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Finding the "golden stocking density": A balance between fish welfare and farmers' perspectives

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The effects of stocking density on fish welfare are complex and involve many interacting parameters. This complex relationship between fish welfare, stocking density and influencing factors make it challenging to define a specific optimal ("golden") stocking density. Indeed, previously published recommendations on stocking density for different species of aquaculture interest are incredibly variable even at the same life stage, and can also vary widely within a rearing unit. Production density can be estimated quite accurately if the farmer has good biomass control and a known water volume, but it is difficult to set minimum and maximum stocking density levels that will protect welfare. However, there is little doubt that stocking densities that are too low or too high can have negative impacts on welfare and/or production. Here, we propose how to select density on captive fish and monitor its potential effects integrating 1) solid welfare assessment based on operational welfare indicators and 2) good management practices. Regulation directly limiting stocking density is likely to be unworkable and ineffective, and a more rational option might be to prescribe acceptable levels of different welfare indicators (e.g., water quality, health, nutritional condition and behavioral indicators), which together with a positive economic balance of the company, allow to estimate the most suitable range of fish density for each particular species, life-stage and production systems.

KEYWORDS
density, fish welfare, operational welfare indicators, fish farming, economic sustainability

Introduction

The artificial conditions in the aquaculture industry pose unnatural challenges to fishes (1), which must deal with space restrictions, unnatural aggregations or inadequate stocking densities that may increase the risk of health issues and welfare impairments, such as infections, social aggressive encounters, food competition, among other stressful conditions (2, 3). Fish stocking density (or rearing density) in aquaculture is understood as the density of fish at any point in time within the rearing system (2). For a variety of reasons, stocking density is a very relevant issue in aquaculture, which is causing intense debate among stakeholders involved in fish farming. From fish farmers to certifiers and even animal advocacy groups, all parties seem to be searching for the "golden stocking density", but such magical number is often sought using biased judgement based on unilateral perspectives in order to support agendas. Here we propose that fish stocking density is a problem that can be studied with an integrative approach based on both the fish welfare and the farmer perspectives. Fish requirements for optimal welfare concerning stocking density in aquaculture are complex and highly dependent on the species and life-stage, as well as on the farm characteristics and farming systems (e.g., methodology, technology used, magnitude, etc.) [e.g. (3)]. All these factors are a unique combination and make it impossible to define the appropriate "golden" number for stocking density without considering both the animal and the farmer perspectives. We propose that this problem should be addressed as a balanced outcome between fish welfare indicators and good management practices (Figure 1).

The balance between fish welfare and farmers' perspectives

Fish and farming system specificities

"Optimum" fish stocking density is a complex variable resulting from a number of interrelated processes, which highly depends on the fish species and life-stage of the animal reared in captivity, but also on the farming characteristics and systems where the animal is reared (3). In addition, stress coping styles of individuals within farmed populations also play a role on how density influences welfare-related reponses to different densities (4) and this interaction between coping styles and density may even vary along the life stage of the animal (5). There is a large body of scientific literature indicating negative effects at different densities in different species, life-stages and production systems. For example, Atlantic salmon (*Salmo salar*) smolts and post-smolts reared in tanks at densities of 15 kg/m^3 presented increased skin and fin damage, lower growth, and higher incidence of agonistic behaviors (6), whereas high stocking densities (35 kg/m^3) also led to increased skin and fin damage. In land-based systems, negative effects on food conversion rate (FCR) and physiological stress markers on Atlantic salmon occur at densities above 75 Kg/m^3 (7). Crowding can also result in aggression, physical damage, and deterioration of water quality (6, 8). Densities above 26.5 kg/m^3 cause decreased growth rate, feed intake and feed utilization in adult Atlantic salmon in sea cages (7). For rainbow trout (*Oncorhynchus mykiss*), the average food consumption of individual fish was found to decrease with increasing density (2, 9). On the other hand, low density resulted in poor feeding response causing mortality through excessive aggressive behavior in this species (2), and both low and high stocking densities of rainbow trout parr and smolts have negative effects on welfare (10).

