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Maturity and fecundity of *Champsocephalus gunnari*, *Chaenocephalus aceratus* and *Pseudochaenichthys georgianus* in South Georgia and Shag Rocks Islands

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Abstract

The reproductive biology of three species of icefishes (family Channicthyidae), *Champsocephalus gunnari*, *Pseudochaenichthys georgianus* and *Chaenocephalus aceratus* in South Georgia and Shag Rocks Islands was studied by means of a histological analysis. Parental care, a widespread behaviour among icefishes such as *C. aceratus*, is not observed in *C. gunnari*, which has a broadcast spawning strategy. There were large differences in total fecundity mainly due to the different sizes reached by each species (total fecundity range was 2,500–21,300 hydrated oocytes). Nevertheless, when comparing relative fecundity values, the average results were, in general, similar for *P. georgianus* and *C. aceratus* (6–9 hydrated oocytes per female gram). However, relative fecundity estimated for *C. gunnari* was 10–37 hydrated oocytes per ovary-free female gram. The difference may be a consequence of the smaller oocyte size of the species as compared to other icefishes. The small diameter of hydrated oocytes was also associated with low values of dry weight. The high relative fecundity recorded for *C. gunnnari* may compensate, in part, for a broadcast spawning strategy.

Keywords: Fish reproduction; Fecundity; Notothenioidei; Channichthyidae; South Georgia; Antarctica

1. Introduction

Demersal fish assemblages in the Southern Ocean are dominated by the Suborder Notothenioidae (Eastman, 2005). One of the six families included in notothenioids, Channichthyidae, are known as icefishes (Everson, 1984). Icefishes or "white-blooded" fishes is unique among the vertebrates in that its members lack erythrocytes and the respiratory pigment haemoglobin (Ruud, 1954). Of the 16 species comprised in channichthyids, *Champsocephalus gunnari*, *Pseudochaenichthys georgianus* and *Chaenocephalus aceratus*, are limited the distribution to the Atlantic Ocean sector (Kock, 2005) and are abundant around South Georgia (Reid et al., 2007).

Some icefish species are the target of commercial fisheries. That was the case of *C. gunnari* around South Georgia during 1970–1990 (Kock, 2005). Others, such

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as *P. georgianus* and *C. aceratus* were caught during several seasons and/or became by-catch in mackerel icefish fisheries (Kock, 1992; Kock et al., 2004).

It is known that most icefishes spawn in late Summer/early Autumn (January/February) – early Winter (May–June) (Kock and Kellermann, 1991; Duhamel et al., 1993; La Mesa et al., 2003). Maturing ovaries are typically filled with ova in two stages of maturation where large yolky oocytes form the current season spawning (Kock and Kellermann, 1991). This is characteristic of species that spawn eggs of one generation simultaneously, as is the case of *C. gunnari*, *C. aceratus* and *P. georgianus* (Permitin, 1973; Macchi and Barrera-Oro, 1995).

Antarctic fishes have developed a series of strategies to facilitate adaptation to the environment. As regards reproduction, some common characteristics are prolonged gametogenesis, delayed maturation, large yolky eggs and low fecundity (Andriashev, 1987; North and White, 1987 in Kock, 2005). In many species reproductive strategies are complemented by a complex reproductive behaviour such as nest guarding (North and White, 1987; Kock, 1989), as suspected by Permitin (1973) for *C. aceratus* that deposits eggs on the bottom (Detrich et al., 2005).

Description of reproductive strategies and fecundity assessment are the fundamental topics in the study of fish biology and population dynamics (Hunter et al., 1992 in Murua and Saborido-Rey, 2003). It was observed that, in many species the size or age of females usually alters the reproductive capacity at different levels which may affect the beginning, duration or frequency of spawning and the fertility and quality of the eggs produced (Marteinsdottir and Steinarsson, 1998; Marteinsdottir and Begg, 2002; Macchi et al., 2004).

The aim of this study was to synthesize information on the reproductive potential of *C. gunnari*, *C. aceratus* and *P. georgianus* and compare the values obtained considering each reproductive strategy. The analysis included the description of length distribution, the estimate of total and relative fecundity; and the relationships between oocytes size and the maternal characteristics were described.

