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Characterization of manures from fish cage farming in Chile

F.J. Salazar *, R.C. Saldana

National Institute for Agricultural Research (INIA), Remehue Research Centre, Casilla 24-O, Osorno, Chile

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Abstract

This study aims to characterize salmonid manures and to determine their potential use in agricultural soils. Sampling was carried out below salmon and trout cages in farms located in lakes and in the sea in the South of Chile during 2002–2003. Manure was analyzed for macronutrients, micronutrients and heavy metals. Results showed a high variability between samples and differences between sea and lake manure. Dry matter contents were low averaging *c.* 12–15%. Manures showed low OM contents with values <*c.* 15% and a neutral pH (*c.* 7.0). Both manures had low total N contents with values of <0.9%, more than 75% of which was in the organic form. Lake manure showed high contents of P (1.56%), Ca (3.89%), Fe (27,948 ppm), Mn (446 ppm), Al (31,789 ppm), As (5.13 ppm), Cd (1.04 ppm), Cr (18.8 ppm), Ni (12.3 ppm), Pb (3.5 ppm) and Zn (393 ppm). Sea manure had high contents of Mg (1.65% ppm), K (0.63%), Na (11.8%) and Cu (89 ppm). Salmonid manure had low nutrients and heavy metal contents and a potential use in agricultural soils, which could reduce the risks of water pollution on water from fish farming.

Keywords: Salmonid manure; Nutrient contents; Fish farming wastes

1. Introduction

Chile is the second salmonid (salmon and trout) producer in the world, generating important income for the national economy. In 2004 Chile exported 355.000 tons of salmonids, which generated an income of FOB US$ 1439 (Subsecretaria de Pesca, 2005). Chilean salmonid farming industry is based on fish cages, which are located in sea and lakes, mainly in Southern Chile. Salmonid farm cages produce large quantities of organic waste. This material can accumulate on the seabed or lake bed below or near the net cage, as well as be suspended in the water column (Schendel et al., 2004).

Aquaculture waste consists primarily of soluble metabolic products as well as solids present in the form of faces and uneaten feed (Thorpe and Cho, 1995), feed additives, and anti-fouling agents (Schendel et al., 2004). Farmed fish are feed with concentrates to provide a balanced diet for optimum growth rates. Feeds contain nutrients such as nitrogen (N) and phosphorus (P) as well as trace elements. The two major nutrients found in concentrated aquatic animal production discharges are N and P, being the N mainly as ammonia, nitrate and organic N (EPA, 2004), where the magnitude of the P losses has been showed to depend on the diet composition (Coloso et al., 2003). For a typical Nordic fish farm Enell (1995) has calculated that for each ton of fish produced 55 kg of N and 4.8 kg of P are generated. In Chile, a study carried out by Rodriguez (1993) showed that for each ton of salmon produced, the equivalent of *c.* 1.4 ton of waste are generated, from this *c.* 1.2 ton are solid wastes, with 20.5 kg of total P and 42.6 kg of total N. This author also stated that 78% of the P was in the solid fraction and 22% in a soluble form. In contrast, 80% of N was in the soluble form and only 20% in the solid fraction.

This organic material represents a potential risk of contaminating the wider environment (Schendel et al., 2004). Although net pens systems do not generate a waste stream like other production systems, waste from the system can adversely affect water quality. The release of nutrients,

* Corresponding author. Tel.: +56 64 233515; fax: +56 64 237746.
E-mail address: fsalazar@inia.cl (F.J. Salazar).

