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# Spreading of feed pellets in a sea cage for salmon farming using an automatic rotor spreader feeding system

A CREATE project

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# Report

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*Summary:*
Efficient production of fish in large cage units demands a feeding practice which is according to the fish's behavioral and physiological requirements. It is generally presumed that spreading the feed pellets uniformly over a large pen surface area improves feed intake. Pneumatic feeding systems are commonly used to spread feed pellets in the cages, however, pellet degradation increases with increasing airspeed. The aim of this study was to describe the surface distribution of feed pellets in sea cages when using a pneumatic feeding system with a rotor spreader. Feeds with three different pellet sizes were used and two different spreader types were tested, both with different orientation of the top unit. The spreader test was carried out with three different airspeeds of the feeding system. The test was carried out in an outdoors square steel cage (24 x 24 meter) with the rotor spreader positioned in the centre of the cage. Styrofoam boxes were used to collect the pellets. The boxes were positioned in a row on each side of the spreader, referred to as two opposite directions. The results showed that the pellets were distributed unevenly over the cage surface. One direction had higher spatial pellet densities and less area covered with feed pellets. The opposite direction showed a more dispersed pattern and longer spreading distance. Between 18.2 % and 79.8 % of the cage surface was covered with feed pellets and spatial pellet densities between 0 g $m^{-2}$ and > 200 g $m^{-2}$ were measured depending on spreader, tilting of the top unit and airspeed. Increasing airspeed gave a longer spreading distance of pellets, measured from the centre. The effect of airspeed was more pronounced for spreader direction with dispersed spreading. Also, with increasing airspeeds the areas with high spatial pellet densities were decreased for both directions, indicating a more uniform spreading with higher airspeeds. The pellet distribution for the different pellet sizes was similar. Spreader type and tilting significantly affected pellet distribution. In conclusion, this experiment showed that when using a pneumatic feeding system, distribution of feed pellets was non-uniform over the cage surface and that spreading area could be manipulated by airspeed, spreader type and tilting position, while the spreading pattern was similar for feeds of different pellet sizes.

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# 1 Introduction

Intensification of salmon farming has led to the use of large sea cages, either rectangular or square, with side lengths up to 20-40 m, or circumferences of 90-157 m. With a depth of about 20-48 m, the cages contain water volumes between 20,000 – 80,000 $m^3$ (Oppedal *et al.*, 2011) and surface area up to 400-2000 $m^2$. The fish biomass can reach up to 2000 tons, the number of individuals is depending on the fish size and can be as high as 200,000-400,000 individuals.

The large units of fish require large amounts of feed to be distributed to the sea cages daily, which is a logistic challenge. A daily feed ratio of 1 % of body weight fed into a sea cage containing 2,000 tons of salmon requires 20 tons of feed per day to be distributed into this cage. The feed is transported to and stored at the fish farming site in large units, and conveyed to the cages in bulk. Consequently, the feed in today's salmon farming is exposed to large forces from pressure and blows, and high physical quality of the feed is demanded to minimise the generation of small particles and dust. Minimal pellet breakage is crucial since even a small fraction of small particles represent significant economic loss. E.g. will 1 % loss in a farm using 20 tons of feed per day equal 200 kg feed loss daily.

When feeding large populations of fish in sea cages, it is a common belief that spreading the feed uniformly and over a large area is beneficial for maximal feed intake. For that purpose, the feeding device is run with high airspeed. However, pellet degradation increases with increasing airspeed ($m\ s^{-1}$) in a pneumatic feeding system (Aas *et al.*, 2011a). On the other hand, high feeding rate ($kg\ min^{-1}$) protects the pellets from breakage, and different feed types show different breakage pattern (Aas *et al.*, 2011a). Thus, using optimal settings of the feeding system is important, particularly when using feeds that are susceptible to breakage.

To further avoid feed loss, a good feeding practice is needed. Feeding practice includes the ration size and the temporal and spatial delivery of feed (Talbot *et al.*, 1999). Suboptimal feeding practice causes economic loss, since it can lead to waste feed, which also represents nutrient discharge to the environment, or to underfeeding, resulting in reduced growth and increased competition between the fish (Talbot *et al.*, 1999).

The quality of the feed pellets has been shown to affect the nutritional responses in the fish (Aas *et al.*, 2011b; Baeverfjord *et al.*, 2006). Aas et al. (2011b) found 20 % difference in feed intake in rainbow trout fed two diets with different physical quality. Since feed utilisation is highest at high feed intake (Einen *et al.*, 1999), and nutrient discharges are lowest at high growth (Einen *et al.*, 1995), the optimal pellet quality may not be the most durable pellets. However, using feeds that are susceptible to breakage requires knowledge of optimal settings of the feeding system. This includes spreading the pellets over a large area, using as low airspeed as possible. Alver et al. (2004) produced a model on waste feed in relation to feed dispersal and water current in an Atlantic salmon sea cage, and suggest that feed distribution is affecting the feeding rate of the fish and that feeding is more efficient and homogeneous among fish when the feed is well spread in the cage. Moreover, if feed is spread too far, it could be lost to the sides of the cages, especially at high water currents (Alver *et al.*, 2004). Thus, it is important to gain more knowledge about feed distribution in sea cages and the relationship to the settings of a feeding system.

The aim of this study was to measure the distribution of feed pellets in a sea cage with a pneumatic feeding system with at rotor spreader attached. Three pellet sizes, three air speeds in the feeding system, two spreader types, and the spreaders oriented (tilted) up or down were tested.

# 2 Material and methods

## 2.1 Location, cage and feeding system

The tests were done outdoors in a square steel cage (24 x 24 meter), which was part of a cage platform located at the Centre for Aquaculture Competence AS (CAC), Hjelmeland, Norway. On the station, a pneumatic feeding system (AkvaMarina CCS Feed System, Akvasmart, AKVA Group, Bryne, Norway) as described in Aas et al. (2011a) was installed. The feed pipe (polyethylene) was 96 m long with outer diameter 90 mm, 5.1 mm thick pipe wall and the inner diameter 79.8 mm. The feed pipe was connected to the selector unit and was attached to the top of the walkway railing, before floating on the water surface in the sea cage. The rotary spreader was attached at the end of the feed pipe and located in the cage centre (Fig. 1).

*Figure 1 Rotor spreader (left) with twistable rotor tip (right). (From AKVA Group)*

The pellet speed was estimated by measuring the duration of time from pellets entered the feed pipe behind the selector unit and until they appeared at the end of the pipe in the cage (Table 1). The number of spreader rotations per minute was counted (Table 1).

*Table 1 Pellet velocity(m $s^1$) in feed pipe and number of rotations per minute of the spreader*

| | Pellet velocity (m $s^{-1}$) | | | Number of rotations per min | |
|---|---|---|---|---|---|
| **Airspeed (m $s^{-1}$)** | 7 mm | 9 mm | 12 mm | Spreader A | Spreader B |
| **20** | 10.1 | 10.1 | 9.6 | 71 | 39 |
| **25** | 12.0 | 12.0 | 11.3 | 98 | 49 |
| **30** | 13.7 | 13.7 | 13.7 | 110 | 67 |

## 2.2 Rotary spreader and tilting positions

The two different spreaders tested were denoted A (RS-90C, Akvasmart, AKVA Group, Bryne, Norway), and B, a recently developed version (RS-90C MK III, Akvasmart, AKVA Group, Bryne, Norway). For changing the tilting positions, the rotor tip was twisted. When tilted up, the opening of the top was in the horizontal plane. For tilting down, the top unit was twisted down 1.2 cm (spreader A) or 1.8 cm (spreader B).