Similarly, very low stocking densities may lead to aggression, stress, and consequent immune depression and health problems on Nile tilapia (*Oreochromis niloticus*) (11), and lower individual weight and lower aggressiveness were found at high stocking densities (12, 13). Cages at a final density of 30 kg/m^3, presented better performance and health indicators of Nile tilapia than at higher densities, and producer gross profits were also higher due cost optimisation of inorganic fertilizers (14). Other examples are the cases of gilthead seabream (*Sparus aurata*) and European seabass (*Dicentrarchus labrax*). Seabream larvae are aggressive in tanks (15, 16) and juveniles and adults can compete for food in cages at low densities (3 kg/m^3) (17). However, high stocking density (40 kg/m^3) produced physiological alterations, such as a decrease in the hepatosomatic index, and production of both hormonal and metabolic alterations including a reduction in thyroid hormone activity (18). High densities (45–60 Kg/m^3) in intensive systems induced stress (19–21), and fin and skin damages (22) on seabass. Nevertheless, it was also shown that stress levels on seabass at high densities decrease with good maintenance conditions (21, 23). All these are just examples to illustrate how complex and controversial is fish stocking density in aquaculture, and suggest that welfare indicators might help to assess the selected density in every farming system (24). Therefore, we recommend that finding an appropriate stocking density (*i.e.,* optimal range) can be only done through the welfare aspects of the fish and good management practices of the farmers, with each company and context producing a unique result.

$$Density_{a,b,c} = \sum Welfare_{i,j,k} \text{ X } \sum Management_{x,y,z}$$

a: Fish species	i: Individual-based WIs	x: Maintenance
b: Life-stage	j: Group-based WIs	y: Procedures
c: Farming system	k: Environmental WIs	z: Training

FIGURE 1
Model representation of the complex components and relations of fish stocking density in terms of fish welfare and good management practices in aquaculture. WI, welfare indicators.

Stocking density, fish welfare and operational indicators

Stocking densities have an impact on the welfare of farmed fish. To address this impact it is essential to (a) define the concept of welfare, (b) find suitable welfare indicators and (c) validate and apply them correctly (25). Welfare is a complex concept and most definitions are broad, reflecting that our understanding of animal welfare and its assessment is influenced by value-based ideas on what is important or desirable for animals (26, 27). The three approaches normally used in animal welfare are: (i) feelings-based approach, related to the animal's mental state and that the animal should be free from negative experiences and have access to positive ones; (ii) function-based approach, which uses good health and the animals' ability to adapt to their environment and the biological and functioning systems as a basis to assess and improve animal welfare; lastly, (iii) nature-based approach, referring to the view that each species express their inherent biological nature requiring respect for the animals' nature and their necessity to have a more natural environment and express a natural behavior (26, 27). Each of the different approaches has led to important improvements in animal welfare (26) and because suffering, health problems and impairment of natural behavior often accompany each other, their integration could help operationalize the animal welfare concept, as behavior combined with both physiological and mental indicators allows an objective measure of welfare (27, 28). Therefore, animal welfare may be defined as the state of the animal and his ability to cope with the environment (29). This definition of welfare allows the measurement and assessment through indicators because: (a) welfare is representative of an individual and not given to him; (b) welfare may vary from very good to very bad; (c) welfare can be measured independently of any ethical matters; (d) information about poor welfare can be given by measures on animal's difficulty to cope with the environment; (e) knowledge on the biology and life-history of the animal in combination with direct measurements of its state must be used to assess vital information; (f) different species may present different coping mechanisms with diverse consequences for its failure (25). It is clear that different species, life-stages and, in fact, individuals will cope differently with different stocking densities. Yet how can we assess this coping?

