REVIEW ARTICLE

A review of the biophysical properties of salmonid faeces: implications for aquaculture waste dispersal models and integrated multi-trophic aquaculture

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Abstract

Knowledge of the quantitative and qualitative properties of salmonid faeces is necessary for aquaculture waste dispersal models, and the design of integrated multi-trophic aquaculture (IMTA) systems. The amount and proximate composition of salmonid faeces can be estimated using a mass-balance, nutritional approach. Indigestible components of salmonid diets have the potential to affect faecal 'cohesiveness' or 'stability'. Nutrient content and density of faeces can vary depending on diet and submersion time. Faecal density has a greater influence on settling velocity than faecal size. Published settling velocity data on salmonid faeces are highly variable due to differences in fish size, rearing systems, collection time, water density, methodology, the mass fraction tested and diet. Most faecal settling data used in published salmonid waste dispersal models are rudimentary and recent information suggests that such models are highly sensitive to this input. The design of open-water IMTA systems and estimation of nutrient capture and recovery from co-cultured filter feeders is difficult due to limited information on particle size, digestibility, settleable and non-settleable mass fractions of salmonid faeces at cage environments. Implications of faecal properties on the accountability for the effects of aquaculture nutrient loading are discussed.

Introduction

The global culture of salmonids (i.e. trout, salmon, charr) has doubled in the past decade from 0.94 million MT in1995 to 1.99 million MT in 2005 (FAO 2007). The intensive cage culture nature of salmonids, accompanied by a rapid expansion in production has lead to several environmental concerns (Naylor, Goldburg, Primavera, Kautsky, Beveridge, Clay, Folke, Lubchenco, Mooney & Troell 2000; Read & Fernandes 2003; Mente, Pierce, Santos & Neofitou 2006). The fate of solid (organic) and soluble (inorganic) nutrients has been one of these concerns, due to the potential for eutrophication.

Two approaches that aim to prevent eutrophication from cage-based salmonid aquaculture are the use of dispersal/deposition models and the co-culture of extractive species. Each approach requires information on the biophysical properties of salmon faeces. Information on the physical properties of salmonid (and other finfish) faeces, in particular, is highly variable and disparate in the scientific literature (Magill, Thetmeyer & Cromey 2006). A thorough

review is therefore warranted to identify knowledge gaps and juxtapose physical properties with compositional data, as a means to assist in the development of these approaches. Influences on the biophysical properties of salmonid faeces, associated empirical data and resultant implications, will therefore be the focus of this review. Information on the properties of feed pellets and faeces from other cultured species may be included where comparisons are necessary or salmonid-based information is lacking. Information on the fate of soluble (inorganic) nutrients, generated directly by excretion or through remineralization of settled particulates, is also required for a full understanding of the nutrient effects of aquaculture systems; it is, however, not the subject of this review.

Aquaculture waste dispersal models

A variety of aquaculture models have been developed as predictive or explanative tools that seek to demonstrate sustainable thresholds of nutrient assimilative capacity. In response to the potential for excessive deposition of organics to the seafloor, as well as transport within the pelagic ecosystem, several models incorporate dispersal components of waste aquaculture solids (Gowen, Brown, Bradley & McLusky 1988; Gowen, Bradbury & Brown 1989; Panchang, Cheng & Newell 1993, 1997; Silvert 1993; Findlay & Watling 1994; Kishi, Uchiyama & Iwata 1994; Sowles, Churchill & Silvert 1994; Hevia, Rosenthal & Gowen 1996; Silvert & Sowles 1996; Dudley, Panchang & Newell 2000; Cromey, Nickell & Black 2002; Gillibrand, Gubbins, Greathead & Davies 2002; Carroll, Cromey, Karakassis, Pearson, Thetmeyer & White 2004; Doglioli, Magaldi, Vezzulli & Tucci 2004; Stigebrandt, Aure, Ervik & Hansen 2004; Corner, Brooker, Telfer & Ross 2006; Chamberlain & Stucchi 2007; Jusup, Geček & Legović 2007; Moccia, Bevan & Reid 2007). The amount, settling velocity and often composition of waste solids are model inputs. The determination of faecal composition and the amount generated is relatively straightforward as detailed in this review. However, knowledge of the physical properties of salmonid faeces and the associated influences under cage culture conditions is rudimentary. Specifically, details on salmonid faecal density, settling velocity, 'stability', settleable vs. non-settleable solids, and size range is either diverse or limited in the published scientific literature. Because most of these models aim to determine where solid organic waste will go, the term 'dispersal' will be used to describe such models in this review, as

it is assumed that quantifying solid waste dispersal is a prerequisite for quantifying deposition per unit area.

Integrated Multi-Trophic Aquaculture (IMTA)

Integrated multi-trophic aquaculture advocates nutrient recovery to achieve sustainability. Integrated multi-trophic aquaculture involves the co-culture of species from multiple trophic levels where nutrient losses from one species are nutritional inputs for another (Chopin, Buschmann, Halling, Troell, Kautsky, Neori, Kraemer, Zertuche-Gonzalez, Yarish & Neefus 2001; Troell, Halling, Neori, Chopin, Buschmann, Kautsky & Yarish 2003; Neori, Chopin, Troell, Buschmann, Kraemer, Halling, Shpigel & Yarish 2004; Neori, Troell, Chopin, Yarish, Critchley & Buschmann 2007). Integrated multi-trophic aquaculture is the modern offspring of traditional aquatic polyculture (Neori *et al.* 2007). In polyculture, production is extensive (low production and low management) and may, in some cases, include only different organisms from the same trophic level. Integrated aquaculture allows intensive management of several monocultures from different trophic levels within the same system, all connected by nutrient transfer through water (Chopin *et al.* 2001; Neori *et al.* 2004). Ideally, co-cultured species in an IMTA system will be harvestable 'crops'; hence, they represent another source of revenue for the farmer and thus are more than just bio-filters. Integrated multi-trophic aquaculture systems can include co-cultured inorganic extractive species such as seaweeds and co-cultured organic extractive species (COES) such as filter and deposit feeders. While there have likely been many incidental IMTA sites in Asia for centuries, IMTA sites in the West have only recently been developed. For example, blue mussels (*Mytilus edulis*) and kelps (*Saccharina latissima* and *Alaria esculenta*) grown adjacent to Atlantic salmon (*Salmo salar*) cages in the Bay of Fundy, Canada, have shown markedly increased growth rates and are now being sold commercially (Reid, Robinson, Chopin, Mullen, Lander, Sawhney, MacDonald, Haya, Burridge, Page, Ridler, Boyne-Travis, Sewester, Marvin, Szmerda & Powell 2008).

