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Chemical fluxes and mass balances in a marine fish cage farm. II. Phosphorus

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ABSTRACT: Phosphorus fluxes were measured in a marine fish cage farm in the Gullmar Fjord, western Sweden. The measured fluxes included fish food, juveniles, harvest, fish loss (dead fish and escapers), sedimentation from the cages and benthic solute release (in situ). Two different types of mass balances were constructed. *The flux method* was based on seasonal input of fish food and juveniles, sedimentation and removal by harvest, fish loss and benthic fluxes. Mass balances according to the flux method were constructed for each of 2 consecutive growing seasons. *The accumulation method* was based on total input of phosphorus through fish food and juveniles, removal by harvest and fish loss, and net accumulation in the sediment over 7 growing seasons. Both types of mass balances gave similar results. Of the total phosphorus input to the farm, 17 to 19 % was recovered in harvest, fish loss constituted 1 to 4 %, and 78 to 82 % was lost to the environment. The environmental loss of phosphorus for each ton of fish produced was 22.4 kg (1985), 19.6 kg (1986) and 21.9 kg (1980 to 1986). Of the loss to the environment, 34 to 41 % was in dissolved form and 59 to 66 % was accumulated in the sediment. On a seasonal basis, the benthic flux transferred 4 to 8 % of the sedimented phosphorus back to the overlying water This constituted about 1 % of the total phosphorus content in the sediment derived from the fish farm.

INTRODUCTION

Aquaculture is a very diversified business. One branch is cultivation of fish in floating net cages in fresh or sea water. This sector has increased rapidly in northern Europe during the last 2 decades. Most fish cultivation in the Nordic countries (Sweden, Norway, Denmark, Finland, Iceland and the Faroe Islands) takes place in coastal marine areas using the net cage technique. In 1986 the total Nordic production of rainbow trout and salmon was 94 000 t and the estimated yield in 1988 was 141 000 t, with the largest part cultivated in Norway (Ackefors & Enell 1990).

There is growing concern about the environmental impact of fish cage farming, and some studies related to this problem have been carried out (Ervik et al. 1985, Gowen et al. 1985, Rosenthal 1985, Enell 1987, Persson 1987, Håkanson et al. 1988). The impact of net cage fish cultivation on the environment is mainly of local concern, resulting in local eutrophication problems. Cultivation may also influence wild fish stocks by transmission of diseases, addition to the gene pool and dispersion of antibiotics. There is increasing evidence that the behaviour of wild fish may be modified by the presence of cages and that the inevitable escapes of caged fish can have significant effects on existing fish communities (Phillips et al. 1985b).

Knowledge of the environmental load from fish farming and of the physical, chemical and biological characteristics of a body of water is important for decisions on the number and size of fish farms that can be established there (Karlgren 1981). Egidius (1984) showed that the ammonia excreted by fish is toxic to the fish themselves at very low concentrations. As the fish are sensitive to their environment, it is important to minimize the environmental impact in order to achieve good results from cultivation and a profitable farm.

Nitrogen is considered to be the limiting nutrient for primary production in coastal areas (e.g. Gundersen 1981), but the role of phosphorus in the system is also important. Stigebrandt (1989) showed that the concentration of total phosphorus in the Kattegatt (the sea area between Sweden and Denmark) has doubled during the last 2 decades (ICES data). There is some evidence that organic material (Nishimura 1982) and soluble phosphorus (Kato et al. 1985) can influence the formation of toxic phytoplankton blooms. This indicates that phosphorus is more important in coastal waters than

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was earlier believed. There is qualitative evidence that accumulation of fish waste on the sediment can be detrimental to Atlantic salmon held there (Braaten et al. 1983, Solb'e & Shurben 1989). The environmental impact requires further careful investigation, both on the fish farm's surroundings and particularly on the farm itself (Phillips et al. 1985a).

Mass balances for fish farms need to be constructed in order to estimate the recovery in harvested fish of an element supplied to a farm, the total and dissolved loss of an element to the environment, and the accumulation of the element in the sediment. It is important to assess the partitioning of the environmental loss into particulate and dissolved fractions, as this relates to how the loss will affect the surrounding area and how the element will be dispersed in the environment.

In a previous paper (Hall et al. 1990), carbon fluxes and mass balances in a marine fish cage farm were reported. This paper presents 2 types of phosphorus mass balances for the farm. One mass balance (the flux method) was based on measured phosphorus fluxes. This type of mass balance was constructed for each of 2 consecutive growing seasons (1985 and 1986). The other mass balance (the accumulation method) was based on the recovery of phosphorus in sediment derived from the farm after 7 growing seasons (1980 to 1986). Both types of mass balance considered phosphorus input through fish food and juveniles, and removal through harvest and fish loss. In a further paper we will present fluxes and mass balances for nitrogen in the farm (Hall et al. unpubl.).