Fish welfare assessment must be based on operational welfare indicators, which are practical and feasible measurements or observations that give information about the degree of fulfillment of the animals' welfare needs, which is assumed to be correlated with the welfare state (30). Fish welfare indicators can be direct "animal-based indicators", centered on observations of attributes of the animal itself, or indirect "environment-based indicators", centered on the resources and environment to which the animals are subjected (31, 32). Animal-based welfare indicators are attributes from the animal itself that may indicate that one or more welfare needs have not been fulfilled (33). They can be based on the individual appearance and physical conditions (33), or on behavioral aspects at both individual and group levels (34). Animal-based welfare indicators measure the result of the treatment on the animals themselves, and therefore, highly applicable for assessing density effects on different farming systems. Animal-based indicators are more directly linked to the state of the fish than environmental indicators, but the latter indicators (e.g., water quality parameters) may predict a problem whilst animal based indicators may only become apparent once the animal is already experiencing poor welfare (33). Proper integration of information is key: growth or survival rates, for example, are not reliable welfare indicators on their own (as they provide overly simplistic information), but they can be considered if accompanied by other direct and also indirect indicators. It must be noted that some authors suggested fish stocking density as an environment-based welfare indicator (33, 35), that must be used in tandem with other indicators when considering fish welfare (8). These authors suggested that fish density can be interpreted as a measure that describes what the animals are subjected to and that influence the fulfillment of one or more welfare needs. However, density *per se* should not be taken as a welfare indicator, as there is no functional meaning or biological need behind these parameters, and highly depends upon environmental factors. Stocking density directly affects fish welfare in a complex way, influencing all other welfare parameters and indicators, and therefore, it must be only considered as a farmer management decision tool.

Good management practices

The welfare needs of captive fish in aquaculture are non-linearly affected by stocking density and those effects are influenced and modulated by standard operational procedures on each farm (3). The potential negative effects of (too low or too high) stocking density may not always be caused by the density of fish *per se*, but rather by inefficient or inappropriate maintenance and procedures at farms. Stocking density influences and is influenced by environmental factors, such as water exchange rate, temperature, or pH, but also depends on fish size and feeding rate (2). Therefore, poor welfare related to fish density can be caused by reduced water quality, reduced feed availability, or social interactions, among others (2). For example, the quality and amount of inflow water will determine whether density results in water quality deterioration to sub-lethal or lethal levels, which is of greatest significance when farms reuse water, either *via* passage through successive systems or by recirculation (2). Inflow rate and system volume will determine the rate of water replacement, and hence the provision of dissolved oxygen (DO) and dilution of metabolic wastes (NH_3 and CO_2). Temperature is also a vital factor correlated to fish density and water quality, determining the rate of metabolism of fish, the solubility of DO, and the toxicity of ammonia; and pH will interact with density by altering the equilibrium of the two forms of ammonia (2). Poor water quality can lead to diseases outbreaks and increase mortalities. Feeding reduces the DO level of the water (36), and food deficiency can

