelp was low. Therefore, phosphorus limitation could not be observed in the kelp farm. Ammonia nitrogen production rate in one netpen is higher than phosphate production rate in twelve netpens (Figures 14 and 15). The ambient phosphate concentration was neglected in the computer model.

6.4. Oxygen

Using the oxygen consumption rate from the oxygen experiment, the expected oxygen consumption for 10, 100 and 1000 x 60 m rope kelp farms was simulated (Figure 17). It can be seen that except for the largest farm (i.e. 1000 x 60 m rope farm) the oxygen consumption rate was below 2.0 kg h^{-1}. This can be compared to a minimum oxygen transfer rate of 140 kg h^{-1} (i.e. with a current

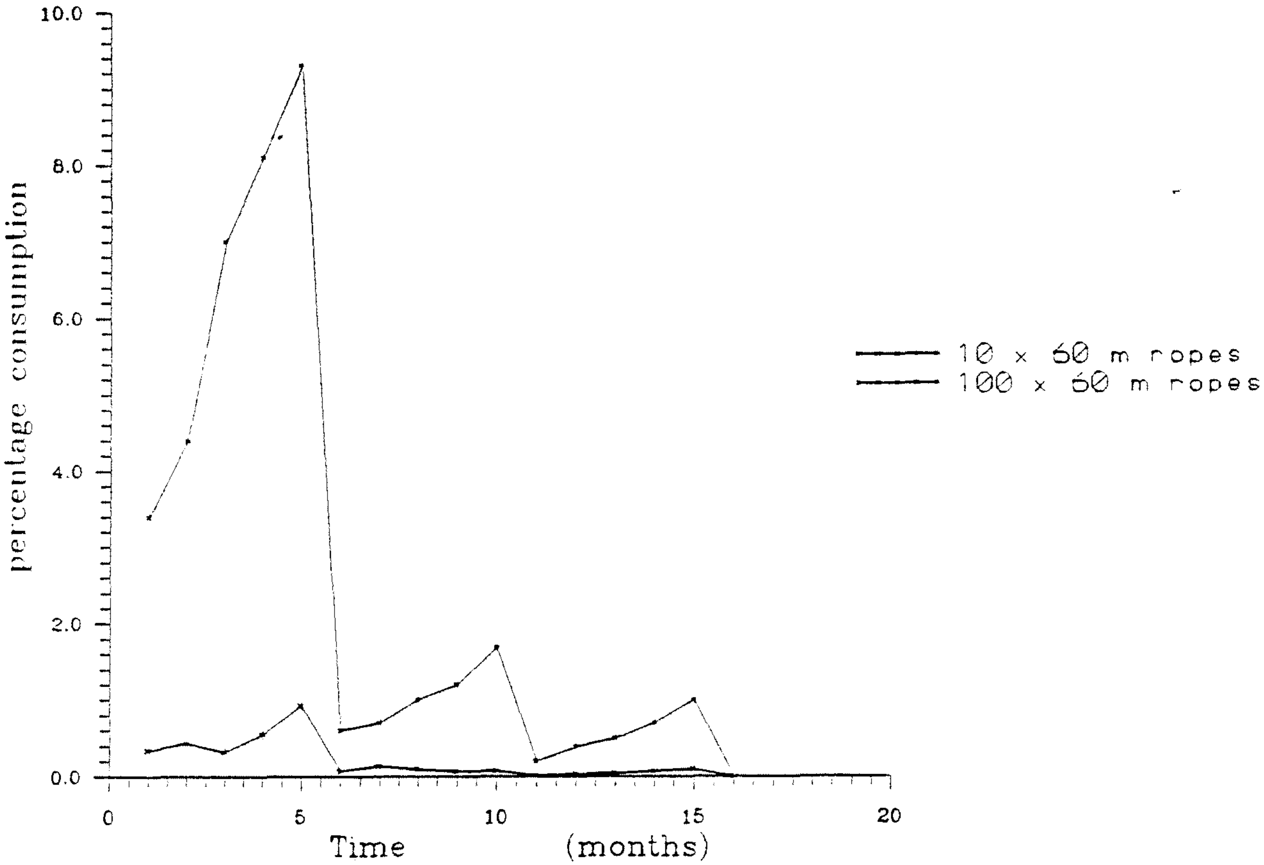

Figure 14. Ratio of ammonia nitrogen consumed by the *Laminaria* to ammonia nitrogen produced by salmon farm. The drops represent the harvesting periods in the *Laminaria* farms.

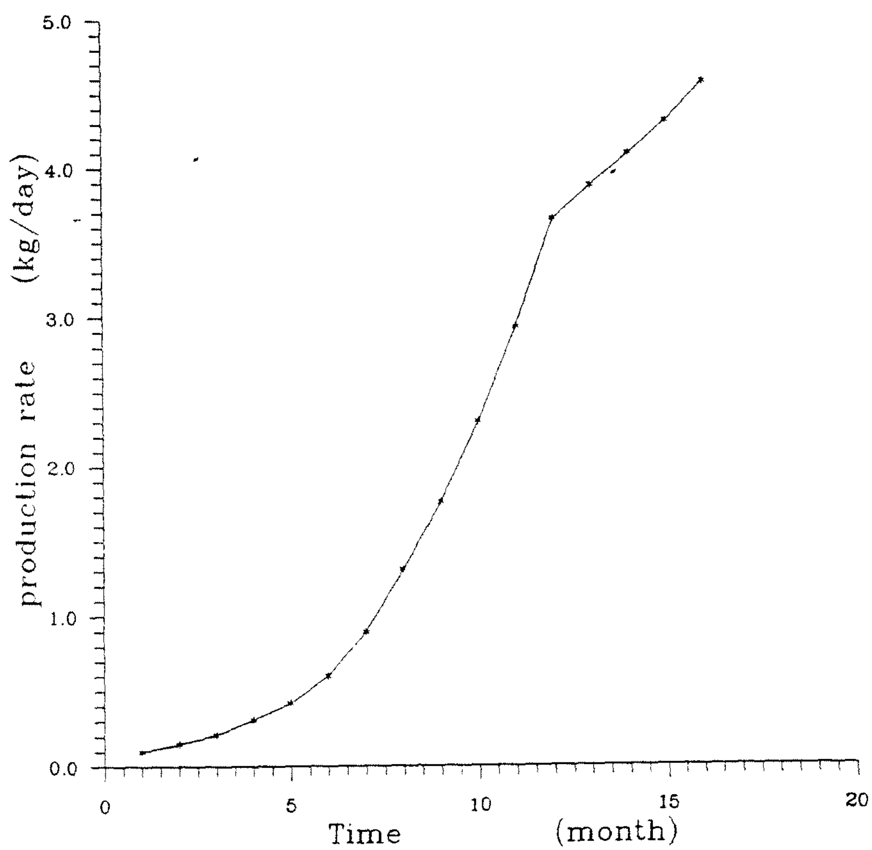

Figure 15. Phosphate available from the Fish Farm
(netpens = 12, Fish Feeding Rate = 1%).

