ESTIMATING THE CARRYING CAPACITY OF MUSSEL RAFT SYSTEMS IN TWO SCOTTISH SEA LOCHS

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Abstract
Two different carrying capacity models were applied to commercial mussel raft systems in two sea lochs on the west coast of Scotland. The mean currents were found to be 0.052 m/s in Loch Etive (LE) and 0.05 m/s in Loch Kishorn (LK). The mussel filtration rate ranged from 0.54 to 2.26 l/h in LK and 0.93 to 2.07 l/h in LE ($p>0.05$). The assimilation efficiency was 19.64% in May and 25.02% in August in LK ($P>0.05$). However, the assimilation efficiency was significantly higher in May (28.23%) than August (21.17%) in LE. Based on the seston clearance model, the carrying capacity was estimated to be 5.7 times greater in LE than the present mussel culture system utilitizes, while the carrying capacity was about 3 times greater in LK than the present culture system utilizes. According to the particulate organic matter model, the Loch Kishorn mussel farm is producing more mussels than the estimated carrying capacity of the system (by a factor of 20-40%), while, in contrast, the mussel production in Loch Etive is considerably below the carrying capacity (by about 40% to more than 100%). The production capacities were found to be more accurate in the particulate organic matter model than in the seston based model at both sites.

Introduction
Mussel culture has a short history in Scotland. Production has almost tripled to aproximately 1000 tons over the last decade (Karayücel, 1997). Rapid expansion of the mussel culture industry has prompted considerable interest in the problem of estimating carrying capacity, i.e. the stock density at which production levels are maximized without negatively affecting growth rates (Carver and Mallet, 1990). The accelerated growth and superior condition of mussels in suspended culture systems results from their maintenance under optimal environmental conditions. Simply stated, this involves maximizing exposure to food while minimizing physical trauma and predation. The rapid growth of this sessile organism is subsidized by physical

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energy flows in nature; mussels require considerable volumes of water to meet their metabolic demands, and these volumes are provided primarily by tidal circulation (Lutz, 1985). Although free energy flows help make mussel aquaculture an extremely efficient means of protein production, limits to the productivity of natural waters necessarily limit the amount of shellfish biomass that can be supported before competition for available nutrients limits overall growth (Lutz, 1985).

The success of suspended culture techniques is directly dependent on production of food and oxygen in the growing waters and upon adequate circulation (Incze and Lutz, 1980; Lutz, 1980; Incze et al., 1981). A consideration of possible biological constraints to mussel aquaculture in an estuary or bay involves an extension of the ecological concept of "carrying capacity" to the culture or husbandry of mussels. By evaluating the ability of a body of water to support dense aggregations of shellfish, the optimal production density can be determined (Lutz. 1985).

The carrying capacity of coastal sites for suspended mussel culture should be modeled and the criteria for determining site selection, stocking density and number of leases should be based on estimated production potential. A major consideration in the site selection process should be carrying capacity of the site, i.e. the maximum level of production that a site might be expected to sustain (Beveridge, 1996). Assessment of carrying capacity will lead to efficient use of finite lease space, optimize mussel growth rates, permit financial planning through project yield, and allow informed regulation of inshore waters for aquaculture and competing interests such as traditional fisheries or leisure activities.

The first carrying capacity model for bivalve molluscs in open, suspended culture systems was developed by Incze et al (1981), and is based on seston clearance by mussels in the system. The second model for carrying capacity was developed by Carver and Mallet (1990). This model is based on food supply [as particulate organic matter (POM)] and food demand (as POM) by mussels in the system. For a number of areas where mussels are cultured, it has been shown that the feeding capacity of the area is related to phytoplankton dynamics (Tenore and Gonzales, 1976; Incze and Lutz, 1980; Rosenberg and Loo, 1983). Current velocity is also important for the availability of food to mussel rafts (Rosenberg and Loo, 1983) and dense mussel beds (Frechette and Bourget, 1985; Wildish and Kristmanson, 1985). The potential yield of mussels and carrying capacity of mussel culture areas have also been calculated from the production and transport of carbon (Rosenberg and Loo, 1983; Rodhouse and Roden, 1987).