The aim of this paper is to report the quantity of phosphorus supplied to the farm with fish food and juveniles that is recovered in the harvest or lost to the environment, and how much of the latter is in the particulate and dissolved fractions. Also, it is demonstrated how much of the particulate fraction accumulates in the sediment, and how much is returned in dissolved form from the farm sediment to the overlying water.

MATERIALS AND METHODS

Experimental site. The fish cage farm is situated on the Swedish west coast, in the Gullmar Fjord, Bohuslän. The species cultivated has been rainbow trout *Oncorhynchus mykiss* (Kendall 1988) since the farm was established in 1980. The main cultivation period is May to December. In some years a small number of fish were kept in the farm during winter, depending on the ice conditions. The fish were distributed equally among the cages with generally 450 to 500 kg fish per cage at the beginning of the growing season, and 1700 to 2300 kg just before harvest. Dry feed (mostly EWOS T51, a Swedish low-energy dry feed manufactured by EWOS AB, Södertälje) was supplied to the fish by a combination of automatic and manual feeding. The farm contained at most 15 net cages, covering an area of maximally 25 × 40 m. Each cage was 7 × 7 m wide and 4 m deep. The cages were separated by rafts and placed about 1.5 m apart. The surface water temperature in this area normally ranges from 0 to 19 °C annually. The bottom depth below the farm was 18 to 21 m. Typical salinity was 20 to 25 (PSU) in the surface water and 30 to 35 (PSU) in the bottom water. Currents around and below the farm were sufficient to keep the bottom water well oxygenated throughout the year. The sediment under the farm was situated below the halocline throughout the year. The top sediment layer, which originates from the fish farm, was completely black, highly reducing, and contained large amounts of water and organic matter. Underlying the top layer there was a light brown, more compacted sediment. The boundary between these sediment layers was very sharp. Sulfate was almost depleted in the interstitial water of the top sediment layer and sulfide concentrations were very high (10 to 13 mM). During part of the year the black sediment surface was almost entirely covered by a white bacterial mat. Gas bubbles, consisting mainly of methane (Hall et al. 1990), were released from the sediment during late summer and fall.

Phosphorus content in fish food and fish. The phosphorus content in whole rainbow trout was assumed to be 0.406 % of fresh weight according to Persson (1987, and references therein). The concentration of organic phosphorus in each of the various fish foods was determined according to the method described below.

The average ratio between fish food input and fish production (conversion coefficient) was calculated according to Persson (1987), who gave the formula $P = B_t - B_0 + E$, where P = production, B_t = biomass at time t, B_0 = biomass at time 0, and E = elimination (fish loss).

Sedimentation. Cylindrical sediment traps with a diameter of 80 mm and a height of 500 mm were used. The height/diameter ratio of 6.2 is within the range recommended to avoid selective trapping (Blomquist & Håkanson 1981). The traps were kept vertical by a gimbal. The hanging line could create turbulence around the traps and to avoid this the traps were oriented towards the current by a fin. Measurements were made on several occasions (see Table 3). Three traps, placed 6 m above the bottom, were used on each occasion. The sampling time was 20 to 48 h. No preservatives were used in the traps. Immediately after collection the particles in each trap were suspended in 2 l of seawater, taken from the upper part of the trap. Two aliquots of the homogenized suspension were filtered through prewashed Nuclepore 0.40 µm filters. Organic

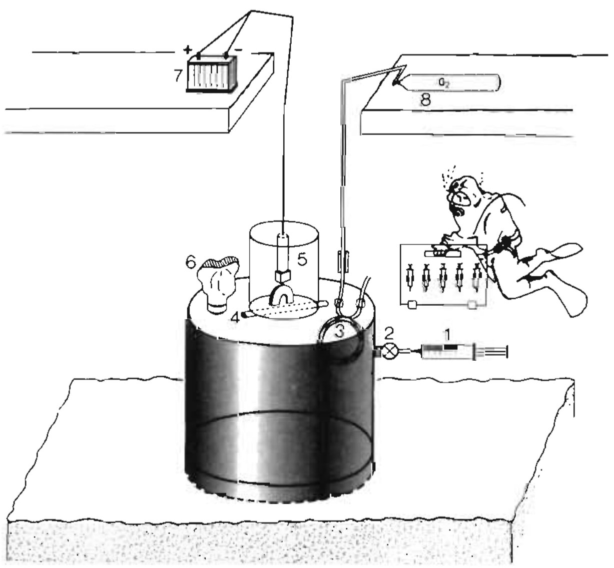

Fig. 1. The benthic flux chamber system used in this study. 1, sample syringe; 2, Teflon valve; 3, Teflon tubing for oxygen diffusion (in the regulated chambers); 4, magnetic bar; 5, electric motor; 6, plastic bags serving as volume compensator; 7, 12 V battery; 8, oxygen cylinder. From Hall (1984)

phosphorus determinations on the filters were carried out as described below. The amount of phosphorus in blank filters was negligible.