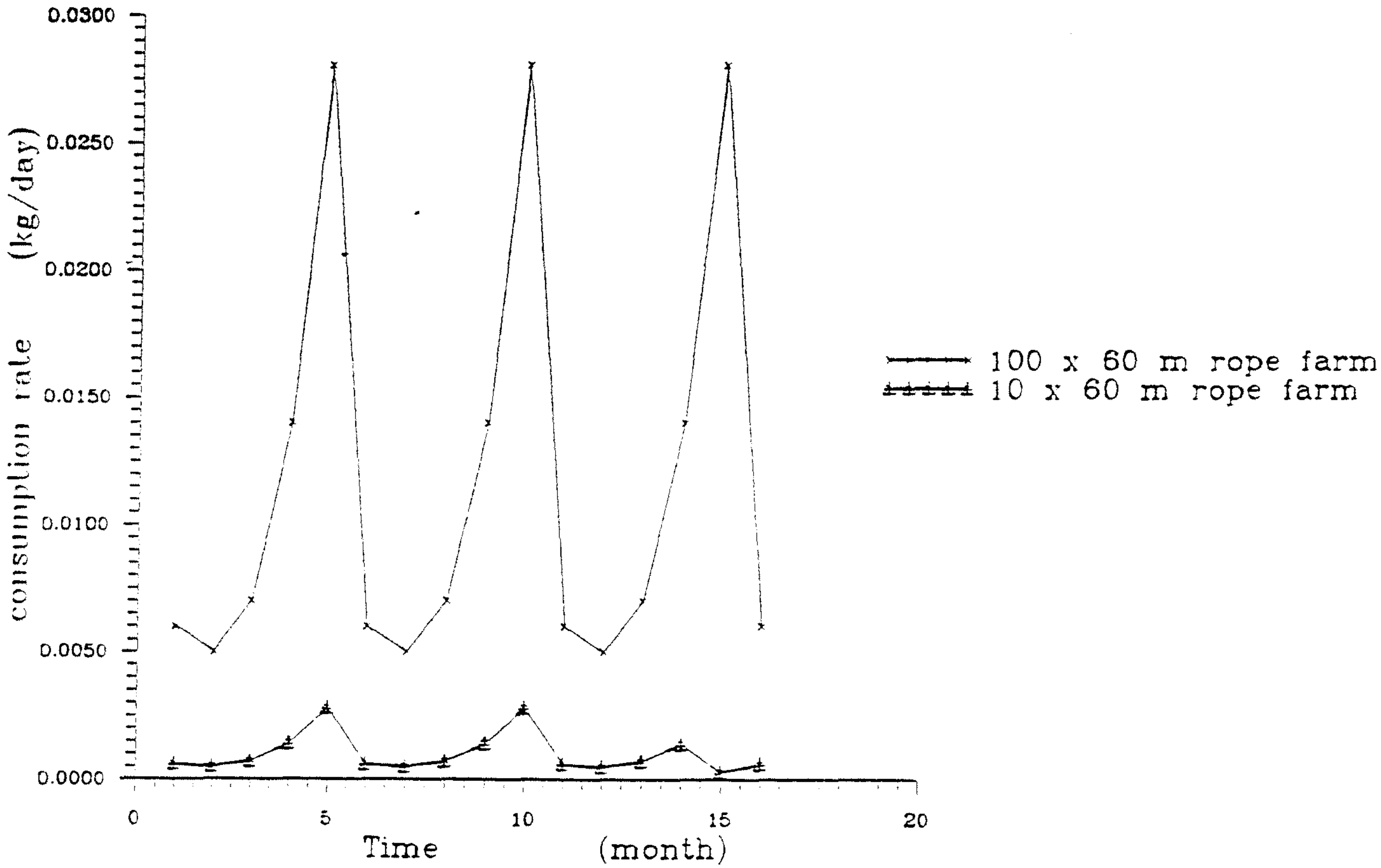

Figure 16. Phosphorus consumption by different *Laminaria* sized farms.

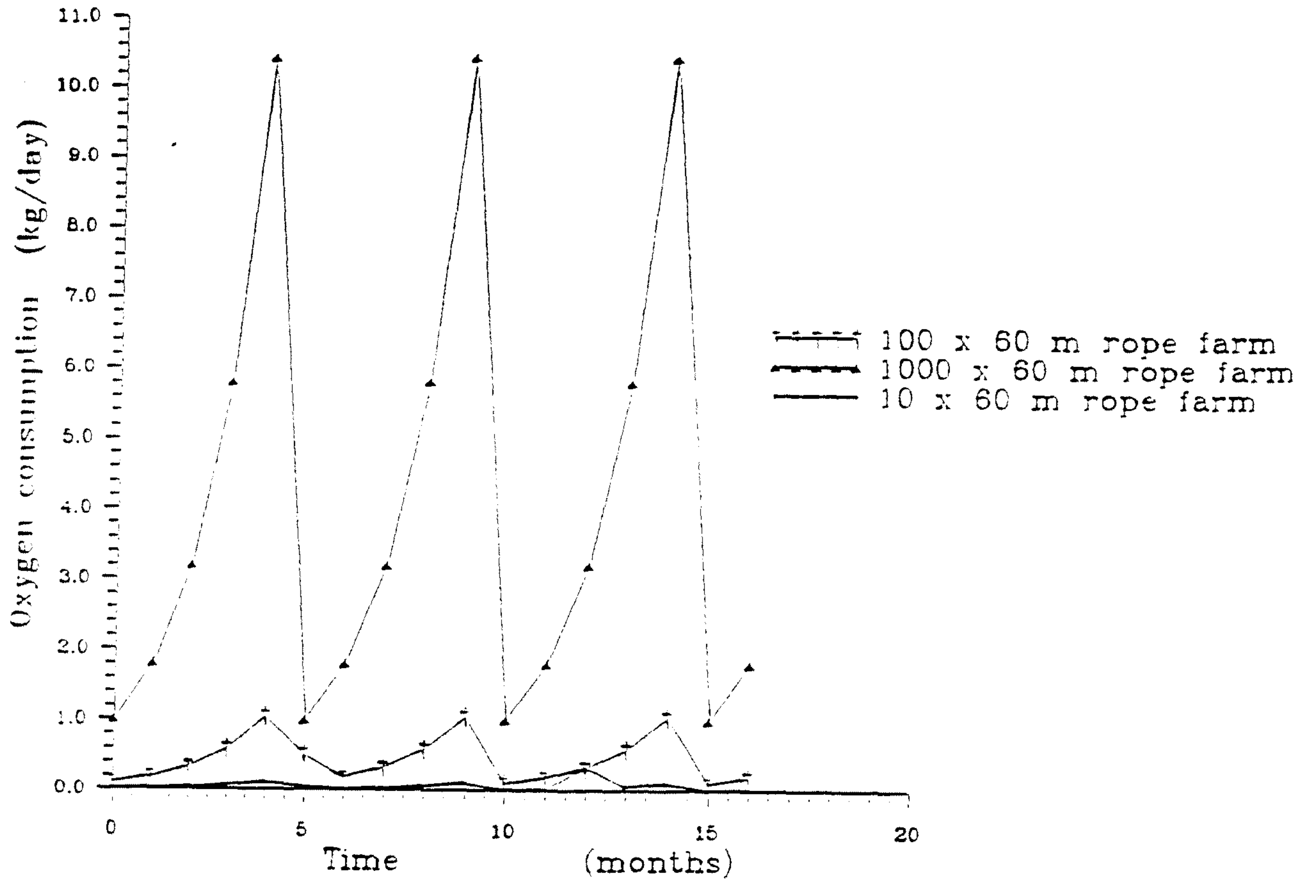

Figure 17. Oxygen consumption by different *Laminaria* sized farms.

speed = 0.1 m s^{-1} and $[O_2]$ = 5.0 mg l^{-1}); therefore, oxygen consumption was less than 1% of the available oxygen.The oxygen transfer to the netpens depends on oxygen concentration, as well as current speed. As the current speed increases, the rate of oxygen transfer also increases.