This experiment was conducted to compare two different carrying capacity models for raft cultured mussels for two sea lochs. The experiment is the first to be carried out at commercial mussel culture sites and may be of benefit to mussel farmers for determining optimum production capacity in the experimental sites.

Materials and Methods

This experiment was carried out in the field on two raft systems under ambient conditions of food availability in May and August 1994. Mussel samples were collected by hand (from a depth of 2 m) from the commercial mussel culture rafts in Loch Etive and Loch Kishorn, Scotland. Clusters of mussels were detached from ropes and individuals were immediately removed by cutting the byssus threads with scissors. Twenty-five individuals were immediately cleaned of fouling organisms to avoid possible clearance of food by other species. Every effort was made to reduce any variation caused by factors other than filtration by the mussels. All experimental mussels were rope grown and approximately the same age (2.5-3 years old). The shell length ranged from 51 to 62 mm (56.36±0.63) in Loch Etive and from 52 to 67 mm (58.32±0.77) in Loch Kishorn (each 11-15 g weight or about 1 g dry meat weight).

Six 500 ml Pyrex conical flasks were used: five contained five mussels each and the sixth was used as a control. Duplicate 1 l water samples were removed from the flask to measure the filtration rate, assimilation, seston and particulate organic matter.

In order to determine seston, particulate organic matter (POM) and the filtration rate, the experiment was conducted in Loch Etive and Loch Kishorn on two occasions, May and August 1994. During each visit, duplicate water samples were taken and transported to the Institute of Aquaculture, University of Stirling, in a cool box. The determination of seston and POM were carried out according to Stirling (1985) methods.

Current measurements were carried out over the ebb and flood tide periods of neap and spring tides using a Braystoke BMF 208 current meter, from an anchored boat. The mean value for the measured currents was used as the "flow rate" (V).

The first model used for carrying capacity was that according to Carver and Mallet (1990). The model is based on food supply (as POM) and food demand (as POM) by the mussels in the system. Multiplying the volume of water by the appropriate POM gives estimates of food supply. Multiplying the filtration rate (l/h) by the average concentration of POM gives the daily ration (mg/day). Food supply (g POM/week) was divided by food demand (g POM/kg mussel) to obtain weekly estimates of the carrying capacity of the system.

The 50 l head tank was kept full continuously by pumping water from a depth of 3 m and stirring. The outlet from the header tank fed the six 500 ml Buchner flasks via a ring system controlled by a main valve. Each off-take from the ring was connected to a "T" adapter from which one tube ran vertically into the flask. Flow rates were controlled with small individual taps. Mussels were placed in the experimental flasks with the inflow at the bottom and the outflow from the top of the flask. The mussels were allowed to acclimate for 30-40 minutes before water sampling. The system was covered by a paper carton to avoid effects from direct sunshine on the experimental mussels.

After all mussels had started active feeding, water samples were collected four times during a one hour period from the outflows of the flasks, including the control flask. At the end of the experiment, mussel feces were collected on Whatman GF/C paper using a pipette, to calculate the assimilation rate. The filtration rates (l/h) were calculated according to Carver and Mallet (1990) using the following formula:

$$\text{Filtration rate} = V(POM_1 - POM_2/POM_1)$$

where POM_1 is the average of POM concentration (mg/l) in the control chamber, POM_2 is the POM concentration (mg/l) in the experimental chambers and V is the flow rate (150 ml/minute) in the experimental chambers. Assimilation was calculated by comparing the POM to seston ratio in the feces with the POM to seston ratio in the food (Conover, 1966).

The second carrying capacity model was based on seston concentration and estimated according to Incze et al. (1981). Provided that seston concentrations are not reduced by more than 50%, the number of tiers which can be included in an ideal system (one which conforms to an ideal set of assumptions) can be determined. The culture system used (Fig. 1) is three-dimensional, having a depth (h), width (w), length (l), and water surface area (a).

The model has the following assumptions: (a) the concentration of particles per liter is homogeneous as it enters each tier, (b) the flow is normal to the face of the tier, (c) flow through the system is laminar, and (d) each mussel filters 1.5 and 1.75 l/h in Loch Kishorn and Loch Etive, respectively (average values).

