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Stocking density effect on survival and growth of early life stages of maraena whitefish, *Coregonus maraena* (Actinopterygii: Salmoniformes: Salmonidae)

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Abstract

The maraena whitefish, *Coregonus maraena* (Bloch, 1779), is often considered a suitable candidate for intensive aquaculture diversification in the EU. However, only a few such farms in Europe are in operation. Rearing this species in recirculating aquaculture systems is a recent innovation, and optimisation is necessary to standardise aspects of larviculture. This 30-day study investigated the effect of stocking densities of 25/L, 50/L, 100/L, and 200/L on the survival and growth of maraena whitefish larvae in a recirculating aquaculture system. The four groups of larvae (initial weight = 7.4 ± 0.1 mg; initial total length = 13.0 ± 0.1 mm) in three repetitions were reared in a recirculating system. Larvae were fed fresh live brine shrimp metanauplii every 3 h at a rate converted to larval stocking density. After the experiment, 10 larvae from each tank (30 of each density group) were weighed on a digital microbalance (ABJ 220-4M KERN, Germany, readout = 0.1 mg) and measured manually on images taken with Leica MZ16 A stereomicroscope and a digital colour camera with 5-megapixel resolution for Leica DFC420 Image Analysis. No significant differences in final body weight, total length, size heterogeneity, condition factor, or survival were found among treatments ($P > 0.05$). The highest non-significant survival rate and growth parameters were observed in larvae reared at 25/L. On the contrary, it is possible to rear maraena whitefish larvae at high stocking density without any subsequent negative consequences for growth and survival. As no significant differences in any evaluated parameter were observed between groups of larvae at the highest and lowest stocking density, we conclude that it is possible to rear maraena whitefish larvae at high stocking density (and 200/L) without any subsequent negative consequences for growth and survival.

Keywords

coregonids, fry, growth metrics, larviculture, recirculation systems

Introduction

The maraena whitefish, *Coregonus maraena* (Bloch, 1779), is a promising species for inland freshwater aquaculture throughout east-central Europe (Mukhachev and Gunin 1999), and northern Europe, especially Finland (Jobling et al. 2010) and Norway (Siikavuopio et al. 2011). Several decades ago, due to predation by the great cormorant *Phalacrocorax carbo*, the population dramatically declined (Suter 1997). Eutrophication has also contributed to the decrease

(Thomas and Eckmann 2007). At present, it is important that re-establishment of whitefish natural production be accompanied by the culture in intensive aqua systems. The recirculating aquaculture system is an important model in worldwide aquaculture, given its cost-effectiveness, low environmental impact, ease of regulating water quality, and final product quality control features (d'Orbcastel et al. 2009). The establishment of coregonid production in recirculating systems requires that optimal larviculture conditions, including stocking density as a crucial factor in the productivity of fish culture systems, be identified.

Excessively high density can produce a stress response, particularly increased plasma cortisol level (Li et al. 2012), impede thyroid hormone production (Herrera et al. 2016), and affect growth (Żarski et al. 2008) and survival (Molnár et al. 2004; Szkudlarek and Zakes 2007). High density can lead to fin erosion, gill damage, fish welfare impairment (Ellis et al. 2002), and promote cannibalism (Liao and Chang 2002). It can decrease food utilization (Sharma and Chakrabarti 1998) and alter metabolic rate (Tolussi et al. 2010) with respect to lipids (Mommsen et al. 1999), carbohydrates (Sangiao-Alvarellos et al. 2005), and proteins (Costas et al. 2008). Finally, high fish density can impair water quality (Montero et al. 1999), reducing oxygen levels and increasing ammonia concentration accompanied with parasitical incidence, moderate hyperplasia and absence of congestion (Azevedo et al. 2006) in commercial production systems. These negative aspects such as cannibalism or aggressive behaviour lead to mass mortality of larvae and cause economic loss (Smith and Reay 1991; Ruzzante 1994) as well as disrupt production stability (Rowland et al. 2006). On the other hand, low stocking density is associated with high production costs (Luz and Santos 2008). Stocking density has been shown to be a limiting factor in fish growth during early development (Webb et al. 2007), while its impact is mitigated in adult fish (Duarte et al. 2004).