## 2.3 Experimental design

An overview of the experimental design is shown in Table 2. Feeds with three different pellet sizes (7, 9 and 12 mm), three airspeeds (20, 25 and 30 m/s), two spreaders (A and B) in two tilting positions (up or down) were tested, and the trial was run in triplicate.

Due to capacity at the fish farming site, the trial was done during two separate periods of time. Therefore, two different batches of 9 mm feeds were used, denoted feed 9* and feed 9, respectively. During the first period, one batch of 9 mm feed (9*) was used to optimise the experimental setup. Subsequently, the tests for spreader A, tilted up or down, and with all air speeds, were run with this feed batch (9*). For the second period, new feed batches were provided (including a new feed 9), and the remaining experimental runs were done with these, using a different cage (Table 2, Fig. 3).

Changing spreader and tilting position requires a fair amount of manpower. Thus, runs were only randomised within replicate, feed type and airspeed.

*Table 2 Experimental design. The trial was run in triplicate.*

| Feed | Pellet size (mm) | Spreader | Tilting position | Airspeed (m $s^{-1}$) |
|---|---|---|---|---|
| 7 | 7 | A | Up | 20, 25, 30 |
| 9 | 9 | A | Up | 20, 25, 30 |
| 9 | 9 | B | Up | 20, 25, 30 |
| 9 | 9 | B | Down | 20, 25, 30 |
| 9* | 9 | A | Up | 20, 25, 30 |
| 9* | 9 | A | Down | 20, 25, 30 |
| 12 | 12 | A | Up | 20, 25, 30 |

Feed 9* is a separate feed batch, and the tests with this feed were done in a different cage during a different period than the remaining tests.

*Feeds*

Four extruded high energy commercial feeds were used during the experiment, denoted feed 7, 9, 9* and 12, reflecting pellet size (and batch: *). The feeds were packed in 500 kg bags and stored on the barge at the station at ambient temperatures. The specimen weight (g per pellet) of the pellets was measured by counting the number of pellets of a 200 g sample in three replicates.

## 2.4 Measurement of spatial distribution of pellets

For each run, a sample of 10 kg of feed was run through the feeding system at a feeding rate of 12.5 kg $min^{-1}$. Pellets were collected in a row of 70 styrofoam boxes (40 x 80 cm, 20 cm high) which were attached to each other on their long sides with two ropes running through the row of boxes. Holes for the rope were made with a warm copper bit (Fig. 2). The rows of boxes were positioned over the diagonal of the cage with 35 boxes on each side of the spreader, and with box number one closest to the centre (Fig. 2). The pellet distribution was measured on the diagonal in the two directions from the centre, because it appeared that the distribution of pellets was different towards the two directions from the centre. The chosen directions reflected the largest variation. The gap between the boxes around the spreader was 50 cm. After each run, the number of pellets in each box was counted (Fig. 2). For orientation of the boxes in the cages, see Fig. 3.

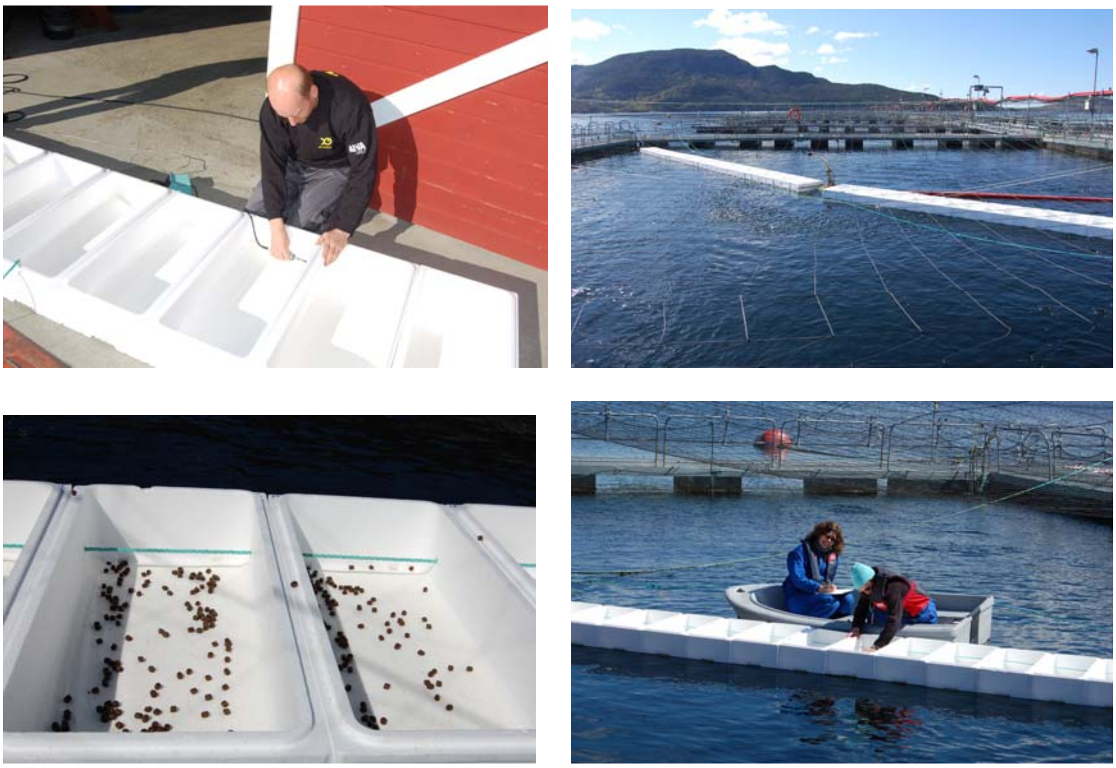


*Figure 2 Holes for the rope were made in the styroform boxes (upper left), and a row of boxes was attached to each other with rope and placed diagonally for collection of feed pellets (upper right). After each run, the collected pellets in each box were counted (lower pictures).*

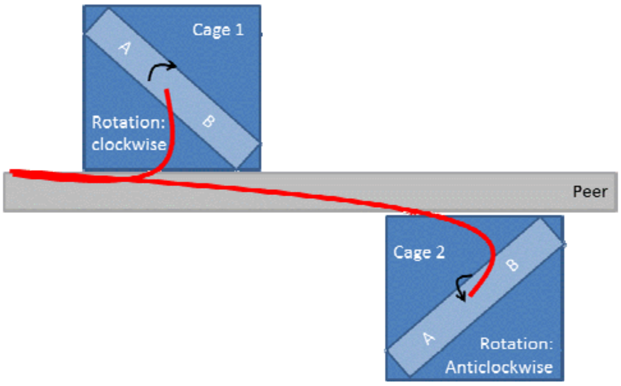



*Figure 3* *Orientation of the two steel cages used for the experiment. Cage 1 was used during Period 1, cage 2 during Period 2.*