Oxygen production by the kelp through photosynthesis would benefit the fish in the netpens. As discussed above, the rate of photosynthesis is 13 times higher than the respiration rate. According to the model, the rate of oxygen production is considerably higher than the consumption rate. The results should not imply that all of this extra dissolved oxygen reaches the netpens. Mixing, current direction, and dilution rates determine the percentage of the produced oxygen reaching the net pens.

VII. LIGHT MANAGEMENT TECHNIQUE

A computer model was developed to analyze the light intensity at different depths and different extinction coefficients (Appendix 4). This model could be used as a tool to manage the kelp farm. The attenuation of solar radiation from the sun to the water column in the ocean was calculated. The solar radiation arriving at the earth's surface is composed of a direct and a diffuse component. This occurs because some of solar radiation is scattered in the atmosphere. Different parameters, such as cloudiness index, seasonal variation and diurnal variation, affect the attenuation of solar radiation from the sun to air/water interface.

The water surface, latitude and hour of the day affect the reflectance of the diffuse and the direct light. In the water column, the attenuation of light beam depends on water depth and the extinction coefficient. Mean hourly solar radiation totals from Canadian Climate Normals (1951 - 1980) for the Vancouver, UBC station were used in the model. In this climate normal, the hourly solar radiation of a typical day of the month, which represents the average hourly solar radiation for that month in the last 30 years, is used.

7.1 Inputs of Light Model

The following input parameters are used to compute the light intensity in the water column at different periods. These parameters can be varied depending on the site location.

1) latitude : latitude of the desired location.

2) depth : the water depth (unit : m).

3) attenuation : attenuation coefficient of water (unit : m^{-1}).

4) hourly solar radiation : Hourly global solar radiation on a horizontal surface for a typical day of each month. This data can be obtained from Canadian Climate Normals (unit : Mega Joules m^{-2}).

5) day number : Typical day number of each month is input as a one dimensional array.

7.2. <u>Outputs of Light Model</u>

1) cloudiness : cloudiness index, which determines what percentage of extraterrestrial radiation reaches the atmosphere.

2) day length : The length of a typical day of each month is calculated (unit : h).

3) depth intensity : light intensity at a certain water depth (unit : $\mu E\ m^{-2}\ s^{-1}$).

4) diffuse intensity : diffuse light intensity reaching water surface (unit : $\mu E\ m^{-2}\ s^{-1}$).

5) beam intensity : beam light intensity reaching water surface (unit : $\mu E\ m^{-2}\ s^{-1}$).

6) transmission : percentage of light transmission at air/water interface during different hours.

7.3. Light Model Analysis

Different simulations were done to analyze light intensity at various depths with different attenuation coefficients. Addey and Loveland (1991) listed attenuation coefficients for a variety of fresh and marine waters to be 0.03 to 0.7 m^{-1}. A wide range of attenuation coefficients from 0.1 to 0.8 m^{-1} was used in the simulations. The attenuation coefficient was calculated using the following equation (Parsons et al., 1988).

attenuation coefficient, Kd = 1.7 / visibility

where :	in summer	visibility = 6.5 m	hence	Kd = 0.26 m-1
	in winter	visibility = 11 m	hence	Kd = 0.15 m-1

At a water depth of 2 m, depending on the attenuation coefficient, the maximum monthly light intensity varies between 240 and 690 μE m^{-2} s^{-1} (Figure 18). As expected, the maximum light intensity occurs in June. Figure 18 is based on the range of attenuation coefficients between 0.11 and 0.60 m^{-1}. The sharp reduction of light intensity due to an increase in light extinction coefficient emphasizes the importance of measuring attenuation coefficient for the desired site (Figure 18). At a water depth of 2 m, light intensity was reduced from 690 to 240 μE m^{-2} s^{-1} when attenuation was increased from 0.11 m^{-1} to 0.60 m^{-1} (Figure 18).

The effect of water depth on light intensity is also examined in the light model. As water depth increases, light intensity decreases. For an attenuation coefficient of 0.1 m^{-1}, light intensity was reduced by 47% when travelling from a depth of 2 to 7 m (Figure 19). The kelp should be grown at a depth, where they would not be photoinhibited or light-limited. Using the computer simulations for light intensity, kelp farmers can determine the optimum depth. In different months of the year the depth of kelp rafts should be changed (i.e. adding or removing floats attached to the ropes) to use the available sunlight. For example, in the summer, the kelp raft should be placed deeper in the water to avoid any photoinhibition.