The amount of seston passing from each tier was found from the following equation:

$$n_2 = n_1 (N - \text{filtration rate} \times M) / N$$

where n_k (mg/l) = the concentration of particles per liter flowing into tier T_k, N (l/h) = the volume of water entering through face "a" per hour (determined according to the formula $N = V \times a \times 10^3$ where V = flow rate and a = area, see Fig. 1) and M = the number of mussels suspended in each tier.

Results

Current measurements were carried out at a depth of 5 m in the water column to represent the mussel culture ropes (actual rope lengths were 8 m in Loch Etive and 10 m in Loch Kishorn). The currents ranged from 0.01 to 0.20 m/s, with a mean of 0.052 m/s, in Loch Etive, and from 0.01 to 0.18 m/s, with a mean of 0.05 m/s, in Loch Kishorn.

The surface area of the system facing the current was 80 m^2 in Loch Etive and 200 m^2 in Loch Kishorn. The mussel filtration rate ranged from 0.54 to 2.26 l/h in Loch Kishorn and 0.93

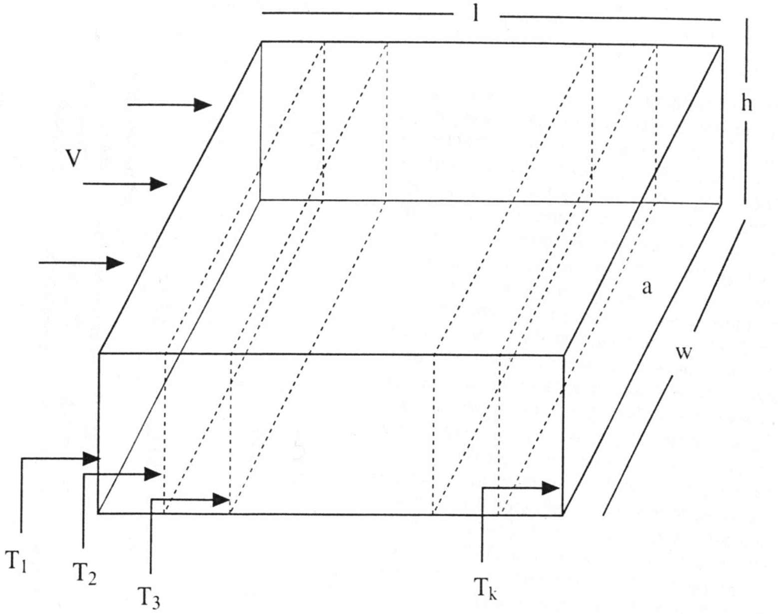

Fig. 1. Model for estimating the impact of intensive mussel cultivation in a raft system (after Incze et al., 1981). T_1, T_2....T_k are tiers (horizontal wooden beams, arranged in parallel, each supporting a row of mussel culture ropes, or droppers) of the mussel culture unit; V is the flow rate of the current; a, the area of the tier; l, h and w, the length, height and width of the raft.

to 2.07 l/h in Loch Etive; these values were not significantly different between sites ($p>0.05$). The filtration rate was higher in August (1.7 l/h) than May (1.1 l/h) in Loch Kishorn ($p<0.05$). In Loch Etive the filtration rate was lower in August (1.5 l/h) than in May (1.7 l/h), but the difference was not significant ($p>0.05$).

The assimilation efficiency varied from 8% to 39% in Loch Kishorn and from 1% to 31% in Loch Etive. The mean values of assimilation efficiency were 19.85±2.89% in Loch Kishorn and 25.02±1.84% in Loch Etive. The differences in assimilation efficiency between the sites were not significant ($p>0.05$). In Loch Kishorn, the assimilation efficiency was 19.64% in May and 20.09% in August ($p>0.05$). However, the assimilation efficiency was significantly higher in May (28.23%) than August (21.17%) in Loch Etive.

An estimate of the carrying capacity was derived from the concentration of seston as water entered the mussel raft system. Mean monthly estimates of seston concentration outside and inside the raft system were used to calculate a theoretical carrying capacity for each site.

In Loch Etive, the average seston concentration was 6.6 mg/l in the sea water before it entered the first tier. When the water passed through the system (10 tiers, supporting 200 culture ropes), the seston concentration was reduced from 6.6 to 5.9 mg/l, which was less than expected. Based on the method used by Incze et al. (1981), the carrying capacity is estimated to be 5.7 times greater in Loch Etive than the present mussel culture system utilizes, i.e. the loch could support a system with 57 tiers in a raft (see Table 1), rather than the 10 tiers currently used.