2. Materials and methods

Samples of *C. gunnari*, *P. georgianus* and *C. aceratus* were collected during the research survey carried out on board of *RV Dr Eduardo L. Holmberg* in the coastal waters of South Georgia and Shag Rocks Islands shelves in May 2013 (Álvarez Colombo et al., 2013). Total length (TL) in centimetres and total weight (TW) in grams were recorded for each fish sampled (n = 533 for *C. gunnari*; n = 155 for *C. aceratus*; n = 70 for *P. georgianus*). Sex was determined and the reproductive developmental stage macroscopically determined using a five-stage maturity key (adapted from Kock and Kellermann, 1991): 1. Immature; 2. Maturing; 3. Gravid; 4. Spent; 5. Resting.

Size at first maturity (L50) was estimated obtaining the percentage of mature or adult specimens (stages 2–5) per 1 cm length class; values were afterwards fitted to a logistic regression with the maximum likelihood method (Kendall and Stuart, 1967). Coefficients of the logistic regressions obtained to estimate L50 for males and females were compared using a Chi-square test (Aubone and Wöhler, 2000). The analysis was performed only for *C. gunnari* due to the low number of individuals obtained for the other species.

For histological examinations, 105 pairs of ovaries of gravid females (with yolked oocytes in hydration or hydrated) of the three species were removed and fixed in 10% neutral buffered formalin (89 for *C. gunnari*, 9 for *C. aceratus* and 7 for *P. georgianus*). The fixed gonads were weighed (GW) to the nearest 0.1 g and the portions of tissue removed from the centre of each ovary dehydrated in ethanol, cleared in xylol and embedded in paraffin. Tissues were sectioned at approximately 4 μm thick and stained with Harris haematoxylin followed by eosin counterstain (García del Moral, 1993).

Total fecundity (TF: number of oocytes released per spawning) was gravimetrically estimated (Hunter et al., 1985). Oocyte resorption processes (atresias) for *C. gunnari* in pre-reproductive phases were observed (Macchi and Barrera-Oro, 1995). Therefore, to determine the presence of atresias, postovulatory follicles (POF: indicators that spawning has already started) and hydrated oocytes, samples of the three species were histologically examined. To avoid bias when estimating fecundity, only ovaries with hydrated oocytes without POF or atresias were used (84 *C. gunnari*, 9 *C. aceratus* and 7 *P. georgianus*). Three pieces of ovary of approximately 2 g each from the anterior, middle and posterior section of each gonad were sampled, weighed (0.1 mg) and the number of hydrated oocytes counted. Total fecundity was the product of the mean number of hydrated oocytes per ovarian unit weight and total ovarian weight (GW). Relative fecundity (RF: number of hydrated oocytes per gram of ovary-free body weight) was estimated as the total fecundity divided by the female weight. The relationship between TF and TL, TF and TW (ovary-

Table 1
Number and gonad stage of specimens sampled during research survey carried out in South Georgia and Shag Rocks area during May 2013.

	Males						Females						N
	1	2	3	4	5	Total	1	2	3	4	5	Total	
C. gunnari	91	131	2	–	15	239	92	91	111	–	–	294	533
C. aceratus	54	23	–	–	2	79	33	34	9	–	–	76	155
P. georgianus	28	12	–	1	–	41	13	8	8	–	–	29	70

(1) immature; (2) developing; (3) spawning capable; (4) regressing; and (5) regenerating (Kock and Kellermann, 1991).

free) was described using a simple linear regression (Draper and Smith, 1981).

Hydrated oocytes diameter (OD) and dry weight (DW) were measured. To that end, ovarian samples of *C. gunnari* (n = 86), *P. georgianus* (n = 7) and *C. aceratus* (n = 9) were collected and samples of 50 hydrated oocytes removed. The longest axis of each oocyte was measured with a Carl Zeiss binocular stereoscope equipped with an image analyzer and the Axion-Vision software. Then, each sample was rinsed in distilled water, dried for 24 h at 60 °C and weighed (0.1 mg). The oocyte dry weight (DW) was considered an index of egg quality, taking into account that dry mass is associated with the quantity of yolk reserves stored in oocytes, considered as one of many factors that could influence quality (Macchi et al., 2006; Mehault et al., 2010).