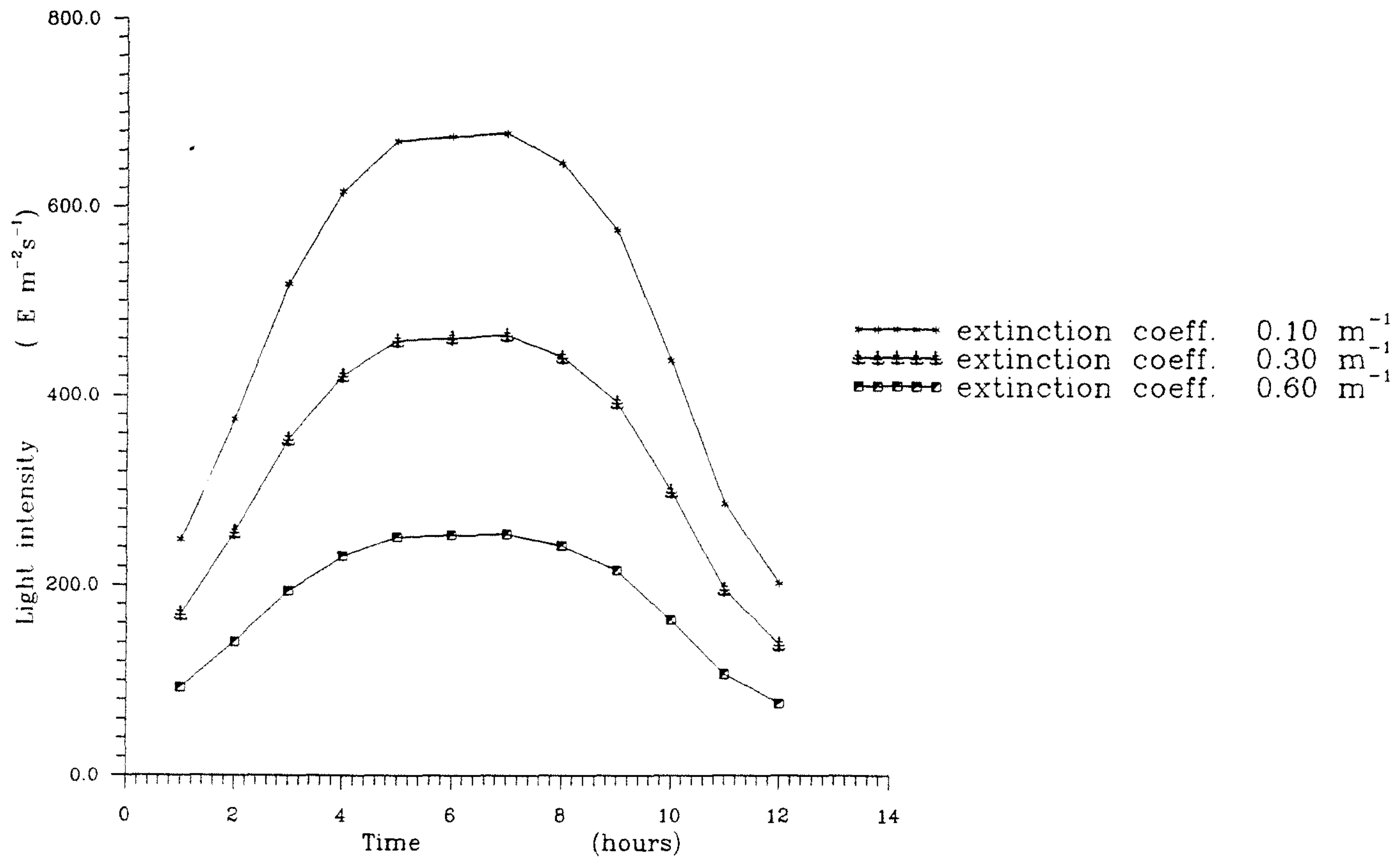

Figure 18. Light intensity reduction due to different extinction coefficients.

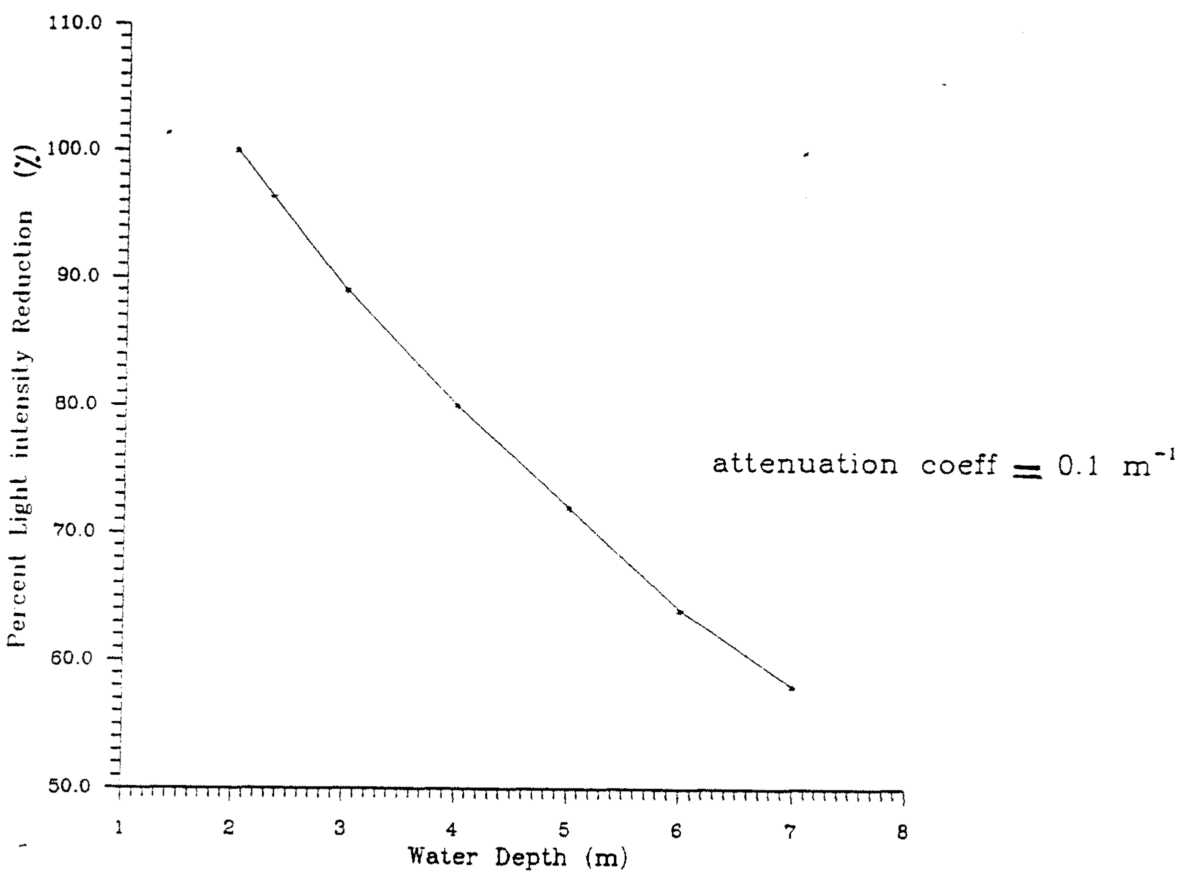

Figure 19. Light intensity reduction as a function of water depth.

VIII ECONOMIC FEASIBILITY

Seaweed farming can be viewed as an additional income for salmon farmers. Two 10 60 m ropes would produce 1600 kg of dry kelp annually. Two 30 60 m rope kelp farms (distance between each rope is 1 m) are the nominal size of the operation. The nominal production rate based on a computer simulation would be 4800 kg of dry kelp each year. The yearly production of an unfertilized farm would be one half of the production of a fertilized farm. This case study analysis is based on 33% of maximum possible production (i.e. % real/nominal usage level of facility is 33%). The selling price of kelp is $ 35 dry kg^{-1}. A minimum yearly revenue of $ 56,000 can be expected from these farms.

In the case study, a manager would receive $18,000 to market the product and oversee production. The cost analysis of the operation shows that the operation is economically feasible (Table 9). In this case study half of the initial capital is borrowed from the bank (11% compound interest, 5 annual payments). It is also assumed that the operator invests $ 26000 (50% of the fixed initial investment) in the project.

The investment amount required for the implementation of the project includes fixed investment, initial construction capital, and initial operating capital (Table 9), and it is $60,000. The pay-back period is 6 years from the start of the operation and 5 years after the first sale (Figure 20). The owner starts to invest on the operation one year before the first harvest (i.e. t = -1, on Figure 20). In four years after the start of the operation, the

Figure 20). In four years after the start of the operation, the total profit exceeds $41,000.

More kelp ropes could result in higher net revenues for the owners, but yield at a higher density needs to be experimentally tested in order to test for light limited growth. Larger sized farms could also be operated, but yield at this option too must be tested in order to test for nitrogen availability. The best option for a manager at this date would be to manage more than one site. This option would give the manager/owner more income.