Optimizing the design of IMTA sites and modelling the nutrient recovery efficiency of such a system necessitates qualitative, quantitative, spatial and temporal data on the nutrients loaded from the upper trophic levels. In the case of COES at fish cages, the biophysical properties of the fish faeces such as nutrient content, digestibility, particle size and factors af-

fecting settling location (i.e. density, mass fractions and settling rate) can have significant implications for augmented growth and nutrient recovery.

The maximum nutrient recovery achievable for open-water IMTA is unknown. This will likely remain same until co-cultured species are grown at scales complementary to site salmon production, and site designs are optimized (Reid et al. 2008). In the interim, 'trial and error' approaches of commercial husbandry and modelling 'nutrient cascades' are the most likely mechanisms to facilitate present IMTA development. Several knowledge requirements for modelling the development of COES are in many ways similar to that required by waste dispersal models, albeit with a greater focus on 'near-field' scales and faecal nutritional content.

Feed and faecal nutrient loss

Over the last decade, advances have been made in the salmon aquaculture industry to improve economic feed conversion ratio or economic FCR (farm feed input/biomass produced). In 2003, world production of salmonids was 1.46 million tonnes (FAO 2005) and the aquafeeds used were 1.9 million tonnes (Tacon 2005). This makes global salmonid feed conversion about 1.3 in 2003 (the last year of available salmonid aquafeed consumption data). This is a significant improvement from the previous decade, where, in 1993, salmonid production was 0.3 million tonnes and aquafeed production was 0.5 million tonnes (FAO 2005); a global economic FCR of 1.7. Reduction of feed loss and improvements in nutrient conversion efficiency reduce the economic FCR. Mortalities and escapes also affect the production of harvestable biomass, which in turn affects the economic FCR. As such, it is not possible to attribute changes in economic FCR to a specific factor. Nevertheless, improvements in global economic FCR of salmonid production do suggest an overall increase in industry efficiency converting nutrients from fish feed to harvestable biomass, regardless of whether lost nutrients are partitioned as faeces, waste feed or present in escaped or dead fish.

Feed loss has long been cited as a major contributor to waste generation from commercial salmon farms. In the pioneering days of intensive salmon aquaculture, waste feed was a significant contributor of solids exiting fish cages. Early estimates of feed loss in open cage aquaculture were around 20% (Beveridge 1987), most likely a significant factor contributing to poor economic FCR. This reduction in the loss of waste feed is in part due to improved waste pellet detection mechanisms such as machine vision (Ang & Petrell 1997; Parsonage & Petrell 2003) that prompts cessation of feed delivery upon detection of waste pellets. It is estimated that due to such technologies, feed wastage is routinely below 5% (Cromey et al. 2002). The actual percentage of feed loss, however, is difficult to determine because it can vary from operation to operation and even from day to day. Some salmon waste dispersal and nutrient loading models use waste feed values between 3% (Cromey et al. 2002) and 5% (Bureau, Gunther & Cho 2003). Using a mass balance method of calculating the composition and quantity of faecal waste (detailed in the following section), a waste feed loss of 3% will comprise approximately 12% of the total solid waste from a typical salmonid feed. The majority of solids lost from intensive cage aquaculture of salmonids will be of faecal origin. Given improvements in nutritional FCR (feed consumed/weight gain) and subsequent reduction in feed loss, data on the physical property of feed pellets are of arguably less importance than data on faecal properties. However, information on settling rates and related physical properties of feed pellets is ironically more available in the scientific literature (e.g. Elberizon & Kelly 1998; Chen, Beveridge & Telfer 1999a; Cromey et al. 2002; Stewart & Grant 2002; Peterson, Sutherland & Higgs 2005; Vassallo, Doglioli, Rinaldi & Beiso 2006). This is presumably because feed pellets are easier to acquire and work with.

Faecal composition and diet

One of the prerequisites for the use of waste dispersal models and development of IMTA systems is determining the solid organic nutrient load. This would ideally incorporate qualitative as well as quantitative information. Factors affecting faecal properties will be largely dietary, specifically the indigestible components. Figure 1 illustrates the generation and fate of nutrient waste from cage-based fish culture. With the appropriate information the faecal components can be calculated.

Complex nutrients (and some associated compounds) fall into several categories such as proteins, lipids (fats), fibre, ash and nitrogen-free extract (NFE, i.e. mostly carbohydrates). The percentage of these complex nutrient groups is often referred to as the proximate composition (Lovell 1989; Hardy & Barrows 2002). Each group may be comprised of sev-
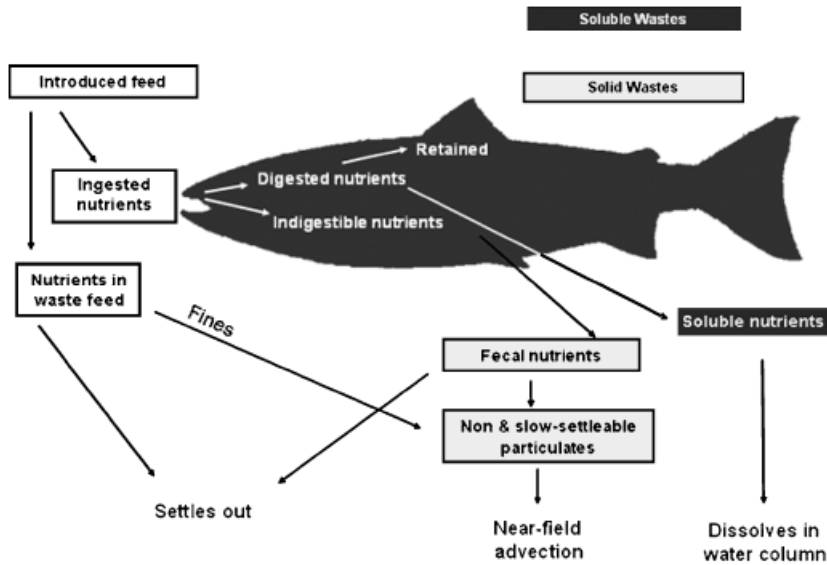
Figure 1 Fate of nutrients in salmonid cage culture. 'Fines' are small particulates that break away from feed pellets. Solid waste is considered organic, and soluble waste excreted directly from the fish is considered inorganic.