Benthic in situ fluxes. The flux chambers (Fig. 1) used in this study were modified from those described by Hall (1984) and Rutgers van der Loeff et al. (1984). Because of the expected high flux, the height of the chambers was increased to 700 mm. This increased the volume by a factor of 2 which in turn decreased the effect of a possible build-up of interfering substances. When placed 100 mm into the sediment, each chamber contained about 120 l of water and covered 0.20 m^2 of sediment. The height of each chamber was measured and the corresponding volume calculated after each experiment. The chambers were equipped with a 75 mm long and 8 mm diameter Teflon coated magnetic stirring bar, revolving at 75 rpm. They were also equipped with Teflon valves for sampling and a flexible membrane consisting of several layers of polyethylene bag that served to compensate for the change in volume during sampling. Fluxes were measured both under constant oxygenated conditions (regulated chambers) and when the oxygen level was allowed to decrease in the chamber (unregulated chambers). The regulated chambers were equipped with a coil of Teflon tubing through which oxygen diffused into the chamber. The Teflon tubing was supplied with oxygen under pressure from the surface. In this way the oxygen level in the chambers could be regulated by varying the pressure of oxygen in the tubing. In the unregulated chambers the activity of benthic organisms and chemical oxygen consumption resulted in depletion of oxygen.

Chamber experiments were carried out over 16 to 24 d in December 1984, May 1985, September 1985 and July 1986. From 2 to 4 chambers were operated during each experiment. The chambers were installed and sampled by Scuba divers. Bottom water temperatures during the experiments ranged from 4 to 16 °C. Samples were collected in polypropylene syringes. Total phosphorus and phosphate samples were filtered and stored frozen in plastic bottles until analysis, which was undertaken at the end of each experiment.

Sediment. Sediment cores were taken in Plexiglass cylinders (120 mm diameter) by divers. Cores were collected in September 1984, May 1985 and July 1986. Immediately after collection the cores were sliced in vertical position under nitrogen atmosphere. Subsamples of the sediment were taken for measurement of water content, which was determined by the weight loss at 105 °C for 24 h or more (constant weight). Determination of particulate organic phosphorus in the dried sediment was performed according to the method described below.

Chemical analysis. Molybdate reactive phosphorus (MRP) was determined spectrophotometrically according to Strickland & Parsons (1972).

Total dissolved phosphorus (total P) was determined by persulphate oxidation according to Valderrama (1981).

Particulate organic phosphorus (POP) in the sediment, sedimenting material, and fish food were digested with concentrated nitric acid and concentrated perchloric acid (Burton & Riley 1956). The released phosphorus was determined spectrophotometrically as MRP (Strickland & Parsons 1972). The standard addition method and a standard sediment sample were used to check the accuracy of the digestion.

Filters with sedimented material for total organic matter determinations were pre-dried to constant weight at 105 °C. Total organic matter was determined by measurement of the weight loss after 10 h at 550 °C (loss on ignition).

Estimation of the amount of farm sediment. In order to estimate first the areal distribution and finally the volume of sediment originating from the farm, Scuba divers swam along the edges of that sediment, sending up buoys to mark the edges. The divers identified sediment derived from the farm by its black and loose appearance. The distances between the buoys and the farm rafts were measured to calculate the area of the farm sediment. The vertical sedimentary distribution of phosphorus was used to indicate the thickness of the farm sediment. The density of wet sediment was calcu-

Table 1. Input data, measured phosphorus concentrations and water contents of the various fish foods used in the farm during 1985, 1986 and 1980 to 1986

Brand name	Input 1985	Input 1986 (kg wet wt)[a]	Input 1980–86	Phosphorus concentration (% dry w/w)	Water content (% wet w/w)
EWOS T51	34 000	8 900	178 200	1.34–1.57[b]	6.7–7.9[b]
EWOS ET92		5 700	5 700	1.13	3.2[c]
EWOS T45			4 200	1.36[d]	7.4[d]
Danish Ørred (Ecolife 16)		3 750	3 750	1.33	8.4
Aller Mølle					
AT67			500	1.50	8.2
46/19			7 000	1.28	10.0
Total input	34 000	18 350	199 350		

[a] Data given by fish farmer
[b] Samples from 2 batches analyzed. One batch was analyzed from each of the other foods
[c] This value appears low
[d] Samples of this food were not available. Means of the phosphorus concentrations and water contents of the other 5 foods analyzed were used

lated as a function of organic matter and water content according to Håkanson (1981, and references therein).