In Europe, the initial rearing of coregonid larvae in intensive indoor tanks is usually practised with stocking densities ranging from 5 to 100 larvae/L (Dabrowski and Poczyczynski 1988; Beltran and Champigneulle 1992; Esmaeilzadeh-Leithner and Wanzenböck 2018). Moreover, larvae rearing of lake whitefish, *Coregonus clupeaformis* (Mitchill, 1818), as similar commercially important species from North America is usually done with low density (30 larvae per L) (Zitzow and Millard 1988, Harris and Hulsman 1991).

The optimal stocking density needs to be determined for each fish species and developmental/reproductive stage to facilitate survival and growth and enable efficient management to maximise production and profitability, as well as to provide proper conditions for fish. Information on stocking density effects on maraena whitefish larvae growth performance and survival is scarce. The goal of the presently reported study was to determine whether stocking density affects the survival and growth of maraena whitefish larvae reared in a recirculating aquaculture system (RAS).

Materials and methods

Eggs and larvae

Maraena whitefish were obtained from in the Szczecin Lagoon (the River Odra estuary), north-western Poland. The broodstock comprised 120 fish at a 1:1 sex ratio. Gametes of three-year-old 60 females (mean weight, 800.4 ± 80.1 g, mean ± SEM; mean total length, 30.2 ± 1.1 cm) and three-year-old 60 males (650.5 ± 49.7 g, mean ± SEM; mean total length, 26.4 ± 0.9 cm) were stripped manually (no hormone stimulation) by commercial fishermen in December 2016 shortly after fish capture and transported to local hatcheries for fertilization and incubation. Eggs (100 mg) were fertilized with 0.5 mL of milt mixed with 50 mL of hatchery water and incubated at the ambient water temperature of the river (2–3°C) with initial water inflow 3 L/min, oxygen saturation to 90%, and pH near 7.0. In February 2017, the eggs were taken to the Department of Lake and River Fisheries (Olsztyn, Poland) where they were distributed among five 8-L Zug jars (n = ~150 000 eggs/jar) in a recirculating system and incubated at 3.0–3.5°C with water inflow 3 L/min, oxygen saturation to 90%, and pH near 7.0. In total, ~750 000 eggs were incubated. After 60 days, eggs were transferred to the second set of 8-L Zug jars and incubated at 8–9°C to accelerate development and hatching. After 5 days, the temperature was increased to 10°C for mass hatching. Hatching success was estimated at 90%, and about 675 000 larvae were available for the experiment. Hatched larvae swam across to a tank (total volume 1 m^3) underlain with 0.2 mm mesh. After 24 h, larvae were transferred to tanks in the RAS.

Experimental system

Four groups of larvae in three replicates were transferred to the experimental aqua system consisting of twelve 2 L aquaria, 96 × 154 × 200 mm. The recirculating system (2300-L total water volume) included a series of filtration sections (total biofilter volume 1500-L), a settling tank (500-L water volume). Thirty fish were weighed and measured to obtain the initial values for weight and length. Maraena whitefish larvae (initial weight, 7.4 ± 0.1 mg, mean ± SEM; initial total length, 13.0 ± 0.1 mm) were placed into each aquarium at stocking density of 25/L (S25), 50/L (S50), 100/L (S100), and 200/L (S200). A biomass by litre (g/L) was 0.185 (S25), 0.370 (S50), 0.740 (S100), 1.480 (S200). A total of 2250 larvae were used in the experiment.

Rearing conditions

The oxygen level, water temperature, and pH were checked daily at 0800 and 1600 h. The pH range was monitored using an OxyGuard H04PP Handy pH meter (OxyGuard International, Denmark). The initial tempera-