3. Results and discussion

Macroscopic staging data showed that, out of the total of *C. gunnari* individuals sampled 34.3% corresponded to juveniles and that, within the group of adults 95.7% showed reproductive activity (stages 2 and 3) (Table 1). Values for *C. aceratus* were 56.1% juveniles and 97.1% adults in reproductive activity. During the cruise only 70 specimens of *P. georgianus* were caught, of which 58.6% juveniles and 96.6% active adults. Reproductive staging confirm that the three species were within the reproductive season. Fig. 1 shows the location of *C. gunnari*, *C. aceratus* and *P. georgianus* totally mature females (with hydrated oocytes). Catches of ripe females confirmed that the three species spawn in Autumn or early Winter in the South Georgia region or nearby.

Although location of most icefish species spawning areas is unknown, *C. gunnari* and *C. aceratus* were reported to move inshore or close to the shore in South Georgia and Kerguelen (Kock, 1981; Duhamel, 1987; Everson et al., 2001). In South Georgia, *C. gunnari* pre-spawning aggregations were found at Fortuna Bay, Cumberland West Bay, Royal Bay fjords and near the

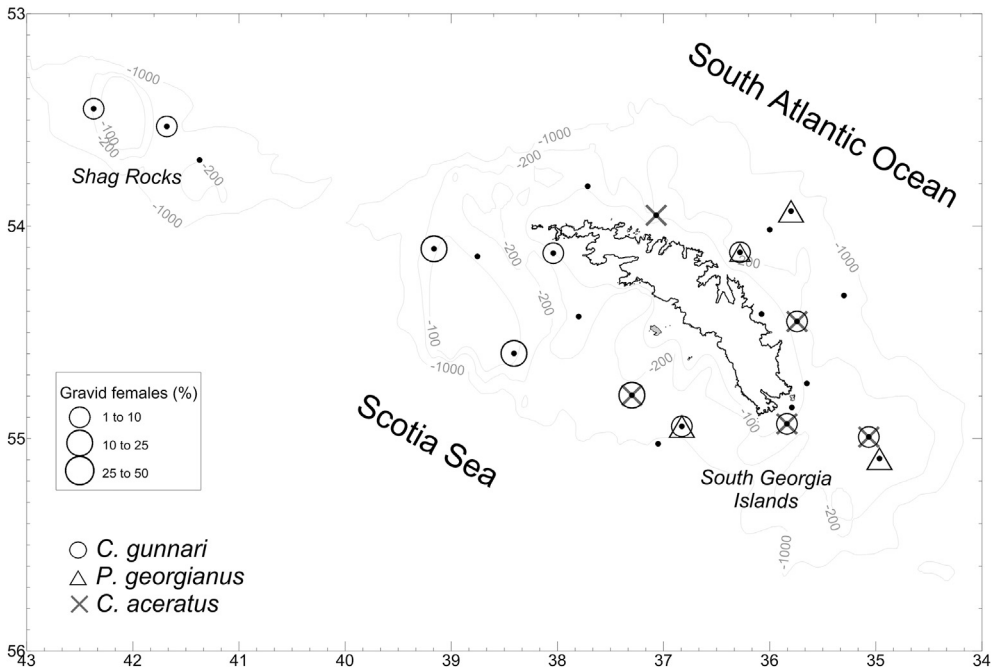

Fig. 1. Spatial distribution of trawl stations (dots) and percentage of *C. gunnari*, *P. georgianus* and *C. aceratus* in spawning capable stage during May 2013. The size of the symbols is proportional to the percentage of gravid females (with hydrated oocytes).

shore in deeper waters (>100 m depth). Reports indicate that most spawning occurs northeast, close to the shelf shore waters (Kock, 1981; Everson et al., 2001) and, to a lesser extent, in Shag Rocks and on the shelf, southwest of South Georgia (Frolkina and Trunov, 2004). The presence of totally mature or hydrated females confirms that *C. gunnari* spawn in South Georgia and Shag Rocks Islands and suggests that P. *georgianus* and *C. aceratus* also spawn in the area or surrounding zone.