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reduction in concentrations of dissolved oxygen, and the accumulation of sediments under the pens or cages can affect the local environment through eutrophication and degradation of benthic communities (Stickney, 2002). The impact on benthic communities of the accumulation of heavy metals in the sediments below the net pens has been identified as a significant impact from salmon farming. Metal can be found in sediments from fish farming as a result of feed additives, sanitization products, or deterioration of machinery and equipment (EPA, 2004). Both copper from marine anti-fouling compounds used on net pens, and zinc from fish feeds, can be toxic in their ionic forms to marine organism (EPA, 2004). According to a review carried out by Nash (2003) for environmental impact of Atlantic salmon in the environment of the Pacific Northwest (USA) two issues appear to carry the main risk for the region: impact on the sediments beneath net-pen farms from bio-deposits, and the accumulation of heavy metals (zinc and copper).

A management practice to reduce this risk for marine environment could be to recover this waste from the sea or lake bed under salmonid cages and apply it to farmland, as a crop fertilizer or soil amendment, which is a common practice for livestock manures and sewage sludge. In USA land application is the most common sludge disposal method for concentrated aquatic animal production industry (Chen et al., 2002). In addition, experimental studies have evaluated the use of fish sludge in crops (Smith, 1985) and grass (Mazzarino et al., 1997). However, fish manures could also contain harmful substances, such as heavy metals and pathogens which would limit their suitability for fertilizing crops. Also, those sludges derived from salt water fish farms could also contain significant quantities of sodium (Na) which may impact on soil structure.

There is a lack of information about the macro and micronutrients contents and heavy metal contents of these materials. In addition, most of the manure characterization studies have focused on fish raceways on land-based facilities (e.g. Naylor et al., 1999), therefore differences in their composition could be expected with respect to manures from fish cages. Characterization of manures from the fish cage farming industry will be necessary in order to know their nutrients value as fertilizers and to determine any potential adverse effects on crops and pastures. The aim of this study was to characterize salmonid manures and to determine their potential use in agricultural soils.

2. Methods

Sampling was carried out below salmon and trout cages in different fish farms located in lakes (6) and sea (7), in the Lake Region of Southern Chile (39–44°S; 71–73°W) from December 2002 to October 2003. All the fish farms sampled were based on net cage rearing system, where juvenile fish (*c.* 12–80 g) are grown in lakes and adults are grown in sea (*c.* 80–3500 g). Manure was collected by divers using a 10 L 'H shape' core sampler from beneath salmonids cages, in the sea (10–50 m depth) or lake (9–27 m depth) bed. A total of 3 L of manure was collected from different parts of the 'waste settling zone' beneath fish cages from the first 7 cm from the sea or lake bed. The samples were stored in plastic containers and refrigerated until they reached the laboratory (<4 °C). A fraction of each manure sample was oven dried until constant weight at 105 °C. Organic matter (OM) was determined by loss on ignition (550 °C, 6 h) in a muffle furnace according to AOAC (1984). Acidity (pH) and electric conductivity (EC) were determined by electrometric method revised by Sadzawka (1990).

The total macronutrients P, K, Ca, Na and Mg and total micronutrients Zn, Fe, Mn and Cu and total Al were determined by acid digestion according to the methodology revised by AOAC (1984) and Sadzawka (1990). After the particulates settle out, a sample was taken for colorimetric determination of total P (Perkin–Elmer model Lambda 3B). Total K and Na were determined by flame photometric method (Perkin–Elmer model 1100B). Total Ca, Mg, Zn, Fe, Mn, Cu and Al were determined by atomic absorption spectrophotometry (Perkin–Elmer model 1100B).

Total nitrogen (N) was determined on fresh manures samples by the Kjeldahl method (Gerhardt model Vapodest 5) according to the methodology described by AOAC (1984). Soluble N (nitrate and ammonium) were determined by direct distillation and titrimetric (Gerrhard model Vapodest 12) method revised by Sadzawka (1990).

The total heavy metals cadmium (Cd), chromium (Cr), nickel (Ni) and lead (Pb) were determined by acid digestion, with acid digestion and hydride generation for arsenic (As), and all of them analyzed using atomic absorption spectrophotometry (UNICAM model 929) by the methodology revised by EPA (1996).