## 2.5 Calculations

$$\text{Pellet velocity (m s}^{-1}) = \frac{\text{Pipe length (96 m)}}{\text{Time from pellets entered pipe till they appeared at the end of pipe (s)}}$$

$$\text{Relative number of pellets per box (\%)} = 100 \cdot \frac{\text{Number of pellet per box}}{\text{Sum of pellets of all 70 boxes}}$$

$$\text{Distance from centre (m)} =$$

$$[\text{Box number} \cdot \text{Box width (m)}] - \frac{\text{Box width (0.4 m)}}{2} + \frac{\text{Gap between boxen in centre (0.5 m)}}{2}$$

$$\text{Specimen weight (g per pellet)} = \frac{\text{Weight of pellet sample (ca 200 g)}}{\text{Number of pellets in sample}}$$

$$\text{Feed (g) per box} = \text{Number of pellets per box} \cdot \text{Specimen weight (g)}$$

$$\text{Spatial pellet density (g m}^{-2}) = \frac{\text{Feed per box (g)}}{\text{Box area (0.4m} \cdot \text{0.8 m)}}$$

$$\text{Relative cage area (\%) with pellet density } X\,g\,m^{-2} = 100 \cdot \frac{\text{Sum of cage area represented with box with spatial density } X\,g\,m^{2}}{\text{Total cage area (circular)}}$$

where

X is a given value for pellet density,

Area of cage with pellet density X g $m^{-2}$ ($m^2$) = {[Distance from centre to outer box side (m)]$^2$·π} - {[Distance from centre to inner box side (m)]$^2$·π},

Total cage area ($m^2$, circular) = {[Number of boxes on one side of the spreader · Box width (m)] + Distance from spreader to box number 1 (0.5 m)}$^2$ · π

## 2.6 Statistics

Relative pellet distribution was analysed using the GLM procedure in SAS 9.2 (SAS Institute Inc., Carey, NC, USA) with distance from centre (box number) as a continuous covariate in the quadratic form. The class variables were either pellet size, tilting on spreader A, tilting on spreader B or spreader type and the data were analysed sorted by direction and within airspeed. The effect of airspeed was analysed for both directions for all data, and the effect of direction was analysed using all data within each airspeed. Data was arcsine transformed.

The full dataset on relative pellet distribution was analysed by principle component analysis (PCA) using the multivariate statistical software tool Unscrambler X, version 10.1 (Camo Software AS, Oslo, Norway). Variables used in this analysis were airspeed, spreader type, tilting, direction and relative number of pellets in the boxes (35 boxes). Pellet size was excluded from the model because size did not significantly affect pellet distribution.

Relative cage areas with certain spatial pellet densities (data of table 4) were analysed by PCA with Unscrambler X for the two spreader types when tilted up (trial spreader type, Table 2). Variables used in this analysis were the cage areas with spatial pellet densities (0 g $m^{-2}$, 0 to 10 g $m^{-2}$, 10 to 100 g $m^{-2}$, >100 $g^{-2}$), airspeed, spreader type and direction. Pellet size was not included in this analysis because the effect of pellet size on pellet distribution was not significant. Tilting was excluded from the data because it was not well explained by the model.

# 3 Results

## 3.1 Cage area

The proportion of the cage area covered with feed pellets (> 0 g $m^2$) ranged from 18.2 % to 79.8 % for the different measurements (Table 4).

## 3.2 Symmetry of pellet distribution

The relative pellet distribution of 7, 9, and 12 mm feed pellets at the airspeeds 20, 25 and 30 m $s^{-1}$, respectively, for the two spreaders (A and B) tilted up or down, is shown in Fig. 4. The data confirmed the visually observed asymmetric spreading of the feed in the two directions. Overall, pellet distribution was denser and less surface area was covered with feed pellets in one direction compared to pellet distribution to the opposite direction.

For tests done on the three pellet sizes (7 mm, 9 mm, 12 mm) on spreader A, tilted up (Table 2) relative pellet distribution was significantly different for the two directions at 30 m $s^{-1}$ for all pellet sizes (Fig. 4 A, B, C).  At airspeed 25 $m^{-1}$ the two directions were significantly different for 7 mm pellets only (Fig. 4 A).

When testing tilting using spreader A pellet distribution in the two directions was significantly different when the spreader was tilted down, in combination with airspeeds 25 and 30 m $s^{-1}$ (Fig. 4 D, E).

Effect of tilting using spreader B, gave significant differences in distribution in both directions when the spreader was tilted up, at airspeeds 25 and 30 m $s^{-1}$ (Fig. 4 F). When it was tilted down, there was no significant difference in spreading pattern between the directions of the spreader at any air speeds (Fig. 4 G).

PCA analysis showed that pellet distribution on the dense direction was correlated to low distances from the centre, while the dispersed direction was correlated to longer distances from the centre (Fig. 5). These results were reflected by the data showing the percentage of cage areas with different spatial pellet densities (Fig. 6). The dense direction was associated with higher proportion of cage areas receiving high spatial pellet densities (>100 g $m^{-2}$) or no pellets at all (0 g $m^{-2}$), while on the dispersed direction, higher proportion of the cage areas was covered with moderate spatial pellet densities (> 0 g $m^{-2}$ to < 10 g $m^{-2}$ and > 10 g $m^{-2}$ to < 100 g $m^{-2}$). The proportion of the cage area which remained empty for feed pellets ranged from 47.3 % to 81.8 % for the dense direction, and from 20.2 % to 77.6 % for the dispersed direction for the different measurements.

*Table 3 Effect of pellet size, tilting of spreader A and B and spreader type on relative pellet distribution. Statistical results were obtained from separate analyses, done within airspeed and sorted by direction with either pellet size, tilting on spreader A, tilting on spreader B or spreader type as factors and the corresponding data (see Table 2). Direction refers to the two opposite sides of the spreader, with asymmetric pellet distribution – dense on one side and dispersed on the other.*

| | | Effects of | | | |
|---|---|---|---|---|---|
| **Direction** | **Airspeed ($m\ s^{-1}$)** | **Pellet size** | **Tilting of spreader A** | **Tilting of spreader B** | **Spreader type** |
| Dense | 20 | NS | NS | NS | NS |
| | 25 | NS | NS | NS | NS |
| | 30 | NS | * | NS | * |
| Dispersed | 20 | NS | NS | * | NS |
| | 25 | NS | NS | * | * |
| | 30 | NS | * | * | * |

## 3.3 Airspeed

Airspeed significantly affected relative pellet distribution for the dispersed direction for all tests, except for spreader B when it was tilted down. On the dense direction, airspeed had no significant effect on pellet distribution for any treatment (Fig. 4 A-G). Overall, high airspeed was associated with pellets at further distance from the centre (Fig. 5), and was related to low and moderate spatial pellet densities (> 0 $g\ m^{-2}$ to < 10 $g\ m^{-2}$ and > 10 $g\ m^{-2}$ to < 100 $g\ m^{-2}$) and negatively correlated to cage areas with no pellets at all (Fig. 6).