Table 1 Estimation of faecal composition and the amount produced from the consumption of a typical Atlantic salmon feed* for grow-out sized (> 2000 g) fish

	Proximate composition (%)†	Digestibility (%)‡	Amount digested (%)	Amount in faeces (%)
Protein (minimum)	39	90	35.1	3.9§
Fat (minimum)	33	95	31.4	1.7
NFE (maximum)¶	10	60	6.0	4.0
Fibre (maximum)	1.5	10	0.15	1.4
Phosphorus (approximately)‖	1.2	50	0.6	0.6
Minerals (maximum)**	6.8	50	3.4	3.4
Moisture (maximum)	8.5			
Total	100			15.0

*Optiline 2000 (used on Canada's west coast). Data provided courtesy of Skretting.

†Same as g 100 g^{-1} feed.

‡Protein and fat digestibility are within ranges provided by Skretting. Minerals, phosphorus, fibre and NFE based on apparent digestibility coefficients (Bureau *et al.* 2003) of salmonids (salmon, charr and trout).

§The amount of nitrogen is 0.624% (indigestible protein/6.25). This is the same as 6.24 g N kg^{-1} feed fed; or 6.86 g N kg^{-1} growth, with a nutritional FCR of 1.1.

¶NFE is what remains after the other nutrient categories are subtracted. It typically comprises the carbohydrates.

‖Phosphorus estimates for Optiline 2000 are based on analysis of 11 mm Orion salmon feed (Peterson *et al.* 2005); a Moore–Clark feed before takeover by Skretting.

**This mineral value (ash) does not include phosphorus (row above). The Skretting-supplied value (all minerals) was adjusted (minus phosphorus) accordingly.

FCR, feed conversion ratio; NFE, nitrogen-free extract.

eral ingredients. Column 2 in Table 1 shows the proximate composition of a typical modern Atlantic salmon, *S. salar* L., feed for grow-out size fish.

Calculating faecal waste is relatively straightforward with information on the proximate composition (typically on feed bag labels) and associated digestibilities. What is eaten, but not digested, will become faeces. A mass balance approach can be used to estimate faecal mass and proximate composition (Cho,

Hynes, Wood & Yoshida 1991, 1994; Cho & Bureau 1998; Bureau *et al.* 2003; Papatryphon, Petit, Van Der Werf, Kaushik & Kanyarushoki, 2006). Accuracy and precision of this approach will largely be a function of data input quality. Papatryphon *et al.* (2006) demonstrated that reasonable predictions can be made with this approach even when pooling data from several farms and incorporating a volumetric component to determine concentrations. Combining the mass of

rainbow trout, *Oncorhynchus mykiss* (Walbum), nutrients loaded with volumetric data, Papatryphon *et al.* (2006) estimated concentrations of ammonia (NH_4^+), total phosphorus and suspended solids, with a mean per cent bias (from measured values) of 25.00%, 18.20% and 9.76% respectively.

Multiplying the apparent digestibility coefficient by the proximate amount estimates the amount digested; the remainder will comprise the faeces. Summing the amount of all indigestible dietary components will determine the overall fraction of faeces produced per unit feed consumed. By applying this approach with a common salmon feed in Table 1, approximately 15% of consumed feed becomes dry faecal matter. This estimate must be combined with feed loss estimates to get the total solid waste amount generated by a fish farm. If, for example, 97% of the feed is consumed, the total solid waste will be 18% (3% waste feed plus 15% faecal waste) of the feed mass offered to the fish.

Effect of diet on faecal cohesiveness and stability

Nutritional strategies for reducing the quantity of cultured salmonid wastes via increased digestibility ('nutrient dense') have been developed and advocated for well over a decade (Cho & Bureau 2001). Only recently, however, have nutritional effects on the physical properties of fish faeces been considered, largely to assist with waste management strategies (Amirkolaie, Leenhouwers, Verreth & Schrama 2005; Brinker, Koppe & Rösch 2005; Ogunkoya, Page, Adewolu & Bureau 2006). The ability of faeces to resist breakage and changes in density, or to disaggregate and disperse, can have major implications for waste management, dispersal modelling and COES in IMTA systems. Various terms have been used to describe these characteristics such as 'faecal cohesiveness' (Ogunkoya *et al.* 2006) and 'faecal stability' (Brinker, Koppe *et al.* 2005).

Studies to date suggest that specific dietary ingredients are largely responsible for changing physical faecal properties, apparently more than changes in proximate composition. For example, feed pellet binders seem to have a significant effect on physical faecal properties. Binders are made from a variety of materials with the intent of preventing feed pellet disaggregation upon submersion in water and reducing the generation of fines (feed dust) during shipping and handling (Hardy & Barrows 2002). Many binders lack nutritional value (Lovell 1989) and are poorly digested. Brinker, Koppe *et al.* (2005) added a guar gum

binder to rainbow trout diets, which generated larger faecal solids and a 40% increase in drum filter removal efficiency of solids and total phosphorus. Other ingredients may have the opposite effect. Ogunkoya *et al.* (2006) added a combination of soybean meal and enzyme cocktail (to increase the digestibility of the soybean meal) to rainbow trout diets, resulting in a reduction of faecal density and sinking speed. They suggested that these properties may have implications for dispersion at fish cages, reducing localized deposition of faecal material and lesser potential impact on benthic biota.

Proximate composition is typically detailed on commercial feed bags (or totes), or readily available from the manufacturer. Details regarding specific ingredients, however, may be proprietary. Commonality of feed ingredients should not be assumed. There are many regional differences in feed ingredients depending on the availability, cost and regulations involved. This is particularly notable in the proportions of fish meal and marine oil that supply dietary protein and lipid components. In Canada, for example, fish meal and oil in Atlantic salmon diets range between 20% and 25%, and 15% and 20%, respectively, whereas in Norway these values range between 35% and 40%, and 27% and 32% respectively (Tacon 2005).