In Loch Kishorn, the seston concentration was 6 mg/l in the water before it entered the first tier. When water passed through the system (consisting of 27 tiers), the seston concentration was reduced from 6 to 4.72 mg/l. In this case the estimation suggests that the loch could support 75 tiers per raft system.

A second method was used to estimate carrying capacity for mussel culture rafts, based on Carver and Mallet (1990). This method uses food supply and food demand in terms of particulate organic matter (POM) and relevant calculations for Loch Etive and Loch Kishorn are shown in Table 2. Daily food ration per mussel was estimated to be 129.0 mg POM/day in May and 79.7 mg POM/day in August 1994 in Loch Etive. In Loch Kishorn, the daily food ration per mussel was calculated as 50.6 mg POM/day in May and 147.7 mg POM/day in August 1994. These estimates suggest a daily carrying capacity of 15,721 kg mussel in May and 24,427 kg mussel in August in Loch Etive, and 47,158 kg mussel in May and 44,492 kg mussel in August in Loch Kishorn. These estimates compare with the actual mussel production values in the raft systems in the two lochs as follows: Loch Etive, 10,000 kg mussel per raft system and Loch Kishorn, 50,000 kg mussel per raft system.

Discussion

Rapid expansion of the mussel culture industry in Britain has prompted considerable interest in the problems of carrying capacity. Heral (1987) reported that uncontrolled increases in stock density will eventually result in reduced growth rates and environmental disruption.

Table 1. Estimates of carrying capacity based on seston concentration according to Incze et al. (1981) for the month of August 1994 (the end of the culture period) in the mussel raft systems in Loch Etive and Loch Kishorn.

	Seston concentration (mg/l)	
Number of tiers in raft system	*Loch Kishorn*	*Loch Etive*
1	6.00	6.60
10	5.54	5.90
20	5.05	5.22
27	4.72	4.79
30	4.59	4.61
40	4.18	4.07
50	3.81	3.60
57	3.56	3.30*
60	3.46	-
70	3.15	-
75	3.00*	-

* Notes the 50% reduction level of seston, equivalent to an estimated 57 tiers in the Loch Etive and 75 tiers in the Loch Kishorn raft systems.

Table 2. Estimates of volume of water (passing through the raft system), particulate organic matter (POM) supply, POM demand and carrying capacity according to Carver and Mallet (1990) for the months of May and August 1994 in the raft systems in Loch Etive and Loch Kishorn.

Site	*Date*	*Volume* (m^3/*week*)	*POM* (*mg/l*)	*Food supply* (*kg POM/week*)	*Filtration rate* (*l/h*)	*Food ration per mussel* (*mg POM/day*)	*Food demand* (*g POM/ kg mussel/week*)	*Carrying capacity per raft** (*kg mussel/day*)
Loch Etive	May	2 515 968	3.2	8,051	1.68	129.02	73.16	15,721
	Aug	2 515 968	2.2	5,535	1.51	79.73	32.37	24,428
Loch Kishon	May	6 048 000	1.9	11,491	1.11	50.62	34.81	47,158
	Aug	6 048 000	3.6	21,773	1.71	147.74	69.91	44,492

*Raft dimensions: Loch Kishorn = 27 m x 20 m x 10 m and Loch Etive = 11 m x 10 m x 8 m.