## 3.4 Pellet size

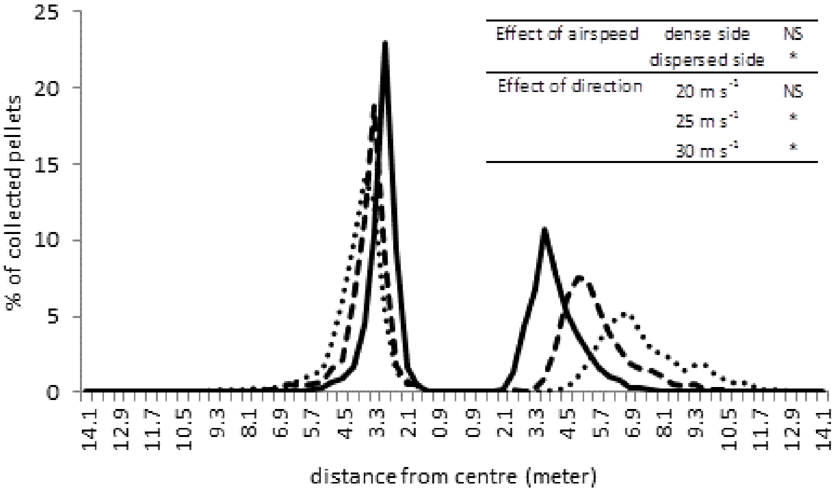
The different pellet sizes 7 mm, 9 mm, 9 mm* and 12 mm significantly differed in specimen weight, which was 0.42 ± 0.0 g, 0.63 ± 0.01 g, 0.64 ± 0.0 g and 1.23 ± 0.01, respectively, for the four feeds. No significant effects of pellet size on relative pellet distribution were observed (Table 3). However, at the highest airspeed (30 $m\ s^{-1}$) 12 mm pellets where thrown significantly longer away from the centre compared to the 7 and 9 mm pellets (data not shown). The maximum spatial pellet density was significantly highest for the 7 mm feed at airspeed 25 $m\ s^{-1}$ compared to 9 mm and 12 mm pellets (data not shown).

*Table 4* *Calculated cage areas (% of total cage area) with spatial pellet densities 0 g m-2, >0 g m-2 to <10 g m-2, >10 g m-2 to <100 g m-2, and >100 g m-2. For this calculation, the cage was assumed to be circular and total area was calculated with radius r = 35 x width of boxes + gap between boxes in center /2. Each box was taken to represent a "ring" area of the cage with distance to center and area of the "ring" depending on box number. The pellet densities (g m-2) were calculated for each box taking into account number of pellets and the specimen weight of the feeds. Data are given as mean ± SD. (n=3).*

| | | | | Dense direction | | | | Dispersed direction | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Pellet size | Airspeed | $0\ g\ m^{-2}$ | >0 to $<10\ g\ m^{-2}$ | >10 to $<100\ g\ m^{-2}$ | $>100\ g\ m^{-2}$ | $0\ g\ m^{-2}$ | >0 to $<10\ g\ m^{-2}$ | >10 to $<100\ g\ m^{-2}$ | $>100\ g\ m^{-2}$ |
| Spreader A | tilited up | 7 mm | 20 | 81.8 ± 2.1[a] | 9.2 ± 2.8 | 6.6 ± 1.4 | 2.4 ± 0.0 | 72.3 ± 4.1 | 8.6 ± 2.0 | 14.6 ± 2.2 | 4.5 ± 0.3 |
| | | 7 mm | 25 | 66.2 ± 9.3 | 19.7 ± 8.9 | 10.6 ± 1.3 | 3.5 ± 0.6 | 46.5 ± 8.9 | 22.8 ± 6.0 | 27.4 ± 4.9 | 3.2 ± 2.2 |
| | | 7 mm | 30 | 50.4 ± 5.3 | 35.2 ± 7.5 | 10.6 ± 2.5 | 3.8 ± 0.9 | 26.3 ± 7.2 | 36.4 ± 9.9 | 37.3 ± 3.3 | 0.0 ± 0.0 |
| | | 9 mm | 20 | 81.2 ± 1.9 | 6.7 ± 1.9 | 8.9 ± 1.0 | 3.2 ± 1.0 | 74.4 ± 2.8 | 8.8 ± 2.9 | 12.5 ± 0.1 | 4.3 ± 0.0 |
| | | 9 mm | 25 | 64.9 ± 4.4 | 19.3 ± 6.7 | 12.0 ± 3.0 | 3.8 ± 0.9 | 53.5 ± 5.2 | 20.1 ± 7.7 | 23.9 ± 6.2 | 2.5 ± 2.9 |
| | | 9 mm | 30 | 57.7 ± 6.4 | 27.6 ± 8.1 | 10.8 ± 2.0 | 3.9 ± 0.7 | 25.0 ± 13.0 | 35.6 ± 7.1 | 39.4 ± 8.2 | 0.0 ± 0.0 |
| | | 12 mm | 20 | 81.3 ± 3.3 | 6.4 ± 1.9 | 9.9 ± 1.4 | 2.4 ± 0.0 | 77.6 ± 3.5 | 5.4 ± 3.8 | 12.5 ± 0.3 | 4.5 ± 0.8 |
| | | 12 mm | 25 | 68.7 ± 9.6 | 15.8 ± 8.7 | 12.7 ± 2.6 | 2.8 ± 1.5 | 51.8 ± 6.5 | 18.3 ± 3.9 | 28.6 ± 5.7 | 1.3 ± 1.2 |
| | | 12 mm | 30 | 56.5 ± 1.8 | 22.5 ± 6.9 | 18.0 ± 7.2 | 3.0 ± 1.4 | 34.5 ± 4.6 | 24.2 ± 6.6 | 41.3 ± 10.4 | 0.0 ± 0.0 |
| Spreader A | tilited up | 9 mm* | 20 | 74.6 ± 1.7 | 9.9 ± 1.9 | 11.5 ± 2.6 | 4.0 ± 1.4 | 62.5 ± 6.5 | 15.2 ± 8.7 | 16.0 ± 2.4 | 6.3 ± 0.4 |
| | | 9 mm* | 25 | 62.6 ± 2.7 | 14.5 ± 1.1 | 18.8 ± 2.2 | 4.2 ± 1.0 | 36.2 ± 0.3 | 21.0 ± 1.9 | 40.9 ± 2.8 | 1.9 ± 1.8 |
| | | 9 mm* | 30 | 48.5 ± 9.5 | 23.7 ± 10.1 | 25.3 ± 3.0 | 2.5 ± 2.9 | 36.4 ± 5.3 | 33.0 ± 3.9 | 30.6 ± 1.4 | 0.0 ± 0.0 |
| | tilited down | 9 mm* | 20 | 77.3 ± 1.2 | 11.3 ± 0.9 | 9.8 ± 2.0 | 1.6 ± 0.7 | 62.3 ± 2.4 | 12.9 ± 2.4 | 20.4 ± 2.4 | 4.4 ± 2.4 |
| | | 9 mm* | 25 | 71.6 ± 2.0 | 17.8 ± 0.8 | 8.6 ± 1.1 | 2.0 ± 0.7 | 40.1 ± 2.6 | 24.3 ± 2.6 | 35.7 ± 2.1 | 0.0 ± 0.0 |
| | | 9 mm* | 30 | 64.0 ± 4.4 | 27.9 ± 3.8 | 5.2 ± 0.4 | 2.9 ± 0.8 | 25.0 ± 12.5 | 27.4 ± 8.7 | 47.5 ± 4.0 | 0.0 ± 0.0 |
| Spreader B | tilited up | 9 mm | 20 | 75.8 ± 2.9 | 9.9 ± 2.0 | 9.0 ± 1.6 | 5.3 ± 0.0 | 69.4 ± 4.1 | 10.1 ± 3.3 | 17.0 ± 4.0 | 3.5 ± 3.2 |
| | | 9 mm | 25 | 64.1 ± 1.0 | 16.9 ± 3.7 | 15.1 ± 5.1 | 3.8 ± 1.4 | 40.8 ± 4.9 | 24.1 ± 3.4 | 35.1 ± 1.9 | 0.0 ± 0.0 |
| | | 9 mm | 30 | 47.3 ± 3.3 | 28.3 ± 2.1 | 23.4 ± 0.2 | 1.0 ± 1.6 | 20.2 ± 7.8[b] | 32.1 ± 9.3 | 47.7 ± 4.0 | 0.0 ± 0.0 |
| | tilited down | 9 mm | 20 | 78.5 ± 4.2 | 11.8 ± 5.6 | 6.5 ± 3.1 | 3.3 ± 0.9 | 75.3 ± 3.5 | 11.0 ± 4.7 | 9.9 ± 1.2 | 3.8 ± 0.0 |
| | | 9 mm | 25 | 64.4 ± 2.6 | 24.1 ± 2.3 | 6.4 ± 0.5 | 5.1 ± 0.3 | 63.3 ± 5.9 | 20.0 ± 3.6 | 13.4 ± 2.9 | 3.4 ± 1.7 |
| | | 9 mm | 30 | 53.6 ± 5.6 | 32.2 ± 5.4 | 8.7 ± 1.2 | 5.6 ± 1.8 | 48.1 ± 4.0 | 31.4 ± 5.0 | 17.3 ± 3.7 | 3.2 ± 1.7 |

