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Estimated content of nutrients and energy in feed spill and faeces in Norwegian salmon culture

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Summary/recommendation:

The annual production of 1.3 million tons of salmon in Norway consumes 1.5 million tons of feed. Some of the energy and nutrients from feed is not digested by the salmon, and ends up in the faeces. In addition, nutrients and energy from uneaten feed also end up in sludge. The total amount of energy and phosphorus in faeces and feed spill is estimated for land based smolt production and for the grow out phase in sea in Norwegian salmon farming. The energy content in faeces and feed spill from land based smolt production is estimated to 242,880 GJ, and 11,785,235 GJ from the grow out phase per year with today’s production volume. The corresponding figures for phosphorus are 225 tons and 9,096 tons, respectively.

Currently, sludge is collected from land based smolt farms. Requirements for cleansing is generally based on reduction in concentration of total suspended solids. Consequently, the fish farmers main effort in sludge handling is technology and systems for such concentration reduction. However, the total flow of nutrients and energy in a fish farming system is poorly documented.

To make wise priorities in investments and energy consumption (in e.g. filtering systems, dewatering and transport), in development of technology and making legislation for cleansing, detailed knowledge of the flow of nutrients and energy in salmon farming is required. This can serve as a guide for resource efficient prioritising of research and development in this area.

Summary/recommendation in Norwegian:

Det produseres 1,3 millioner tonn laks og omsettes 1,5 millioner tonn fôr årlig i Norge. Energiinnholdet i faeces og fôrspill fra landbasert settefiskproduksjon er estimert til 242.880 GJ, og 11.785.235 GJ fra sjøfasen per år med dagens produksjon. De tilsvarende tall for fosfor er henholdsvis 225 tonn og 9.096 tonn.

For å gjøre gode prioriteringer i investeringer, i utvikling av teknologi og fastsetting av rensekrav, er det nødvendig med detaljert kunnskap om flyt av næringsstoff og energi i lakseoppdrett. Slik kunnskap kan ligge til grunn for effektiv prioritering av forskning og utvikling på dette feltet.

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1 Estimation of potential sludge production in Norwegian aquaculture

Feed spill and faeces from aquaculture, mostly in the form of particles, contains large amounts of energy and nutrients and may thus be an important resource. The waste particles from land based salmon farming is commonly collected and forms a sludge that is transported to central plants. Technology for sludge collection and transport and disposal of sludge represent large costs for the fish farmer, and therefore sludge is often considered a problem.

Faeces contains the same components as feed, but with a different energy density and different ratio between nutrients. Faeces have high concentration of minerals (thereamong phosphorus) and undigested carbohydrates, and low concentration of fat and protein, compared to feed. The sludge thus contains the same nutrients as feed, but with varying composition depending of ratio between feed spill and faeces in the sludge. Considering the total flow of energy and nutrients in food production and other production systems, sludge is an important resource.

Salmon feed has high energy content (~25 MJ/kg), which is about 90 % of the energy in coal and 60 % of that in petrol, and approximately 20 % of the energy in salmon feed is not digested. On a dry matter basis thus, aquacultural sludge contains a considerable amount of energy, although varying with varying ratio of feed spill and faeces in the sludge. Considering approximately 1.5 million tons of feed used in Norwegian aquaculture per year (Ytrestøyl et al., 2015), the energy in faeces and feed spill amount to considerable amounts of energy and the sustainability of salmon farming depends on effective utilisation of this energy.

Phosphorus (P) is a limited resource, and is required for all food production, plant production included, and therefore requires special attention. Developing technology for reclaiming P from aquacultural sludge would be of high value. However, P in feed is poorly digested (~30 %, depending on P source) and further development of feed ingredients and feed to increase digestibility may be an alternative way of increasing the utilisation P from salmon feed.

One of the challenges in today's sludge treatment, is the lack of effective technology for collection of waste particles and dewatering of sludge. In open sea cages, there is presently no commercial technology for sludge collection available and no alternatives for utilisation. In most land based farms however, the sludge is collected. Ideally, all waste particles should be captured in the filtering system at a salmon farm, and the final sludge should have high dry matter content so that further transport and handling not involves large amounts of water. Analyses of sludge from various farms have shown highly variable dry matter content, and often far below 10 % (Ytrestøyl et al., 2013).