The chemical and physical data gathered were ordered, tabulated and analyzed statistically, the average and standard error being calculated for each parameter.

3. Results and discussion

Nutrient contents were low in both Salmonid manures; in general were lower than those values reported for salmon and trout manures collected from raceways (Westerman et al., 1993; Naylor et al., 1999) and animal manures and sewage manures elsewhere (e.g. MAFF, 2000). Mazzarino et al. (1998) also showed that salmonid sludge, both dredged and directly collected beneath the cages contained similar quantities of N (3%). The P contents of the dredged and directly collected sludges were also similar (10%) but, greater than the range shown in Table 1. Both salmonids manures showed a high variability in their chemical contents, which is common for most of the organic wastes (Smith and Chambers, 1993; Nicholson et al., 1999). For fish manure this variability has been associated with management practices, species and size of the fish, feed and

Table 1
Total macronutrient contents in salmonid and dairy manures (dry weight basis)

Macronutrient	Lake manure[a]	Sea manure[a]	Trout manure[b]	Dairy manure[c]
N	0.94 (0.076)	0.41 (0.031)	2.83	3.00
P	1.56 (0.342)	0.81 (0.084)	2.54	0.52
K	0.06 (0.006)	0.63 (0.061)	0.10	2.89
Ca	3.89 (0.729)	2.62 (0.189)	6.99	n.d.
Mg	0.40 (0.018)	1.65 (0.120)	0.53	0.52
Na	0.24 (0.012)	11.80 (1.246)	n.d.	n.d.

( ) = values between parenthesis are standard error of the mean.
n.d. = Not values determined in this study.
[a] This study.
[b] Naylor et al. (1999), collected from raceways.
[c] MAFF (2000).

Table 2
Chemical and physical characteristics of salmonid and dairy manures (fresh weight basis)

Manure origin	Dry matter (%)	pH (u)	Organic matter (%)	Electric conductivity (mS)
Lake manure	12.3 (0.57)	6.9 (0.05)	14.8 (1.28)	8929 (3192.5)
Sea manure	15.2 (2.08)	7.2 (0.04)	11.1 (0.71)	27028 (1967.8)

( ) = values between parenthesis are standard error of the mean.

feeding systems and water flow dynamics (e.g. Westerman et al., 1993).

Both manures had low dry matter (DM) contents averaging *c*. 12–15%. Manures collected were highly diluted, which could results in a high disposal cost of agricultural land applications. Manures showed low organic matter (OM) contents with values of <15% and a neutral pH (*c*. 7.0) (Table 2). Salmonid manures had much lower OM contents than other types of organic residues such as cattle manure or sewage sludge. This low OM content for sea and lake manures could be the result of contamination with sand due to water currents under the sea or lake. Fish manure collected directly beneath the Salmonid cages using a 'bag rearing system' showed higher values of OM *c*. 75% (Dumont, personal communication). A number of publications have mentioned the importance of manures as a source of organic matter for soils (e.g. Pain, 2000). However, the advantages of the use of fish manure as soil amendments in the South of Chile would be reduced due to the high OM content of its volcanic soils (Sadzawka and Carrasco, 1985).

Lake and sea manures had low total N contents (dry weight basis) with values of <0.9%. A lower N content was observed in sea manure compared to lake manure. Sea salmonid cages are located in deeper water than the cages located in lakes; therefore particle N sedimentation could be washed away more easily from sea cages than the ones located in lake. Approximately 75% and *c*. 95% of the total N content was in the organic form, for the lake and sea manures, respectively. The soluble N fraction was mainly as ammonia N, with average values of 2232 (±336.0) mg kg^{-1} for lake manure and 233 (±27.0) mg kg^{-1} for sea manure. Nitrate was very low for both manures averaging 60 (±22.1) and 134 (±23.9) mg kg^{-1} for lake and sea manure, respectively. This form of nutrients is of great importance because of their availability for plant use or because of the risk of losses (to water, soil or air).