* A separate batch of 9 mm feed was used, and tests performed in cage 1. (Cage 2 was used for the rest of the trial).
[a] Minimum cage area covered with pellets for this measurement (18.2 % = 100 % - 81.8 %).
[b] Maximum cage area covered with pellets for this measurement (79.8 % = 100 % – 20.2 %).

(A)

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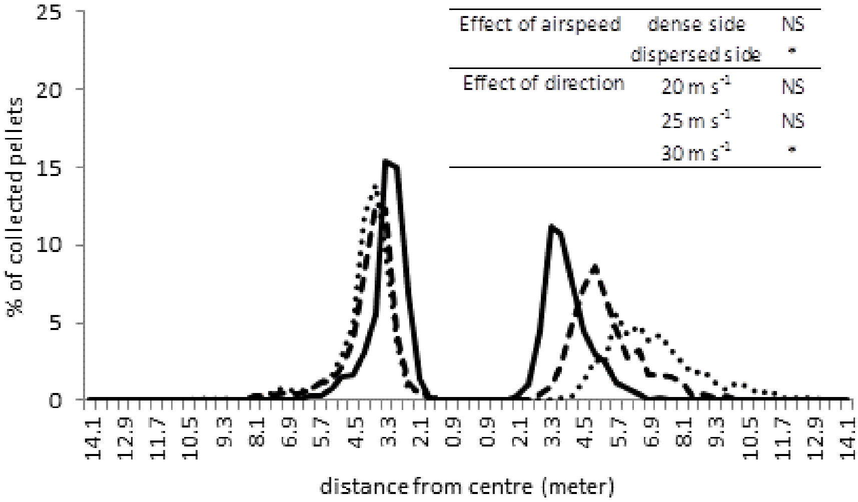
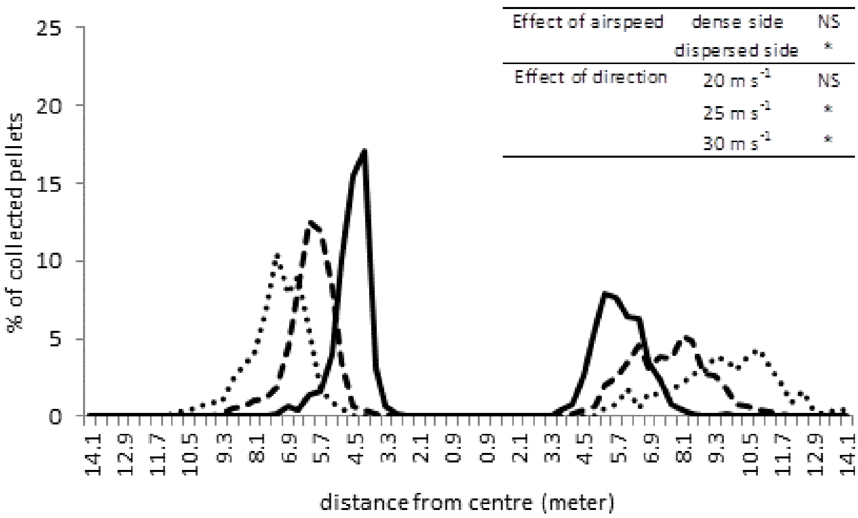



(C)

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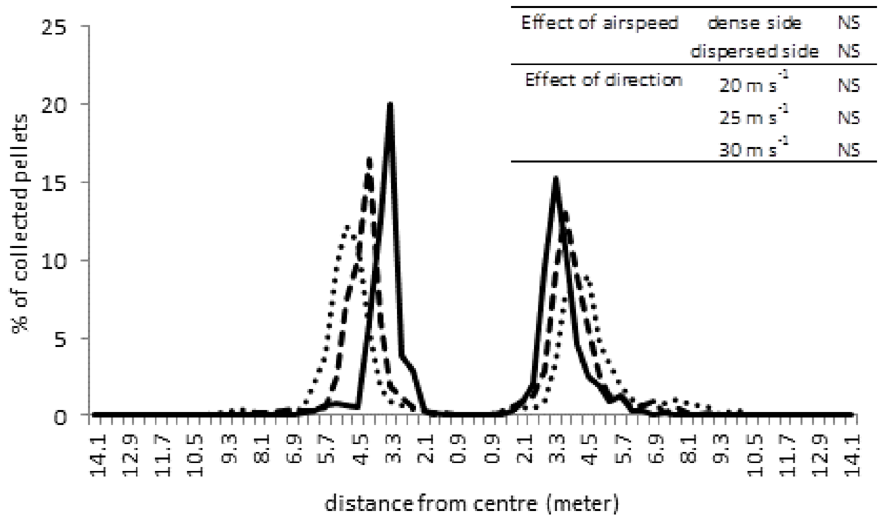
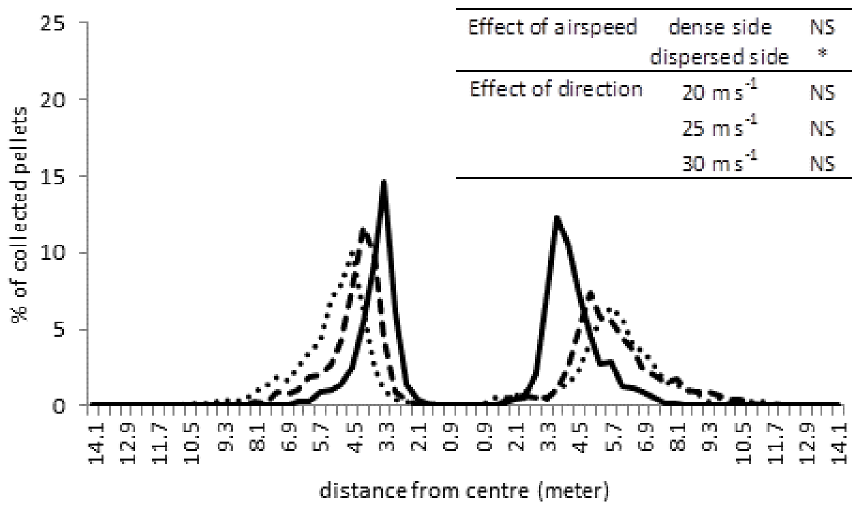
(D)