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promote competition, aggressiveness or social stress in captive fish. Stocking densities directly influence social interactions, promoting the formation of dominance hierarchies, where individuals use different tactics to compete for limited resources such as food, impairing the welfare of the farmed fish (37). Therefore, good management practices ensuring good welfare of farmed fish according to the species, life-stage and farming systems used should be in place. This implies, for example, exhaustive water quality controls and monitoring, hygiene and biosecurity control programs, adjusted feeding protocols, or the implementation of appropriate environmental enrichment strategies (38). It is worth mentioning that Good Management Practices should include the implementation of tailored fish welfare assessment protocols, based on operational welfare indicators, helping the refinement and efficiency of such practices in each aquaculture facility, including the monitoring of fish stocking density effects. In addition, all procedures carried out in aquaculture facilities must be carried out by trained and qualified personnel to ensure good monitoring of density effects and fish welfare status. Last but not least, all these management procedures that a farmer can do in order to assess and improve the welfare of their captive fish, including the adjustment or correct selection of fish stocking density, must be combined with the economic profitability of the company (Figure 2). Besides the ethical and moral importance of caring for captive animals, good welfare potentially benefits all the diverse parties interested in fish culture. From an economic perspective (up to a point and in many cases), good production and good welfare go hand in hand, poor welfare often impacting on production related traits (1). Public concern about the welfare of farmed fish has been confirmed in surveys at European scale (see https://comresglobal.com/polls/eurogroup-for-animals-ciwf-fish-welfare-survey/) and consumer pressure is responsible for enhanced control and regulation in welfare assurance schemes (e.g. RSPCA Assured, ASC, Friend Of the Sea, GlobalGAP, BAP, CertifiedHumane.org and the Global Animal Partnership) and by policy advice or regulation at national and international/European level (e.g. World Organization for Animal Health (OIE), Norwegian Food Safety Authority). Therefore, in some markets at least, there are premiums to be charged for fish cultured under welfare assurance schemes (33). Additionally, ensuring good welfare in farmed fish is an important aspect of job satisfaction for fish farm workers (39, 40). In simpler terms, fish under good welfare will represent a higher yield and a higher financial income for the business in developed markets.

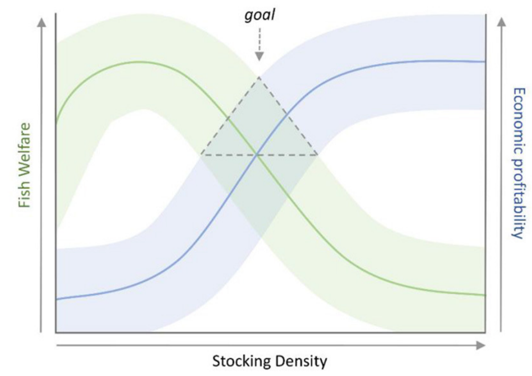

FIGURE 2
Schematic representation of the relationships of stocking density with fish welfare status and potential economic profitability in the aquaculture industry. The dashed triangle area represents the theoretical goal of the industry. Shaded areas of light green and light blue represent theoretical confidence intervals.

Discussion

Previously published recommendations on stocking density for different species of aquaculture interest are incredibly variable even at the same life stage, and can also vary widely within a rearing unit, most likely because the effects of stocking density upon welfare are complex and involve many interacting parameters [e.g. (2, 3)]. This complex relationship between fish welfare, stocking density and influencing factors make it challenging to define a specific optimal stocking density but there is little doubt that stocking densities that are too low or high can have negative impacts on welfare (6). Production density can be estimated quite accurately if the farmer has good biomass control and a known water volume, but it is difficult to set minimum and maximum stocking density levels that will protect welfare (35). Therefore, a preferable approach to monitoring the effects of density on captive fish is the application of fish welfare assessments based on operational welfare indicators, ensuring that, consequently, good management practices are in place. Legislation directly limiting stocking density is likely to be unworkable, and a more practical option might be to prescribe acceptable levels of different welfare indicators (e.g., water quality, health, nutritional condition and behavioral indicators), which together with a positive economic balance of the company, allow to estimate the most suitable range of fish density for each particular species, life-stage and production systems. It is natural that certification schemes or regulatory bodies may desire a value to aim at. Our proposal is that this number (if present) should be seen as recommendation, and that solid welfare indicators in such a scheme or regulation should be the main component for assessment of compliance. In this sense, current or prospective certification bodies that aim to address fish welfare in aquaculture should avoid relying on a fixed value and rather focus on welfare aspects and good management practices. In the absence of legislation, these certification labels will not only improve the quality of life and welfare of captive fish, but will also bring ethical and economic benefits to aquaculture companies.

Author contributions

PA-L and JS conceptualized the study. JS, PR-L, and PA-L wrote the manuscript. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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