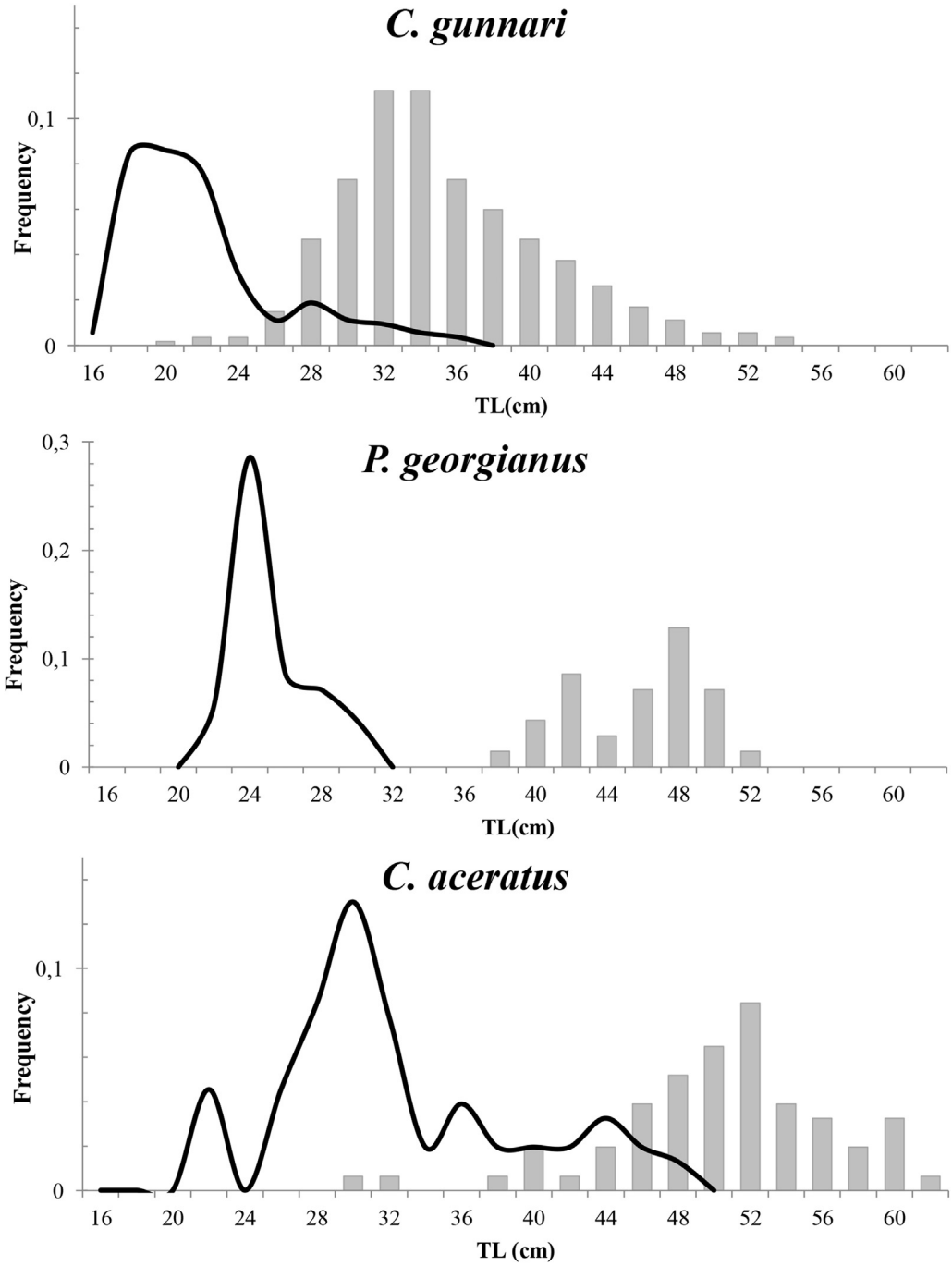

Fig. 2. Length frequency distribution obtained for juveniles (line) and adults (grey bars) of icefish species in South Georgia and Shag Rocks Islands area during Autumn 2013.