(E)




(F)

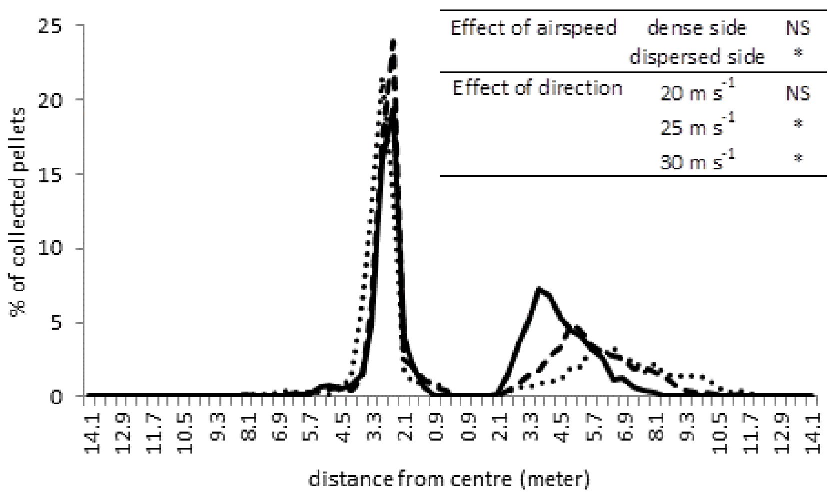



*Figure 4 Continues on next page*

(G)

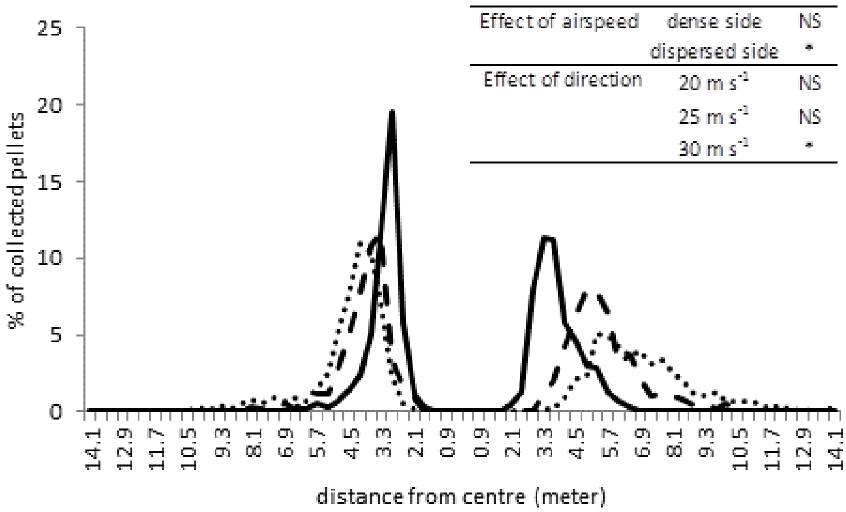



*Figure 4* *Relative pellet distribution at three different airspeeds; 20 m s$^{-1}$ (continuous line) 25 m s$^{-1}$ (broken line) and 30 m s$^{-1}$(dotted line). Distance from the centre is given as the middle of the box used to collect the pellets.* Results of statistical analyses (effect of airspeed by direction for each "treatment", and effect of direction by airspeed for each "treatment") are shown in the figures. NS not significant, * significant at $p<0.05$.

*A) Pellet size 7 mm tested on spreader A when tilted up (cage 2)*
*B) Pellet size 9 mm tested on spreader A when tilted up (cage 2)*
*C) Pellet size 9 mm tested on spreader B when tilted up (cage 2)*
*D) Pellet size 9 mm tested on spreader B when tilted down (cage 2)*
*E) Pellet size 9* mm tested on spreader A when tilted up (cage 1, separate feed batch)*
*F) Pellet size 9* mm tested on spreader A when tilted down (cage 1,separate feed batch)*
*G) Pellet size 12 mm tested on spreader A when tilted up (cage 2)*

## 3.5 Tilting

Tilting of spreader A was significantly affecting relative pellet distribution at 30 m $s^{-1}$ for both directions, but not for the two lowest airspeeds. For spreader B, tilting was significantly affecting pellet distribution on the dispersed direction at all three airspeeds, while no effect was observed for spreader B on the dense direction (Table 3). The PCA showed that tilting down was associated with distribution of pellets in a shorter distance from the centre, while tilting up was associated with a larger distances from the centre (Fig. 5). The effect of tilting on spreading symmetry gave different results for the two spreaders. Spreader A tilted down resulted in unsymmetrical pellet distribution (see symmetry of pellet distribution) and gave high spatial pellet densities on the dense side (Fig. 4 E). When spreader A was tilted up, the spreading was symmetrical for the two directions (Fig. 4 D). A different pattern was observed for spreader B. A more symmetrical spreading was observed for spreader B when it was tilted down (Fig. 4 G), compared to upward tilting (Fig. 4 F).