In the quest to find a more sustainable and cost-effective salmon diet, reduction of marine-based ingredients (i.e. fish meal and marine oil) in salmonid feeds must be accompanied by suitable dietary replacements. Some ingredients that have been tested as replacements for marine ingredients include: canola meal, pea meal, soybean meal, canola (rapeseed) oil, maize gluten meal, soybean protein concentrate, feather meal, poultry by-product meal, poultry oil and the crystalline amino acids lysine and/or methionine (Watanabe 2002; Tacon 2005). While data on the effects of the indigestible portions of these ingredients on the physical properties of faeces may have been assessed by commercial feed companies, it appears largely absent from published scientific literature.

Regional differences in feed composition, ongoing replacement of marine ingredients and the sourcing of ingredients without contaminants imply a continual evolution of salmonid feed development. This suggests that the application of faecal property data from the literature to dispersion or IMTA models should be used with caution. Feeds used in published scientific studies may not be the same feeds used at sites in which the models are to be applied. Even if the brand name and proximate composition are the same, it may be difficult to determine whether individual in-

gredients have changed since the study was published, unless the feed manufacturer is willing to provide ingredient information.

Faecal particle size

Particle size is important for the design and optimization of recirculation system methods for the removal of waste solids (e.g. Patterson, Watts & Timmons 1999; Cripps & Bergheim 2000). In IMTA systems, particle size is important for filter feeders such as shellfish or other organisms that are capable of consuming organic particles (Cross 2004; Lander, Barrington, Robinson, MacDonald & Martin 2008). Particle size appears of less direct importance for waste dispersal models. While there is likely to be a relationship between particle size and the ratio of settleable to suspended solids, particle size data are not necessary to determine the settling rates of various mass fractions.

Most research on particle sizes of waste aquaculture solids has been done with land-based, recirculation or flow-through systems, considering the combined waste of feed pellets and faecal solids. These studies largely focus on improving removal techniques, in particular suspended solids (Kelly, Bergheim & Stellwagen 1997; Brinker & Rösch 2005), because the removal of small particulates cause many technical and cost-effectiveness problems in recirculation systems (Patterson *et al.* 1999; Cripps & Bergheim 2000; McMillan, Wheaton, Hochheimer & Soares 2003). Patterson *et al.* (1999) demonstrated that the power law for particle size, applied to recirculation systems, can be used to calculate the frequency of particle size classes below 1000 μm. Larger particles are less numerous but occupy more total volume, while smaller particles are more numerous but occupy less total volume. This is manifested as a hyperbolic relationship. Cripps (1995) discovered a similar phenomenon sampling suspended solids from the effluent of a hatchery rearing Atlantic salmon and sea trout < 12 g. Although most of the particles were smaller than 20 μm, 'larger' particles (< 160 μm) made up the bulk of the volume.

This relationship appears to differ somewhat when only settleable solids are accounted for. Elberizon and Kelly (1998) 'screen-sampled' all waste solids (waste feed and faeces) settled in standpipes from tanks holding 250 g Atlantic salmon. They reported that 13.1% of the mass was above 2000 μm, 16.6% between 1000 and 2000 μm and 28.7% between 500 and 1000 μm. Consequently, 41.6% was below 500 μm and the median diameter of this fraction was 114.4 μm. Only one study juxtaposed settleable and suspended solids of the total solid waste mass fraction. Wong and Piedrahita (2000) estimated that 27% of solid wastes, collected at the end of a series of raceways holding 20–40 cm rainbow trout, were suspended solids. However, there were no accompanying particle size data.

Influence of rearing system on particle size

In land-based systems, abrasion against physical structures (e.g. tanks, screens, drains), aeration, water falls (Brinker & Rösch 2005), pumping (McMillan *et al.* 2003) and the mixing effects of fish movement and feeding activity (Brinker & Rösch 2005; Rasmussen, Lauren, Craig & McLean 2005) will cause a reduction in the size of faecal particulates. However, it has also been reported that some agglutination processes will counteract turbulence-induced particle decomposition, resulting in less overall size reduction than would be expected simply from mechanical breakdown (Brinker & Rösch 2005).

Different mechanical and hydraulic phenomena will, of course, occur at open-water, commercial fish cages. There will be the potential effects of net crossings and much larger numbers of fish (several thousands in a cage) than would occur in tank-based systems. However, the extent these effects have in sea cages on the breakdown or cohesiveness of faecal material is largely unknown at this time. Caution, therefore, needs to be taken when extrapolating particle size data collected from land-based systems to cage production settings.

Influence of fish on particle size

Fish size and species can affect the size of faecal particulates and potentially other physical properties such as settling rates. Big fish produce a greater variability in faecal sizes (Chen, Beveridge & Telfer 1999b; Buryniuk, Petrell, Baldwin & Victor 2006). The importance of this effect is such that the production of larger particulates by larger fish is a significant consideration in the design of waste treatment in recirculation systems for European seabass (Franco-Nava, Blancheton, Deviller, Charrier & Le Gall 2004).

While potentially important, only a few studies using modern commercial feed have associated different fish size classes with different faecal size classes. Buryniuk *et al.* (2006) tested different sized

faecal collection mesh under cages holding 1–5 kg Atlantic salmon. Faeces from 1 kg salmon were not captured on mesh openings above 4 mm; faeces from larger fish (e.g. 5 kg) could be captured on mesh sizes as large as 25 mm. Magill *et al.* (2006) collected faeces under cages of sea bream and bass to estimate faecal particle numbers and associated volumes. There were significant differences in particle volume of faeces generated from three different fish size classes (all below 400 g).

Most literature data on salmonid faecal particle size distributions have been generated from a single-size class of fish. With the exception of Chen *et al.* (1999b), Chen, Beveridge, Telfer and Roy (2003) who used salmon up to 1.6 kg, and Buryniuk *et al.* (2006) who collected faeces from 1 to 5 kg salmon, other studies have used relatively small fish. This presents a potential problem extrapolating faecal sizes to a cage-culture setting. Atlantic salmon in marine cages are frequently harvested between 3 and 6 kg (Gillibrand *et al.* 2002; Department of Fisheries and Oceans 2007), spending the majority of their grow-out time at fish sizes much greater than the fish sizes used in many literature studies.

Differences between related species may also affect physical faecal properties. Magill *et al.* (2006) discovered significant differences between volume and settling rates of faeces produced by gilthead sea bream and sea bass fed the same diet. The mean size of particles from the sea bream and sea bass ranged from 0.3 to 2.5 mm (1.4 mm mean) and 0.3 to 6.2 mm (1.12 mm mean) respectively. Differences in physical faecal properties among salmonid species (fed the same diets) are unknown.