RESULTS

Input of phosphorus to the farm

The measured phosphorus concentrations in the various fish foods used in the farm during the growing seasons 1980 to 1986 and the amounts of fish food utilized are given in Table 1. The phosphorus content in the fish foods was in the range 1.13 to 1.57 % (dry w/w). The higher values were obtained for the most frequently used fish foods. The input of juveniles is presented in Table 2.

Removal of phosphorus from the farm

Harvest and fish loss (mortality and escape of fish) data are presented in Table 2. A fish mortality of 10 %, equally distributed during the growing season, was estimated by the fish farmer for each year except 1986, for which a mortality of 22 % was estimated. Dead fish were removed and disposed of on shore. In August 1984 there was an escape of about 1900 kg fish from the farm. These fish have been included in the fish loss. An estimated weight of dead fish was given by the fish farmer. Even though escapers seem to stay close to the farm area (Beveridge 1984, Phillips et al. 1985b, Scuba divers' and local fishermen's observations), they are reported as fish loss under output from the farm.

Using the procedure given by Persson (1987) (see 'Materials and methods') the average conversion coefficients in the fish farm were 2.14 (1985), 2.00 (1986) and 2.13 (1980 to 1986).

Table 2. *Oncorhyncus mykiss*. Juvenile input, harvest, fish loss (escape and death) and fish production in the farm during 1985, 1986 and 1980 to 1986. Phosphorus content in whole rainbow trout was assumed to be 0.406 % (wet w/w) according to Persson (1987)

	1985 (kg)	1986 (kg)	1980–1986 (kg)
Juveniles	3 700	3 200	26 340
Harvest	18 300	10 500	109 140
Fish loss	1 230	1 880	10 900
Fish production	14 600	7 300	82 800

During 1986, the phosphorus content in sedimenting material varied between 0.28 and 0.65 %. In 1985, no phosphorus determinations were made on sedimenting material, but assuming the content of phosphorus to be proportional to the content of organic matter in the sedimenting material gave a value of 0.93 %.

The measured sedimentation rates of phosphorus are given in Table 3.

Benthic in situ fluxes

The measured benthic fluxes of phosphate are given in Table 3. Comparisons between benthic phosphate release and total phosphorus release showed that fluxes of phosphorus compounds other than phosphate were negligible. The oxic fluxes were 16 to 85 % of the

Table 3. Measured sedimentation rates, and benthic solute fluxes of phosphorus under the farm during 1984, 1985 and 1986

Period	Sedimentation (mmol P m^{-2} d^{-1})	Benthic phosphate fluxes (mmol P m^{-2} d^{-1})
Dec 1984		
Cham. A (unreg.)		1.05
Cham. B (reg.)		0.16
May 1985	21.3[a]	
Cham. A (unreg.)		0.58
Cham. 1 (unreg.)		0.60
Cham. B (reg.)		0.36
Cham. 2 (reg.)		0.92[b]
Jun 1985	21.3[a]	
Sep 1985	42.5[a]	
Cham. 1 (unreg.)		6.75
Cham. B (reg.)		3.31
Cham. 2 (reg.)		5.10
Oct 1985	38.3[a]	
Nov 1985	33.9[a]	
May 1986	4.8[c]	
Jun 1986	46.2[c]	
Jul 1986	30.0[c]	
Cham. A (unreg.)		0.81
Cham. 2 (reg.)		0.69
Aug/Sep 1986	34.2[c]	
Sep/Oct 1986	11.6[c]	
Nov–Jan 1986/87	11.3[d]	

[a] Calculated value, assuming that the phosphorus concentration is proportional to the organic matter content
[b] This value seems high
[c] Value represents the mean of 6 subsamples (2 aliquots from each of 3 sediment traps)
[d] Value estimated for period (see text)