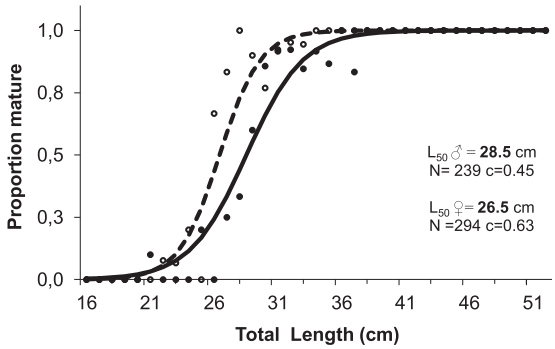

Fig. 3. Sexual maturity curves for males and females of *Champsocephalus gunnari* from South Georgia and Shag Rocks Islands area.

Icefish are among the largest of Antarctic fish. With the exception of the genera *Pagetopsis*, *Dacodraco* and *Champsocephalus esox* which grow smaller than 30–40 cm, all other species exceed 55 cm in maximum size. The largest icefish species found was *C. aceratus* with 75 cm (Kock, 2005). Size distribution of *C. gunnari* adult individuals varied from 20 to 54 cm TL with a 33 cm TL modal value; for *C. aceratus* it was 30–63 cm TL with a 52 cm TL mode

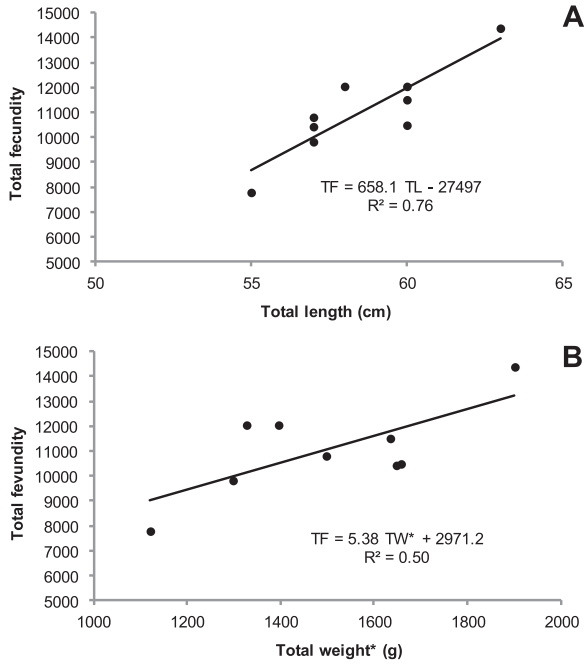

Fig. 5. *Chaenocephalus aceratus* total fecundity (TF) as a function of A) total length (TL) and B) total weight (TW*) obtained during May 2013.