Faecal settling rate

Data on salmonid faecal settling rates from the literature are detailed in Table 2. Literature on empirically derived settling rates are difficult to compare, due to differences in diets, water viscosity (e.g. temperature and salinity), species, collection times, fish size and methodologies, all of which have the potential to affect reported values. Calculating faecal or pellet settling rate does not appear to be a viable option either. Stokes law, which can calculate the settling rate of solid objects in liquids, does not work with fish faeces nor with feed pellets (Elberizon & Kelly 1998; Chen *et al.* 2003; Magill *et al.* 2006). It has been postulated that this is largely due to the non-spherical shape of faeces and feed pellets, because Stokes law assumes spherical shape (Elberizon & Kelly 1998). There has been some

work modifying Stokes law for irregular shapes such as cylinders and ellipsoids to estimate settling velocity of euphausiid and copepod faeces (Komar, Morse, Small & Fowler 1981). There is no literature, however, to indicate these modifications have been tested on fish faeces. In any case, these variants of Stokes law still require particle density and dimensional data, both measures necessitating empirical data collection on fish faeces, efforts analogous to the direct collection of faecal settling data.

Effects of faecal size and density on settling rate

While there appears to be a clear relationship between size and feed pellet settling rate (Cromey *et al.* 2002; Sutherland, Amos, Ridley, Droppo & Peterson 2006; Vassallo *et al.* 2006), similar relationships with faeces are more disparate. Chen *et al.* (1999b, 2003) reported no significant relationship between faecal pellet size and settling velocity within the size ranges they tested (4.0–8.4 mm; combined range from two studies), while Elberizon and Kelly (1998) reported median settling differences for size fractions > 2.0 and > 0.5 mm, as 3.1 and 1.4 cm s^{-1}, respectively, for Atlantic salmon faeces in freshwater. Magill *et al.* (2006) demonstrated a definitive relationship between faecal particle size and settling velocity, assessing faecal size ranges between 0.3 and 6.8 mm of faeces (detection limit of 0.3 mm) from sea bream and sea bass.

While salmonid faecal mass on its own is reported as a poor predictor of settling rate (Chen *et al.* 2003), density (mass/volume) appears to be of greater significance (Chen *et al.* 2003; Ogunkoya *et al.* 2006; Moccia *et al.* 2007). Ogunkoya *et al.* (2006) and Moccia *et al.* (2007) measured faecal density directly and found a general positive relationship between sinking speed and density. Ogunkoya *et al.* (2006) reported that faeces from 50 to 120 g rainbow trout, fed eight different experimental diets, had a density range of 1.023–1.038 g cm^{-1} and associated settling velocities of 2.7–3.4 cm s^{-1} respectively. Moccia *et al.* (2007) reported that the median densities of faeces from 400 g rainbow trout, fed three different commercial diets, ranged from 1.033 to 1.040 g cm^{-1} and had associated settling velocities (50% of the mass fraction) between 4.33 and 6.06 cm s^{-1}.

Chen *et al.* (1999b) suggested that as faecal pellets fall through water, they disintegrate and absorb water, thus reducing their settling rate. This reference to water absorption seems in contrast to findings by Wong & Peidrahita (2000), who demon-

Table 2 Literature settling rates of salmonid faeces

Study	Settling rate	Species and size	Method	Rearing environment	Additional details
Panchang *et al.* (1993, 1997)	Mean: 3.2 cm s⁻¹ (70% of measures 2–4 cm s⁻¹) Range: <1 to <6 cm s⁻¹	Atlantic salmon smolts (1/4 lbs)	Faecal collecting by siphoning and re-suspending in graduated cylinder Time between defecation and settling test not reported Settling test in graduated cylinder	Recirculation (freshwater assumed; 10.1–10.7 °C)	Commercial dried feed
Findlay and Watling (1994)	Mean: 2.0 cm s⁻¹	Atlantic salmon (0.5–0.55 kg)	Sediment traps deployed under salmon cages for 2–6h intervals Intact faecal pellets tested Settling rate assessed over 10 cm	Marine cages	Few intact faecal pellets collected in sediment traps; mostly 'fine flocculent material' collected
Elberizon and Kelly (1998)	Particles >2000 μm: 2.9 ± 1 cm s⁻¹ Particles >500 μm: 1.5 ± 1 cm s⁻¹	Atlantic salmon (0.025 kg)	Daily samples of all waste solids collected from tank standpipes Samples passed though sieves of >2000 μm and >500 μm; then tested in settling column	Flow-through, freshwater tanks	Commercial feed 60% of mass >500 μm
Chen *et al.* (1999b)	Standard diet faeces: 6.3 ± 1.2 cm s⁻¹ (20 psu) 5.3 ± 0.8 cm s⁻¹ (33 psu); High-energy diet faeces; 6.6 ± 1.3 cm s⁻¹ (20 psu) 5.4 ± 2.0 cm s⁻¹ (33 psu) Range: 3.7–9.2 cm s⁻¹	Atlantic salmon (0.7–1.0 kg)	Faecal stripping and handnet collection of 'newly evacuated material' Stored −20 °C, thawed before testing Settling tube: 1.25 m length, 10 cm diameter (Perspex tube)	Seawater recirculation (15 °C, 20 and 33 psu)	Differences in settling velocities between salinities is reported as significant (P<0.05)
Wong and Piedrahita (2000)	Faecal strips: 0.7 cm s⁻¹ Median (mass-basis): 1.7 cm s⁻¹ Median settleable phosphorus (mass-basis): 1.15 cm s⁻¹	Rainbow trout (0.11 kg)	Faecal stripping and collection from quiescent zone of a second raceway in series UFT-type settling column	Raceway (17 °C freshwater)	Mass-fraction settling curve generated Faeces from stripping settle slower than faeces from raceway Empirical measures of settleable solids only 27% of sample non-estimated as non-settleable
Dudley *et al.* (2000)	Mean: 3.2 cm s⁻¹	Model applied to 1.5 kg Atlantic salmon	NA	Applied in marine system	The AWATS model Faecal settling velocity from Panchang *et al.* (1993)
Gillibrand *et al.* (2002)	Mean: 3.2 ± 1.1 cm s⁻¹	Model applied to 20-month production period; harvest assumed at 3+ kg	NA	Applied in marine system	Faecal settling velocity from Cromey *et al.* (2002)

(*Continued*)