Since fish typically utilize only 30% of the ingested N and P, the remainder is voided. Most of the voided N is dissolved, whereas for P the majority is associated with the solid material (Coloso et al., 2003). The low content of the soluble N form in Salmonid manure collected in this study is probably the result of loss of soluble N in the water column before it reaches the sea or lake bed. Fish excrete the majority of their nitrogenous wastes across the gills as ammonia (Hall et al., 1992). Salmon manure collected in this study showed lower contents of N than fish manure collected from Salmonids rearing using raceways (Westerman et al., 1993; Naylor et al., 1999) and cattle manures (Westerman et al., 1985; MAFF, 2000) (Table 1). In addition, N in cattle slurry has higher values of soluble N (i.e. ammonium) than the values observed in Salmonid manure (Table 1). Naylor et al. (1999) compared fish manure with manure from beef, poultry and swine. He mentioned that the nutrient composition of trout manure is similar to that of other animal manures. Like livestock manure, the composition of fish manure is also highly variable due to differences in animal, age, feed, manure handling, and storage conditions.

The N:C ratio was 9.3 and 17.9 for lake and sea manure, respectively. Several authors have mentioned that organic materials with C:N ratios >15 will initially immobilize N, whilst C:N ratios <15 will result in net mineralization (e.g. Beauchamp, 1986). For trout manure mineralization studies carried out by Westerman et al. (1993) have indicated potential available N for growing crops to be about 20% of the N in manure. Mazzarino et al. (1998) demonstrated that between 10% and 50% of the organic N was mineralized from dredged salmon sludge. Laos et al. (2000) measured mineralization rates (23%) in salmon sludge. Alfaro et al. (2004) demonstrated that 52% of the organic N in salmon sludge from below sea cages was mineralized in 90 days. This compared to a value of 39% for the sludge taken from below the lake cages. According to this studies N from fish manure, when applied to soil, can behave as a slow release N fertilizer.

Lake manure showed higher contents of P and Ca than sea manure. In contrast, sea manure had higher K, Mg and Na contents than lake manure (Table 1). Both manures had lower concentrations of K that cattle manure (Table 1). The low concentration of K in salmonid manures could be explained because most of the K is in a soluble form, which can be easily washed away by water currents, avoiding this nutrient to reach the sea or lake bed, where the organic wastes are accumulated.

For Na higher concentration were observed in sea manure compared to lake manure (Table 1). The high concentration of Na in sea manure could be attributed to the natural concentration of this nutrient in sea water. In addition, average electrical conductivity (EC) values of sea manure were higher than those determined for lake manure (Table 2). When applying manures to farmland high EC and Na content could be a limitation depending on the susceptibility and demand of the crop. In this context, a pot experiment comparing the effects of different fish sludge application rates on barley showed crop failure with the highest rate equivalent to 80 tons ha^{-1} due to excessive salinity (Myhr, 1989).

In general, lake manure showed higher micronutrient contents than sea manure (Table 3). High concentrations of Fe and Al were observed in both manures, especially in lake manure. A similar high level of Fe and Al has been reported by Salazar et al. (2003) for dairy slurry. It is important to mention that most of the Al was in a 'non exchangeable' form (data not published). Therefore, if manure is applied to farmland it should not affect crops negatively.

These high values of Fe and Al may be associated with background contents of the lake sediments originating from the volcanic soils of the South of Chile (Sadzawka and Carrasco, 1985). In addition, another contribution could be the tributary surface waters, which are originated in the Andes Mountains (Schalscha and Ahumada, 1998).

Heavy metal concentrations were low (Table 3), being below the limit established by Chilean legislation for sewage sludge and for biosolids for use on land according to the European Union limit values for Cd, Cr, Cu, Ni, Pb and Zn (Council of the European Communities, 1986). For cattle manures most of the heavy metals appear to be originating from feed ingredients (Nicholson et al., 1999). As in the case of cattle manures, trace amounts of metals are added to feed in the form of mineral packs to ensure that essential dietary nutrients are provided for the cultures of aquatic animals (EPA, 2004).