ture without supplemental heat was 10°C. Water temperature ~19°C was regulated by a HAILEA HC-1000A cooler (China). The temperature was gradually elevated from 10°C to 19°C (3°C/day). Oxygenation was maintained using two SICCE Syncra 5.0 pumps (5000 L/h) (Italy). Ammonia, nitrate, and nitrite concentrations were analysed using HACH, LCK 304, LCK 339, LCK 341 (Germany) with a HACH DR5000 spectrophotometer (Germany). Disinfection used a 30 W UV MCT Transformatoren GmbH steriliser (Germany). NaCl was added at 1 g/L weekly to maintain a 16:1 chloride:nitrogen ratio. A constant inflow of 0.4 L/min was ensured. Dead larvae were removed and counted during daily cleaning. The level of organic matter remained low. A low CO_2 level was maintained via aeration and keeping alkalinity stable. During the 30-day trial, basic physico-chemical parameters were following: temperature = 19.1 ± 0.0°C, pH = 8.7 ± 0.0, O_2 saturation = 85.8 ± 0.9%, O_2 concentration = 7.9 ± 0.1 mg/L, NH_4^+ = 0.1 ± 0.0 mg/L, NO_2 = 0.8 ± 0.1 mg/L, NO_3 = 21.2 ± 5.4 mg/L.

Feeding

Larvae were fed fresh live metanauplii of brine shrimp, *Artemia salina* (Ocean nutrition, HE > 230 000 NPG, Belgium) (20–24 h old, 0.4–0.5 mm) four times daily at 3 h intervals during the light phase (0830 to 1730 h). The feeding level was fixed to the range of 500–700 *Artemia* sp. metanauplii per fish per day at a rate converted to larval stocking density (Table 1). The daily ratio was based on a previous experiment (unpublished data). Furthermore, this ration was in slight excess as some uneaten metanauplii were observed in tanks at the end of the day. The feeding level was adapted according to losses of larvae during the experiment and fish body weight (Fiogbé and Kestemont 2003) using the formula

$$R_{opt} = 4.89W^{-0.27}$$

where R_{opt} = optimal daily feeding level, W = body weight [g].

Sampling and measurements

After the experiment, 10 larvae from each tank (30 of each density group) were weighed on a digital microbalance (ABJ 220-4M KERN, Germany, readout = 0.1 mg) and measured manually from images taken with Leica MZ16 A stereomicroscope and a digital colour camera with 5-megapixel resolution for Leica DFC420 Image Analysis.

Table 1. Concentration of brine shrimp (*Artemia salina*) fed to larvae of maraena whitefish, *Coregonus maraena* (Bloch, 1779) in a 30-day trial.

Group	Whitefish stocking density		*Artemia* feeding dose	
	[larvae/L]	[larvae/2L]	[mL/L]	[mL/2L]
S25	25	50	2.5	5
S50	50	100	5.0	10
S100	100	200	10.0	20
S200	200	400	20.0	40

Values for 2 L relate to the volume of 2-L aquarium.

A sample size of ten larvae per tank, 30 larvae per treatment, was used as in a number of studies (Kaiser et al. 2003, Mahmood et al. 2004, Fletcher et al. 2007, Celada et al. 2008, Nowosad et al. 2013, Palińska-Żarska et al. 2014, Laczynska et al. 2016).

The survival rate (SR), size heterogeneity (SH), and condition factor (K) and specific growth rate (SGR) were assessed as follows:

$$SR\ (\%) = 100 \times (Nf/Ni)$$

in which N_i and N_f = initial and final number of larvae, respectively;

$$SH\ (\%) = 100 \times (SD/W_m)$$

in which SH = size heterogeneity; SD = mean standard deviation of weight of 10 randomly selected larvae/tank; W_m = mean weight [mg] of 10 larvae/tank.

$$K = 100\ 000 \times W \times (TL^3)^{-1}$$

in which W = mean weight [g] of 10 larvae/tank; TL = mean total length [mm] of 10 larvae/tank

$$SGR\ (\%) = 100 \times [(\ln W_t - \ln W_0)/d]$$

in which W_t and W_0 are final and initial weight of larvae, respectively [g]; d = duration of the experiment [days].

Statistical analysis

Statistical analyses were performed using STATISTICA 12.0 (StatSoft, Praha, Czech Republic). Data are presented as mean ± SEM. The effects of stocking density on W, TL, SR, K, SH, and SGR were analysed by one-way ANOVA with stocking density as a fixed variable. Differences were considered significant at $P < 0.05$. Prior to ANOVA, SR, K, SH, and SGR were arcsine-transformed. All data were tested for homogeneity of variance using the Cochran, Hartley, and Bartlett test, and for normality with the Shapiro–Wilk normality test. The parametric Tukey test was used for assessing differences among groups in W, TL, SR, SH, K, and SGR (Table 2).