Table 2 Continued

Study	Settling rate	Species and size	Method	Rearing environment	Additional details
Cromey *et al.* (2002)	Mean: 3.2 ± 1.1 cm s^{-1} Range: 1.5–6.3 cm s^{-1}	Atlantic salmon (3.39 kg)	Faeces collected by sediment traps under cages, tested within an hour in a glass cylinder (28.9 cm length, 6.7 cm diameter)	Marine cages	The DEPOMOD model
Chen *et al.* (2003)	High-energy diet: 5.8 ± 1.2 cm s^{-1} Standard diet: 5.8 ± 0.9 cm s^{-1} Range: 3.7–9.2 cm s^{-1}	Atlantic salmon, (0.664–1.709 kg)	Faecal collection by handnet immediately after defecation, (tested within 2 min) 1.25 m length, 10 cm diameter (Perspex tube)	Recirculation (10 °C, 33 psu)	
Stucchi *et al.* (2005)	Mass fractions of 15%, 70% and 15% are assigned 4, 3 and 2 cm s^{-1} respectively	Model applied to Atlantic Salmon (1 kg)	NA	Applied in marine system	Mass fraction settling rates estimated from Cromey *et al.* (2002), Panchang *et al.* (1997), Chen *et al.* (1999b), and Wong and Piedrahita (2000)
Ogunkoya *et al.* (2006)	Control diet faeces mean: 3.5 cm s^{-1} Range of experimental diet faeces: 2.7–3.9 cm s^{-1}	Rainbow trout (0.050–0.120.5 kg)	'Freshly egested' faeces siphoned from tank Settled in graduated cylinder 35.5 cm length and 6.5 cm diameter	Flow through, freshwater, tanks (15 °C)	Measured faecal cohesiveness, density and sinking velocity of faeces from six different diets
Corner *et al.* (2006)	Mean: 3.2 ± 1.1 cm s^{-1} Range: 1.5–6.3 cm s^{-1}	Model applied to Atlantic salmon (size not reported)	NA	Applied in marine system	Faecal settling values taken from Cromey *et al.* (2002)
Jusup *et al.* (2007)	Mean: 3.2 ± 1.1 cm s^{-1} Range: 1.5–6.3 cm s^{-1}	NA	NA	Applied in marine system	Faecal settling values taken from Cromey *et al.* (2002)
Moccia *et al.* (2007)	50% of the faecal mass fraction from three commercial feeds settles between 4.33 and 6.08 cm s^{-1}	Rainbow trout (400 g)	Faecal collection (0–14 h) trap in tank outflow Settled in column 152 cm in length, 10.6 cm in diameter	Tank (flow through, freshwater, 8.5 °C, 15 L min^{-1})	Mass fraction curve generated Faeces from three commercial trout feeds tested
Chamberlain and Stucchi (2007)	Mean: 3.2 ± 1.1 cm s^{-1}	Model applied to Atlantic salmon (size not reported)	NA	Applied in marine system	Faecal settling values taken from Cromey *et al.* (2002)

Values are expressed in means ± standard deviations (cm s^{-1}).

strated that at the larger mass fractions, trout faeces collected in raceways settle faster than faecal strips, suggesting water uptake increases density and settling velocity. This apparent contradiction could be explained by the presumption that the response of faecal density to water uptake would be a function of whether the materials in the faeces 'replaced' by water (e.g. nutrient leaching) are of greater or less density than water.

Theoretically, factors that affect water viscosity, such as salinity and temperature, should also affect the settling rate. An increase in salinity causes a decrease in settling rate of salmon feeds (Chen *et al.* 1999a) and Atlantic salmon faeces (Chen *et al.* 1999b). Elberizon and Kelly (1998) reported that the settling velocities of salmon feed pellets in freshwater does not significantly vary between 2 and 13 °C. There are no apparent literature data comparing faecal settling rates at different temperatures.

Effect of diet on faecal settling rate

Because different dietary ingredients have the potential to affect faecal properties such as 'cohesiveness' and 'stability', different feeds may generate faeces with different densities consequently affecting settling rate. Moccia *et al.* (2007) tested the settling velocities of faeces from 400 g rainbow trout fed commercial feeds from three different manufacturers. Faecal sinking velocity from one of the diets was significantly different from the other two diets for at least 95% of the settleable mass fraction, suggesting a change in commercial feeds may or may not result in different faecal settling velocities.

Small changes in proximate composition of the feed do not appear to significantly affect settling velocity. Chen *et al.* (2003) reported no difference in settling velocity between faeces generated from a high-energy diet of 30% lipid and a standard diet of 20% lipid. Both feeds were from the same manufacturer for the same sized fish; hence, it is assumed individual ingredients did not differ between feeds, just the proportions. Lipid digestion of commercial salmonid feeds is routinely 95% (Bureau *et al.* 2003). This translates to very minor changes in faecal composition (relative to feed consumed), between the two diets and probably negligible changes in density and settling velocity. However, such results may differ substantially if the proportion of lesser digestible components such as NFE or fibre changed substantially. Further research on these aspects is warranted.

Post-egestion changes

One possible limitation with the collection of settling velocity data and estimates of faecal compositions may be the change in faecal density via water uptake (and nutrient loss) before collection for input into settling chambers. It is reported that feed pellets (Vassallo *et al.* 2006) and faecal pellets absorb water within minutes of submersion (Chen *et al.* 1999b; Vassallo *et al.* 2006), which should theoretically affect the density and settling rate. Chen *et al.* (2003) reported that Atlantic salmon faeces lose between 4% and 14% carbon, and 9% and 16% nitrogen after 2.5 min submersion in water with no significant leaching after this. Post-leaching settling rates were not measured in that particular study; hence, the effects of potential density changes on settling rate were unknown. However, an earlier study by the same authors found no significant difference in settling rates between the faecal strips (< 5 mm) squeezed from the fish and faeces (< 7 mm) netted from tank water (Chen *et al.* 1999b). This seems to contrast with Wong and Piedrahita (2000) who investigated settling properties of aquaculture solids to acquire empirical data for removal efficiency equations by testing faecal strips and recently settled material from the quiescent zone in a raceway (a second raceway in series). There was no difference in settling velocities in the lower 40% ($< 0.3 \, \mathrm{cm \, s^{-1}}$) of the mass fraction (of which 27% was suspended solids) from either collection method. However, at the larger mass fractions, their data indicated 80% of the faecal strips settled at velocities of $1.5 \, \mathrm{cm \, s^{-1}}$ or less and only 60% of raceway solids did the same, suggesting larger faecal pellets immersed in water are denser and may settle faster than faeces that have just been egested from the fish.