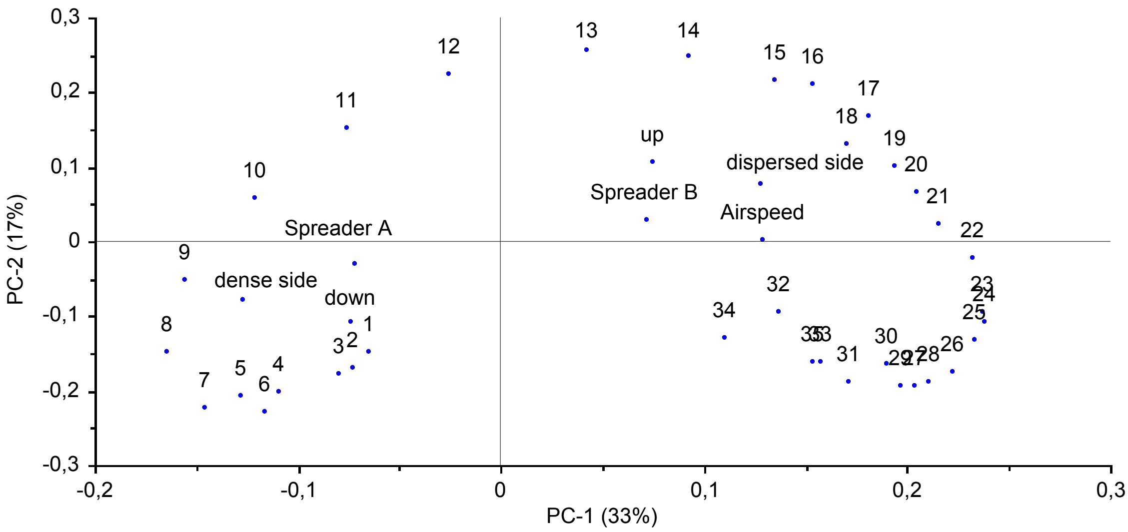



*Figure 5 Loading plot of PCA analysis shows the relationship between selected parameters (direction, airspeed, tilting and spreader type) and relative number of pellets per box. Principal component 1 (PC1) is given on x axis, and principal component 2 (PC2) is shown on y axis, and the variation explained by PC1 and PC2 respectively is given with the axis titles. For the categorical variables direction, tilting and spreader type, the levels of the variables (dense and dispersed direction; up and down; spreader A and spreader B) are given in the plot. Airspeed and relative number of pellets in boxes 1 to 35 were numeric variables.*

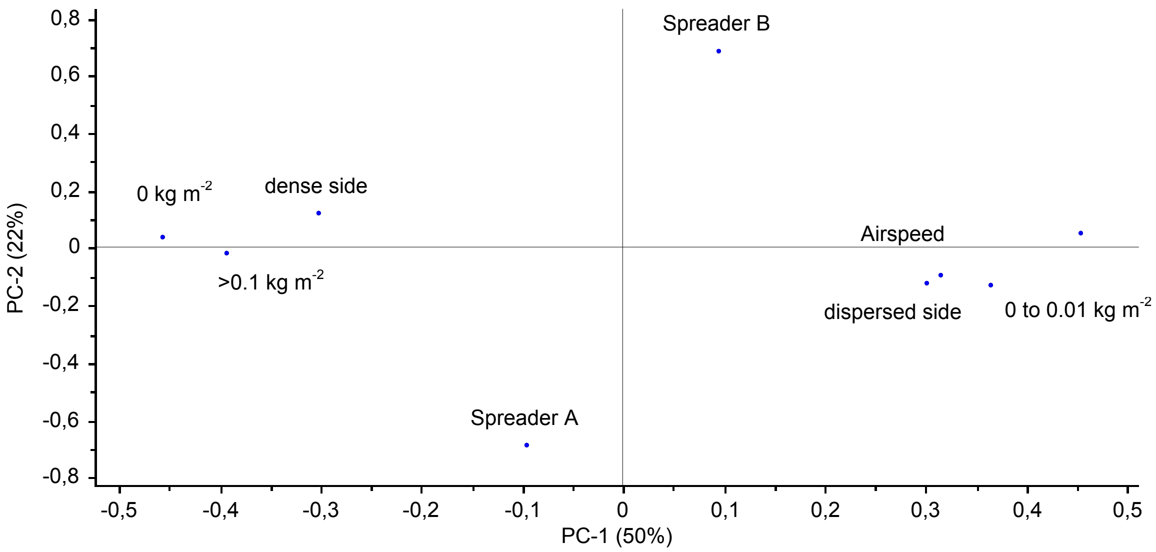



*Figure 6* *Loading plot of PCA analysis showing the relationship between cage area (%) with different pellet densities, spreader type and direction, tested with spreaders tilted up in the same cage with the same batch of 9 mm feed. Principal component 1 (PC1) is shown on the x-axis and the principal component 2 (PC2) on y-axis, and the variation explained by PC1 and PC2 is given with the axis titles.*

## 3.6 Spreader type

Relative pellet distributions were significantly different for the two spreader types when both were tilted upward, at airspeed 25 m $s^{-1}$ for the dispersed direction, and at 30 m $s^{-1}$ for both directions. At low airspeed (20 m $s^{-1}$) there was no difference between the two spreader types (Table 3). PCA analysis showed that spreader B distributed the pellets with further distance from the centre than spreader A (Fig. 5). Spreader type did not have a strong relationship to spatial pellet densities (Fig. 6).

# 4 Discussion

## 4.1 Pellet distribution pattern

The results from the experiment showed that pellets were not distributed uniformly over the cage surface, leading to areas with high spatial pellet densities and to areas which received little or no pellets. In a feeding situation this can lead to increased aggression and variation in feed intake and growth (Hatlen et al., 2006; Noble et al., 2008; Storebakken and Austreng, 1987) unless the feeding system is optimized to homogeneous distribution of pellets. There was a positive effect of airspeed on the proportion of cage areas covered with feed pellets at medium spatial pellet densities. Tilting and spreader type had no clear association to areas with certain spatial pellet densities. This indicates that the factors tested had a significant impact on spreading and in practice, a feeding system can be adjusted to modify the spreading area. The non-uniform spreading over the cage area can be explained by the design of the top unit and the constant airspeed used for each measurement. The same forces are applied to the pellets, being thrown to similar distances and directions.

To our knowledge there exists no information about the relationship between spatial pellet density (g $m^{-2}$), feed intake and feed loss in published literature. It is suggested that salmon with a weight of 125 - 5000 g need to ingest 10 - 30 pellets at a daily ration (1 % of body weight) and can ingest two to four pellets per minute at the beginning of a meal (Talbot, 1993) gradually decreasing to 0.7 to 1.4 pellets per minute in the second half of a meal depending on fish size (Talbot et al., 1999). Based on several studies on different fish species, complex factors like appetite and gastric evacuation rate affect the feeding behavior of the fish, complicating the feeding management (Oppedal et al., 2011; Talbot, 1993). To optimize feed intake, the feeding system should be adjusted to give a spreading pattern with appropriate spatial pellet densities. Generally, overfeeding and high feed delivery rates can contribute to feed loss (Alver et al., 2004; Ang and Petrell, 1998), while underfeeding can reduce growth, increase FCR, increase competitive behavior and fin damage (Hatlen et al., 2006; Helland et al., 2010; Noble et al., 2008, Storebakken and Austreng, 1987). These previous findings may explain the positive effects on growth rate observed when feed dispersion area was increased in sea cages (Thomassen and Lekang 1993). The latter authors made a comparison of point feeding, sector distribution and circular distribution and showed that large distribution area gave improved growth performance. This is in line with findings of Ang and Petrell (1998) who recommend spreading of pellets widely and unpredictable in order to reduce competitive behavior and pellet loss. However, the present study demonstrated that it is challenging to distribute the pellets uniformly over a large surface, even when a rotor spreader was used. Besides, distribution of pellets near the wall of the net pen may result in increased feed loss as reported by Alver et al. (2004), though these latter authors indicated a reduced feed waste with better feed dispersal. Using high air speed to spread feed over a large area also increased pellet breakage (Aas et al., 2011a).