Results

At the conclusion of the trial, no significant (P>0.05) differences among treatments were observed in SR, W, TL, SH, K, or SGR (Table 2). The highest SR (92.7% ± 2.4%),

Table 2. One-way ANOVA results for the factor stocking density on total length (TL), body weight (*W*), size heterogeneity (SH), condition factor (*K*), survival rate (SR), and specific growth rate (SGR) of larvae of maraena whitefish, *Coregonus maraena* (Bloch, 1779).

Parameter	Source of variation	SS	DF	*F*	MS	*P*
TL	SD	0.9	3.0	0.3	2.3	0.2
W	SD	466.3	3.0	155.4	2.7	0.1
SH	SD	22.7	3.0	7.6	0.2	0.9
K	SD	0.0	3.0	0.0	2.2	0.2
SR	SD	3.6	3.0	1.2	0.2	0.9
SGR	SD	0.0001	3.0	2.1	0.00005	0.2

SD = stocking density; SS = sum of square; DF = degrees of freedom; *F* = distribution fitting; MS = mean square; *P* = probability.

Table 3. Effect of stocking density on growth and survival of larvae of maraena whitefish, *Coregonus maraena* (Bloch, 1779), in a 30-day growing trial.

Group	SR [%]	TL [mm]	*W* [mg]	SH [%]	*K*	SGR [%]
S25	92.7 ± 2.4	30.7 ± 0.3	147.9 ± 5.8	22.5 ± 4.3	0.51 ± 0.01	0.50 ± 0.003
S50	91.3 ± 1.5	30.4 ± 0.2	135.7 ± 1.6	20.3 ± 3.6	0.48 ± 0.01	0.49 ± 0.001
S100	91.33 ± 1.1	30.4 ± 0.1	135.1 ± 3.5	21.1 ± 4.9	0.48 ± 0.00	0.49 ± 0.003
S200	91.8 ± 1.0	30.0 ± 02	131.3 ± 5.2	18.7 ± 2.3	0.49 ± 0.01	0.49 ± 0.004

Groups represent stocking densities of 25, 50, 100, and 200 larvae/L, respectively; SR = survival rate, TL = total length, *W* = body weight, SH = size heterogeneity, *K* = condition factor, SGR = specific growth rate.

W (147.9 ± 6.3 mg), TL (30.7 ± 0.4 mm), SH (22.5% ± 1.1%), *K* (0.51 ± 0.01), and SGR (0.50 ± 0.003%) was observed at S25 (Table 3).

Discussion

The fact that growth–weight parameters did not differ significantly means that maraena whitefish growth was not influenced by stocking density at the tested levels. Slightly lower (non-significant) growth was found with increasing stocking density. It is important to sustain uniformity of fish size in aquaculture (Biswas et al. 2010). The effect of stocking density on larva size heterogeneity may be species-dependant. For instance, the relation of stocking density to size heterogeneity has been reported to be positive in red tilapia *Oreochromis niloticus* (Linnaeus, 1758) × *Oreochromis mossambicus* (Peters, 1852), when stocking density was 0.1, 0.2, 0.4, 0.8, 1.6, and 3.2 fry per litre (Huang and Chiu 1997), but negative in Arctic charr, *Salvelinus alpinus* (Linnaeus, 1758), with stocking density 10, 20, 28, 40, 60, 80, and 100 fry per litre (Wallace et al. 1988). We found size variation with respect to stocking density at the levels tested to be negligible with the only non-significant more uniform size in the S200 group and the least uniform in the S25 group. North et al. (2006) observed the same trend, with the highest size heterogeneity observed in rainbow trout, *Oncorhynchus mykiss* (Walbaum, 1792), reared in low stocking density and vice versa.