A larger kelp farm could also reduce the nutrient loading in the surrounding environment more effectively. The number of netpens in each fish farming site could then be increased. This additional income (i.e. more fish production) could be another justification for this type of integrated production unit.

Table 10. Cash flow analysis for two 10 rope *Laminaria* farms for a 5 year period.

		YEAR 2	YEAR 3	YEAR 4	YEAR 5	YEAR 6
Revenue	0.00	56,000	57,120	58,262	59,428	60,616
TAX	0.00	3,680	3,510	3,329	3,144	3,017
AFTER TAX INCOME	0.00	52,320	53,610	54,933	56,284	57,599
FIXED CAPITAL COST	19,983	0.00	0.00	0.00	0.00	0.00
DIRECT COSTS	30,000	31,503	33,078	34,732	36,468	38,292
INDIRECT COSTS	10,930	10.930	10,930	10,930	10,930	0.00
TOTAL COST	60,910	42,433	44,008	45,662	47,398	38,292
ANNUAL PROFIT		9,887	9,602	9,271	8,886	19,307

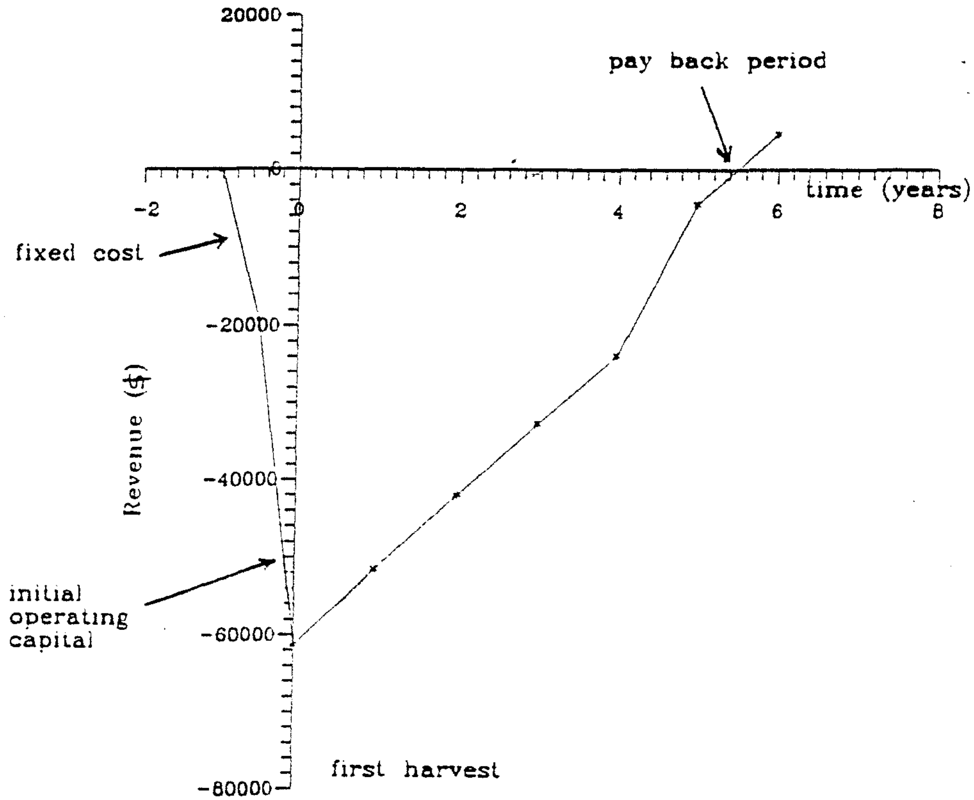

Figure 20. Break-even analysis for a 20 60 m *Laminaria* farm.

IX. CONCLUSIONS AND SUGGESTIONS FOR FURTHER WORK

The purpose of this study was to assess the feasibility of an integrated kelp and salmon culture. *Laminaria* culture positioned up to 40 m away from fish netpens would enhance kelp growth and reduce nutrient loading. Two 10 60 m kelp farms, each positioned at one end of a fish farm, would produce 1600 kg (dry mass) of kelp annually. The kelp farms begin 10 m from the netpens. Free fertilizer from the netpens is a very important parameter in encouraging fish farmers to consider this integrated system, because the kelp production could be double that of an unfertilized kelp site. The kelp farm can be considered as an additional income for fish farmers. It could bring in a net profit of $20,000.0 /year, plus reduce the nutrient loading by 1%.

In order to model the kelp growth, nutrients, temperature, and light were considered. Equations were developed relating water temperature and nitrogen to kelp growth. A set of experiments were conducted to relate growth and nitrogen availability. The experiments confirmed a linear relationship between kelp growth and nitrogen availability. Therefore, as fish grew and excreted more waste, more nitrogen is available for the kelp growth. Ammonia nitrogen production rate in one netpen reached up to 6 kg day^{-1}, whereas nitrogen consumption rate for a 10 60 m rope kelp farm was about 0.2 kg day^{-1}.

A submodel was developed to calculate light availability at different depths and attenuation coefficients. This model served as a management tool to change the depth of kelp rafts with respect to available light intensity. As light availability decreased (i.e. in the winter), the ropes should be raised higher to avoid light limited growth.

The experiments and the model confirmed that phosphorus was not a limiting factor for kelp growth. Phosphorus excretion by fish in the netpens provided a continuous source for the kelp farm. On the other hand, phosphorus uptake was minimal. For a 10 60 m rope kelp farm, the maximum calculated uptake rate is less than 4.0 g day^{-1}. Therefore, the ratio of N:P taken up by the kelp was 50:1.

One of the considerations in this study was to check oxygen limitation for the fish at night. The results of the experiment and the model show that for a 10 60 m rope kelp farm, oxygen consumption was less than 1% of the available oxygen. Therefore, no oxygen depletion would occur in the netpens for this farm size.

Kelp production 10 m from a netpen farm could also be looked upon as a method to decrease the nutrient loading of water. The fish farmers could apply for new licences (i.e. to increase the number of their netpens) and hence more revenue. This could be a possible opportunity revenue for fish farmers.

Suggestions for Further Work :

1. A pilot scale integrated kelp and salmon culture should be developed to assess the actual feasibility of this project.
2. Actual current patterns across the netpens should be analyzed, in order to have a better assessment of nutrient dilution at different distances from the netpens.

3. The feasibility of larger kelp farms could be analyzed. This depends on nitrogen concentration at different positions beside fish netpens. Large sized *Laminaria* farms could be introduced as a waste management system, which reduce nitrogen loading from the netpens.
4. The effect of kelp size and density on light penetration in the water column should be considered in order to find the proper spacing of ropes.
5. The *Laminaria* nutrient and growth model should be validated at different temperature conditions.
6. The economical feasibility of larger kelp farms on different sites should be investigated.
7. The effect of netpen arrangement to current direction and kelp farm position should be studied.
8. The nutrient release by netpens should be validated.