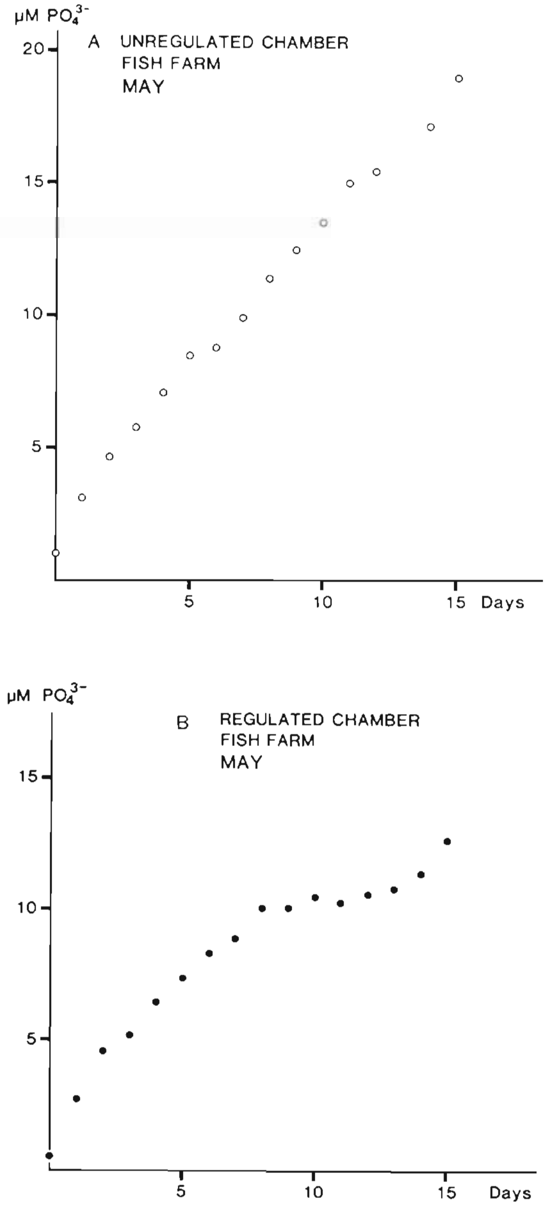

Fig. 2. Evolution of phosphate (µmol l^{-1}) in an (A) unregulated and (B) regulated chamber during the May 1985 flux chamber experiment

anoxic fluxes, except in one chamber during May 1985. Fluxes in both regulated and unregulated chambers were constant during the first several days or in most cases throughout the whole experiment (examples are shown in Fig. 2). The given benthic fluxes are initial ones. The highest flux (6.75 mmol m^{-2} d^{-1}) was measured in September 1985 in an unregulated chamber. The lowest flux (0.16 mmol m^{-2} d^{-1}) was measured in December 1984 in a regulated chamber.

Sediment under the farm

The area of farm sediment was measured by divers to be 3800 m^2. This was 3.8 times the area of the farm itself (1000 m^2). Most of the farm sediment was accumulated directly under the farm. Outside the cages the sediment was mainly spread along one side. At one corner of the farm, the farm sediment extended just 5 m beyond the cages, while on the other side it reached ca 35 m from the outer edges of the cages along the whole side. The distribution pattern of farm sediment was most likely influenced by the current, the bottom topography and the position of the cages.

The average phosphorus content in the farm sediment was 1.52 % (dry w/w) and ranged between 1.42 and 1.64 %. Phosphorus showed an almost constant distribution with depth in the farm sediment and decreased rapidly in the underlying sediment layer (Fig. 3). Because of this, phosphorus was considered a good indicator of the thickness of the sediment layer originating from the farm. The thickness of the farm sediment was 18 cm below the cages and became gradually thinner with distance from the farm edge. A total volume of wet farm sediment of ca 459 000 dm^3 was calculated. The average water content in the farm sediment was 82.7 %, giving a density of 1.078 g cm^{-3}. Using these values and a phosphorus content of 1.52 %, a net phosphorus accumulation of 1300 kg was calculated in the farm sediment for the period 1980 to 1986.

The dissolved fraction of the environmental phosphorus load from the farm was 119.7 kg (27.5 %) during 1985, 73.1 kg (31.7 %) during 1986 and 748.5 kg (29.5 %) during 1980 to 1986. (Percentages refer to % of total P input to farm.)

DISCUSSION

Phosphorus in fish food and sedimenting material

The content of phosphorus in fish food seems to be high compared to the values given by the manufacturers. Other fish food investigations also reported higher values than the manufacturers, e.g. Karlgren (1981), Persson (1986), Pettersson (1986) and Enell (1987). To our knowledge no fish food studies have presented lower values than the manufacturers. The lower value for the EWOS T51 food samples (Table 1) has been used in calculations because it was considered more representative. This is supported by the amount of fish food used from the different batches and that this value is quite similar to those of other investigations (Karlgren 1981, Persson 1986, Enell 1987).