Stocking density can influence mortality rate, with survival often negatively correlated with stocking density as shown for silver perch, *Bidyanus bidyanus* (Mitchell, 1838) (see Rowland et al. 2006). Fish species can be classified as density-independent or density-dependent. Tilapia larvae (Huang and Chiu 1997) were reported to be density-dependent. Survival was high and not significantly affected by stocking density in the presently reported study, thus maraena whitefish seem to be density-independent, and stocking density is not likely a limiting factor in their survival in intensive rearing. High survival in all groups indicates that high-density aquaculture may be suitable for the production of this species. This phenomenon was also seen in Kupren et al. (2011) for asp, *Leuciscus aspius* (Linnaeus, 1758); ide, *Leuciscus idus* (Linnaeus, 1758); and chub, *Squalius cephalus* (Linnaeus, 1758).

Stocking density has been reported to be an important factor in fish growth (Saoud et al. 2008) and is of particular concern in the welfare of intensively farmed fish (Ashley 2007, Wocher et al. 2011). Mortality (Ellis et al. 2012), as well as susceptibility to pathogen infections and fin damage (Turnbull et al. 1998, Jones et al. 2011), in farmed fish, are generally considered important indicators of welfare. Ashley (2007) suggests that unsuitable stocking density can result in damage or death of fish. Negative effects of high stocking density on fish growth and survival can be attributed to impaired water quality associated with accumulation of fish metabolites and carbon dioxide, with accompanying decline in pH level (Hosfeld et al. 2009). As no technical problems or disease occurred during the course of our study, we can conclude that water quality and stocking density effects were accurately evaluated. The high survival rate at all density levels and lack of observable damage to fins are evidence of appropriate rearing conditions with respect to fish welfare.

Conclusions

No significant differences in any evaluated parameter were observed between groups of larvae at the highest and lowest stocking density. It is possible to rear maraena whitefish larvae at high stocking density with no subsequent negative consequences for growth and survival. This study examined fry and early-stage larvae, but a further study, focusing on juvenile and adult maraena whitefish, is warranted. The effects of stocking density on stress hormone response, body composition, and haematological and biochemical parameters of maraena whitefish should be studied.

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References

Ashley PJ (2007) Fish welfare: Current issues in aquaculture. Applied Animal Behaviour Science 104(3–4): 199–235. https://doi.org/10.1016/j.applanim.2006.09.001

Azevedo TMP, Martins ML, Bozzo FR, Moraes FR (2006) Haematological and gill responses in parasitized tilapia from the valley of Tijucas River. Scientia Agrícola 63(2): 115–120. https://doi.org/10.1590/S0103-90162006000200002

Beltran RR, Champigneulle A (1992) Studies on the improvement of the first feeding on a dry diet for *Coregonus lavaretus* L. larvae. Aquaculture 102(4): 319–331. https://doi.org/10.1016/0044-8486(92)90185-N

Biswas G, Thirunavukkarasu AR, Sundaray JK, Kailasam M (2010) Optimization of feeding frequency of Asian seabass (*Lates calcarifer*) fry reared in net cages under brackishwater environment. Aquaculture 305(1–4): 26–31. https://doi.org/10.1016/j.aquaculture.2010.04.002

Celada JD, Aguilera A, Carral JM, Saez-Royuela M, Melendre PM (2008) Rearing tench (*Tinca tinca* L.) larvae on live feed (*Artemia*) and on two transition schedules from live to dry diets. Journal of Applied Ichthyology 24(5): 595–600. https://doi.org/10.1111/j.1439-0426.2008.01078.x

Costas BC, Aragão JM, Mancera MT, Dinis Conceição LE (2008) High stocking density induces crowding stress and affects amino acid metabolism in Senegalese sole *Solea senegalensis* (Kaup 1858) juveniles. Aquaculture Research 39(1): 1–9. https://doi.org/10.1111/j.1365-2109.2007.01845.x

d'Orbcastel ER, Person-Le Ruyet J, Le Bayon N, Blancheton JP (2009) Comparative growth and welfare in rainbow trout reared in recirculating and flow through rearing systems. Aquacultural Engineering 40(2): 79–86. https://doi.org/10.1016/j.aquaeng.2008.11.005

Dabrowski K, Poczyczynski P (1988) Laboratory experiment and mass rearing of coregonid fish fed exclusively dry diets. Aquaculture 69(3–4): 307–316. https://doi.org/10.1016/0044-8486(88)90338-9

Duarte OS, Reig PL, Ambrosio JPP, Sánchez P, Oca BJ, Flos BR (2004) Effect of stocking density on the behaviour and welfare of Senegal sole (*Solea senegalensis*). European Aquaculture Society, Barcelona, 308 pp.