These observations complement data on the comparison of faecal collection techniques to assess digestibility. Spyridakis, Metailler, Gabaudan and Riaza (1989) measured lipid and protein digestibility via the examination of faecal material from sea bass. Faeces, collected by stripping (abdominal pressure), dissection, anal aspiration (suction), thieving (filtration), tank siphoning and clarification (decantation), showed a definitive stepwise increase in digestibility values. The relative amount of lipid and protein content in the faeces decreased at each 'stage' of collection. Nutrient content ranged from 12% to 13% difference between stripping (highest content) and clarification collection (lowest content) techniques.

Such observations suggest that various processes are continually affecting physical properties throughout the 'life span' of the faeces. This also suggests that nutrient leaching aspects may require consideration for model inclusion, either as potential effects to settling velocity or as estimates of faecal nutrient composition upon settling.

Implications for salmonid waste dispersal models

The suitability of settling velocity data will, in part, be dictated by the goal of a particular model. If a model aims to predict whether a significant amount of solids would deposit beyond the cage-site lease area, then only settleable solids need be included. Such a model would complement a performance-based standards approach (Levings, Helfield, Stucchi & Sutherland 2002) to benthic monitoring. If a model aims to determine flux to the pelagic and benthic ecosystem, then all solids, including settleable, slow and non-settleable solids, would need to be accounted for. Such a model would be more akin to facilitate an ecosystem-based management approach (Rensel, Buschman, Chopin, Chung, Grant, Helsley, Kiefer, Langan, Newel, Rawson, Sowles, McVey & Yarish 2006). The latter is perhaps much more complex as the 'coupling' of several components may be required. In addition to information on the loading of solid wastes, benthic re-suspension, mass of soluble nutrients (i.e. total ammonia nitrogen, orthophosphate) and carbon dioxide loaded, volumetric data to determine concentrations, detailed hydrodynamic data on far-field transport, and oxygen removal from fish respiration or organic solids degradation may be necessary for a more complete assessment of nutrient loading impacts (Silvert & Cromey 2001; Cromey & Black 2005; Rensel et al. 2006).

One challenge in the application of aquaculture models that account for nutrient load to the pelagic ecosystem is the limited information on the partitioning of settleable, slow and non-settleable solids from salmonid cages. Most data on the settling velocity of salmonid faeces involve the collection of settled faeces to place in a settling column, thereby excluding, by default, some non- and slow settleable particulates. Studies that have addressed 'suspended solids' have done so in the context of land and re-circulation systems, data that are arguably not reliable for extrapolation to cage-based settings.

Salmonid faecal settling rate data in published waste dispersal models

One of the assumptions traditionally used in aquaculture disperal models is that the distribution of faecal settling velocity is normal. For the DEPOMOD model development, Cromey et al. (2002) collected faeces in traps within an hour of deposition, under cages holding fish averaging 3.4 kg, and measured settling rates of these faecal pellets in a column. Settling velocity ranged from 1.5 to 6.3 cm s^{-1} with a mean and standard deviation of 3.2 ± 1.1, with results similar to Panchang et al. (1993). Normality was assumed. However, this may have been strictly a simplifying assumption. Upon examination of the data distribution, the area outside ± one standard deviation lies between 1.5 and 2.1 cm s^{-1} in the lower 'tail', and between 4.3 and 6.3 cm s^{-1} in the upper 'tail'. This suggests that the data distribution is not symmetrical and therefore not normal. A test for normality was not reported. A Monte Carlo simulation was run to 'generate' settling velocity data, from a normal distribution. Any 'misclassification' of settling velocity frequency, however, seemed to have a negligible effect on the end point. The overall model fit does suggest that the approach was valid because predicted deposition values were ± 20% of measured values.

Other models have applied the DEPOMOD settling data distribution with the same assumptions (Gillibrand et al. 2002; Corner et al. 2006; Jusup et al. 2007). Magill et al. (2006), supplying DEPOMOD with faecal settling data collected from sea bream and sea bass, found that the model was highly sensitive to changes in settling velocity. The data distribution of the settleable fractions, of both sea bream and sea bass, was non-normal even after transformation. While these settling rate data were not based on salmonid faeces, it does indicate that the settleable fraction of faeces in a cage environment has the potential to be non-normal. This reported sensitivity of DEPOMOD to faecal settling data suggests that applying data sets from one cage setting to another can introduce uncertainty.

A distinction should be made here between a data distribution of settling velocity and a distribution of settling velocities associated with a mass fraction. Both Wong and Piedrahita (2000) and Moccia et al. (2007) plotted settling velocity against cumulative salmonid faecal mass fractions. Inferences made from these studies suggest that the larger mass fractions are skewed towards the higher settling velocities. If the goal of a model is to associate a mass of

solid waste deposited per area at various distances from the fish cages, entering settling velocity distributions into dispersal models (e.g. Monte Carlo simulation) without accounting for the mass fractions may also introduce additional uncertainty.

To date, few published salmonid waste dispersal models have partitioned faecal mass fractions with settling velocity data. Stucchi, Sutherland, Levings and Higgs (2005) applied faecal mass fraction data, estimated from literature values (see Table 2). However, model estimates of organic flux to the bottom were four to five times higher than the observed sedimentation rates. They suggest that this inaccuracy was largely due to uncertainty in biomass distribution between pens, waste feed estimates, current data, limited number of observations and uncertainty of flux measurements derived from sediment traps due to inherent limitations of the methodology when deployed in shallow waters close to shore. Despite greater sophistication in settling velocity inputs, the extent of other confounding influences was unknown and differences in the application of settling velocity data could not be assessed in this instance.

Recently, modifications to salmonid waste dispersal models for application to other species have involved empirical collection and consequent application of mass fraction settling data. For example, Cromey, Nickell and Treasurer (2007), modifying DEPOMOD for cod (CODMOD), collected such data for cod faeces. Upon model application, approximately 60% of the deposition at benthic sampling stations was predicted satisfactory. The remaining stations were under-predicted, likely due to cage rotation issues and complex hydrography (Cromey *et al.* 2007).