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APPENDIX 1. GROWTH CALCULATIONS

The procedure to develop equation 16 is as follows :

At T = 10 to 15°C growth(1) = 1.5 x ammonium concentration

At T > 15 to T = 20°C, growth decreases so that

T = 16	growth(2) = 0.88 growth(1)
T = 18	growth(2) = 0.64 growth(1)
T = 20	growth(2) = 0.40 growth(1)

Therefore, a linear relationship between temperature and growth is obtained.

$$growth(2) = growth(1) \times ((-0.12\ T) + 2.8)$$

At T < 10 to T = 5°C, growth again decreases so that

T = 9	growth(3) = 0.92 growth(1)
T = 8	growth(3) = 0.84 growth(1)
T = 6	growth(3) = 0.68 growth(1)
T = 5	growth(3) = 0.60 growth(1)

Therefore, another linear relationship between temperature and growth is obtained.

$$growth(3) = growth(1) \times ((0.08\ T) + 0.2)$$

APPENDIX 2. PHOSPHATE CALCULATIONS

A set of calculations are done to compare phosphate availability (from the salmon effluent) and phosphate consumption by the kelp in the raceways.

volume of water in each raceway = 2.7 m x .25 m x 0.05 m
= 0.0338 m^3

water flow rate in each raceway = water velocity x area
= 0.1 m s^{-1} x (0.05 m x 0.25 m)
= 1.25 x 10^{-3} m^3 s^{-1}

water exchange rate = volume / flow rate
= 0.0338 / 1.25 x 10^{-3} = 27 s

Number of water exchanges per hour = 3600 s / 27 s = 133 h^{-1}

phosphate concentration in each raceway (see section 5.2.1) is as follows :

Raceway 1 :	1 : 3 dilution	: 0.71 μM
Raceway 2 :	1 : 8 dilution	: 0.31 μM
Raceway 3 :	1 : 20 dilution	: 0.14 μM

Sample Calculation for raceway 3 :

Phosphate requirement per hour = uptake rate x mass of kelp

uptake rate = 0.47 μmol g db^{-1} h^{-1} (see section 3.3)
dry mass of kelp = 9.3 g (Table 3)

Phosphate requirement per hour = 0.47 x 9.3 = 4.4 μmol h^{-1}

phosphate available in the raceway per hour =
0.14 μM x 33.8 l x 133 h^{-1} = 630 μmol h^{-1}