Ellis T, North B, Scott AP, Bromage NR, Porter M, Gadd D (2002) The relationships between stocking density and welfare in farmed rainbow trout. Journal of Fish Biology 61(3): 493–531. https://doi.org/10.1111/j.1095-8649.2002.tb00893.x

Ellis T, Berrill I, Lines J, Turnbull JF, Knowles TG (2012) Mortality and fish welfare. Fish Physiology and Biochemistry 38(1): 189–199. https://doi.org/10.1007/s10695-011-9547-3

Esmaeilzadeh-Leithner S, Wanzenböck J (2018) Suitability of two agglomerated commercial microdiets for rearing larvae of different strains of *Coregonus lavaretus* under cold-water conditions. Aquaculture Nutrition 24(1): 260–268. https://doi.org/10.1111/anu.12554

Fiogbé ED, Kestemont P (2003) Optimum daily ratio for Eurasian perch *Perca fluviatilis* L. reared at its optimum growing temperature. Aquaculture 216(1–4): 234–252. https://doi.org/10.1016/S0044-8486(02)00409-X

Fletcher Jr RC, Roy W, Davie A, Taylor J, Robertson D, Migaud H (2007) Evaluation of new microparticulate diets for early weaning of Atlantic cod (*Gadus morhua*): Implications on larval performance and tank hygiene. Aquaculture 263(1–4): 35–51. https://doi.org/10.1016/j.aquaculture.2006.09.019

Harris KC, Hulsman PF (1991) Intensive culture of lake whitefish (*Coregonus clupeaformis*) from larvae to yearling size using dry feeds. Aquaculture 96(3–4): 255–268. https://doi.org/10.1016/0044-8486(91)90156-2

Herrera M, Rodiles A, Sanchez B, Lopez JM, de La Roca E (2016) Physiological stress responses to captivity in early developmental stages of the wedge sole *Dicologoglossa cuneata* (Moreau). Aquaculture Research 40(3): 732–740. https://doi.org/10.1111/are.12531

Hosfeld CD, Hammer J, Handeland SO, Fivelstad S, Stefansson SO (2009) Effects of fish density on growth and smoltification in intensive production of Atlantic salmon (*Salmo salar* L.). Aquaculture 294(3–4): 236–241. https://doi.org/10.1016/j.aquaculture.2009.06.003

Huang WB, Chiu TS (1997) Effects of stocking density on survival, growth, size variation, and production of tilapia fry. Aquaculture Research 28(3): 165–173. https://doi.org/10.1111/j.1365-2109.1997.tb01029.x

Jobling M, Arnesen AM, Befey T, Carter C, Hardy R, LeFrancois N, Keefe R, Koskela J, Lamarre S (2010) The salmonids (Family: *Salmonidae*). In: LeFrancoid N, Jobling M, Carter Blier CP (Eds) Finfish Aquaculture Diversification. CAB International 234–288. https://doi.org/10.1079/9781845934941.0234

Jones HAC, Noble C, Damsgård B, Pearce GP (2011) Social network analysis of the behavioural interactions that influence the development of fin damage in Atlantic salmon parr (*Salmo salar*) held at different stocking densities. Applied Animal Behaviour Science 133(1–2): 117–126. https://doi.org/10.1016/j.applanim.2011.05.005

Kaiser H, Endemann F, Paulet TG (2003) A comparison of artificial and natural foods and their combinations in the rearing of goldfish, *Carassius auratus* (L.). Aquaculture Research 34(11): 943–950. https://doi.org/10.1046/j.1365-2109.2003.00948.x

Kupren K, Żarski D, Krejszeff S, Kucharczyk D, Targońska K (2011) Effect of stocking density on growth, survival and development of asp *Aspius aspius* (L.), ide *Leuciscus idus* (L.) and chub *Leuciscus cephalus* (L.) larvae during initial rearing under laboratory conditions. Italian Journal of Animal Science 10(3): 178–184. https://doi.org/10.4081/ijas.2011.e34