Several studies have emphasized the importance of water movement in maintaining a constant supply of particles to suspension feeders (e.g. Incze et al., 1981; Rosenberg and Loo, 1983; Frechette and Bourget, 1985; Wildish and Kristmanson, 1985). The pattern and rate of particle renewal varies, however, depending on the hydrography of the system; in estuaries for example, particle movement may be dominated by river outflow, whereas in coastal inlets, particle movement may be dominated by tidal currents (Carver and Mallet, 1990). Current speeds higher than 0.06 m/s are categorized as strong for mussel culture. In Loch Etive and Loch Kishorn, the recorded current speeds are comparable with values reported from other mussel culture sites; for example 0.1 m/s in Killary Harbour (Rodhouse et al., 1985), 0.05-0.3 m/s in Birterbury, Ireland (Wilson, 1987) and 0.05-0.9 m/s in the Ria de Arosa in Spain (Figueras, 1990). In the present study, the mean current velocity was found to be 0.052 m/s in Loch Etive and 0.05 m/s in Loch Kishorn ($p>0.05$). Farming installations (raft and long-lines) reduce water velocity, so the current speed in the middle of farms comprising several rafts can be considerably lower than those at the inflow; this can create mussel growth differences within and between the rafts, depending on their size and position (Karayücel, 1996). A moderate current velocity of 0.02-0.05 m/s is typically suggested to be adequate for suspended mussel culture (Sutterlin et al., 1981, Larsson, 1985), as a higher velocity makes mooring of rafts and long-lines difficult and undermines the ability of mussels to remain attached without spending extra energy on byssus production. Food supply depends not only on the rate of water movement, but also on the quantity and quality of the particles in the water.

Rodhouse and Roden (1987) recommended that only 50% of the food supply in Killary Harbour should be diverted towards mussel culture, otherwise they predicted severe modifications of the environment and decreasing mussel yields per unit area. Similarly, Incze et al. (1981) specified in their carrying capacity model that the mussels should deplete only 50% of the available food supply. Widdows

(1978) calculated that a 1 g dry weight mussel requires only 0.6 mg/l POM to achieve maximum growth efficiency; at a filtration rate of 2.5 l/h, this is equivalent to 36 mg POM/day, which is less than the value found in this study. If this is so, in this case the carrying capacity was underestimated. Therefore, more specific information is needed on the quantity and quality of food required to maintain maximum growth efficiency of *Mytilus* under various environmental conditions. Doering and Oviatt (1986) suggested that, without good field data, attempts to predict carrying capacity may be misleading.

Incze et al. (1981) developed a carrying capacity model which is based on maintaining critical levels of particle flow through culture areas. The application of this alternative model depends on prior knowledge regarding seasonal patterns in seston composition and the other environmental conditions which are conducive to growth of the cultivated species.

Incze et al. (1981) reported that the estimation of carrying capacities for bivalves in open systems is complicated by several factors: (a) seasonal and size related changes in the energy demands of the cultured organism; (b) seasonal changes in the abundance and nature of potential food substrates found in the natural waters; (c) a general lack of knowledge concerning the degree to which bivalves utilize various particles in the seston; and (d) the difficulty of quantifying water mixing and flow through in most culture areas.

It is not possible to compare our findings with those from other studies due to several factors which affect the carrying capacity in a particular site such as seston, particulate organic matter, temperature, salinity, filtration rate and raft size. However, Incze et al.(1981) found that in a Spanish raft system the number of tiers should be twice that actually operating in the raft.

Incze et al. (1981) accepted that current velocity should be the same in all parts of the raft system but, in fact, decreases from the front to the back of the system. As a result, the carrying capacity will be lower than the calculated value. Unfortunately, measuring the current decrease across the raft was ignored in the present study.

Time of year affects the carrying capacity. Winter is known to be a period of stress to mussels because of low energy reserves in the tissues and high metabolic demand due to gametogenetic activity, but the degree to which external energy sources can be used during this season is unknown.

There is a big difference in estimated carrying capacity of systems when we compare the food supply and food demand model (filtration of POM) used by Carver and Mallet (1990) and the seston clearance model used by Incze et al. (1981).

The present seston clearance model is offered as an approach, not a solution. According to the seston model developed by Incze et al. (1981) and used in the present study, the number of tiers should be 57 which is almost six times higher than the number of tiers on the existing raft system in Loch Etive, while the number of tiers should be 75 in Loch Kishorn which is three times higher than the existing value. According to the model based on food supply and food demand, the carrying capacity is estimated to be 15-25 t in Loch Etive and 44-47 t in Loch Kishorn. However small size (<50 mm) mussels were ignored in the estimations. According to the mussel farmers, a raft system can achieve 10-15 t production in Loch Etive and 40-50 t in Loch Kishorn. According to the present findings, there are about 11 t of mussels in a single raft in Loch Etive and 49 t in Loch Kishorn. In conclusion, these results show that the particulate organic matter model might give better results than the seston based model at commercial mussel culture sites.

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