Based on data for yearly feed consumption and salmon production in Norway (Ytrestøyl et al., 2015), chemical analyses of feed and faeces, and digestibility measurements, the total potential production of sludge in Norwegian aquaculture can be estimated. Since both technical solutions and use of the sludge is different between land based fresh water farming and farming in open sea cages, the two situations are considered separately below.

1.1 Estimation of sludge production from smolt production in fresh water

Approximately 300,000,000 smolt with mean weight 80 g are produced annually, which amounts to 24,000 tons of smolt. With economic feed conversion ratio (FCR, tons feed used/tons fish produced)

1.0, this implies 24,000 tons of feed consumed. An assumption is made that the biological FCR is 0.7 (tons feed eaten/tons fish produced), and the remaining feed offered to the fish is spill feed. Given the feed composition and nutrient digestibility given in Tables 1-3, sludge from smolt production contains a dry matter content of 10,716 tons, an energy content of 242,880 GJ, and 225 tons of P annually (Tables 1-3).

A certain amount of the sludge exists as dissolved compounds or dispersed particles that cannot be captured by common mechanical filtering. This amount is unknown and will probably vary depending on characteristics of feed and faeces and other factors like water retention time in the tanks, water velocity and bends in pipes, pipe length from tanks to filters and filter characteristics. In one particular case, the amount of water soluble P (as phosphates) was estimated to roughly 10 % of the total P in sludge from a land based recirculation system (Aas, 2016).

Table 1 Estimate of annual amount of dry matter in sludge from Norwegian smolt production in fresh water.

	Dry matter
Content in feed, % ‘as is’	94
Apparent digestibility, %	75
Amount traded, tons	22,560
Amount eaten, tons	15,792
Amount in feed spill, tons	6,768
Amount in faeces, tons	3,948
Total amount in sludge, tons	10,716

Table 2 Estimate of annual amount of energy in sludge from Norwegian smolt production in fresh water.

	Energy
Content in feed, MJ/kg ‘as is’	23
Content, MJ/kg in dry matter	24.5
Apparent digestibility, %	80
Amount traded, GJ	552,000
Amount eaten, GJ	386,400
Amount in feed spill, GJ	165,600
Amount in faeces, GJ	77,280
Total amount in sludge, GJ	242,880[1]

1 Comparable to the use of electricity of 3,300 Norwegian households annually.

Table 3 Estimate of annual amount of phosphorus in sludge from Norwegian smolt production in fresh water.

	Phosphorus
Content in feed, % 'as is'	1.3
Content, % in dry matter	1.4
Apparent digestibility, %	40
Amount traded, tons	312
Amount eaten, tons	218
Amount in feed spill, tons	94
Amount in faeces, tons	131
Total amount in sludge, tons	225[1]

[1] Comparable to the use of phosphorus fertilizer for 15,000 hectar agricultural land in Norway.

1.2 Estimation of sludge production from the grow out phase

Approximately 1.3 million tons of salmon is produced annually in Norway (Ytrestøyl et al., 2015), by large in open sea cages, and a total 1.5 million tons of feed is traded annually (Ytrestøyl et al., 2015). Currently, sludge from salmon kept in open sea cages is not collected due to lack of technology and because the effluents are expected to be well within the carrying capacity of the recipient water body. Also, there are regular surveys on potential effects on the bottom fauna. In addition, there is no existing solution for how this waste can be effectively utilized. Economic FCR 1.15 (Ytrestøyl et al., 2015) and biologic FCR 1.0 is assumed for salmon in the grow out phase. Given the assumptions for feed composition and nutrient digestibility as shown in Tables 4-6, faeces and feed spill from salmon in the grow out phase have an energy content of 11,785,235 GJ, and contains 9,096 tons of phosphorus (Tables 4-6).

An increasing amount of salmon above 80 g is grown in land based systems using brackish water (salinity 12 ‰) or in semi-closed containments in sea. Both these options eases the possibility for collection of sludge, compared to open sea cages. The sludge from sea water and brackish water will contain chloride, which is a challenge for certain uses. However, if the sludge is dewatered effectively by filtering off the water (and not by drying), it should be possible to obtain low salt concentration in the sludge.