Appendix 3. COMPUTER GROWTH MODEL

```
#include<stdio.h>
#include<math.h>
#include<conio.h>

/*  This program calculates kelp growth and harvest based on
   */
/*   the available ammonia nitrogen concentration from a fish farm
  */



#define OXYGEN_CONC      5            /*   mg/l   */
#define CURRENT_SPEED    0.05         /*  current speed  m/s  */
#define INITIAL_FISH_WT  0.04         /*  initial fish mass   */
#define PH               8.2
#define time             30           /*  days  */
#define mort             10           /*  percent per year    */
#define NETPENS          12
#define FEED             1            /*  FEEDING RATE   %    */
#define Rope             10           /*  number of ropes   */
#define ambient          0            /*  ambient ammonium
                                      concentration in micromols*/
#define length           60           /*  length of each rope */
#define FEEDING_RATE     2
#define ATTRITION_P      .0011
#define ATTRITION_Q      2.9E-6
#define PLANT_NUM       4           /*  number of clusters in each
m of rope */
#define NETPEN_VOL       2.25E3       /* volume of each netpen  */
#define FLOW_AREA        300          /* net pen flow area in  m2
   */
#define STOCK_DEN         10              /* final stocking density
kg/m3       */
#define SALINITY         25
#define CLUSTER            5          /* surviving plants in each
cluster */
#define PHOSP            1.1       /* % phosphorous content of dry
pellets */
#define fish_phosp       0.4      /* % phosphorous content of fish
mass */
#define INITIAL_KELP    10            /*  initial kelp mass   */

  int flag;
  float Temp[36] = {8, 7, 7, 8, 9, 10, 11, 11, 12, 11, 10,9,
              8, 7, 7, 8, 9, 10, 11, 11, 12, 11, 10,9,
              8, 7, 7, 8, 9, 10, 11, 11, 12, 11, 10,9};
```

```
main()
{
    float fish_weight;                    /* mass of each fish in kg
*/
    float Total_fish_mass[18];            /* total fish mass in kg
 */
    float Total_ammonium[18];
    float Total_ammonia[18];
    float percent_ammonium[18];
    float ammonium_concen[18];
    float ionized_ammonia[18];
    float kelpraft_concen[18];
    float kelp_growth[18];
    float oxy_consumpt;
    float kelp_mass;
    float new_kelp_mass;
    float PERCENTAGE;
    float phosph_prod;
    float total_kelp_mass;
    float initial_fish_number;
    float KILO_AMMONIA;     /*  KG ammonia produced per day   */
    float NH4_consumpt;     /*  kg ammonia consumed per day  */
    float PO4_consumpt;     /*  kg phosphor consumed per day */
    float old_kelp_mass;
    float ambient;          /*  ambient nitrogen concentration
*/
    float new_fish_wt;
    float old_fish_mass[18];
    float kelp_raft_conc[18];
    float Ammon_uptake;
    float Ammon_mol_hr;
    float GROWTH1[18];      /* specif. G for fish between 30 &
150 g  */
    float GROWTH2[18];      /* specif. G for fish between 150 &
600 g */
    float GROWTH3[18];      /* specif. G for fish between 600 &
2000 g */
    float GROWTH4[18];      /* specif. G for fish larger than
2000 g  */
    int month, temp, harvest;

  for (month = 0; month <= 17; month++)
    {
     flag                     = 0;
     Total_fish_mass[month]   = 0;
     Total_ammonium[month]    = 0;
     Total_ammonia[month]     = 0;
     initial_fish_number      = 0;
     percent_ammonium[month]  = 0;
     ammonium_concen[month]   = 0;
     ionized_ammonia[month]   = 0;
     kelpraft_concen[month]   = 0;
```

```
        kelp_growth[month]       = 0;
        old_fish_mass[month]     = 0;
        harvest                  = 0;
        kelp_mass                = 0;
        phosph_prod              = 0;
        total_kelp_mass          = 0;
        Ammon_uptake             = 0;
        Ammon_mol_hr             = 0;
        kelp_raft_conc[month]    = 0;
        GROWTH1[month] = 0;
        GROWTH2[month] = 0;
        GROWTH3[month] = 0;
        GROWTH4[month] = 0;

       }
       clrscr();
   /*    printf("temp=%f\n",Temp[2]);  */
       dummy = pow(10, (9.245 + 0.002 * SALINITY));
       fish_weight = INITIAL_FISH_WT ;
       kelp_mass = INITIAL_KELP;


       /* calculating the initial fish  number   */
       /* for a final fish mass of 3 kg          */

       initial_fish_number = NETPEN_VOL * NETPENS * STOCK_DEN *
                    (1 + (mort * 1.5/1000))/3;


        printf(" KELP FARM IN m2 = %f\n",FARM_AREA);

/*      printf(" INITIAL FISH NUMBER = %f\n",initial_fish_number);
*/

       for (month = 0; month <= 17; month++)
       {
        GROWTH1[month] = ((0.15 * Temp[month] + 0.1)/100) + (2 *
        ambient);
    /* printf(" GROWTH1 =  %f\n",GROWTH1[month]);  */
        GROWTH2[month] = ((0.12 * Temp[month] - 0.014)/100) + (2 *
        ambient);
    /* printf(" GROWTH2 = %f\n",GROWTH2[month]);  */
        GROWTH3[month] = ((0.079 * Temp[month] + 0.014)/100) + (2 *
        ambient);
/*      printf(" GROWTH3 =  %f\n",GROWTH3[month]);  */
        GROWTH4[month] = ((0.050 * Temp[month])/100) + (2 *
        ambient);
/*      printf(" GROWTH4 =  %f\n",GROWTH4[month]);    */
        flag = time * month;
        if (fish_weight > 0.03  && fish_weight <= 0.15 )
        new_fish_wt = fish_weight * pow(2.71,(GROWTH1 [month] *
        time));
```

```
      if (fish_weight > 0.15  && fish_weight <= 0.60 )
        new_fish_wt = fish_weight * pow(2.71,(GROWTH2[month] *
      time));
      if (fish_weight > 0.60  && fish_weight <=  2.0 )
        new_fish_wt = fish_weight * pow(2.71,(GROWTH3[month] *
      time));
      if (fish_weight > 2.0)
       new_fish_wt = fish_weight * pow(2.71,(GROWTH4[month] *
      time));

       fish_weight = new_fish_wt;    /* new mass of one fish in kg
*/
       printf(" FISH  MASS =  %f\n",fish_weight);
       printf(" month =  %i\n",flag);

    /* Calculating total fish mass in the net pens   */
    /* and ammonia produced                          */
       old_fish_mass[month] = Total_fish_mass[month];
       Total_fish_mass[month] = initial_fish_number * fish_weight
                     *( 1 - (mort* time * month)/36000);
       printf(" total fish mass %f\n",Total_fish_mass[month]);

    /* total ammonia in mg per sec  */
       Total_ammonia[month] = 0.0289 * Total_fish_mass[month] *
       FEED * 0.116;
  /*      PHOSPHATE PRODUCTION IN KG/DAY                   */
  /*      PHOSPHOROUS   PHOSPHOROUS   PHOSPHOROUS          */

     /* phosphorous production , 23% in dissolved form , 52%    */
     /* reaches the kelp farm                                    */
        phosph_prod = 0.23* 0.52 * 0.0162 * Total_fish_mass[month]
              * FEED / 100.0;

       printf("   phosphorous   in   the   kelp   farm    kg/day
=%f\n",phosph_prod);

       KILO_AMMONIA  = Total_ammonia[month] * 3600 * 24/1E6;
       printf(" kilo ammonia per day  = %f\n",KILO_AMMONIA);


       percent_ammonium[month] = 100;
 /*    -----------------------------------------------------------
   */
 /*    ammonium flow  rate in kelp raft  in micromol per liter per
hour   */

    Ammon_mol_hr = KILO_AMMONIA * percent_ammonium[month]
                 * 1.0E+9 * 0.52 * 0.056 / 24.0;

    printf("NH4   production   by   fish   miromol/hr
=%f\n",Ammon_mol_hr);
```

```
/* total ammonium in mg per second  */
   Total_ammonium[month] = percent_ammonium[month] *
                           Total_ammonia[month] / 100  ;

/*       printf(" total ammonium in mg per s
         =%f\n",Total_ammonium[month]);*/

/*       PHOSPHORUS   PHOSPHORUS  PHOSPHORUS   */

 /* phosphorus production , 23% in dissolved form , 52%    */
 /* reaches the kelp farm                                  */


   printf(" phosphorous in the kelp farm  kg/day
          =%f\n",phosph_prod);

 /* ammonium concentration in mg/l */
   ammonium_concen[month] = Total_ammonium[month] /
                      (FLOW_AREA * CURRENT_SPEED * 1000);

  /* [ammonium] in micromols at the kelp raft   */
    kelpraft_concen[month] = ammonium_concen[ month]  * 0.52
    * 55.56;
   printf(" kelp raft concentration =
           %f\n",kelpraft_concen[month]);

  if (Temp[month] >= 5 && Temp[month] <= 10)
      kelp_growth[month] = 1.5 * kelpraft_concen[month]*
     ((0.08 * Temp[month]) + 0.2);
  if (Temp[month] > 10  && Temp[month] <= 15)
      kelp_growth[month] = kelpraft_concen[month] * 1.5;
  if (Temp[month] > 15  && Temp[month] <= 20)
      kelp_growth[month] = 1.5 * kelpraft_concen[month] *
                  ((-0.12 * Temp[month]) + 2.8);
/*      printf("KELP    GROWTH    percent       per    day    =
%f\n",kelp_growth[month]);*/

   /* NUMBER OF HARVESTS */
   if (kelp_mass >= 400)
      {
      harvest = harvest + 1;
      kelp_mass = 10;
      printf("harvest number =     %i\n", harvest);
      old_kelp_mass = 0;
      total_kelp_mass = 0;
      }
   /* individual kelp mass  in  grams */
   /* considering ambient concentration */

   if (kelp_growth[month] < 1.0)
      {
```

```
            kelp_growth[month] = 1.0;
           }

       new_kelp_mass = kelp_mass * pow(2.72,
                       (kelp_growth[month]*time/100));
       kelp_mass = new_kelp_mass;
/*     printf("new_kelp_mass = %f\n",new_kelp_mass);   */
       /* total kelp mass in the farm  in kg  */
       old_kelp_mass = total_kelp_mass;
       total_kelp_mass = Rope x length * CLUSTER/PLANT_NUM *
                         kelp_mass/1000;
       NH4_consumpt = (0.002*(total_kelp_mass -
                      old_kelp_mass))/(30.0);
       PO4_consumpt = (0.000042*(total_kelp_mass -
                      old_kelp_mass))/(30.0);
      printf("total kelp mass%f\n",total_kelp_mass);

      /* ammonium consumption  by the kelp farm */
      /* UPTAKE RATE 7 to 10 micromol/g dry wt/hr  */
       Ammon_uptake = total_kelp_mass * 1000.0;
       PERCENTAGE = 100.0 * (Ammon_uptake/Ammon_mol_hr);
       printf("NH4 CONSUMPTION BY KELP miromol/hr =%f\n",
       Ammon_uptake);
       printf("PERCENTAGE AMMONIUM CONSUMPTION =%f\n",PERCENTAGE
       );
       printf("Phosphorus CONSUMPTION BY KELP kg/day
      =%f\n",PO4_consumpt);

       /* oxygen consumption at night by the kelp  kg/hr */
       oxy_consumpt = total_kelp_mass*0.026*0.001;
       printf("OXYGEN CONSUMPTION BY KELP kg/hr
       =%f\n",oxy_consumpt);

             }
  }
```