Phosphorus in sedimenting material was calculated to be 0.93 % of the total sedimenting material during 1985. This seems high compared with the values from 1986. The value was based on the assumption that the phosphorus content is proportional to the organic matter content. The average organic matter content was 33.5 % in 1986 and 49.9 % in 1985 of total sedimenting material. An explanation may be that the farmer fed the fish more often and with smaller amounts each time during 1986 than during 1985.

Assumptions made when constructing the mass balances

The area used when calculating the seasonal sedimentation from the farm was 3.8 times larger than the area corresponding to the actual number of cages utilized each season. The factor 3.8 is the total area of farm sediment (3800 m^2) divided by the area corresponding to the maximum number of cages ever used (1000 m^2). The sedimenting particles were assumed to be equally dispersed over the area directly under the

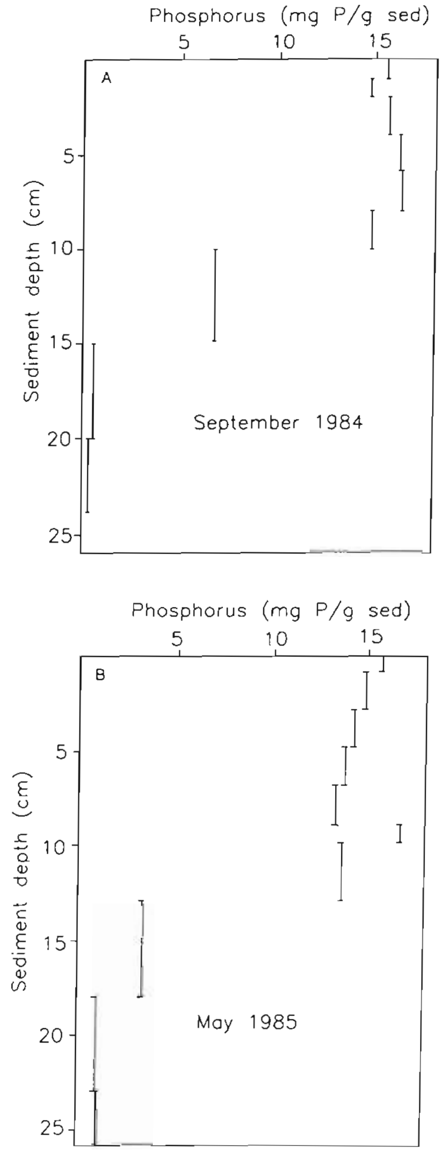

Fig. 3. Concentration of phosphorus (mg P g^{-1} sed.) as a function of depth in the sediment below the fish farm in (A) September 1984 and (B) May 1985

cages and the sedimentation rate to gradually decrease in the area outside this. The sedimentation rate measured during one period was assumed to be valid through half of the time remaining until the next measurement. However, based on the annual variation of sedimentation rates during 1985, it was assumed that the high total sedimentation rate measured in September/October 1986 was not representative of the last period (November to January) of the latter season. The sedimentation rate during these months was set to 50 % of the total sedimentation during September/October 1986, and the phosphorus concentration was assumed to be the average of the measured values during the season.

Table 4. Definitions of parameters used in the phosphorus mass balances

Parameter	Definition
Total environmental loss	Input with fish food and juveniles minus removal with harvest and fish loss[a]
Dissolved environmental loss	Benthic flux plus solute release from the cages (flux method)
	Total environmental loss minus sediment accumulation (accumulation method)
Fish loss	Fish mortality and escape
Solute release from the cages	Total environmental loss minus sedimentation
Sediment accumulation	Sedimentation minus benthic flux (flux method)
Benthic flux	Measured dissolved phosphorus release from sediment

[a] The fish loss was not considered part of the environmental (aquatic) loss, because it consisted mostly of dead fish and these were disposed of on-shore

The area used to calculate the seasonal benthic flux was assumed to be equal to the area used to calculate the seasonal sedimentation. The flux was assumed to be constant in space below the cages and gradually decreasing in the area outside the cages. Fluxes in December 1985 were assumed to be equal to the fluxes measured in December 1984. Benthic fluxes during the growing season of 1986 were measured in July and estimated for the other months assuming that the annual variation observed during 1985 was valid also during 1986.

The parameters used in the mass balances are defined in Table 4.

Possible sources of error in the mass balances

Other processes than those described in the mass balances may possibly add or remove phosphorus from the fish farm or the underlying sediment. Plankton is transported by currents into the cages and may act as external food for the fish. This is probably a negligible source of phosphorus in the budgets, because of the relatively small size of plankton (compared with food pellets) and the large supply of fish food.