Sea manure had higher As, Cd, Cr, Ni, Pb and Zn concentration than lake manure. Both manures have similar heavy metal concentrations, except for Cr, than those found by Naylor et al. (1999) for trout manure collected from raceways. In general, metals of these manures are within the range of those reported for dairy and beef cattle by Nicholson et al. (1999) (Table 3). According to Nash (2003) the environmental impact of Atlantic salmon in the environment of the Pacific Northwest (USA) presents a risk because of accumulation of zinc and copper.

Fish sludge contains nutrients and organic matter, which can be returned to the land to fertilize crops and provide organic material to certain soils. This represents a low cost

Table 3
Micronutrient and heavy metal concentration in salmonid, dairy and pig manure (mg kg^{-1}, dry weight basis)

Element	Lake manure[a]	Sea manure[a]	Trout manure[b]	Dairy slurry[c]	Pig slurry[c]	EEC directive[d]
Al	31789 (1297)	10506 (1317)	n.d.	n.d.	n.d.	n.d.
As	5.13 (0.581)	3.02 (0.144)	2.20	1.44	1.68	n.d.
Cd	1.04 (0.149)	0.55 (0.036)	1.13	0.33	0.30	20–40
Cr	18.8 (0.71)	14.8 (1.02)	3.86	5.64	2.82	n.d.
Cu	45 (0.9)	89 (11.6)	33.4	62.3	351	1000–1750
Fe	27948 (1345)	10885 (850)	1,942	n.d.	n.d.	n.d.
Mn	446 (29)	101 (8.1)	488	n.d.	n.d.	n.d.
Ni	12.3 (0.55)	7.6 (0.50)	4.94	5.4	10.4	300–400
Pb	3.50 (0.22)	2.53 (0.04)	5.54	5.87	2.48	750–1200
Zn	393 (70)	188 (13)	605	209	575	2500–4000

( ) = values between parenthesis are standard error of the mean.
n.d. = no values determined or established in this study.
[a] This study.
[b] Naylor et al. (1999), collected from raceways.
[c] Nicholson et al. (1999).
[d] Directive 86/278/ECC, limit values (Council of the European Communities, 1986).

'disposal' option. Its use would result in a reduced requirement for 'bagged' fertilizer and could therefore save farmers money. Therefore, a Good Management Practice to reduce water pollution from fish cage farming could be manure collection from beneath the cages and its use in agricultural soils. EPA (2004) assumed that collected solid from fish operations could be land applied as fertilizer at agronomic rates and therefore no adverse impacts to soil are expected to occur due to solid waste when applied in compliance with the regulation. Limitations in using fish manure in agriculture could be odor, the large quantity required, and problems with crusting. Studies (not published) carried out by authors showed 'grass burnt' when fish manure from sea cage farming was applied on surface to a pasture at a rate of 60 tons ha^{-1}. However, this effect disappears after three weeks.

Field and laboratory studies have shown the potential use of this organic waste in crops (Smith, 1985) and grass (Mazzarino et al., 1997). In addition, soils in the South of Chile, where most of the cattle and fish farm production is concentrated, are of volcanic origin, and characterized by the high acidity and aluminum contents and, therefore, high capacity for P retention (Sadzawka and Carrasco, 1985). In addition, soil surveys have shown that there are an important proportion of these soils with low or moderate levels of nutrients. Thus, the recycling of fish sludge as fertilizer represents an opportunity to reduce the risk of water pollution and increase soil fertility.

4. Conclusions

Manures from salmonid farm cages located in the sea and in lakes in the South of Chile had low nutrients and heavy metal contents. However, these organic residues as other animal residues have a potential use as fertilizers in agricultural soils, especially in low fertility soil of South Chile. The use of salmon manure in these soils could be an important alternative for recycling this organic waste, reducing the direct risks of water pollution from the fish farming industry.