Table 4 Estimate of annual amount of dry matter in sludge from Norwegian salmon produced in the grow out phase.

	Dry matter
Content in feed, % 'as is'	94
Apparent digestibility, %	70
Amount traded, tons	1,364,880
Amount eaten, tons	1,185,340
Amount in feed spill, tons	179,540
Amount in faeces, tons	355,602
Total amount in sludge, tons	535,142

Table 5 Estimate of annual amount of energy in sludge from Norwegian salmon produced in the grow out phase.

	Energy
Content in feed, MJ/kg 'as is'	24.5
Content, MJ/kg in dry matter	26.1
Apparent digestibility, %	77
Amount traded, GJ	35,574,000
Amount eaten, GJ	30,894,500
Amount in feed spill, GJ	4,679,500
Amount in faeces, GJ	7,105,735
Total amount in sludge, GJ	11,785,235

Table 6 Estimate of annual amount of phosphorus in sludge from Norwegian salmon produced in the grow out phase.

	Phosphorus
Content in feed, % 'as is'	0.9
Content, % in dry matter	1.0
Apparent digestibility, %	35
Amount traded, tons	13,068
Amount eaten, tons	11,349
Amount in feed spill, tons	1,719
Amount in faeces, tons	7,377
Total amount in sludge, tons	9,096

For comparison, the average Norwegian household used 20,230 kWh per year in 2012 (www.ssb.no), which equals 73 GJ (1 kWh equals 3.6 MJ or 0.0036 GJ). The energy content of faeces and feed spill from Norwegian salmon farming is thus equivalent to the energy consumption in 160,000 households. Moreover, 15,200 tons of phosphorus were spread on agricultural areas in Norway in 2013 (Gundersen, 2014). Faeces and feed spill from Norwegian salmon farming thus contains phosphorus equal to 60 % of the amount used by Norwegian agriculture.

2 Knowledge gaps and hypotheses for utilisation of sludge

2.1 Catch and utilisation of sludge

For the land based salmon farming, cleaning of the effluent water and collection of sludge is required, and it is a challenge to meet the requirements on a day to day basis. The water content of the sludge is high and variable, which is challenging for the further handling, storage and transport of sludge. The existing ways of increasing the dry matter content may be technically difficult, labour-intensive, energy consuming, costly and may also release odour to the surroundings. The process may include the addition of polyacrylamide, which used for water absorption and more efficient dewatering. Various polyacrylamides are used for several purposes, such as water treatment and industrial processes where solids are separated from the water phase. However, the fate of these is not well documented. The approach to the treatment of aquacultural sludge has more character of a 'fire fighting' than a total understanding of nutrient and energy flow in the system and benefit/cost-effective approach to the challenges addressed.

2.1.1 The necessity for effective dewatering technology

For effective utilisation of sludge from aquaculture, both a complete collection of the waste particles and effective dewatering of the sludge is necessary. Low dry matter content of the sludge implies transport and/or storage of large amounts of water. If used as an energy source , the sludge needs to be dried to give a high energy yield. However, this process should be energy efficient so less energy is spent on drying and transport than the yielded energy. A common experience is that sludge contains 5-15 % dry matter. This varies depending on the ratio between faeces and feed spill, but also due to technical properties of the two fractions, and of tanks, pipes and filters.

Normally, the dry matter content of just fish faeces is found to be in the range 10-15 % in digestibility studies, where faeces are collected and analysed and dry matter content can be estimated. The dry matter content in salmon faeces depends mainly on the feed properties, and is often well below 15 %. Thus, by passive, mechanical filtering, the faeces in the sludge cannot reach higher dry matter content than this.

Effective filtering and dewatering of sludge also depends on a certain particle size of feed and faecal particles, water speed, retention time, turbulence and technical solutions for filtering. Thus, high physical quality of feed and faeces is crucial.

2.1.2 Today's utilisation of energy from sludge

Biogas production

Presently, sludge from land-based aquaculture is commonly transported to central plants where waste from various sources is used for biogas production and/or as soil enhancer. Clearly, effective dewatering is necessary to reduce cost and energy used for transport.

There are also biogas plants currently being developed for use at one single land based farm. Biogas production itself does not reduce the volume of sludge substantially, and dewatering and handling of the rest material is still necessary.