Currents and resuspension may disperse particles away from the immediate vicinity of the farm. This would result in underestimation of sedimentation if the particles are dispersed over an area larger than that used to calculate seasonal sedimentation. Dispersion of particles would also result in a larger benthic flux because of the increased bottom area. The reported high sinking rates of particles from trout cage farms (Gowen et al. 1985, and references therein) and the relatively shallow water column (16 m) below the cages, however, suggest that current dispersion of particles is a small contribution to the removal of phosphorus from the farm.

The importance of resuspension below the farm was not estimated. The bottom area influenced by the farm corresponds to the dispersion of particles over several seasons. In the flux method the area for calculation of sedimentation and benthic flux depends on the number and position of cages during each season.

Removal of phosphorus from the farm sediment could also occur through grazing by fish and epifauna. Occasionally fish were observed below the cages during Scuba diving. Beveridge (1984) estimated that ca 1.5 % of the overall phosphorus load was removed by escapers. If these escapers take fish food on its way down to the sediment the loss will be included in solute phosphorus release from the cages in the mass balances. If fish are grazing on the sediment the food loss will be counted as sedimented in the flux method and still as a solute release in the accumulation method. Considering the highly reducing and very sulphidic conditions in the farm sediment, grazing by fish and mobile epifauna on the sediment is most likely an insignificant process. A similar conclusion was made for fish pond sediments by Avnimelech et al. (1981).

Assuming that the calculations of sedimentation and benthic flux are correct, resuspension and grazing by fish and epifauna can be calculated. The total sedimentation measured according to the flux method minus the total benthic flux during the same time period, together with the total accumulated amount of phosphorus measured according to the accumulation method, can be used to give an estimate of the sum of these possible errors (see next section).

Comparison of the mass balances

The 3 mass balances agreed very well. The recovery in harvest of the phosphorus input to the farm varied from 17 to 19 % of the total phosphorus input. The contribution of fish loss ranged from 1 to 4 %. The higher values represent 1986 when there was a high mortality in the farm. The loss to the environment of the total phosphorus input (fish food and juveniles) agreed well in all 3 mass balances, being 82 % (1985), 78 % (1986) and 81 % (1980 to 1986). The sedimented fraction of the total phosphorus input was 57 % (1985) and 51 % (1986). The benthic flux of dissolved phosphorus back to the overlying water was 2.5 % (1985) and 4.0 % (1986). The accumulated fraction was 54 % (1985), 46 % (1986) and 51 % (1980 to 1986). The flux method

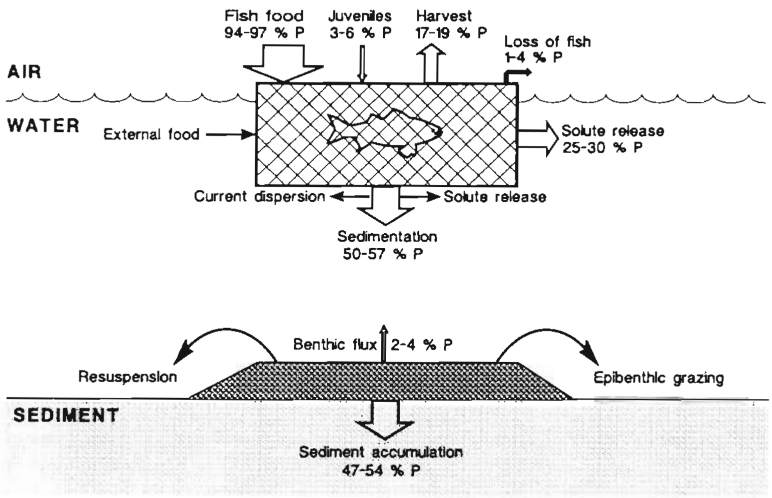

Fig. 4. Phosphorus mass balances in the fish farm according to the flux and the accumulation methods. Unquantified arrows represent processes that constitute possible sources of error in the mass balances. The actual numbers for each mass balance are given in Table 5. The percentages are % of total phosphorus input to the farm (fish food + juveniles)

and the accumulation method for construction of mass balances gave very similar results. Originally we expected that the sediment accumulation of phosphorus obtained by the flux method would be a little higher than the corresponding value from the accumulation method, because of resuspension, fish grazing and epifaunal reworking. The small difference between the methods means that the removal of phosphorus is too small to give any observable difference. Another possibility is that some of the assumptions on the sedimentation/benthic flux area in the flux method or the volume of the accumulated farm sediment in the accumulation method are erroneous. However both methods give a good estimation of how much phosphorus and in what form enters the environment from a fish farm.