Given the present state of dispersal model development at fish cages, a variety of 'site-specific' factors seemingly have the potential to supersede accuracy and sensitivity issues surrounding faecal settling velocity. Consequently, the sensitivity of model outputs to individual model inputs such as settling velocity is dynamic and proportional to the 'dominant influences' of site-specific conditions. Further research is warranted to determine if accounting for these complexities improves model accuracy, and, if so, if the improvement in accuracy justifies the increased complexity of the model.

Implications for IMTA systems

An optimized IMTA system should convert as much nutrient waste as possible into harvestable biomass of another cultured species. There are three primary considerations with respect to salmonid faeces. First, faeces from the fed trophic level must be sufficiently digestible and meet or supplement the nutritional needs of the COES. Selecting for COES that have good FCR for salmonid faeces will maximize solids nutrient recovery and augment growth rates. Waste solids that are ingested, but indigestible, will be 'repackaged' and egested as faeces from the COES. Clearly this should be minimized as it will decrease the amount of nutrients captured and may cause benthic impacts similar to those if the salmonid faeces had not been intercepted. It should be possible to select COES whose dietary requirements can be matched with the appropriate ratios of complex nutrients in salmonid faeces. Calculating the proximate composition of cultured fish faeces can be relatively straightforward, as shown previously. A significant limitation at this time, however, is the lack of knowledge of COES digestibilities of components that are indigestible to the fish. In other words, while gross energy of salmonid faeces can be easily calculated, determination of digestible and metabolizable energy extractable by COES may require significant nutritional research.

Secondly, faecal particle sizes must be within the ingestible size range for the COES. Heavy faecal pellets that fall directly below fish cages will accumulate and can be potentially assimilated by co-cultured deposit feeders such as polychaetes (Tsutsumi, Kinoshita, Srithongouthai, Sato, Nagata, Inoue, Yoshioka, Ohwada & Hama 2005) and sea urchins (Cook & Kelly 2007). Several COES presently cultured at open-water IMTA sites are, however, filter feeders such as blue mussels (Lander *et al.* 2004) and oysters (Cross 2004). Filtered food particulates must meet specific size requirements. Faecal particle size information and associated mass fractions are necessary for designing IMTA sites and modelling nutrient recovery. Blue mussels, for example, can filter particulates between 10 and 1000 µm (Newell, Shumway, Cucci & Selvin 1989; Davenport, Smith & Packer 2000). If, for example, only 10% of the total solid nutrient load from fish cages are within that size class, the mussels will never be able to recover more than this and other species must be deployed to ingest the other size fractions or the particles may have to be resized through various mechanical means.

Thirdly, COES must be placed at optimal locations to intercept or access the bulk of faecal particulates within the size range of interest to them. The design and modelling of IMTA systems must account for the settling distribution of heavier particulates and the advection

pathways of non- and slow settleable particulates. In this respect, similar issues that confront aquaculture dispersal models also confront IMTA design.

Conclusions

Several developments are presently underway that are resulting in greater accountability within the aquaculture industry for the effects of nutrient loading. Some of these developments include increasing consideration of aquaculture in ecosystem-based management (Rensel *et al.* 2006), aquaculture nutrient credits (Thomson 2006; Neori *et al.* 2007) and the assessment of energy efficiency as a measure of aquaculture sustainability (Tyedmers, Pelletier & Ayer 2007). Consequently, there is a growing need for improved awareness of energy losses from cage-based salmonid aquaculture and associated potentials for nutrient assimilation or recovery. Dispersal models and IMTA are methods to address this by facilitating sustainable thresholds of nutrient assimilative capacity, or converting nutrient waste to harvestable commodities respectively. However, effective implementation of either approach requires accurate information on solid aquaculture waste. Such information on dissolved nutrients from aquaculture is also required, but was not the focus of this review.

The most significant information shortcoming appears to be the absence, or high variability, of data, reported in the literature on physical properties of salmonid faeces in the context of open-water cage systems. There are little or no conclusive data on faecal particulate size classes, the ratio of settleable vs. non-settleable solids and settling velocity data juxtaposed with mass fractional data. It is therefore difficult to determine which physical faecal property data should be considered negligible, robust or sensitive for inputs into aquaculture dispersal models or IMTA planning.

Future data collection on these properties may benefit from video and image analysis of faeces (e.g. Cromey *et al.* 2007) defecated directly into a settling chamber (as opposed to collecting faecal pellets before settling chamber introduction), as a means to calculate immediate post-defecation settling rates and particle size while avoiding the potential confounding effects of faecal pellet collection. This could be combined with the existing approach of timed drawdown from the chamber bottom to capture separate mass fractions (Wong & Piedrahita 2000; Moccia *et al.* 2007). Particulates in the remaining water could then be filtered and dry-weighed to deter-

mine the overall proportion of non-settleable faeces. A similar video and image analysis approach could also assess particle size and settling rates at fish cages. Simultaneous comparisons of particle attributes inside and outside fish cages could provide insight into the effects of cage hydrodynamics and net crossings. However, other approaches would be needed to determine the ratio of settleable and non-settleable particles at fish cages.

While there is much less uncertainty regarding faecal composition from a nutrient loading perspective, only limited research has been directed towards the effects of feed ingredients on physical properties. Rapid evolution and changes in aquafeed ingredients suggest that periodic assessment of physical faecal properties such as settling rates should occur. Given the size of world aquaculture, projected growth and consequent increases in aquafeed development, a significant amount, if not the majority of aquaculture nutritional research, will occur within industry. The assessment of new diets and ingredients will involve digestibility studies necessitating faecal collection (Hardy & Barrows 2002). This is an ideal opportunity to simultaneously assess the biophysical properties of faeces generated from new ingredients and diets. As such, it would be more appropriate for academic, government and industry researchers to collaborate on such projects to reduce duplication of efforts in this area. The need for such data in the design of IMTA systems and the dispersal modelling of aquaculture solids will only increase in the foreseeable future.

This review has attempted to highlight knowledge gaps and areas where additional research on the biophysical faecal properties of salmonid faeces may be warranted. Future research and expansion of sustainable salmonid-based aquaculture will increasingly occur in the context of ecosystem-based management. The continued replacement of marine ingredients in feed, the use of aquaculture models and increased IMTA development are arguably the most promising mechanisms to achieve this. Future research on the biophysical properties of salmonid and other fish faeces must be therefore conducted to accommodate the specific data requirements necessitated by these approaches.

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