Laczynska B, Nowosad J, Bilas M, Krejszeff S, Müller T, Kucharczyk D, Żarski D (2016) Effect of age, size and digestive tract development on weaning effectiveness in crucian carp, *Carassius carassius* (Linnaeus, 1758). Journal of Applied Ichthyology 32(5): 866–872. https://doi.org/10.1111/jai.13100

Li D, Liu Z, Xie C (2012) Effect of stocking density on growth and serum concentrations of thyroid hormones and cortisol in Amur sturgeon, *Acipenser schrenckii.* Fish Physiology and Biochemistry 38(2): 511–520. https://doi.org/10.1007/s10695-011-9531-y

Liao IC, Chang EY (2002) Timing and factors affecting cannibalism in red drum, *Sciaenops ocellatus*, larvae in captivity. Environmental Biology of Fishes 63(2): 229–233. https://doi.org/10.1023/A:1014244102276

Luz RK, Santos JCE (2008) Densidade de estocagem e salinidade da agua na larvicultura do pacama. Pesquisa Agropecuária Brasileira 43(7): 903–909. https://doi.org/10.1590/S0100-204X2008000700015

Mahmood SU, Ali MS, Anwar-Ul-Haque M (2004) Effect of different feed on larval/fry rearing of climbing perch, *Anabas testudineus* (Bloch), in Bangladesh: II Growth and survival. Pakistan Journal of Zoology 36: 13–19.

Molnár T, Hancz C, Bódis M, Müller T, Bercsényi M, Horn P (2004) The effect of initial stocking density on growth and survival of pike-perch fingerlings reared under intensive conditions. Aquaculture International 12(2): 181–189. https://doi.org/10.1023/B:AQUI.0000032079.62056.8c

Mommsen TP, Vijayan MM, Moon TW (1999) Cortisol in teleosts: Dynamics, mechanisms of action, and metabolic regulation. Reviews in Fish Biology and Fisheries 9(3): 211–268. https://doi.org/10.1023/A:1008924418720

Montero D, Izquierdo MS, Tort L, Robaina L, Vergara JM (1999) High stocking density produces crowding stress altering some physiological and biochemical parameters in gilthead seabream, *Sparus aurata*, juveniles. Fish Physiology and Biochemistry 20(1): 53–60. https://doi.org/10.1023/A:1007719928905

Mukhachev IS, Gunin AP (1999) A review of the production of cultivated whitefishes (*Coregonus* spp.) in the Urals and west Siberia. Advances in Limnology 57: 171–181.

North BP, Turnbull JF, Ellis T, Porter MJ, Migaud H, Bron J, Bromage NR (2006) The impact of stocking density on the welfare of rainbow trout (*Oncorhynchus mykiss*). Aquaculture 255(1–4): 466–479. https://doi.org/10.1016/j.aquaculture.2006.01.004

Nowosad J, Żarski D, Biłas M, Dryl K, Krejszeff S, Kucharczyk D (2013) Dynamics of ammonia excretion in juvenile common tench *Tinca tinca* (L.), during intensive rearing under controlled conditions. Aquaculture International 21(3): 629–637. https://doi.org/10.1007/s10499-012-9596-3

Rowland SJ, Mifsud C, Nixon M, Boyd P (2006) Effects of stocking density on the performance of the Australian freshwater silver perch (*Bidyanus bidyanus*) in cages. Aquaculture 253(1–4): 301–308. https://doi.org/10.1016/j.aquaculture.2005.04.049

Ruzzante DE (1994) Domestication effects on aggressive and schooling behaviour in fish. Aquaculture 120(1–2): 1–24. https://doi.org/10.1016/0044-8486(94)90217-8

Sangiao-Alvarellos S, Guzmán JM, Láiz-Carrión R, Míguez JM, Martín Del Río MP, Mancera JM, Soengas JL (2005) Interactive effects of high stocking density and food deprivation on carbohydrate metabolism in several tissues of gilthead sea bream *Sparus auratus.* Journal of Experimental Zoology. Part A, Comparative Experimental Biology 303(9): 761–775. https://doi.org/10.1002/jez.a.203