2.1.3 Utilisation of nutrients from sludge

Agricultural fertilizer
Some sludge is spread on agricultural fields nearby the fish farming site. Spreading on agricultural fields is an attractive idea when distances are short, and nutrients such as P, but also nitrogen, potassium and micronutrients can be utilized for new food production. However, there are limited periods of time during the year when fertilizers can be spread, and in most cases, there are limited areas available. Furthermore, the sludge must be within limits for mineral concentrations allowed in fertilizers, the nutrients may not be readily available for plants, and strong odor may be a problem.

The rest fraction from waste treatment plants after biogas production is generally used as a soil enhancer. Whether it can be used for food production depends on the quality of the rest fraction. Some heavy metals, and chloride if salt water is used for the fish, may be a problem. One additional concern is the addition of polyacrylamide, used by several waste handling plants and also at fish farms.

Aquaponics
Aquaponics is an option for using waste nutrients from aquaculture. This may be most relevant for the fraction of nutrients that is dissolved in water. Aquaponics requires extra area, investments, knowledge and man-power, and the light and temperature conditions in Norway limits the effectivity of such production. Large quantities of plant production is required for catching the effluent nutrients.

Release of sludge to the sea
In some cases, sludge is released to the sea. In some locations, where the recipient capacity is high, this may not cause environmental problems. Expansion in smolt production capacity may be hampered by limited recipient capacity of the water body. Resource efficient ways of keeping the production/recipient-system in balance will be required. Unless integrated mulitrophic aquaculture (IMTA) is applied at the site, releasing the sludge into the sea causes loss of valuable nutrients and energy, and increases the flow of e.g. phosphorus from land to sea.

2.2 Gaps in knowledge and technology

2.2.1 Approach

Today's approach lack a total system approach to the nutrient and energy flow in the farming system and the collection and use of sludge. The benefit/cost might be greatly improved if there is more complete understanding of the flow of nutrient and energy in the aquaculture production system.

2.2.2 Today's sludge collection

Technology and solutions for collection and dewatering of sludge should be optimised. Efficiency in particle collection needs to be improved, which may increase volume of collected sludge four fold. Besides, more efficient technology for dewatering/drying of sludge is required in order to increase the dry matter content of the sludge.

2.2.3 Faeces quality

The properties of faeces are affected by the feed and can be improved. A pellet-like structure of faeces is desirable for effective collection, whereas some feeds result in faeces that disintegrates to small particles.

2.2.4 Digestibility of feed

High digestibility of nutrients and energy from feed reduces the amount of sludge. The digestibility is particularly important for phosphorus, which is a limited resource. Development of methods to increase phosphorus digestibility from feed and feed ingredients is essential, and must be done in accordance with the phosphorus requirement of the fish. It may be beneficial to remove indigestible carbohydrates from the ingredients prior to feed production rather than collecting them as sludge for further treatment.

2.2.5 Feeding systems

Technology and routines that eliminate feed spill, while maintaining full growth of the fish, is required to eliminate feed spill in the sludge. Current practice indicate 30 % feed spill, but reduced feed intake may reduce the metabolic efficiency and health of the fish. Therefore, improved systems should be developed.

2.2.6 Improved effluent collection

The effectiveness at this stage will depend on what one want to catch and the nature of this. Existing sludge collection technology is adapted to current feed and feeding technology. There should be potential for large improvements if these are developed together and based on a better understanding of how each component can contribute to a better result in the total picture.

2.2.7 Concluding remarks

It is a demand from society that the land based smolt producers capture the sludge from their production. This is technically challenging and it raises questions about what is the smart way of further handling and use. Today the smolt producers are the problem owners and fight the problem by fulfilling the requirements set for their license to operate. One approach to the problem is continuous improvement of the existing techniques and solutions in accordance with existing requirements and rules.

There are potential for more benefit/cost-effective solutions if this complex situation is approached by establishing an overview of the total flow of nutrients and energy in the system and start developing new solutions where we see the largest potentials for improvements in taking care of nutrients and energy.

It will be easiest to start with developing solutions for land based smolt producers and from there go to the more challenging situations in closed containment systems in brackish or full sea water and finally develop solutions for open cage systems.

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