Appendix 4. LIGHT SUBMODEL

```
#include <math.h>
#include <stdio.h>
#include <io.h>
#include <stdlib.h>

/* This program calculates monthly solar intensity at different */
/* water depths and for different water clarities               */

#define   solar_constant  4.921        /* mega joules per m2 */
#define   latitude        49.3         /* degrees      */
#define   water_depth     2            /* depth of water in m*/
#define   attenuation     0.11         /* attenuation coefficient
1/m */
#define   pi               3.14
#define   goofy            0
#define   months           11
#define   hours            23
#define   constant         284

int       i,j;
float     val;
float     declination;                /* declination angle */
float     hour_angle[24];             /* in radians */
float     sun_angle[24];
float     cloudiness_index[12];
float     cloudiness_ind;
float       AVERAGE_R[12];
float      I_global[12][24];           /* hourly global radiation
(from data file)*/
float     I_beam[12][24];             /* hourly beam radiation */
float       I_underwater[2][24];            /* hourly underwater
radiation */
float       beam_transmit[24];
float     I_depth[12][24];            /* hourly underwater rad. at
dept h d*/
float        AVG_BOTTOM_R[12];
float     I_diffuse[12][24];          /* hourly diffuse radiation
*/
float     H_beam[12];                 /* daily beam radiation */
float     H_diffuse[12];               /* daily diffuse radiation
*/
float     H_extra[12];                  /* daily extraterrestrial
radiation */
float     H_global[12];               /* daily global radiation */
float     H_underwater[12];           /* daily underwater rad. at
depth d */
float     I_beamwater[12][24];
float     I_diffusewater[12][24];
float      day_length[12];                  /* day length at each
```

```
typical day */
float     day_angle;
float     ws,ws1;                          /* sunrise hour angle */
float     Eo,k,m;
i                     n                     t
day_number[12]={17,47,75,105,135,162,198,228,258,288,318,334};

 main()
  {
FILE *inp;
inp = fopen("global.dat","r");

/* INITIALIZATION */

  for(i=0; i<=months; i++) {

     H_beam[i]       = 0;
     H_diffuse[i]    = 0;
     H_extra[i]      = 0;
     H_global[i]     = 0;
     day_length[i]   = 0;
     AVG_BOTTOM_R[i] = 0;
     cloudiness_index[i] = 0;
     for (j = 0; j <= hours; j++) {
     hour_angle[j]   = 0;
     I_beam[i][j]    = 0;
     I_diffuse[i][j] = 0;
      I_beamwater[i][j]   =0;
      I_diffusewater[i][j] =0;

     }
   }

     for(i=0; i<=months;  i++)  {
     for(j=0; j<=hours; j++)   {
        fscanf(inp,"%f ", &I_global[i][j]);
     /* I_global[i][j]= I_global[i][j] * pow(10,6); */
     /*   printf("ghi=%f\n",I_global[i][j]); */
        H_global[i] = H_global[i] + I_global[i][j];
       }
/*   printf("H_global=%f\n",H_global[i]);  */
      }

      /* calculating daily extraterrestrial radiation */

     printf("water depth= 2m , attenuat = 0.11\n");

      for(i=0; i<=months;  i++)  {

        day_angle = 2 * pi * day_number[i] / 365 ;
        Eo = 1 + 0.033*cos(day_angle);
        printf("Eo=%f\n",Eo);
```

```
        val = sin((day_number[i]- 82)*(0.986)*pi/180);
/*      printf("value=%f\n",val);   */
         declination = asin(0.4*val)*180/pi ;
         printf("decli angle=%f\n",declination);

    ws = acos(tan(declination*pi/180)*tan(latitude*pi/180)*(-1)) ;
        printf("ws=%f\n",ws);

        day_length[i] = 2 * ws * 180 / (pi * 15);
        printf("day length=%f\n",day_length[i]);

        H_extra[i] = (24/pi)*(solar_constant*Eo)*((ws*
        sin(declination*pi/180)*sin(latitude*pi/180))+
        cos(declination*pi/180)*cos(latitude*pi/180)*sin(ws ));

/*      printf("EXRTATER=%f\n",H_extra[i]);    */

        /************** calculating cloudiness index  */

            cloudiness_index[i] =H_global[i]/H_extra[i];

     /*       printf("cloudiness=%f\n",cloudiness_index[i]); */
        /************* calculating diffuse daily radiation */

        H_diffuse[i] = (0.958 - 0.982 * cloudiness_index[i]) *
                  H_global[i];
/*       printf("Diffuse=%f\n",H_diffuse[i]);          */
        for(j=0; j<=hours;  j++) {

          hour_angle[j] = pi - (j*pi/12);
     /*    printf("hourangle=%f\n",hour_angle[j]); */

          s   u   n   _   a   n   g   l   e   [   j   ]        =
sin(declination*pi/180)*sin(latitude*pi/180) +

cos(declination*pi/180)*cos(latitude*pi/180) *
                      cos(hour_angle[j]);
     /*   printf("sunangle=%f\n",sun_angle[j]);  */

        /*************  calculating diffuse hourly radiation */

          if( I_global[i][j] > goofy) {


            I_diffuse[i][j]    =    H_diffuse[i]    *    pi    *
(cos(hour_angle[j]) -
                    cos(ws))/(sin(ws)-ws*cos(ws))/24;

         /*   printf("Diffuse Hourly=%f\n",I_diffuse[i][j]); */
        /*************  calculating beam hourly radiation  */

            I_beam[i][j] = I_global[i][j] - I_diffuse[i][j];
```

```
/*        printf("BEAM RADIATION=%f\n",I_beam[i][j]); */
        /*****************************************************/
        /*****************************************************/
        /*       WATER SURFACE REFLECTION OF THE BEAMS       */

            I_diffusewater[i][j] = 0.934 *  I_diffuse[i][j];

                b e a m _ t r a n s m i t [ j ]    =    0 . 3 0 5 4 4    +
9.9798*pow((pi/2-sun_angle[j]),2)+
                      12.044*pow((pi/2-sun_angle[j]),3) -
                      6.8773*pow((pi/2-sun_angle[j]),4) +
                      1.4872*pow((pi/2-sun_angle[j]),5);

            printf("transmission= %f\n",beam_transmit[j]);

            I_beamwater[i][j] = I_beam[i][j] * beam_transmit[j] /
100;

            I_underwater[i][j]    =    I_beamwater[i][j]    +
I_diffusewater[i][j];

/*          printf("underwaters= %f\n",I_underwater[i][j]);    */
        /*****************************************************/
        /*****************************************************/
        /***** LIGHT ATTENUATION DUE TO WATER DEPTH  ********/

           k = -1 * water_depth * attenuation;
           I_depth[i][j] =  4.6 *  pow(10,6)*I_underwater[i][j] *
           pow(2.72,k) / 3600;


           if(I_depth[i][j] >= 0)
           {
           AVERAGE_R[i] = AVERAGE_R[i] + I_depth[i][j];
           }
          }
          }

           AVG_BOTTOM_R[i] =  AVERAGE_R[i] / day_length[i] ;
          printf("average bottom in microEin.
                 is=%f\n",AVG_BOTTOM_R[i]);
         }
   }
```

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1 - "Integrated Salmon and Kelp production" K. Mazhari, R.J. Petrell
~~Intensiv~~
Engineering Aspects of intensive Aquaculture.
Proceedings from the Aquaculture Symposium.
Cornell University April 4-6, 1991

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