Saoud IP, Ghanawi J, Lebbos N (2008) Effects of stocking density on the survival, growth, size variation and condition index of juvenile rabbitfish *Siganus rivulatus.* Aquaculture International 16(2): 109–116. https://doi.org/10.1007/s10499-007-9129-7

Sharma JG, Chakrabarti R (1998) Effects of different stocking densities on survival and growth of grass carp, *Ctenopharyngodon idella*, larvae using a recirculating culture system. Journal of Applied Aquaculture 8(3): 79–83. https://doi.org/10.1300/J028v08n03_08

Siikavuopio SI, Knudsen R, Amundsen PA, Sæther BS, James P (2011) Effects of high temperature on the growth of European whitefish (*Coregonus lavaretus* L.). Aquaculture Research 44(1): 8–12. https://doi.org/10.1111/j.1365-2109.2011.02999.x

Smith C, Reay P (1991) Cannibalism in teleost fish. Reviews in Fish Biology and Fisheries 1(1): 41–64. https://doi.org/10.1007/BF00042661

Suter W (1997) Roach rules: Shoaling fish are a constant factor in the diet of cormorants (*Phalacrocorax carbo*) in Switzerland. Ardea 85: 9–27.

Szkudlarek M, Zakes Z (2007) Effect of stocking density on survival and growth performance of pikeperch, *Sander lucioperca* (L.), larvae under controlled conditions. Aquaculture International 15(1): 67–81. https://doi.org/10.1007/s10499-006-9069-7

Thomas G, Eckmann R (2007) The influence of eutrophication and population biomass on common whitefish (*Coregonus lavaretus*) growth – the Lake Constance example revisited. Canadian Journal of Fisheries and Aquatic Sciences 64(3): 402–410. https://doi.org/10.1139/f07-019

Tolussi CE, Hilsdorf AWS, Caneppele D, Moreira RG (2010) The effect of stocking density in physiological parameters and growth of the endangered teleost species piabanba, *Brycon insignis* (Steindachner, 1877). Aquaculture 310(1–2): 221–228. https://doi.org/10.1016/j.aquaculture.2010.10.007

Turnbull JF, Adams CE, Richards RH, Robertson DA (1998) Attack site and resultant damage during aggressive encounters in Atlantic salmon (*Salmo salar* L.) parr. Aquaculture 159(3–4): 345–353. https://doi.org/10.1016/S0044-8486(97)00233-0

Wallace JC, Kolbeinshavn AG, Reinsnes TG (1988) The effects of stocking density on the early growth in Arctic charr, *Salvelinus alpinus* (L.). Aquaculture 73(1–4): 101–110. https://doi.org/10.1016/0044-8486(88)90045-2

Webb Jr KA, Hitzfelder GM, Faulk CK, Holt GJ (2007) Growth of juvenile cobia, *Rachycentron canadum*, at three different densities in a recirculating aquaculture system. Aquaculture 264(1–4): 223–227. https://doi.org/10.1016/j.aquaculture.2006.12.029

Wocher H, Harsányi A, Schwarz FJ (2011) Husbandry conditions in burbot (*Lota lota* L.): Impact of shelter availability and stocking density on growth and behaviour. Aquaculture 315(3–4): 340–347. https://doi.org/10.1016/j.aquaculture.2011.01.051

Żarski D, Kucharczyk D, Kwiatkowski M, Targońska K, Kupren K, Krejszeff S, Jamróz M, Hakuć Błazowska A, Kujawa R, Mamcarz A (2008) The effect of stocking density on the growth and survival of larval asp, *Aspius aspius* (L.), and European chub, *Leuciscus cephalus* (L.), during rearing under controlled conditions. Archives of Polish Fisheries 16(4): 371–382. https://doi.org/10.2478/s10086-008-0025-1

Zitzow RE, Millard JL (1988) Survival and growth of lake whitefish (*Coregonus clupeaformis*) larvae fed only formulated dry diets. Aquaculture 69(1–2): 105–113. https://doi.org/10.1016/0044-8486(88)90190-1