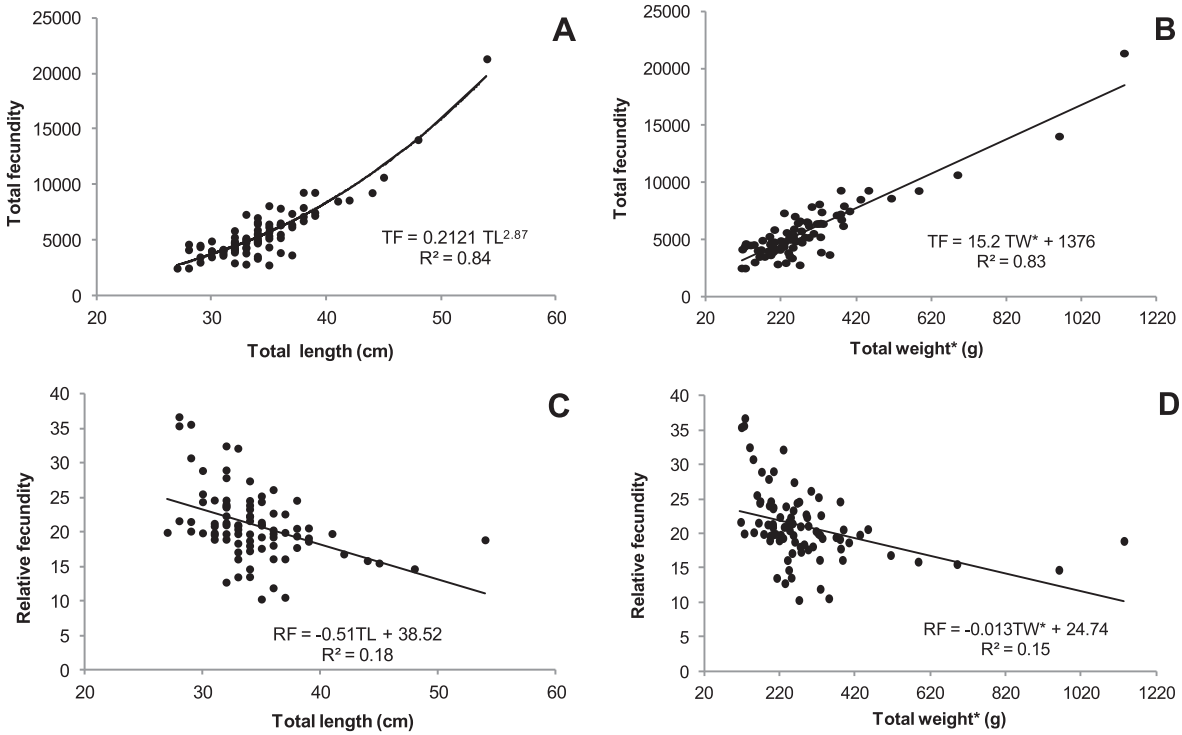

Fig. 4. *Champsocephalus gunnari* total fecundity (TF) as a function of A) total length (TL) and B) total weight (TW*) (without ovary) and relative fecundity (RF) as a function of C) total length (TL) and D) total weight (TW*) obtained during May 2013.

and *P. georgianus* showed 2 groups between 38 and 52 cm TL with 42 and 48 cm TL modal values, respectively (Fig. 2).

Size at first maturity was only estimated for *C. gunnari*, the only species with an adequate sample size. It was observed that males mature at a larger sized than females ($\chi 2 = 6.44$, df = 1, $P < 0.05$) (Fig. 3). Bringing 150 individuals of both sexes together, length at first maturity averaged 27.4 cm TL. This value is similar to that obtained by Everson et al. (1996) for South Georgia and Shag Rocks Islands.

C. gunnari total fecundity (TF) had a power relationship to total length and a linear relationship to total weight of individuals ($P < 0.001$; Fig. 4A and B) with an average of 5656 hydrated oocytes (CI $_{95\%} = 560$). Relative fecundity (RF) was estimated at 10 - 37 hydrated oocytes/g of female (ovary-free) with an average of 21 hydrated oocytes (CI $_{95\%} = 1$). Despite the fact that RF evidenced a large dispersion in relation to female length and weight, negative trends were found in both cases ($P < 0.001$; Fig. 4C and D).

C. aceratus TF showed a linear relationship to total length and weight ($P < 0.05$; Fig. 5) with an average of 11,040 hydrated oocytes (CI $_{95\%} = 1{,}180$). RF was 6–9 hydrated oocytes/g of female (ovary-free) with an average of 7 hydrated oocytes (CI $_{95\%} = 0.6$). No significant relationship was obtained between RF and female size ($P > 0.1$).

P. georgianus TF showed a linear relationship to weight ($P < 0.1$; Fig. 6A) but no significant relationship was obtained between this variable and total length and had an average of 7,325 hydrated oocytes (CI $_{95\%} = 448$). RF was 6–8 hydrated oocytes/g of female (ovary-free) with an average of 7 hydrated oocytes (CI $_{95\%} = 0.47$). As observed for *C. gunnari*, RF showed negative trends in relation to female length and weight (Fig. 6B and C), however were not significant ($P = 0.06$ and $P = 0.07$ respectively).

TF and RF values obtained for the three species agreed with those reported by other authors (Kock and Kellermann, 1991; Alekseeva and Alekseev, 1997; Kock, 2005). It was observed that *C. gunnari* and *P. georgianus* RF decreased as length and weight of females increased, characteristic already mentioned for *C. gunnari* (Alekseeva and Alekseev, 1997) but has not been reported for *P. georgianus*.