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References

Alfaro, M.A., Salazar, F.J., Valdebenito, A., 2004. Nitrogen mineralisation from fish sludge as affected by plant uptake. In: Hatch, D., Chadwick, D.R., Jarvis, S., Roker, A. (Eds.), Proceedings 12th Nitrogen Workshop: Controlling N Flows and Losses. Institute of Grassland and Environmental Research, Exeter, UK, pp. 136–137.

AOAC, Association of Official Agricultural Chemist, 1984. Official methods of analysis of the Association of Official Agricultural Chemist, 14th ed., Washington, DC (USA), 1141 p.

Beauchamp, E.G., 1986. Availability of nitrogen from three manures to corn in the field. Canadian Journal of Soil Science 66, 713–720.

Chen, S., Summerfelt, S., Losordo, T., Malone, R., 2002. Recirculating systems, effluents, and treatments. In: Tomasso, J. (Ed.), Aquaculture and the Environment in the United States. In: A Chapter of the World Aquaculture Society US Aquaculture Society, Baton Rouge, LA, pp. 119–140.

Coloso, R.M., King, K., Fletcher, J.W., Hendrix, M.A., Subramanyam, M., Weis, P., Ferraris, R.P., 2003. Phosphorus utilization in rainbow trout (*Oncorhynchus mykiss*) fed practical diets and its consequences on effluents phosphorus levels. Aquaculture 220, 801–820.

Council of the European Communities, 1986. EEC Council Directive 86/248/EEC, Protection of the environment, and in particular of the soil, when sewage sludge is used in agriculture, Community Legislation in Force, Document 386L0278.

Enell, M., 1995. Environmental impact of nutrients from Nordic fish farming. Water Science and Technology 31, 61–71.

EPA, Environmental Protection Agency, 1996. Acid digestion of sediments, sludges and soils. In: Methods for Evaluating Solid Wastes, EPA Method 3050B, Environmental Protection Agency (USA). Available from: <http://www.epa.gov/epaoswer/hazwaste/test/pdfs/3050b. pdf>.

EPA, Environmental Protection Agency, 2004. Technical development document for the final effluent limitations guidelines and new source performance standards for the concentrated aquatic animal production point source category. Environmental Protection Agency (USA). Available from: <http://www.epa.gov/guide/aquaculture/add/chapter4-508.pdf>.

Hall, P.O.J., Holby, O., Kollberg, S., Samuelsson, M.O., 1992. Chemical fluxes and mass balance in a marine fish cage farm. 4. Nitrogen. Marine Ecology–Progress Series 89, 81–91.

Laos, F., Satti, P., Walter, I., Mazzarino, M.J., Moyano, S., 2000. Nutrient availability of composted and noncomposted residues in a Patagonian Xeric Mollisol. Biology and Fertility of Soils 31, 462–469.

MAFF, Ministry of Agriculture, Fisheries and Food, 2000. Fertiliser recommendations for agricultural and horticultural crops, 7th ed., HMSO, London (UK), Reference Book 209, 176 p.

Mazzarino, M.J., Walter, I., Costa, F., Laos, F., Roselli, L., Satti, P., 1997. Plant response to fish farming wastes in volcanic soils. Waste Management 26, 522–528.

Mazzarino, M.J., Laos, F., Satti, P., Moyano, S., 1998. Agronomic and environmental aspects of utilisation of organic residues in soils of the Andean-Patagonian region. Soil Science and Plant Nutrition 44, 105–113.

Myhr, K., 1989. Fish farm waste material as fertilizer for barley grown for green fodder. Norsk Landbruksforsking 3, 71–78.