The mass balances for the fish farm are presented in Fig. 4 and Table 5 for the growing seasons 1985, 1986 and the period 1980 to 1986.

Comparison with previous studies

Phosphorus mass balances have previously been reported for fish cage farms. Some of these are constructed in a way similar to our accumulation method and indirectly include the leakage of phosphorus from the sediment. To our knowledge there has been just one phosphorus mass balance (other than this study) reported which directly included leakage of phosphorus from the sediment (Aure & Stigebrandt 1989). Stigebrandt (1986) presented a theoretical calculation on the leakage from the sediment, which is used in Aure & Stigebrandt (1989). The latters' findings (up to 6.8 mmol P m^{-2} d^{-1}) are quite similar to ours. Reported results on environmental loss of phosphorus from cage farms vary between 77 to 88 %; Phillips et al. (1985a) reported an environmental phosphorus loss of 85 %, Persson (1986) 87 %, Enell (1987) 82 %, Folke & Kautsky (1989) 77 % and Molvær & Stigebrandt (1989) 88 %. These results agree well with this investigation (78 to 82 %). Values for the fraction of phosphorus accumulated in the sediment vary in the literature. This probably depends on whether the calculations were made for one season (neglecting leakage from the sediment, grazing and resuspension) or if the accumulation method is used. Enell (1987) reported that 64 % of the total phosphorus input was accumulated in the sediment, Phillips et al. (1985a) 66 %, Stigebrandt (1986) 57 % and Persson (1986) 38 %. Considering that these values do not include leakage or resuspension from the sediment (except Persson 1986), they agree well with our results.

Environmental implications

This study has quantified the environmental phosphorus load from a fish cage farm, and the composition of this load. The environmental effects, which also depend on the physical, chemical and biological characteristics of the receiving system, cannot be clearly understood from the present study. They have to be investigated separately and considered in relation to other substances which could effect the environment.

The sediment derived from the farm was extremely rich in organic material and very sulphidic. The seasonal range of measured benthic oxygen uptake rates was 90 to 180 mmol m^{-2} d^{-1}, which is 12 to 15 times rates measured on normal coastal sediments of the Gullmar Fjord (Hall et al. 1989).

The environmental load of phosphorus for each ton of fish produced was 22.4 kg (1985), 19.6 kg (1986) and

Table 5. Summary of the phosphorus mass balances in % of total P input

Components of mass balances	1985 kg P (%)	1986 kg P (%)	1980–86 kg P (%)
Fish food	419.5 (96.5)	217.6 (94.4)	2429.3 (96.0)
Juveniles	15.0 (3.5)	13.0 (5.6)	106.9 (4.0)
Harvest	74.3 (17.1)	42.6 (18.4)	443.1 (17.4)
Loss of fish	5.0 (1.1)	7.6 (3.3)	7.7 (1.7)
Solute release	108.8 (25.0)	63.8 (27.7)	
Sedimentation	246.4 (56.7)	116.5 (50.5)	
Benthic flux	10.9 (2.5)	9.3 (4.0)	
Sediment accumulation	235.5 (54.2)	107.2 (45.5)	1300.2 (51.3)
Total environmental loss	355.2 (81.7)	180.3 (78.2)	2048.5 (80.8)
Dissolved environmental loss	119.7 (27.5)	73.1 (31.7)	748.5 (29.5)

21.9 kg (1980 to 1986). These values agree well with those given by Persson (1987) who states that a conversion factor of 2.0 and a phosphorus content in the fish food of 1.3 % give a phosphorus load of 22 kg. Of the total phosphorus load to the environment, 66.3 % (1985), 59.5 % (1986) and 63.5 % (1980 to 1986) was in particulate form. The total discharge of nutrients from a fish farm with a production of 50 t yr^{-1} would correspond to the discharge from a purification plant for a town of about 7000 inhabitants (assuming a 90 % reduction of phosphorus in the plant; Håkanson et al. 1988).

Ackefors & Enell (1990) have calculated that 0.6 % of the total phosphorus load to adjacent sea areas in Sweden was derived from aquaculture in 1986. This suggest that fish farms could cause local eutrophication problems if they are situated in sensitive areas. In a wider context, the farms are not important compared with the phosphorus load to Swedish sea areas from municipals (14.6 %), industries (15.8 %), rivers excl. agriculture (52.8 %) and agriculture (16.2 %) (Ackefors & Enell 1990).

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