The hydrated oocyte diameter reported for icefish species was around 4.2–5.0 mm, except for the *Champsocephalus* genus (Kock, 2005). Previous reports indicate that egg diameter varies from 2.7 mm in *C. esox* (Calvo et al., 1999) to 3.2–3.7 in *C. gunnari* (Kock, 1981; Duhamel, 1991). In this study *C. gunnari*

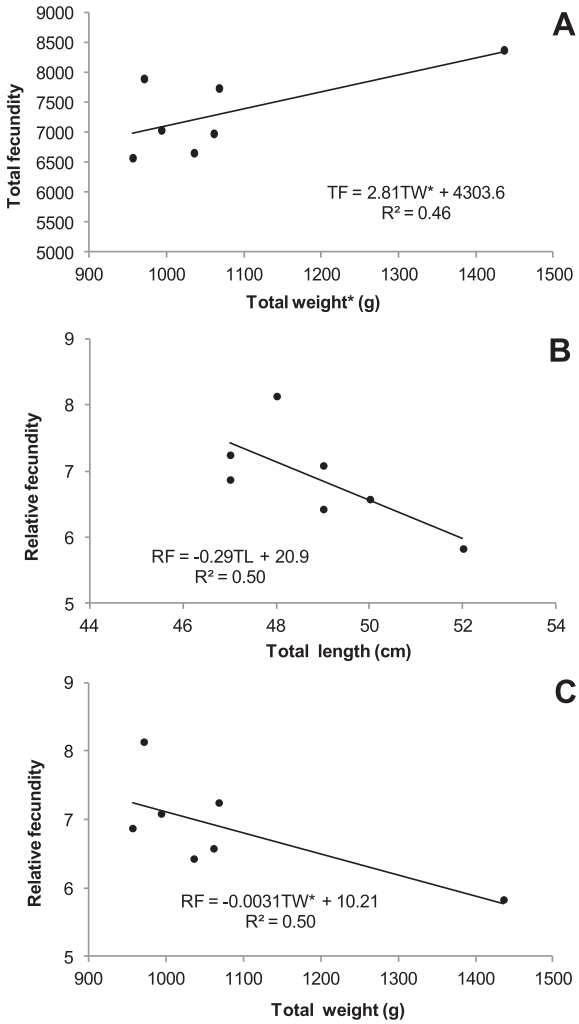

Fig. 6. Pseudochaenichthys georgianus total fecundity (TF) as a function of A) total weight (TW*) and relative fecundity (RF) as a function of B) total length (TL) and C) total weight (TW*) obtained during May 2013.

hydrated oocyte diameter was between 1.22 and 2.5 mm with an average of 1.65 mm (CI $_{95\%} = 0.05$) and had a significant positive relationship to female size and weight ($P < 0.0001$; Fig. 7A and B). Those lower values may be attributed to the fact that eggs of the ovaries selected were not fully hydrated. Oocyte dry weight also showed a positive relationship to female size ($P < 0.0001$; Fig. 7C and D) with an average value for a sample of 50 hydrated oocytes that amounted to 21 mg (CI $_{95\%} = 1.1$).

Kock (1981) suggested that old females of *C. gunnari* spawn earlier than young (smaller) ones and/or tend to produce larger eggs. The increase of oocyte mass and diameter with female size would contribute to the hypothesis of a maternal effect on the spawning

quality of the species; however, this remains to be tested. Different authors suggest that the improved quality of large eggs results in larger larvae and greater viability (Hinckley, 1990; Wootton, 1994; Trippel, 1998). On the other hand, it is possible that the increase in oocyte diameter with female size would partially compensate the decrease in relative fecundity observed for large individuals.

The results obtained in this study show that *C. aceratus* and *P. georgianus* hydrated oocyte diameter values were similar to those previously reported by Kock (2005). For *C. aceratus* it was 3.36–4.04 mm with an average value of 3.66 mm (CI $_{95\%=}$ 0.16). Oocyte dry weight for a sample of 50 eggs was 288–437 mg with an average of 352 mg (CI $_{95\%}$ = 33). These variables did not show any trend in relation to female size. For *P. georgianus* hydrated oocyte diameter was 2.62–3.53 mm with an average of 3 mm (CI $_{95\%}$ = 0.25); oocyte dry weight was 216–351 mg with a mean of 385 mg (CI $_{95\%}$ = 47). As observed for *C. aceratus*, said variables did not show any relation to female size. It is possible that the lack of relation between egg quality and female size for both species is the consequence to the small number of mature ovaries available to perform the analysis.