Nash, C.E., 2003. Interactions of Atlantic salmon in the Pacific Northwest: VI. A synopsis of the risk and uncertainty. Fisheries Research 62, 339–347.

Naylor, S., Moccia, R., Durant, G., 1999. The chemical composition of settleable solid fish waste (manure) from commercial Rainbow trout farm in Ontario, Canada. North American Journal of Aquaculture 61, 21–26.

Nicholson, F.A., Chambers, B.J., Williams, J.R., Unwin, R.J., 1999. Heavy metal contents of livestock feed and animal manures in England and Wales. Bioresource Technology 70, 23–31.

Pain, B.F., 2000. Control and utilization of livestock manures. In: Hopkins, A. (Ed.), Grass: Its Production and Utilization, third ed. British Grassland Society, Blackwell Science Ltd., Oxford (UK), pp. 343–364.

Rodriguez, R., 1993. Determinacion cuantitativa de la carga de desechos ingresados al lago Ranco por efecto del cultivo de especies salmonideas. In: Tesis de grado presentada como parte de los requisitos para optar al titulo de Licenciado en Biologı´a Marina, Facultad de Ciencias, Universidad Austral de Chile, Valdivia, Chile, 156 p.

Sadzawka, A., 1990. Metodos de analisis de suelos. In: INIA serie La Platina No. 16, Instituto de Investigaciones Agropecuarias, Ministerio de Agricultura, Santiago, Chile.

Sadzawka, A., Carrasco, M., 1985. Quimica de los suelos volcanicos. In: Tosso, J. (Eds.), Suelos volcanicos de Chile, Instituto de Investigaciones Agropecuarias, Ministerio de Agricultura, Santiago, Chile. pp. 337–490.

Salazar, F.J., Dumont, J.C., Santana, M.A., Pain, B.F., Chadwick, D.R., Owen, E., 2003. Prospeccion del manejo y utilizacion de efluentes de lecheria en el Sur de Chile. Archivos de Medicina Veterinaria 35, 215–225.

Schalscha, B.E., Ahumada, T.I., 1998. Heavy metals in rivers and soils of Central Chile. Water Science and Technology 37, 251–255.

Schendel, E.K., Nordstrom, S.E., Lavkulich, L.M., 2004. Floc and sediment properties and their environmental distribution from a marine fish farm. Aquaculture Research 35, 483–493.

Smith, J.H., 1985. Fertilizing agricultural land with rainbow trout manure for growing silage corn. Soil Science Society of America Journal 49, 131–134.

Smith, K., Chambers, B., 1993. Utilizing the nitrogen content of organic manures on farms-problems and practical solutions. Soil Use and Management 9, 105–112.

Stickney, R.R., 2002. Impacts of cage and net pen culture on water quality and benthic communities. In: Tomasso, J. (Ed.), Aquaculture and the Environment in the United States. In: A Chapter of the World Aquaculture Society US Aquaculture Society, Baton Rouge, LA, pp. 105–118.

Subsecretaria de Pesca (Chile Government), 2005. Informe sectorial de Pesca y Acuicultura. Subsecretaria de Pesca, Departamento de Analisis Sectorial, Gobierno de Chile, Mayo 2005, p. 20.

Thorpe, J.E., Cho, C.Y., 1995. Minimising waste though bioenergetically and behaviorally based feeding strategies. Water Science and Technology 31, 29–40.

Westerman, P.W., Safley Jr., L.M., Barker, J.C., Chescheir, G.M., 1985. Available nutrients in livestock waste. In: Agricultural Waste Utilization and Management, Proceedings of the Fifth International Symposium on Agricultural Wastes, Chicago, Illinois (USA), pp. 295–304.

Westerman, P.W., Hinshaw, J.M., Barker, J.C., 1993. Trout manure characterization and nitrogen mineralization rate. In: Wang, J.K. (Ed.), Techniques for modern aquaculture. American Society of Agricultural Engineers, Michigan (USA), pp. 35–43.