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Review

Precision fish farming: A new framework to improve production in aquaculture

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Aquaculture production of finfish has seen rapid growth in production volume and economic yield over the last decades, and is today a key provider of seafood. As the scale of production increases, so does the likelihood that the industry will face emerging biological, economic and social challenges that may influence the ability to maintain ethically sound, productive and environmentally friendly production of fish. It is therefore important that the industry aspires to monitor and control the effects of these challenges to avoid also upscaling potential problems when upscaling production. We introduce the Precision Fish Farming (PFF) concept whose aim is to apply control-engineering principles to fish production, thereby improving the farmer's ability to monitor, control and document biological processes in fish farms. By adapting several core principles from Precision Livestock Farming (PLF), and accounting for the boundary conditions and possibilities that are particular to farming operations in the aquatic environment, PFF will contribute to moving commercial aquaculture from the traditional experience-based to a knowledge-based production regime. This can only be achieved through increased use of emerging technologies and automated systems. We have also reviewed existing technological solutions that could represent important components in future PFF applications. To illustrate the potential of such applications, we have defined four case studies aimed at solving specific challenges related to biomass monitoring, control of feed delivery, parasite monitoring and management of crowding operations.

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1. Introduction: a technological journey from terrestrial animal production to intensive fish farming

1.1. *Modern intensive fish farming*

Modern intensive fish aquaculture comprises all life stages of the fish from brood-stock/eggs to fully-grown adults. The hatchery phase is typically conducted in indoor tanks, where one is able to control the environmental conditions and other external factors affecting the fish. While some species are raised in tanks all the way to marketable size, most industrially farmed finfish species are transferred to outdoor ponds or sea-cages for the final ongrowing phase. This is because the volume of water required by a fish depends strongly on its size, and a gradual scaling of the production unit volume as the fish grow is easier to facilitate in the sea or ponds than in indoor tanks. Sea-based fish farming also exposes fish to natural fluctuations in important features of the production environment (e.g. water flow, temperature and light intensity). Although this limits the farmer's ability to control the production conditions, and increases the chance that stressors such as pollutants, pathogens and parasites are introduced into the population, the simplicity and cost-effectiveness of open systems makes this approach more competitive today (Iversen, Andreassen, Hermansen, Larsen, & Terjesen, 2013).

Currently, Atlantic salmon (*Salmo salar* L.) are the most significant farmed sea-based finfish species with more than 2.3 Mt produced globally in 2014 (FAO, 2016). In Norwegian salmon production, ongrowth is conducted in flexible sea-cages located in sheltered coastal areas, or at locations more exposed to environmental forces (Bjelland et al., 2015, pp. 1–10). As with many other industries, salmon farming has sought to reap the benefits of economies of scale, meaning that both farm size and the size of individual cages has increased with the intent of producing more fish per employee, leading to increased profitability (Hallam, 1991). As a result, production cages at current Norwegian salmon farms often have a circumference of up to 157 m, contain a volume of approximately 40,000 m^3, and hold up to 200,000 individual fish. Considering that a typical fish farm consists of 8–16 separate cages, this means that each farming crew (typically 5–10 people in total) may be responsible for several million animals, amounting to a biomass of up to 15,000 t. Sea-based production of salmon is therefore a very large-scale intensive form of seafood production.

Much of the human historical knowledge on animal husbandry has been built on a direct relationship between farmer and animal. However, such relationships are not possible to establish with a population consisting of millions of individual animals living under water, making it almost impossible to evaluate the animals and collect information on the status of the population through direct observation. This challenge will be further amplified by the present trend towards moving aquaculture operations to more environmentally exposed areas, which will render the farms less accessible to farmers (Bjelland et al., 2015, pp. 1–10). Due to these factors, a regime based on direct observation alone may be insufficient to acquire the levels of knowledge, monitoring and control required to tackle the challenges of modern fish farming. Instead, what is required for modern large-scale fish farming are technological tools that enable remote monitoring of large populations of fish in a manner that yields data that can be used to adjust and modify day-to-day operations to optimise the growth and survival of the fish. The idea of applying such principles to commercial fish production may be traced back to the original thoughts and philosophies of Jens Glad Balchen (Balchen, 1979).

1.2. *Precision Livestock Farming*

Livestock production is the second largest supplier of food for human consumption behind vegetable/cereal agriculture. Although there have been several initiatives concerning automated sensing and detection of farm animal responses (e.g. Van der Stuyft, Schofield, Randall, Wambacq, & Goedseels, 1991; Maatje, De Mol, & Rossing, 1997), and mathematical modelling of animal behavioural and physiological dynamics (e.g. Bastianelli & Sauvant, 1997; Kristensen & Kristensen, 1998) in the 80's and 90's, the first conceptual framework of Precision Livestock Farming (PLF) was not established until the turn of the millennium by Berckmans (2004). While the general principle of using technology and automation to improve precision in industrial production is directly transferrable from the process and manufacturing industries to PLF, the transition of focus from inert products to live animals introduces the following additional complications that need to be taken into account when developing PLF methods:

- Observation and monitoring is more challenging, as animals at times exhibit complex behaviour that may be difficult to observe and interpret.
- Animals may move and are not always willing or able to cooperate with the farmer, making the implementation of automated actions more difficult.
- In addition to covering the basal requirements for survival, animal needs are also linked with their ability to exhibit certain behaviours, and maintain a certain perceived quality of life, or welfare.

Berckmans (2004) stated three distinct conditions that a system would need to fulfil if it was to achieve sufficient levels of monitoring and control to be considered a PLF system:

1) *Animal variables* (i.e. parameters related to the behavioural or physiological state of the animal) need to be measured continuously with cost-effective robust sensor technology,
2) a reliable model for predicting (expectation of) how *Animal variables* will dynamically vary in response to external factors at any moment must be available, and
3) predictions and on-line measurements are integrated in an analysing algorithm for automatic monitoring and/or control.

PLF methods are often defined using a common terminology denoting the different components in a PLF-system (Table 1).

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