Considering the three species together, it may be concluded that they share reproduction features such as being total spawners with determinate fecundity and having a short reproductive season with differences in the reproductive tactics. As already mentioned, some icefish species such as *C. aceratus* are known to exhibit parental care, a quite widespread behaviour among icefishes (Detrich et al., 2005). Previous nesting reports of other notothenioid families suggest that it may be a relatively common phenomenon in the suborder species (Arkhipkin et al., 2013). However, the presence of *C. gunnari* eggs floating in the water column around Kerguelen Islands (Koubbi et al., 1991) indicates a broadcast spawning strategy.

With regard to the reproductive potential, there are large differences in fecundity values mainly due to the different maximum sizes reached by each species (TF range was 2,500–21,300 hydrated oocytes). Nevertheless, when comparing relative fecundity values, the average results were similar for *P. georgianus* and *C. aceratus* (6–9 hydrated oocytes per female gram) while for *C. gunnari* mean RF ranged 10 – 37 hydrated oocytes per ovary-free female gram, owing to smaller oocytes. The small diameter of hydrated oocytes was also associated to low values of dry weight. The high RF recorded for *C. gunnnari* would be associated, in part, with a broadcast spawning strategy. Species with parental care tend to produce a lower number of larger eggs, suggesting that parental care is

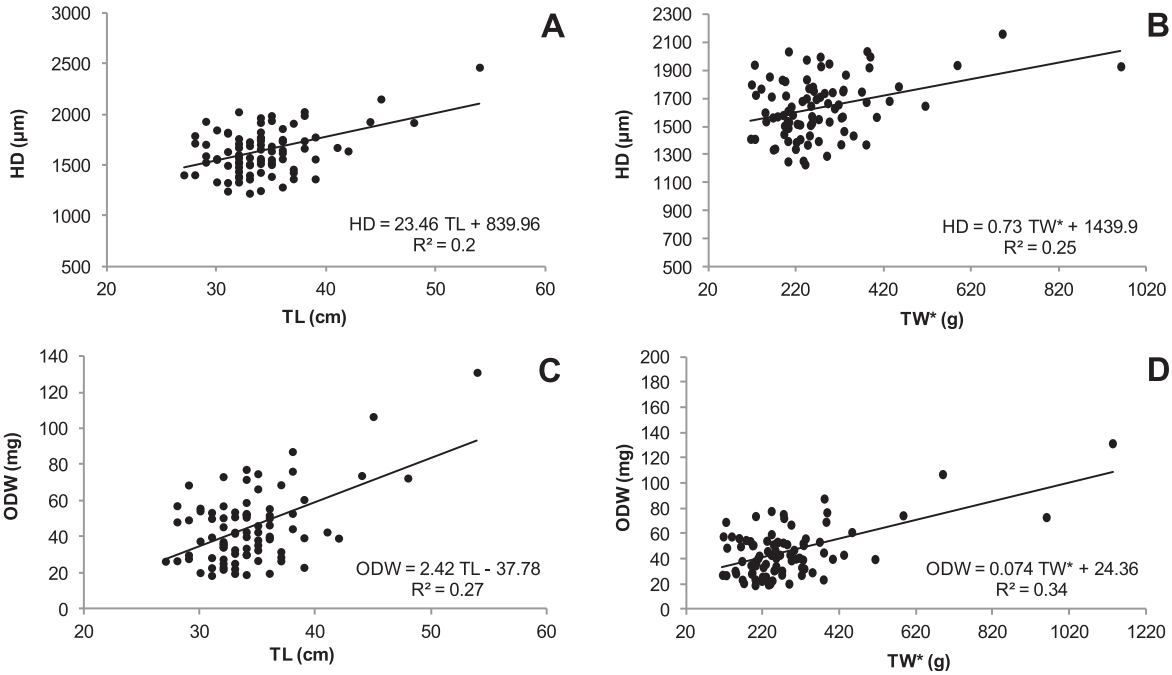

Fig. 7. *Champsocephalus gunnari* hydrated oocyte diameter (HD) as a function of: A) total length (TL) and B) total weight (TW*) and hydrated oocyte dry weight (ODW) as a function of: C) TL and B) TW* of females sampled during May 2013.

only effective for larger eggs and there is a trade-off between egg size and egg number (Helfman et al., 1997).

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