For most measurements, the spreading pattern was not symmetrical for the two directions of the spreader leading to an uneven distribution of feed pellets over the cage surface. One explanation may be that free rotation of the spreader was restricted due to the stiffness of the feed pipe connected to the spreader. The spreader was positioned in the center and attached to the sides of the steel cage by use of ropes. The attachments to the spreader unit could contribute to the imbalanced rotation of the spreader. The imbalanced rotation may have affected the acceleration of the pellets and the angle of the pellets leaving the spreader. Pellet distribution on the dispersed direction was influenced by airspeed, while the opposite direction was not affected by airspeed and thereby creating increasingly asymmetric spreading pattern for the two directions with increasing airspeeds. It is expected to find longer spreading distances with increasing airspeeds as observed for the dispersed direction. For the dense direction, it appears that the forces on the pellets, even at high airspeeds, blew the pellets in a low angle resulting in a short spreading distance. In practical farming situation, it may be beneficial to utilize the non-symmetic of spreading with regards to wind direction and water current. If most pellets are thrown to the windward/ towards the current direction, less pellets may be lost through the net pen wall.

High airspeed was associated with the larger spreading distance of pellets, larger proportion of cage areas covered with feed pellets, and larger proportion of cage areas covered with low to medium spatial pellet densities. This was more pronounced for the dispersed direction, but was also noted for the dense direction. An explanation may be the stronger acceleration of pellets at high airspeeds. Consequently, pellets were thrown further away from the cage center. Under practical feeding situations, varying the airspeed may increase the cage area covered with feed pellets.

Spreader type had a strong impact on pellet distribution. The higher height above water of the more recent developed spreader could explain the longer spreading distances for spreader B, compared to spreader A. Tilting the top unit of spreader A and B affected pellet distribution, mostly in terms of symmetry to both directions, with effects of tilting being different for spreader A and B. When tilting down spreader A, an unsymmetrical pellet distribution was observed, while upward tilting on spreader A showed a symmetrical pellet distribution for the two directions. The unsymmetrical pattern was created by the high spatial pellet density for the dense direction as a result of downward tilting of spreader A. When spreader B was tilted downwards, a dense spreading pattern was observed for both directions, thus being symmetrical. As earlier suggested, as a consequence of downwards tilting of spreader B, the pellets may have left the spreader tip with a lower angle, and airspeed had no effect on the spreading distance. The different effects of tilting for spreader A and B could be related to the rotation velocity. Spreader B had a slower rotation velocity compared to spreader A (Table 1) causing less imbalance resulting in symmetrical spreading when tilted down.

Pellet size had no significant effect on relative pellet distribution. This can be explained by the same pellet velocity for the different pellet sizes (Table 1). Thus, the force applied to the pellets was equal for the three pellet sizes, resulting in similar spreading of pellets over the cage surface. However, with the same velocity, a greater mass has more inertia (Newton's law of motion). The 12 mm pellets were heavier and therefore more inert to gravity compared to 7 mm pellets, which were lighter and less inert to gravity grouping closer to the center. The differences in maximum spatial pellet density and spreading distance for the different pellet sizes can therefore be explained by the difference in specimen weight.

## 4.2 Feeding management, automatic feeding systems and physical feed quality

In order to facilitate high feed intake (Talbot, 1993) and to avoid generation of waste feed (Ang and Petrell, 1998), feeding rate, number of meals and feed distribution should be adjusted to meet the physiological and behavioral demand of the fish. Thus, in addition to a well-balanced diet, the feeding system and operation of the feeding system is essential. However, feeding the fish to satiation, and at the same time maintain low feed waste is a challenge (Bergheim & Åsgård, 1996; Thomassen & Lekang, 1993). Sveier & Lied (1998) did not find any differences in growth rate, feed utilization or final weight when comparing feeding in one hour compared to 22 hours a day. The experiment was carried out in tanks with 38 Atlantic salmon per tank and could indicate that feeding regime may be of less significance in small units with good control of feed intake. In contrast, Ang & Petrell (1998) reported that feeding regime and delivering of feed affected waste feed generation and availability of feed under practical farming conditions using cages between 13 x 13 x 20 m and 15 x 15 x 20 m. These findings may suggest that feeding practice in large sea cages with high number of fish is of greater importance than in small tanks. Several studies have indicated that when salmon is fed to satiation, feeding regime itself has no significant effect on production parameters, e.g. growth, FCR (Noble et al., 2008; Talbot, 1993; Talbot et al., 1999). Talbot (1993) suggested that feed intake and growth will be hampered if salmon is fed to satiation less than once per day.

Many components of a feeding system can differ: location and volume of silo, dosing, transport media, length and configuration of pipe from silo to cages, location of feeding point, method of feed dispersion in the cage. Certain types or settings of feeding system might be more suitable for specific conditions because environmental conditions (wind, water current), physical feed quality, status of the fish (size, appetite) etc. differ. The development of large cage systems is technically feasible, but the management of large biomass, including feeding of large volumes of fish is considered as one of the main challenge for successful future use of large units. Using rotor spreaders has been suggested as a solution to feed large volume of fish in large sea cages and is common in modern salmon farming sites. Pneumatic feeding systems demand high physical feed quality, produced by use of extrusion technology, and the feed industry supplies more and more durable pellets to minimize losses due to pellet degradation. The settings of a feeding system, such as airspeed can be used to control pellet degradation to a certain extent (Aarseth et al., 2006; Aas et al., 2011a). However, as shown in the present study, low airspeeds impair spreading of pellets over the cage surface. Other variables in the feeding system also affect degradation of pellets such as feeding rate, transport media, transport distance and pipe bends (Aarseth et al., 2006; Aas et al., 2011a). Pellets quality is also affected by storage (Zimonja et al., 2008), as well as choice of ingredients and processing technology (Glencross et al., 2010; Morken et al., 2011; Sørensen et al. 2011; Sørensen et al., 2010; Sørensen et al., 2009, Sørensen, in press), and often the quality varies in commercial feeds (Aas et al., 2011a). Recent publications have reported that there may be an interaction between physical quality of feed and feed intake, gastric evacuation rate and nutrient digestibility (Aas et al., 2011b; Bæverfjord et al., 2006; Glencross et al., 2011; Sveier et al., 1999; Sørensen 2011; Venou et al., 2009). The present experiment indicated that spreading of feed pellets with a pneumatic feeding system might impose high pellet quality, because a positive effect of airspeed on spreading radius and moderate spatial pellet density over the cage surface was found when using high airspeed.

Overall, physical feed quality (feed technology), feeding management and the nutritional response in fish are closely related. These topics should be considered together, and due to this trade-off characteristic, decisions might imply compromises.

# 5 Conclusion

In conclusion, this experiment showed that when using a pneumatic feeding system, distribution of feed pellets was non-uniform over the cage surface and that spreading area can be controlled by airspeed, spreader type and tilting position, while the spreading pattern was similar for feeds of different pellet sizes.

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